World as system self-synthesized by quantum networking

by John Archibald Wheeler

The quantum, strangest feature of this strange universe, cracks the armor that conceals the secret of existence. In contrast to the view that the universe is a machine governed by some magic equation, we explore here the view that the world is a self-synthesizing system of existences, built on observer-participancy via a network of elementary quantum phenomena. The elementary quantum phenomenon in the sense of Bohr, the elementary act of observer-participancy, develops definiteness out of indeterminism, secures a communicable reply in response to a well-defined question. The rate of carrying out such yes-no determinations, and their accumulated number, are both minuscule today when compared to the rate and number to be anticipated in the billions of years yet to come. The coming explosion of life opens the door, however, to an all-encompassing role for observer-participancy: to build, in time to come, no minor part of what we call *its* past—*our* past, present, and future—but this whole vast world [1].

The world: A great machine or a great idea?

What is the structure of the world? Machinery, in the shape of a magic equation governing a geometry-like field in a supersymmetric manifold of ten or some other magic number of dimensions? Or an idea so obvious that it is not obvious?

Idea? To illustrate the flavor of that word, one idea plus one model of that idea—inadequate, incomplete, and conceivably totally incorrect—is worth a hundred generalities. Let one such idea-plus-model serve as background for all that follows. Its information-theoretic character, the perspectives it suggests, the issues it raises, and the probing questions that Rolf Landauer asks about it provide occasion to report it here. The idea? The world is a self-synthesizing system of existences. The model of how such a self-synthesizing system might be conceived to operate? The meaning circuit of **Figure 1**. That system of shared experience which we call the world is viewed as building itself out of elementary quantum phenomena, elementary acts of observer-participancy. In other words, the questions that the participants put—and the answers that they get—by their observing devices, plus their communications of their findings, take part in creating the impressions which we call the system: that whole great system which to a superficial look is time and space, particles and fields. That system in turn gives birth to the observer-participants.

An "idea account" of the world of intercommunicating existences, one based on quantum-plus-information theory: How should it be viewed as relating to a continuum-plus-field-theoretic analysis? Not contradictory, but mutually illuminating. We do not say, "Thermodynamics is wrong, statistical mechanics is right." To do so, to deny the mutually supportive relation between these two outlooks on heat science, would be a total misunderstanding. Similarly here, between two very different views of the world—magic equation and magic idea—the future must be expected to bring us, not contradiction, but mutual illumination.

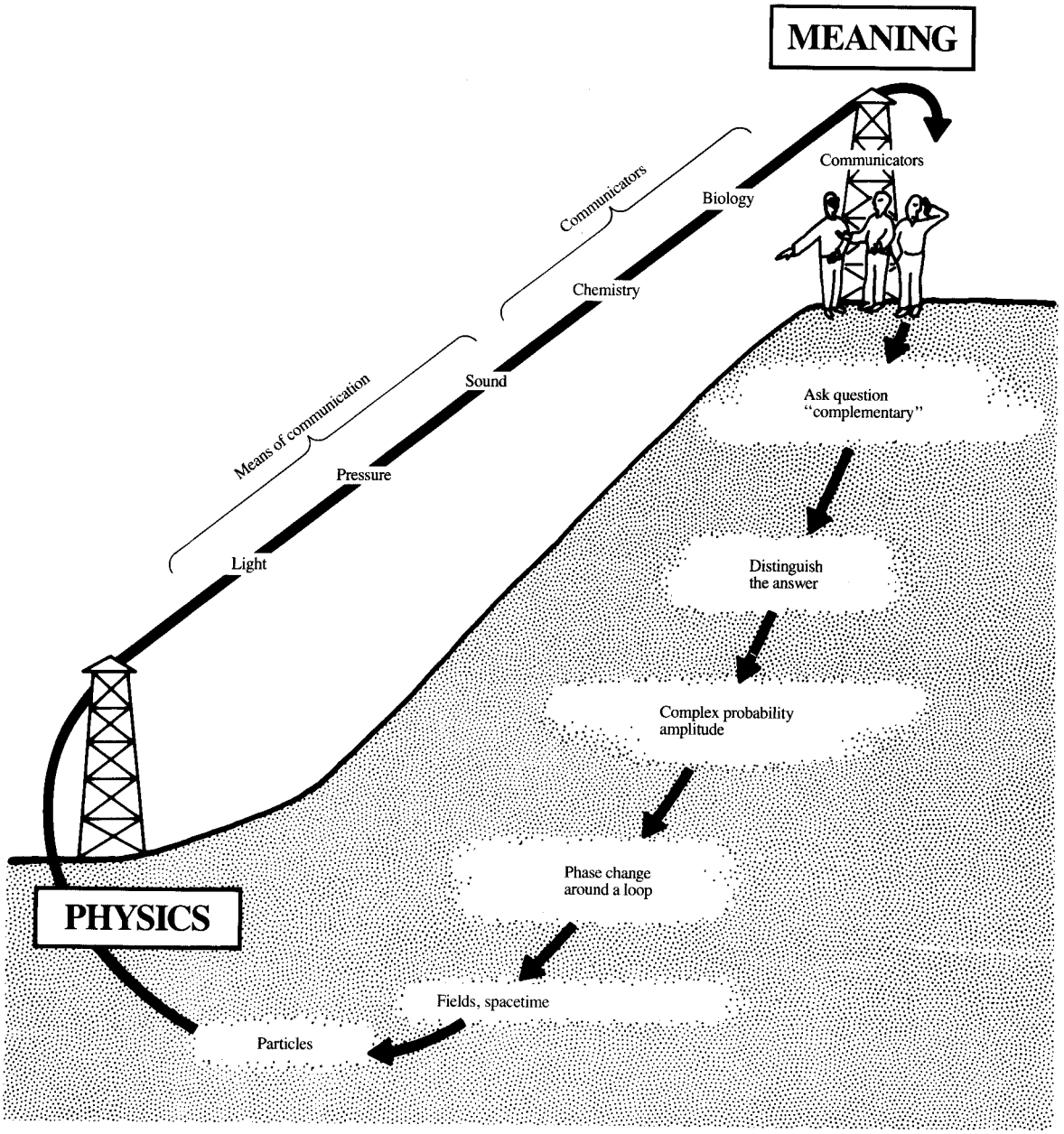

Figure 1

World viewed as a self-synthesizing system of existences. Physics gives light and sound and pressure–tools to query and to communicate. Physics also gives chemistry and biology and, through them, observer-participators. They, by way of the devices they employ, the questions they ask, and the registrations that they communicate, put into action quantum-mechanical probability amplitudes and thus develop all they know or ever can know about the world.

