Recent Thinking about the Nature of the Physical World: It from Bit[a]

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Serge Korff is to be admired for his adventures within Russia and for leaving it; for his leadership in the affairs of the New York Academy of Science; and for his pioneering work in the realm of cosmic rays. All mark him as an exceptional scientist. Would that he and I could walk and talk once again, this time about advances on yet another frontier—the nature of the physical world.

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Among all the mysteries that still confront us in our probing of nature, none present more challenge than these,

1. How come existence?
2. How come the quantum?
3. How come "one world" out of the registrations of many observer-participants?

How can we move ahead on these foundational issues? Hardly better than under the guidance of a working hypothesis. There is one that has survived much winnowing. It animates and steers this report. This account therefore not only begins with questions. It ends with questions.

The central point? The thesis *it from bit*: every *it*, every particle, every field of force, even the spacetime continuum itself, derives its way of action and its very existence entirely, even if in some contexts indirectly, from the detector-elicited answers to yes or no questions, binary choices, *bits*. Otherwise stated, all things physical, all *its* (FIGS. 1 and 2), must in the end submit to an information-theoretic description.

Can rocks, life, and all we call existence be based on something so immaterial as yes-no bits of information? Such an account, if ever we

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[a] Adapted from a paper presented at the First Andrei Sakharov International Physics Conference, Moscow, May 1991.

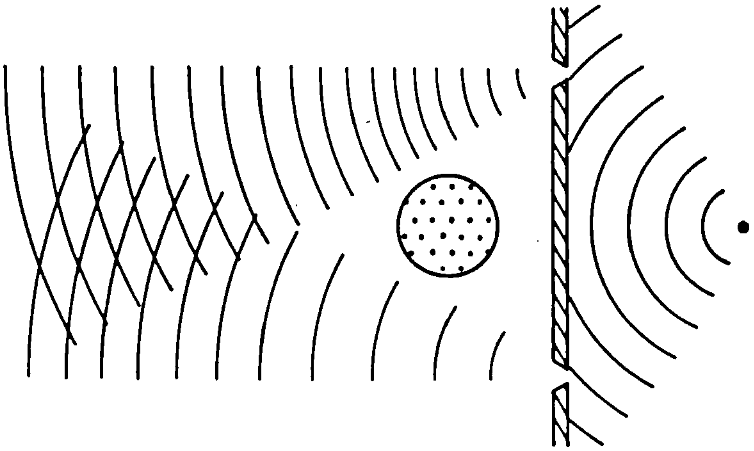

FIGURE 1. In the double-slit electron-interference experiment of the type invented by Aharonov and Bohm,[8] the interference fringes—fringes registered by a full coverage of electron counters arrayed at the right, just off-page—experience a shift of relative phase, (*electron charge*)×(*magnetic flux through the domain bounded by the two electron paths*) / ($\hbar c$), that reveals and measures the flux. We reverse this language when we turn to the it-from-bit interpretation of nature. The magnetic field, we say, and by extension every field and space geometry itself, has no function, no significance, no existence except insofar as it affects, directly or indirectly, the count of yes-or-no elementary quantum registrations.

gain the insight to spell it out, cannot but leave us all as real as ever. The photon already admits to description along this line. Does the photon exist in the atom before the act of emission? No. In the detector after the act of registration? No. Exist on its way from atom to detector? Pure talk. Yet despite that talk the photon is as real as anything we know, whether river, flame, DNA, or particle. No escape does the quantum principle permit, Bohr tells us, from "a radical revision of our attitude as regards physical reality" and a "fundamental modification of all ideas regarding the absolute character of physical phenomena." That's the miracle of the quantum principle. How come? And at the center of that miracle stands complementarity (Box 1) with its ever amazing feature, "No question? No answer!" (Box 2). That miracle: what secret of nature does it conceal? To discover that secret, only nine years remain to us before Planck's century will have run out!