In a double-slit electron-interference experiment of the type proposed by Aharonov and Bohm, the interference fringes experience a phase shift proportional–so it is customary to say–to the flux of magnetic field through the domain bounded by the two electron paths. We reverse the language when we turn to the idea interpretation of nature. We speak of the magnetic field–and, by extension, spacetime and all other fields, and the whole world of particles built upon these fields–as having no function, no significance, no existence, except insofar as they affect wave phase, affect a 2-slit interference pattern, or, more concretely, affect the counting rate of elementary quantum phenomena. Fields and particles give physics and close the loop.

It is a strange business to report about what we don't know. It is no stranger, however, than recounting the first half of a detective story of which the second half is missing. We know how difficult it is to pick out the clues, let alone

assess them, unless we marshall them against the background of an idea. The idea here? Existences form a self-synthesizing system. The clues? Four stand out. Let us first list them, with brief commentaries. Then let us go back over each clue more carefully, asking how it bears on the suspicion that the quantum *is* the foundation of physics, that the world *is* a self-synthesizing system.

1. *No continuum.* Modern mathematical logic denies the existence of the conventional number continuum. Physics can do no other but follow suit. No natural way offers itself to do so except to base everything on elementary quantum phenomena, with their information-theoretic yes-no character.
2. *Observer-participancy.* The electron's momentum, the electron's position, do not exist out there independent of us. Not until we have installed and set the observing device and found what reading it registers do we have the right to say to ourselves and report to others that the chosen physical quantity had such and such a value. This is the inescapable sense in which we are participators in establishing what we have the right to say about the past. Minuscule though the part is today that such acts of observer-participancy play in the scheme of things, there are billions of years yet to come. There are billions upon billions of living places yet to be inhabited. The coming explosion of life opens the door to an all-encompassing role for observer-participancy: to build, in time to come, no minor part of what we call *its* past—*our* past, present and future—but this whole vast world.
3. *Austerity.* There is not one great field theory, neither electrodynamics, geometrodynamics, chromodynamics, nor string theory, which does not capitalize on the mathematical identity, the triviality, the logical tautology that the boundary of a boundary is zero. In this sense almost all of the machinery of physics is built on almost no machinery. This circumstance invites us to believe that all of physics is built on no machinery at all; that existence operates on the principle of total austerity.
4. *Timelessness.* The deepest insights we have on time today come out of Einstein's 1915 and still standard theory of general relativity in its quantum version. This quantum geometrodynamics tells us that the very concepts of spacetime and of before and after break down at ultrasmall distances. In tomorrow's deeper dispensation, we know that time cannot be an entity primordial and precise supplied—as elasticity once seemed to be—free of charge from outside physics. Like elasticity, the very concept of time must be secondary, approximate, derived: derived from profound considerations of a quantum flavor.

As we take a closer look at these four clues, we ask: To what extent do they comport with the concept of the totality of all existences as a self-synthesizing system? To what extent do these four items of evidence create difficulties for this closed-circuit view of nature? What are some of the problems calling for further investigation?

We cannot rightfully proceed with this assessment of the "idea theory" of the world without at least one word about the beautiful modern developments on the other side of the divide, in the heartland of the machinery view of nature, the domain of grand unified field theory and string theory. There, at least, one measure of progress is available. The kind of mathematics to be called on is clear: that synthesis of algebraic and differential geometry given us by Atiya, Singer, and other leaders in the field. Of the findings available out of that mathematics, has physics put to use at most a tenth? Then that number, in default of any other, tells something of our headway. On the idea side of the divide, however, we do not even know what the mathematics is, except that it cannot but be based on the integers and capitalize, surely, on information theory and on the guiding principle of many-body physics, "More is different."

No continuum

The continuum of number theory: Who could dispense with it who works with matter and motion, particles and fields, space and time? Yet Hermann Weyl, who in earlier years took the concept of the continuum so seriously that he published a great treatise on the subject, in later years reversed his position, explaining, "[L. E. J.] Brouwer made it clear, as I think beyond any doubt, that there is no evidence supporting the belief in the existential character of the totality of all natural numbers." More generally, he adds, "belief in this transcendental world [of mathematical ideals, of propositions of infinite length, and of a continuum of numbers] taxes the strength of our faith hardly less than the doctrines of the early Fathers of the Church or of the scholastic philosophers of the Middle Ages."

Kurt Gödel, commonly identified as an idealist in mathematical logic in contrast to the constructivist Brouwer, nevertheless reported to his biographer Hao Wang, regarding the construction of the mathematical line, "According to this intuitive concept, summing up all the points, we still do not get the line; rather the points form some kind of scaffold on the line."

William Van Orman Quine, speaking from the world of mathematical logic, goes further: "Just as the introduction of the irrational numbers ... is a convenient myth [which] simplifies the laws of arithmetic ... so physical objects are postulated entities which round out and simplify our account of the flux of existence. ... The conceptual scheme of physical objects is [likewise] a convenient myth, simpler than the literal truth and yet containing that literal truth as a scattered part."

In brief, the physical continuum, and with it all the beautiful machinery of physics, is myth, is idealization. Existence, what we call reality, is built on the discrete.

Puzzle number one: If the world is founded on the discrete, why does every workaday description of it have to employ the continuum?

The lesson of the elementary quantum phenomenon

To the discreteness lesson of Weyl and Quine, out of the worlds of mathematics and logic, nothing in all of physics says a more vigorous "yes" than the elementary quantum phenomenon. There is not a sight we see, a pressure we feel, a sensation we detect which does not go back to elementary quantum phenomena for its explanation. On the discrete yesses and nos of these elementary quantum phenomena, on these iron posts of observation, we plaster in the papier-mâché of the continuum by an elaborate work of imagination and theory. However, despite this apparent continuum of everyday experience—the quantum teaches us—the world has at bottom an information-theoretic character.

No piece of the puzzle lies closer to hand than the quantum. In a letter of 1908 to his friend Laub, Einstein was already urging, "This quantum business is so incredibly difficult and important that everyone should busy himself with it." But how come the quantum? Out of what deeper idea derives its necessity in the construction of existence?

The quantum character of nature it is natural to assess differently according to whether one adopts the machinery or the idea vision of nature. In the machinery view, it is the role of the quantum to supply a rule for quantizing the master equation. In the idea view, the quantum cracks the armor that hides the secret of existence.

For a new understanding of how information fits into the scheme of things, we are indebted to no one more than Rolf Landauer. His work, and that of Szilard, Christodoulou, Bekenstein, Hawking, Fredkin, Toffoli, Bennett and others, has created new ties among information as bits, information as negentropy, information as mass-energy, and information as elementary quantum phenomena. The way of thought of information theory, we nevertheless can believe, will be of as much help in the new enterprise—to understand self-synthesis as plan without plan—as it already has been in the task of explaining entropy in terms of the elementary yes, no actions of the famous demon. More than one distinguished investigator—Kelvin, Maxwell, Szilard, Landauer, and Bennett—had to contribute an important idea before the final point became totally clear: The "thermodynamically costly act, which prevents the demon from breaking the second law, is not (as is often supposed) the measurement by which the demon acquires information about the molecule being sorted, but rather the resetting operation by which this information is destroyed in preparation for making the next measurement." We are seeing the dawn of a new third era of physics:

Era I — Motion with no explanation of motion: the parabola of Galileo and the ellipse of Kepler.

Era II — Law with no explanation of law: Newton's laws of motion, Maxwell's electrodynamics, Einstein's geometrodynamics, modern chromodynamics, grand unified field theory, and string theory.

Era III — Information-based physics.

No feature of quantum theory is more central than the complex probability amplitude, no question more frequently asked than "How come this complex probability amplitude?" and no answer more satisfying than that given by information theory at the hands of R. A. Fisher, E. C. G. Stueckelberg, and W. K. Wootters. That answer has two parts: the asking of a question and the distinguishing of an answer.

Fisher found himself forced into a probability amplitude—a real probability amplitude—by his pre-modern-quantum-theory 1922 work in the field of population genetics. This work Wootters clarified, extended, and generalized in his 1980 Ph.D. thesis, in which he also spells out the relation to quantum theory.

An example? We find ourselves in the midst of a tribe of people who speak an unknown language. Are they the Eddas, who are friendly? Or are they the Thors, who are cannibals? All we have to go on is the color of the eyes of the sixteen warriors who encircle us. Our scouts have told us that 67.3% of the Eddas have grey eyes; 32.7%, blue eyes; whereas for the Thors the proportions are the other way around. Our statisticians have told us that, if the majority of the sixteen pairs of eyes are grey, we have close to a twelve-to-one chance of being safe. And so they are—and so we are! That is distinguishability in action.

Unfortunate explorers, we find ourselves on a new journey to a new continent confronted anew by the old issue. Are the sixteen who now surround us the friendly Aeolians or the deadly dangerous Boreans? At first sight, it appears that it will be much more difficult to be certain of our appraisal. Why? Because the differences are now so much less between the two tribes in count of grey and blue eyes. This conclusion bases itself (plane $p_{\text{grey}} + p_{\text{blue}} + p_{\text{brown}} = 1$ in the upper left-hand diagram of **Figure 2**) upon the separation of the two representative points in question in a linear probability diagram, a separation large in the one continent, small in the other.

Statistical analysis, however, shows that if the grey eyes are again in the majority, we again have close to a twelve-to-one assurance of being safe. The linear diagram is misleading because it is based on probabilities. To make distinguishability properly shine out, we should use not probabilities but probability amplitudes; not linearly related quantities that lie on a sector of a plane, but quadratically related quantities that lie on a sector of a sphere,

$$(p_{\text{grey}}^{1/2})^2 + (p_{\text{blue}}^{1/2})^2 + (p_{\text{brown}}^{1/2})^2 = 1.$$

In brief, the proper depiction of distinguishability demands Hilbert space. The angle in Hilbert space between two nearly identical probability-amplitude vectors (stippled lines in lower right-hand diagram, Figure 2), Wootters shows, is the proper measure of their distinguishability.

The Fisher tool for measuring distinguishability, his probability amplitude, is a real number. The complex