Along the way of progress on these deep issues, one obstacle has stood out dismayingly. Physics for long has proved unable to carry through to the end the analysis of any already existing field theory without recourse to renormalization, cutoff, or approximation. The last

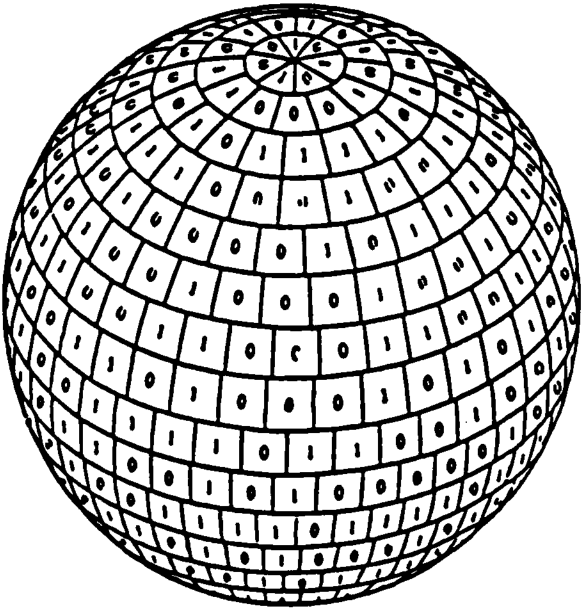

FIGURE 2. A second example of *it from bit*. The *it*, the area of the horizon of a black hole, expressed in units of the basic Bekenstein-Hawking area[12,13]

$$4\,(\hbar\, G/c^3)\log_e 2$$

is given by the *bit* count, N, of that black hole. Here N represents the number of bits of information it would have taken to distinguish the initial configuration of particles and fields that fell in to make this particular black hole from the 2^N alternative quantum configurations that would have produced a black hole externally identical to it.[14] This diagram is reproduced from Wheeler,[11] p. 220.

few years, however, have seen a wonderful new development. Ashtekar,[2] Jacobson and Smolin,[3] Rovelli,[4] and others, in advance after remarkable advance over the past decade,[5] have won their way to a representation of the quantum dynamics of geometry in terms of loops—loops that reduce themselves to knots, and these knots are distinguishable[6,7] one from another by pure binary-digit numbers.

Spacetime geometry, among all the entities of physics, rates as the one most challenging to try to subject to an information-theoretic analysis. Like every branch of 20th century physics, it submits to the quantum principle. However, it offers for quantization the only truly fundamental dynamic system of which the foundation principles are thoroughly explored and understood. It is only against the background of spacetime that we know how even to begin to treat particle physics. Spacetime dynamics by itself, on the other hand, needs no particles or other fields to constitute a rich field of analysis. Thus pared—for convenience of presentation—geometrodynamics gives us gravity waves, black holes made by implosion of gravity waves, gravitational geons, all in the context of one or another cosmology curved up into closure by its content of effective gravity-wave energy.

Spacetime geometry, moreover, does not rate as any esoteric branch of physics. The grip of spacetime on mass—we know from Einstein's battle-tested and still standard theory of 1915 (1) displays in action a star actor on the scene of dynamics, (2) enforces the law of conservation of total "momenergy"[11] in the crash of mass against mass, and (3) provides the standards against which the very measurement of force first becomes possible.

Box 1. PERSPECTIVES ON COMPLEMENTARITY:
WHAT IT IS, WHAT IT MEANS

- Complementarity in brief: No question? No answer! (Box 2)
- Bohr's early statement of the principle of complementarity: "...any given application of classical concepts precludes the simultaneous use of other classical concepts which in a different connection are equally necessary for the elucidation of the phenomena."
- Einstein: "You believe in a dice-playing God and I in perfect laws in the world of things existing as real objects...."
- Harald Høffding's question regarding the familiar double-slit interference experiment: Where can the light quantum be said to be in its passage from point of entry to point of reception? Bohr's response: "To be? To be? What does it **mean**, 'to be'?"
- Observation creates the phenomenon observed? No. Observation disturbs the phenomenon? No.
- No elementary quantum phenomenon **is** a phenomenon until it has been "**brought to a close**" by "an **irreversible act of amplification**." [9]
- "...[I]t was long natural to regard the observer as in effect looking at and protected from contact with existence by a 10cm slab of plate glass. In contrast, quantum mechanics teaches the very opposite. It is impossible to observe even so miniscule an object as an electron without in effect smashing that slab and reaching in with the appropriate measuring equipment. Moreover, the installation of apparatus to measure the position coordinate, *x*, of the electron automatically prevents the insertion in the same region at the same time of the equipment that would be required to measure its momentum, *p*; and conversely."
- [T]he account [of the finding] must be given in plain language...."
- "Meaning is the joint product of all the evidence that is available to those who communicate." [10]
- "Physics does not deal with physics. Physics deals with **what we can say** about physics."

Box 2. NO QUESTION? NO ANSWER! — THE GAME OF TWENTY QUESTIONS IN ITS SURPRISE VERSION

"Is it a member of the animal kingdom?" "No." "Mineral kingdom?" "Yes." Strangely, each new respondent requires a yet longer time of reflection before he summons up his yes or no reply. Soon I approach my twenty-question limit and must venture all upon a single word. "Is it 'cloud'?" I ask. Long agonized thought by the respondent; then a reluctant, "Y...es." Everyone bursts out laughing. While I was out of the room, they explain, they had agreed *not* to agree on a word. There was no word in the room when I entered. Everyone could respond "yes" or "no" as he pleased — with only one small proviso. The respondent, whatever his answer, had to have a word in mind compatible with his own reply and with all the others. Otherwise, challenged and unable to reply, he lost and I won. The Game of Twenty Questions in its Surprise Version was as difficult for my friends as for me. No wonder it took time for them to answer!

The game in its two versions illuminates physics in its two formulations, classical and quantum. First, the word already existed in the room -- we thought -- independent of any question that we might or might not ask. But it didn't. Likewise the electron has a position and a momentum inside the atom -- physics once thought -- independent of any act of observation. But it doesn't. Second, no information about the word came into being except by question asked, as no information develops about the electron except by experiment made. Third, if I had posed different queries I would have ended up with a different word. Likewise, the installation of equipment to measure the position of the electron automatically makes it impossible to install in the same place at the same time equipment to measure the momentum of the electron, and conversely. Fourth, partial power only did I have to influence the outcome by my choice of questions. A major part of the decision lay in the hands of my friends. Similarly, the experimenter decides what feature of the electron he or she will measure; but "nature" decides what the magnitude of the measured quantity will be. The conclusion? Does the world exist "out there?" No.

As animators of this report there stand three questions, unanswered at its start and unanswered at its end: (1) What new insights does this wonderful new loop-and-knot representation provide? (2) In what ways can physics as a whole capitalize on it? (3) What gaps must be closed if ever a full information-theoretic account of existence is to be achieved?

Our account will begin with the dynamics of space geometry. Next, we shall recall the features which the quantum imposes on geometry at the Planck scale of distances, $L^* = (\hbar G/c^3)^{1/2} = 1.6 \times 10^{-33}$ cm: fluctuations, a foam-like structure, and a breakdown in the very concepts of *before* and *after*. Then we turn to the loop representation, and reduction of loops to knots. Previous analysis of this quantum geometrodynamics gave central place to the probability amplitude, $\Psi\ ({}^{(3)}G)$, in its dependence on 3-geometry, but the new representation deals with $\Psi(L)$ in its dependence on loop, *L*. This quantity is sometimes, and perhaps always—preliminary indications suggest—expressible as a superposition of pure states of the form $\Psi(K)$, much as Maxwell's field-everywhere lets itself be described as a superposition of many a Faraday not-everywhere line of force.

We shall not enter into the detailed mathematics of this loop-theoretic representation. Instead, we sketch its main findings. Then we outline the challenges to be faced in translating it, by correspondence-principle reasoning, into familiar geometric language—working to connect the new with the known. And beyond that, connect the new with the unknown? That's the issue most challenging of all. What are the problems and prospects for using the findings of the loop representation to illuminate the theme of it-from-bit, the "how come" of the quantum and the mystery of existence?