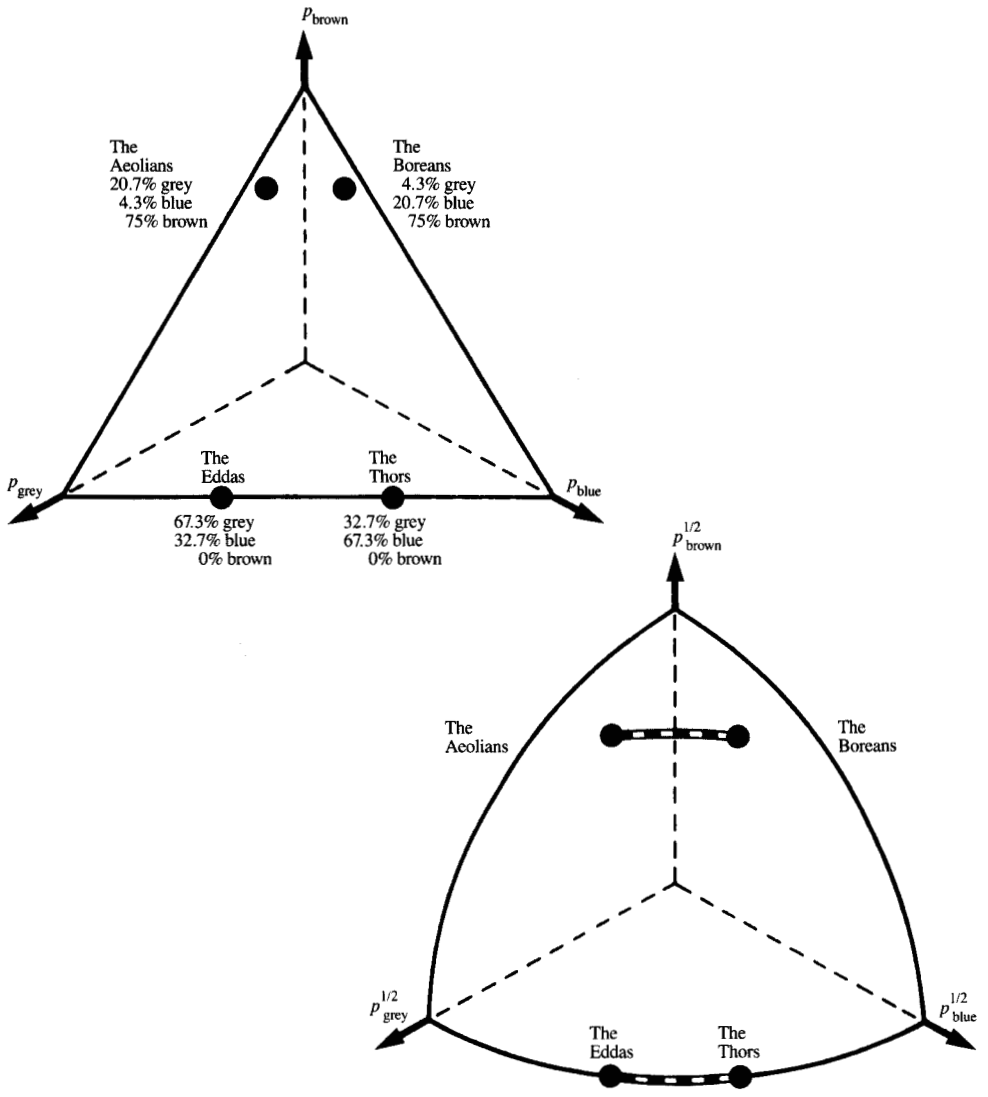

Figure 2

From probabilities to probability amplitudes as tool for determining distinguishability. Triangle above: probabilities of gray, blue, and brown eyes for tribes plotted in three-dimensional probability space. Quarter-sphere below, Hilbert space: same information with axes now measuring "probability amplitudes." The angle (dashed arcs) between two points in this Hilbert space measures the distinguishability of the two populations. W. K. Wootters is thanked for assistance in preparing this diagram.

probability amplitude of quantum physics is a complex number. How come? No consideration presents itself more forcefully than this: Fisher, distinguishing one population from another, is pure observer. The quantum-level experimenter, or his observing device, dealing with the elementary quantum phenomenon, is observer-*participant*.

For Fisher to ask one typical question about his population, eye color, does not stand in a complementary relationship to his asking another typical question, height. To ask of an electron its position, however, does stand in a complementary relation to demanding its momentum. The device for measuring position and the device for measuring

momentum simply cannot be installed in such a way as to operate in the same region at the same time. More: In default of a measurement of the one or the other, we do not even have the right to attribute either position or velocity to the electron. No choice of question? No answer! Participation reveals itself in the demand for choice.

Observer-participancy, showing as it does in this requirement for choice, and belonging as it does to the world of the small, displays some analogy to the familiar game of "find the word in twenty questions" in its surprise version. The ones to whom I must put my questions have—unbeknownst to me—agreed *not* to agree on a word. Each answers my question by a yes or no as he pleases—with one small proviso. If I challenge, and he cannot produce a word compatible with his own reply and with all previous answers, he loses and I win. The game is as difficult for everyone else as it is for me.

Is the word sitting there in my friends' custody, waiting for me, as I suppose, when I enter the room? No. The word with which we end up is not even on the docket before I choose and pose my questions. In this game, as in quantum physics, no question, no answer. What word comes out, moreover, depends on my choice of questions. Different questions? Or the same questions in a different order? Different outcome. The outcome, however, does not depend on my choices alone. My friends also have a hand in it, through their selection of answers. In summary, the game of twenty questions, in its surprise version, promotes me from observer to observer-*participant*.

Observer-participancy is the central feature of the world of the quantum. We used to think of the electron in the atom as having a position and a momentum whether we observed it or not, as I thought the word already existed in the room whether I guessed it or not. But the word did not exist in the room ahead of time, and the electron in the atom does not have a position or a momentum until an experiment is conducted to determine one or the other quantity. The questions I asked had an irretrievable part in bringing about the word that I found—but I did not have the whole voice. The determination of the word lay in part with my friends. They played the role that nature does in the typical experiment, where so often the outcome is uncertain, whether with electron or with photon. In brief, complementarity symbolizes the necessity to choose a question before we can expect an answer:

> *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." (Bohr's abbreviated 1934 version of the principle of complementarity, propounded by him in his famous fall 1927 Como lecture to penetrate what Heisenberg had not penetrated in his spring 1927 principle of indeterminacy.)

We once thought, with Einstein, that nature exists "out there," independent of us. Then we discovered—thanks to Bohr and Heisenberg—that it does not.