THE UNDERSTANDING OF QUANTUM GEOMETRODYNAMICS BEFORE ASHTEKAR

Geometrodynamics, the battle-tested and still standard account of gravity that Einstein proposed in 1915, gives us its central idea today as a single simple sentence: "Spacetime tells mass how to move; and mass tells spacetime how to curve."[11] The grip of spacetime on mass far from being weak, (1) enforces the law of conservation of total "momenergy"[11] in the crash of mass against mass, and (2) provides the standards against which the very measurement of force first becomes possible.

How "quantize general relativity?" Bad question—so bad that it has resisted many years of effort to answer it. Eventually the community had to recognize that already in the classical theory the dynamic object is not 4-D spacetime. Spacetime does not wiggle. It is 3-D space geometry that undergoes the agitation. The history of *its* wiggling registers itself in frozen form as 4-D spacetime. What then is Einstein's classical theory of gravity all about? It is about the *dynamics of 3-geometry*, or geometrodynamics—the Einsteinian analog of Maxwellian electrodynamics.

Against this new way of thinking no obstacle so strongly interposed itself as the absence of any currently available quantitative global command of the totality of all 3-geometries. The metric coefficients, g_{mn}, in the familiar expression for proper distance, *ds*,

$$(ds)^2 = g_{mn}(x^1,x^2,x^3)\, dx^m dx^n \tag{1}$$

are local. The curvature components $R_{klmn}\,(x^1,x^2x^3)$ calculated from them are equally local, equally unable—taken locally—to provide more than a worm's-eye view of one 3-geometry, ${}^{(3)}G$, equally short of mastering the manifold of all ${}^{(3)}G$. The image suggests itself of the dealer in used automobile parts on the outskirts of a great city. He has set aside 10,000 square meters for car fenders alone, fenders from all models from all makers from all years: a great collection of 2-geometries, ${}^{(2)}G$. Small differences from one ${}^{(2)}G$ to another fall in the province of local methods to quantify. Global mathematization, however, of the totality of all conceivable 2-geometries, and *a fortiori* all conceivable 3-geometries, demands methods of quite another power.

These global methods: does the problem at hand demand them? Yes and no. Yes for quantum, no for classical gravity. In classical geometrodynamics, scenarios of lively astrophysical interest have already received computer analysis by one or another technique of discretization that provides a practical approximation to traditional differential geometry. Why don't closely related methods apply in the quantum domain? Because each small forward step in the quantum-dynamic evolution of 3-geometry brings into play the totality of all conceivable configurations of the 3-geometry—not the small changes characteristic of classical geometrodynamics. How come?

The dynamics of 3-geometry, ${}^{(3)}G$, both classical and quantum, unrolls in superspace, S (FIG. 3). Superspace is that infinite-dimensional manifold, each point of which represents one ${}^{(3)}G$. Two nearby points in superspace represent two 3-geometries that differ only little in shape.

Let the representative point move from one location in superspace to another. Then the 3-geometry alters as if alive—a cinema of the dynamics of space. Misner, Thorne, and Wheeler,[15] have this to say:

> The term 3-geometry makes sense as well in quantum geometrodynamics as in classical theory. So does superspace. But spacetime does not. Give a 3-geometry, and give its time rate of change. That is enough, under [generic circumstances], to fix the whole time-evolution of the geometry; enough, in other words, to determine the entire four-dimensional spacetime geometry, provided one is considering the problem in the context of classical physics. In the real world of quantum physics, however, one cannot give both a dynamic variable and its time rate of change. The principle of complementarity forbids. Given the precise 3-geometry at one instant, one cannot also know at that instant the time-rate of change of the 3-geometry. In other words, given the geometrodynamic field coordinate, one cannot know the geometrodynamic field momentum. If one assigns the intrinsic 3-geometry, one cannot also specify the extrinsic curvature [of that 3-geometry in any purported 4-geometry].
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> The uncertainty principle thus deprives one of any way whatsoever to predict, or even to give meaning to "the deterministic classical his-

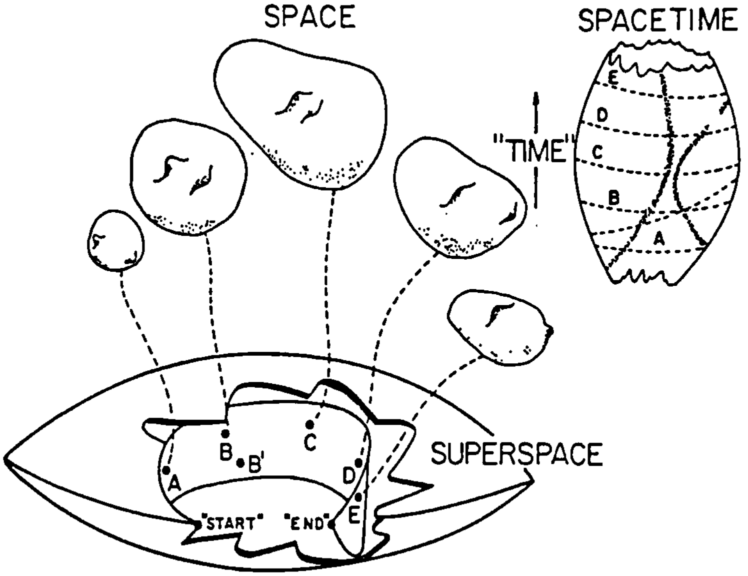

FIGURE 3 Space, spacetime and superspace. Upper left: Five sample configurations, A,B,C,D,E, attained by space in the course of its expansion and recontraction. Below: Superspace and these five sample configurations, each represented by a point in superspace. Upper right: Spacetime. Diagram from Ref. 15, p. 1183.

tory of space evolving in time." *No prediction of spacetime, therefore no meaning for spacetime,* is the verdict of the quantum principle. That object which is central to all of classical general relativity, the **four-dimensional spacetime** geometry, simply **does not exist**, except in a classical approximation.

These considerations reveal that the concepts of spacetime and time are not primary but secondary ideas in the structure of physical theory. These concepts are valid in the classical approximation. However, they have neither meaning nor application under circumstances where quantum geometrodynamic effects become important. Then one has to forego that view of nature in which every event, past, present, or future, occupies its preordained position in a grand catalog called "spacetime," with the Einstein interval from each event to its neighbor eternally established. There is no spacetime, there is no time, **there is no before, there is no after.** The question of what happens "next" is without meaning.

That spacetime is not the right way does not mean that there is *no* right way to describe the dynamics of geometry consistent with the quantum principle. Superspace is the key to *one* right way to describe the dynamics.

DYNAMICS OF GEOMETRY DESCRIBED IN THE LANGUAGE OF SUPERSPACE

"Time," time is spelled with a "*t*"? Search about as we may in superspace, nowhere can we catch any sight of it. Of 3-geometries, yes; of time, no. Out of these 3-geometries, however, can we reconstruct time? In classical theory, yes; in quantum theory, no.

Classical theory, plus initial conditions, confronted with that overpowering totality of ${}^{(3)}G$'s which constitute superspace, picks out that single bent-leaf of superspace which constitutes the relevant classical history of 3-geometry evolving with time. Otherwise put,

> (1) Classical geometrodynamics in principle constitutes a device, an algorithm, a rule for calculating and constructing a leaf of history that slices through superspace. (2) The ${}^{(3)}G$'s that lie on this leaf of history are YES 3-geometries [YES with respect to the prescribed initial conditions!]; the vastly more numerous ${}^{(3)}G$'s that do not are NO 3-geometries. (3) The YES ${}^{(3)}G$'s are the building blocks of the ${}^{(4)}G$ that is [the relevant] classical spacetime [for this problem, with its specified initial conditions]. (4) The interweavings and interconnections of these building blocks give the [relevant spacetime; that is, the appropriate] ${}^{(4)}G$ its existence, its dimensionality and its structure. (5) In this structure every ${}^{(3)}G$ has a rigidly fixed location of its own. (6) In this sense one can say that the "many-fingered time" [carried by] each 3-geometry is specified by the very interlocking structure itself.
>
> How different from the textbook concept of spacetime! There the geometry of spacetime is conceived as constructed out of elementary objects, or points, known as "events." Here, by contrast, the primary concept is 3-geometry, *in abstracto*, and out of it is derived the idea of event. Thus, (1) the event lies at the intersection of such and such ${}^{(3)}G$'s; and (2) it has a timelike relation to (earlier or later than, or synchronous with) some other [nearby event], which in turn (3) derives from the intercrossings of other ${}^{(3)}G$'s. . . .
>
> Quantum theory upsets the sharp distinction between YES 3-geometries and NO 3-geometries. It assigns to each 3-geometry not a YES or a NO, but a probability amplitude,
>
> $$\Psi({}^{(3)}G) \tag{2}$$
>
> This probability amplitude [oscillates with greatest amplitude] near the classically forecast leaf of history and falls off steeply outside a zone of finite thickness extending a little way on either side of the leaf.[15]