Not all of the surprises hidden in the quantum had to be uncovered to reveal how it comes about that the probability amplitude of the quantum world must be a complex number. This discovery Stueckelberg published in 1960. He used as foundation for his argument Heisenberg's spring 1927 principle of indeterminacy. The key point in the reasoning, however, we realize in retrospect, was complementarity, complementarity in the sense of choice: No choice, no answer. Complementarity stands revealed as the cryptic message of Schrödinger's complex-valued ψ.

Complementarity was not the last idea feature of nature to be revealed in the quantum. Bohr had to enunciate a further concept in 1935 to cope with the issue about "reality" raised by Einstein, Podolsky, and Rosen earlier that year. This is the elementary quantum phenomenon, "brought to a close" by an "irreversible act of amplification."

It would be difficult to give an example of an elementary quantum phenomenon simpler than the split-beam experiment of **Figure 3**. Twenty-four photons enter in a twenty-four-hour day. Before we analyze what happens, let us describe it in wrong but at first sight tempting language: Half of the photons, on the average, penetrate the first half-silvered mirror. They follow the low road to the lower total reflector. They bounce up to trigger the detector at the upper right. The other photons, twelve on the average, are reflected at the first half-silvered mirror. They follow the high road and set off the counter at the lower right. Insert, however, the second half-silvered mirror. Give it a well-chosen elevation. Then we ensure mutual cancellation of the two partial waves on their way to the counter at the upper right, one of them the reflected wave that has come from the high road, the other the transmitted wave that has come from the low road. That counter registers not at all. In contrast, the two partial waves traveling to the counter at the lower right have identical phase. They totally reinforce. All twenty-four photons arrive at the lower counter.

Treat the same photons sometimes as waves and sometimes as particles? Surely quantum mechanics is logically inconsistent! This was Einstein's position in the first phase (1927–1933) of his twenty-eight-year-long wrestle with modern quantum theory. Schrödinger, too, expressed his unhappiness, saying that if he had known of all this *Herumspringerei*—all this jumping about between wave and particle interpretations—to which quantum theory would lead, he would never have had anything to do with it in the first place. Bohr's reply to both was simple. We can leave out the second half-silvered mirror, or we can put it in. However, we can't do both at the same time. Complementarity, yes; contradiction, no.

Querying Bohr one evening, his favorite professor, the old Danish philosopher Harald Høffding, put to him this question about a similar and even better known idealized test case, the double-slit experiment: "Where can the photon be said to be in its passage from the slit to the photographic plate?" "To be?" Bohr replied, "To be? What does it mean, 'to be'?"

The same question poses itself with even greater force in the delayed-choice version of either the double-slit or the split-beam

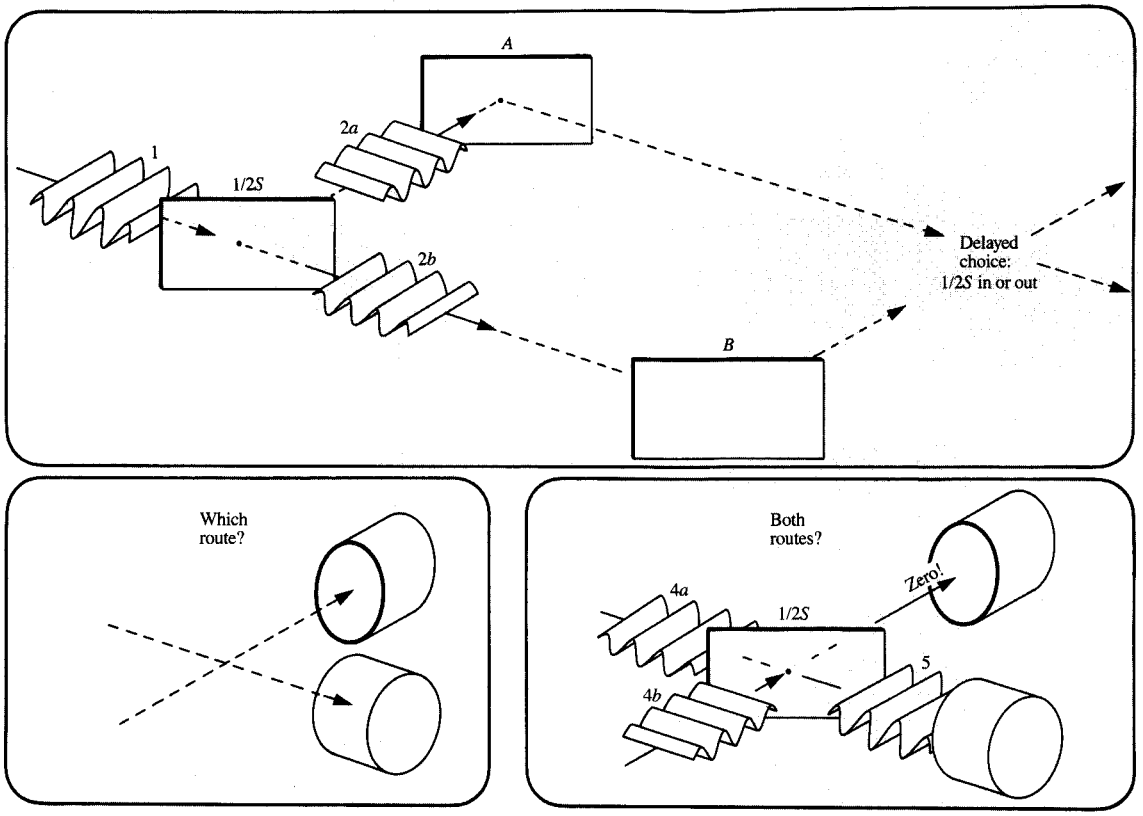

Figure 3

Beam splitter (above) and its use in a delayed-choice experiment (below). In the arrangement at the lower left, half of the photons, on the average, go into the upper counter and are registered there. However, when a half-silvered mirror is introduced and properly positioned (lower right), that counter gives zero counts. All the photons go to the counter at the lower right. The choice whether to put in the half-silvered mirror or to take it out can be made at the very last minute. It is wrong to say that one decides, after the photon has "already done its travel," that the photon "has come by one route" (or "by both routes"). The photon is a great smoky dragon, its teeth sharp where it bites the one counter or the other, its tail sharp at its birthplace, but in between totally smoky.