Quantum theory demands and physics supplies the correct wave equation to describe how the dynamics of geometry unrolls,

$$-\frac{\nabla^2\psi}{(\delta^{(3)}\mathcal{G})^2} + {}^{(3)}R\psi = 0 \tag{3}$$

in abbreviated form[16]; or, properly spelled out,[16]

$$\left(G_{ijkl}\frac{\delta}{\delta\gamma_{ij}}\frac{\delta}{\delta\gamma_{kl}} + \gamma^{1/2}\,{}^{(3)}R\right)\Psi[{}^{(3)}\mathcal{G}] = 0 \tag{4}$$

where

$$G_{ijkl} \equiv \tfrac{1}{2}\gamma^{-1/2}(\gamma_{il}\gamma_{jl} + \gamma_{il}\gamma_{jk} - \gamma_{ij}\gamma_{kl}) \tag{5}$$

This so-called WDW equation transcribes into quantum language the very heart of Einstein's classical geometrodynamics: for every probe hypersurface, in whatever way curved, through every event, it is required that[15] the sum of extrinsic curvature plus intrinsic curvature shall be zero—zero here only because for the sake of simplicity we have excluded from the stage all actors except space geometry.

The WDW equation is not today's tool to master quantum gravity because no one has yet discovered how to use it. The world of 3-geometries is a strange and unfamiliar one. The dealer in automobile fenders knows the location in his lot of each 2-geometry. We, by contrast, still lack the coordinates to specify location in the world of 3-geometries. Until we master the manifold of the independent variable, ${}^{(3)}G$, we have scant hope either to find a family of solutions, $\Psi({}^{(3)}G)$, or to read in all fullness their message about fluctuations.

Fluctuations around a classical configuration are familiar in every domain where the quantum makes itself felt. In the case of the harmonic oscillator, from the ground-state probability amplitude for this, that, or the other position, x,

$$\Psi(x) = (m\omega\pi\hbar)^{1/4}\exp[-(m\omega/2\hbar)x^2] \tag{6}$$

we recognize that this coordinate undergoes fluctuations Δx of the order of magnitude $(\hbar/m\omega)$.$^{1/2}$ In the case of electromagnetism, we analyze the field into a collection of independent harmonic oscillators, with ground state wave function given by a product of factors of the form appearing in Eq. (6). Then we transform this product back into terms of the field coordinate, that is, in terms of the divergence-free magnetic field $\boldsymbol{B}(x)$ itself, to find the probability amplitude for this, that or the other distribution of field, expressed[15] as the functional

$$\Psi\boldsymbol{B}(x,y,x)) = N\exp[-\,I] \tag{7}$$

Here N is a normalization factor and I is the double integral over all space, with respect to the volume element $d^3x_1\, d^3x_2$, of the scalar product of the magnetic fields at the two points divided by the inverse square of the distance between them; more precisely,

$$(1/16\pi^3 \hbar\, c r_{12}^2) \mathbf{B}(x_1) \cdot \mathbf{B}(x_2) \tag{8}$$

It follows from this expression that the magnetic field in a region of extension L undergoes fluctuations of the order of magnitude

$$\Delta B \sim (\hbar c)^{1/2}/L^2 \tag{9}$$

The smaller the region of space under consideration, the larger are the field magnitudes which occur with appreciable probability.

Similar considerations apply to space geometry. "Quantum fluctuations in the geometry are superposed on and coexist with the large-scale, slowly varying curvature predicted by classical deterministic general relativity. Thus, in a region of dimension L, where in a local Lorentz frame the normal values of the metric coefficients will be $-l, l, l, l$ there will occur fluctuations in these coefficients of the order $\Delta g \sim L^*/L$ and . . . fluctuations in the curvature of space of the order $\Delta R \sim L^*/L^3$," where L^* is, as earlier, the Planck length. "These fluctuations have to be viewed, not as tied to particles and endowed with the scale of distances associated with particle physics ($\sim 10^{-13}$cm), but as pervading all space ("foam-like structure of geometry' [ref. 16, p. 262]) and characterized by the Planck distance ($\sim 10^{-33}$cm)."[16] They deprive the very concepts of before and after—and therefore even the notion of time itself—of all meaning and application.

In all the long history of physics, quantum theory comes as the first messenger to tell us that time has no basic status in the description of nature. In its place we have received a new tool, 3-geometry, to treat correctly what "time" did incorrectly.

THE DYNAMICS OF GEOMETRY IN THE LOOP REPRESENTATION

Ashtekar, Jacobson, Rovelli, Smolin and their colleagues have translated the dynamics of geometry from the language of $^{(3)}G$'s to the language of loops. Without entering into the mathematics of this transformation, the subject by now of more than 190 papers,[5] we can capture some of the flavor of it by recalling alternative ways to look at a more familiar field, electromagnetism. Maxwell's description deals with the electric and the magnetic fields as functions of four coordinates in Lorentz spacetime, x,y,z,t. The same solution of Maxwell's equations lets itself be presented as the Fourier superposition of plane waves, each endowed with its own amplitude, polarization and wave number, $k_x,k_y,k_z$and circular frequency $\omega = (k_x^2 + k_y^2 + k_z^2)^{1/2}$. Fock space representation goes to yet another level of abstractification, dealing not with the amplitude of each of these modes of oscillation, but with the number of quanta in the mode. Still another description, however, preceded those of Maxwell, of harmonic analysis and of Fock: that of Faraday. In it the center of attention is the electric or the magnetic line of force itself. The Faraday line supplies a happy analog for the Ashtekar loop. Both lines and loops put at the center of attention, not the local field (obtained by differentiation of the appropriate potential) but the integral of the relevant potential around a loop. In electromagnetism this idea has become familiar:

$$\begin{tikzcd}[row sep=small]
 & \text{Field} & F_{\mu\nu} \\
\begin{matrix}A_\mu \\ \text{Vector} \\ \text{Potential}\end{matrix} \arrow[ur, "\partial"] \arrow[dr, "\oint"'] & & \\
 & \text{Flux} & \Phi
\end{tikzcd}$$

Moreover, the magnetic flux Φ expresses itself in direct physical terms as well by one or other familiar measuring techniques as by it-from-bit definition a la Aharonov and Bohm (FIG. 1).

Ashtekar invented the analogous loop-integral method to deal with geometry:

$$\begin{tikzcd}[row sep=small]
 & \text{Curvature} & R^{\alpha\beta}_{\mu\nu} \\
\begin{matrix}\text{“}\Gamma^{\alpha}_{\beta\gamma}\text{”} \\ \text{Connection}\end{matrix} \arrow[ur, "\partial"] \arrow[r, "\text{“}\oint\text{”}"'] & \text{Loop Variable} & T
\end{tikzcd}$$

Here the connection, differentiated, gives curvature, whereas integrated around a loop it gives a two-index loop variable T. This connection, however, as signified by the quotes, is not the one familiar in texts of relativity and it is not normally a real-valued quantity. To give a little impression of its character it may be enough to note that electromagnetism admits a similar complex "connection" built by combining magnetic potential A with the imaginary unit i times the electric field E. If the writings of Oliver Heaviside and his followers could make complex-valued quantities familiar to every engineer dealing with electrical machinery, the work nowadays being published on loop representation may well provide similar enlightenment to all concerned with the dynamics of geometry.