experiment. We can delay our choice whether to put in the second half-silvered mirror or to leave it out. We can delay that choice until the photon has passed through the first half-silvered mirror, has undergone reflection at the next mirror, and has arrived almost at the point of crossing of the two beams. To interpose this delay in our choice makes no difference in the outcome. This, theory tells us; and this, independent delayed-choice experiments in three different laboratories already confirm. This finding shows how wrong it is to say that, with mirror out, we find out "which route" the photon traveled, or, with mirror in, what the difference in phase is in a "two-route mode of travel." It is wrong to speak of what the photon is doing between the point of entry and the point of registration.

The right word, Bohr emphasized, is phenomenon. In today's words, no elementary quantum phenomenon is a phenomenon until it is a registered phenomenon—that is, indelibly recorded or brought to a close, in Bohr's phrase, by an irreversible act of amplification, such as the avalanche of electrons in a Geiger counter or the blackening of a grain of photographic emulsion or the click of a photodetector.

The elementary quantum phenomenon is a great smoky dragon. The mouth of the dragon is sharp where it bites the counter. The tail of the dragon is sharp where the photon enters. But about what the dragon does or looks like in between we have no right to speak, either in this or in any delayed-choice experiment. We get a counter reading, but we neither know nor have the right to say by what route it came.

Normally the quantum dragon operates so far beneath the everyday hardware of physics that we have to pursue it to its lair to catch it biting. Thus, this plank we see yielding a little as we sit on it. This yielding we interpret as elasticity. This elasticity we understand in terms of the linkage between molecule and molecule intermediated by hydrogen bonds. A single hydrogen atom we can arrange to detect in the laboratory. When finally we speak of the electron of a single atom as residing in this, that, or the other quantum state of excitation, we begin to close in on the dragon. No bite yet, however; still totally smoky. As smoky as the photon is in the split-beam experiment before we have put photodetectors in the way to register its arrival, so smoky is the dragon that we call the electron before we have arranged equipment to get it out where it can accomplish an irreversible act of registration—or to get out and register some equivalent entity, such as a photon, that has interacted with it. Only with this registration do we have the basis for the elementary question plus the yes-or-no answer of observer-participancy.

The elementary quantum phenomenon is the strangest thing in this strange world. It is strange because it has no localization in space or time. It is strange because it has a pure yes-no character—one bit of meaning. It is strange because it is more deeply dyed with an information-theoretic color than anything in all physics. This strangeness makes it natural to ask not only what lies behind and beneath the elementary quantum phenomenon, but also—*puzzle number two*—what role it has in building all that is.

How subtle the divide is between what we call somethingness and nothingness! That lesson of the elementary quantum phenomenon we see in a new form when we turn to the role played in the construction of field theory by the principle that the boundary of a boundary is zero.

Austerity

"So far as we can see today, the laws of physics cannot have existed from everlasting to everlasting. They must have come into being at the big bang. There were no gears and pinions, no Swiss watchmakers to put things together, not even a pre-existing plan. If this assessment is correct, every law of physics must be at bottom like the second law of thermodynamics, higgledy-piggledy in character, based on blind chance.

"There is no simpler illustration of the second law than the way molecules distribute themselves between two regions in proportion to the volumes of those two regions .... Every heat engineer knows he can design his heat engine reliably and accurately on the foundation of the second law. Run alongside one of the molecules, however, and ask it what it thinks of the second law. It will laugh at us. It never heard of the second law. It does what it wants. All the same, a collection of billions upon billions of such molecules obeys the second law with all the accuracy one could want. Is it possible that every law of physics, pushed to the extreme, will be found to have the character of the second law of thermodynamics, be statistical and approximate, not mathematically perfect and precise? Is physics in the end 'law without law,' the very epitome of austerity?

"Nothing seems at first sight more violently to conflict with austerity than all the beautiful structure of the three great field theories of our age, electrodynamics, geometrodynamics, and chromodynamics [under which latter heading, for convenience's sake, we speak also of Klein–Kaluza and string theory in their various forms]. They are the fruit of hundreds of experiments, scores of gifted investigators and a century of labor. Impressive treatises spell out the physics and mathematics of all three theories. How can anyone possibly imagine all this richness coming out of a higgledy-piggledy origin?

"Only a principle of organization which is no organization at all would seem to offer itself. In all of mathematics, nothing of this kind [is] more obviously [available] than the principle that 'the boundary of a boundary is zero' [or, in mathematical terminology, $\partial\partial = 0$]. Moreover, all three great field theories of physics use this principle twice over, once in the form that 'the one-dimensional boundary of the two-dimensional boundary of a three-dimensional region is zero,' and again in the form that 'the two-dimensional boundary of the three-dimensional boundary of a four-dimensional region is zero' [or the pair of equivalent higher-dimensional statements in any version of field theory that operates in a higher-dimensional manifold]. This circumstance would seem to give us some reassurance that we are talking sense when we think of almost all of physics being founded on almost nothing." [J. A. W., *Physics and Austerity: Laws Without Laws*, Anhui Science and Technology Publications, Hefei, Anhui, People's Republic of China, 1982.]

To spell out the boundary principle in the context of electrodynamics would be too trivial to serve as good illustration; in the domain of chromodynamics and string theory, too technical; but just right in geometrodynamics. Gravitation is a theory of intermediate difficulty, great interest, and widely recognized beauty. In it the central idea lends itself to statement in the single word "grip." Spacetime grips mass, telling it how to move. Mass grips spacetime, telling it how to curve.

What help do we get in understanding the grip of gravity from the principle that the boundary of a boundary is zero?

In older times we looked on mass or charge as primary, as source, as the ultimate entity, and regarded the gravitational or electromagnetic field as secondary. The source "knew" that it wanted to be conserved. The field ran along behind as slave, obedient to its wish. Today we regard the field as primary and the source as secondary. Without the field to govern it, the source would not know what to do. It would not even exist.

When two gigantic spaceships smash into each other, much is destroyed. One quantity, we know, is conserved, the energy-momentum 4-vector. What master is so powerful that it can hold those two mighty spaceships in straight-line motion before they hit

and see to the conservation law in the crash itself? Spacetime! Spacetime grips them both. Spacetime, right where they are, enforces the conservation of momentum and energy.

How does nature wire up momentum-energy—momenergy—the source, to spacetime geometry, the field, so as to guarantee conservation of the source, and do this automatically, without benefit of a corps of Swiss watchmakers, with no gears or pinions at all? By applying the principle $\partial\partial = 0$ at the 2-3-4-dimensional level.

It is automatic that there shall be no creation of source in the region of space $\Delta x\Delta y\Delta z$ during the time Δt. How so?

It is the first part of this question to ask what we mean by "no creation" in the 4-dimensional cube $\Delta x\Delta y\Delta z\Delta t$; that is, to enquire how we test for no creation. A look at the eight 3-dimensional faces of that 4-dimensional cube is enough to disclose the test. Evaluate the amount of momentum-energy contained within one of those eight 3-cubes, say the cube with dimensions $\Delta x\Delta z\Delta t$, located at the distance $\Delta x/2$ to the "right" of the center of the 4-cube. Make the same evaluation for each of the other seven 3-cubes. Add up the results, with due regard to sign. Is the total zero? Then conservation is upheld in this sense: The amount of momenergy in $\Delta x\Delta y\Delta z$ at the end of the time interval Δt differs from the amount in $\Delta x\Delta y\Delta z$ at the beginning of that time interval by exactly the amount transported in across the six faces of $\Delta x\Delta y\Delta z$ during the time Δt. There must be no discrepancy, no creation of momenergy out of the emptiness of space.

Now for the remaining part of our question: By what *automatic* means does geometrodynamics meet this test of zero creation? Answer: It identifies the content of momenergy inside each 3-cube as the sum—with due regard to sign—of contributions from the six 2-faces that bound that 3-cube.

The detail? With eight 3-cubes, and six 2-faces per 3-cube, the 4-cube of concern to us presents us with $8 \times 6 = 48$ faces. Each of these faces makes its own individual contribution to the momenergy inside one or another of the 3-cubes; makes its own contribution, consequently, to the bookkeeping balance which is to tell us that there has been no creation at all inside $\Delta x\Delta y\Delta z\Delta t$. A zero balance, yes. But how? Now it comes. These faces butt up against each other in pairs. Not a single face is exposed to the outside. Moreover, each face makes a contribution equal in magnitude and opposite in sign—conventions about sign being what they are—to the contribution of its partner face. Zero total, yes; and, most remarkable of all, zero automatically. Conservation from a tautology, from a stupidity, from the central identity of algebraic geometry, $\partial\partial = 0$, in the form which states that the 2-dimensional boundary (here: those 48 faces!) of the 3-dimensional boundary of a 4-dimensional region is automatically zero.

Machinery? Absent. Absent from the law of conservation of source in not only gravitation but also every other great field theory. A closer look, however, discloses a residue of machinery. It gives each theory its own characteristic form. In gravitation the key device is spacetime curvature. It associates a rotation with circumnavigation of any chosen 2-face of a 3-cube. The six faces of the elementary 3-cube thus present us with six rotations. Add them? Use that sum over the faces of the 3-cube to define the content of momentum-energy within the 3-cube? That dream collapses. To ask for the sum of those six rotations is to ask for the result of circumnavigating, in turn, the six 2-faces of the 3-cube. In the necessary travel we traverse each edge of the cube twice, once in one direction, then again in the opposite direction. Total cancellation results whenever the cube is small enough so that we can neglect second-order terms. That is the boundary principle in action, not in its previously used 2-3-4 form but now in its 1-2-3 form: The 1-dimensional boundary of the 2-dimensional boundary of a 3-dimensional region is automatically zero.

Elementary mechanics teaches us to expect an object to start rotating even when the vector sum of the forces acting upon that object is zero. What counts in producing rotation is not the forces themselves but their moments. Moments about what point? That does not matter, because the vector sum of the forces is zero.

Similarly in geometrodynamics. We expect momenergy within a 3-cube even though the sum of the rotations over the faces of that 3-cube is zero. What measures the content of momenergy is not the rotations themselves but their moments. Moments of rotation about what point? That does not matter, because the sum of the rotations is zero. In this elementary idea—due to the insight of Élie Cartan—we have before us the whole way of action of Einstein's great theory of gravity: the grip of spacetime on mass, and the grip of mass on spacetime.

Relativistic gravitation theory today is an enormous subject, reaching from the structure of black holes to the deflection of light, and from gravitational waves to cosmology. To understand all this physics, simple geometric constructions suffice. Nowhere is this geometric simplicity of the subject more evident than in its central device, the grip that couples mass with spacetime geometry, the moment of rotation.

Problem: If in gravitation and the other great field theories we can derive so much from so little, why can't we go the rest of the way and obtain everything from nothing? What holds us back from a physics of total austerity? Two obstacles, above all: dimensionality and time.

About dimensionality there was no doubt in the days from Newton to Einstein. There was doubt only about which one or another of a dozen arguments supplied the authentic magic derivation for the magic number three. A very different idea has received much instructive investigation in our own day: Yes, there is a magic dimensionality, but no, it is not three. The extra dimensions are envisaged as curled up into closure in a space so small as not to be susceptible to investigation by any everyday means. Particle masses appear as organ-pipe resonances in this microspace. The new question, What is the right dimensionality, has replaced the old question, What is the right derivation for three.