Two features of the loop representation stand out: first, the geometrodynamic wave Equation (3) translates into an appreciably simpler-looking equation for the new probability-amplitude function $\Psi(T)$. Second, this equation admits a countable infinity of exact solutions of the form $\Psi(T) = \Psi(K)$, where K is a symbol to distinguish one knot class from another.[2-4] The difference between loop and knot sounds almost trivial. It is immense. The loop has some of the attributes of location associated with it; the knot, none. Crossing number, yes; location, no.

Admitting solutions of the form $\Psi(K)$, the quantum geometrodynamic equation evidently also admits a continuous infinity of solutions, of the form

$$\Psi(T) = \textstyle\sum_n c_n \Psi(K_n) \tag{10}$$

However, it is not yet known whether the most general solution lets itself be expressed in the knot form as in Eq. (10).

A knot? No knot exists in one dimension nor in a simply-connected 2-space. Moreover, in a space of four or more dimensions, a knot lets itself be untied. Thus it is not unreasonable that the knot should make its presence felt in the dynamics of the geometry of exactly three dimensions. But does this involve any insight into the *physics* of what is going on? The quest for such an understanding leads, at the moment, to more questions than answers!

SEEKING CORRESPONDENCE, TO LINK WITH WHAT WE KNOW

Newtonian mechanics and quantum mechanics: how the two relate we learned from Bohr's principle of correspondence and Feynman's concept of sum over histories. Nowadays everyone who works on Rydberg atoms knows how to construct out of Schrödinger wave functions a wave packet that follows the old Bohr prescription. However, we are about as far as we could be at the moment from having any comparable way to connect with knots the entities which we know, and know well: gravity waves, and black holes built of them, and closed space model universes populated by such black holes and waves. Where is any correspondence to be seen? Evidently question after question begs for solution, among them these:

1. How to transform back and forth between $\Psi({}^{(3)}G)$ and $\Psi(K)$?

2. How to build a wave packet that traces out a classical leaf of history in S (FIG. 3)?
3. Does a knot imply a finite universe?
4. Does a traditional (${}^{(4)}G$ throw any light on the asymptotics of knots?
5. In the new representation of quantum geometrodynamics, what status does a wormhole acquire?
6. Does the new representation still allow us some understanding of "spin $\frac{1}{2}$ without spin $\frac{1}{2}$" in terms of the 2^n distinct triad fields that can be laid down upon a (${}^{(3)}G$ that happens to be endowed with n wormholes?
7. What becomes of Teitelboim's "square root of general relativity" in the new representation?
8. Can one deduce the pure gravity-wave radiation of a black hole out of pure knot physics?

When knot geometrodynamics makes headway with these issues, it will bid fair to outdo the quantum mechanics of 1924–1925 in the new understanding it brings, the new power it confers, and the new depths it plumbs.

FROM KNOTS TOWARDS ALL LAW FROM NO LAW?

When at length we shall succeed in walking back and forth easily on the yet to be opened road between physics and knot theory, we shall be, not at the end of the road, but at the beginning of a new and greater exploration. The questions "How come existence?", How come the quantum?", and "How come 'one world' out of the registrations of many observer-participants?" will call out for answer with a new urgency, under a new light, and from a new framework.

The thesis "it from bit" proposes itself as that framework. No other hypothesis is evident which will respond to complementarity—"No question? No answer!"—and to four sister demands:

(1) **No tower of turtles**; that is, structure A is not to be explained by an underlying structure B, which would be explained by a still deeper structure C, on and on, to never-ending depths. Instead, existence must possess something of the character of a self-excited circuit[1] The next demand is corollary to this one.

(2) **No law.** Or no law except the law that there is no law!

(3) **No continuum.** "Just as the introduction of the irrational numbers... is a convenient myth [which] simplifies the laws of arithmetic... so physical objects," Willard Van Orman Quine points out,[17] "are

postulated entities which round out and simplify our account of the flux of existence . . . The conceptual scheme of physical objects is a convenient myth, simpler than the literal truth and yet containing that literal truth as a scattered part." A corollary of (3) stands as a final injunction:

(4) **No space, no time.** "We will not feed time into any deep-reaching account of existence. We must derive time—and time only in the continuum idealization—out of it. Likewise with space."[1]

No path into this new land offers itself today with greater promise than the marvelous loop-and-knot representation of the quantum mechanics of geometry.

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