A third assessment imposes itself on us here: Nature, examined penetratingly, has no dimensionality at all. Dimensionality implies exactly what mathematical logic denies, the continuum. The appearance of a continuum, however, is undeniable, and with it the appearance of a dimensionality. It is difficult to appraise this apparent continuity and this apparent dimensionality as other than cover-up, plastered over a more subtle structure that has neither continuity nor dimensionality.

Puzzle number three: How are we to reconcile the demand for structure with the demand for total austerity?

Timelessness

When we appraise dimensionality as cover-up, when we rank

continuum as illusion, then we must also interpret time as myth.

The concept of time was not handed down from heaven. Neither was it supplied free of charge from outside for the benefit of physics. The very word is a human invention, and the problems that come with it are of human origin. The miracle is only this, that a notion with so little undergirding has managed to stretch, without snapping, to encompass so much. Einstein's 1915 geometrodynamics continues to serve as the generally agreed authority for all that time now means and measures.

Time today is in trouble: (1) Time ends—Einstein's theory tells us—in big bang and gravitational collapse. (2) Past and future are interlocked in a way contrary to the causal ordering presupposed by time, in this sense: According to how the observing equipment in the here and now is set one way or another, that choice has irretrievable consequences for what we have the right to say about the past, even the past billions of years ago, before there was any life. The past has no existence except as it is contained in the records, near and far, of the present. (3) Quantum theory denies all meaning to the concepts of "before" and "after" in the world of the very small, at distances of the order of the Planck length, $L = (\hbar G/c^3)^{1/2} = 1.6 \times 10^{-33}$ cm. Spacetime is the classical history of space geometry evolving deterministically in time. The very notion stands in utter contradiction to the long-known lessons of complementarity and indeterminism about the quantization of any classical field theory. A proper quantum account of the dynamics of geometry teaches us that—except in the above-Planck-length approximation—there is no such thing as spacetime.

It is not enough in dealing with these difficulties to quantize Einstein's geometric theory of gravity according to the pattern for quantizing any other standard field theory; not enough to write down the resulting often-discussed wave equation,

$$-\{\delta^2\psi/[\delta^{(3)}G]^2\} + {}^{(3)}R\psi = 0;$$

not enough—despite all the fascination and instructiveness of the work of Everett, De Witt, Hartle, and Hawking towards interpreting the result—to calculate in this way the probability amplitude $\psi[^{(3)}G]$ for this, that and the other 3-geometry. This whole line of analysis presupposes that there is such a thing as "the universe."

Even to utter that noun is to hear as if it were yesterday Lord Rutherford standing in the Cavendish Laboratory hallway thundering, "When a young man in my laboratory uses the word 'universe,' I tell him it is time for him to leave." We try to avoid the very concept of universe in the present account because of all the ideological presuppositions **(Table 1)** latent in the word. World: a multiplicity of existences? Yes. Universe? No.

The minuet? How harmonious, how fascinating, how beautiful. Yet all the while we watch we know that there is no such thing as a minuet, no adherence with perfect precision to a pattern, only individuals of different shapes and sizes pursuing different plans of motion with different accuracies. Let this clearer view suggest the totally different idea of a multi-existence world that the concept of observer-participancy would offer in place of the assumption-laden word *universe.*

Table 1 The concepts of *universe* and of *multiple-existence world* compared and contrasted.

	Universe	*World of existences*
Machine	Yes	No
Time	Yes	No
Record of change	Conditions on a sequence of spacelike hypersurfaces	Yes or no records of a multitude of observer-participators
Mathematics	Continuous fields	Discrete yes or no
Dynamics	Via machinery	Via asking questions

The word *timelessness*, in summary, stands for the thesis that at bottom there is not and cannot be any such thing as time; that we have to expect a deeper concept to take its place. Events, yes. A continuum of events, no.

Puzzle number four: How to derive time without presupposing time.

The world of existences as a system self-synthesized by quantum networking

No time, no law, no machinery, and no continuum: Four clues more pregnant with guidance it would be difficult to imagine. Immensely more difficult is this—how to employ these clues, how to unravel the secret of existence, how to get *numbers* and *predictions.* If we have no answers, we have at least one encouragement. It generally carries us at least eighty percent of the way towards the solving of a deep puzzle to ask enough nearly right questions!

We see how powerful our four clues are when we compare and contrast the schematic diagram of Figure 1 for the world as a system self-synthesized by quantum networking with two other self-synthesizing systems, the modern worldwide telecommunications system and life.

Beginning with a single telegraph line connecting a single sender and a single receiver and expanding to a global multi-mode network, telecommunications constitute today an industry ever more immense in its extent. However, that growth is no machine. It is an immensity of demands and responses. The telecommunications industry is not telecommunication. The telecommunications industry is telecommunication plus life. Only so could telecommunications become what it is today, a self-synthesizing system.

That other self-organizing system, life itself, likewise shows a fantastic complexity of structure. However, its marvels go back for explanation, we know, to mutation plus natural selection. Life, like telecommunications, is in a continual state of evolution.

Both self-synthesizing systems show this immense difference from existence—that they submit to time, the *outside* metronome which drives them—whereas elementary quantum phenomena leap across time and, on the Figure 1 model of world as self-synthesizing system, *generate* time. There are other differences, among them the following.

No place to "start." A closed circuit

There was a toehold for the telecommunications system to start its self-synthesis: the community of potential communicators plus the expanding power of physics to provide new means of communication. Life, too, had a pre-existing foundation on which to build itself—chemistry in the fullest sense of the word chemistry. But the world of existences: Where and when and on what foundation can it possibly be imagined to build itself? Might not one just as well speak of making of "airy nothing a local habitation and a name"?

Whoever would sail the craft of reason through the sea of mystery to find a foundation for existences has to steer his way between twin rocks of destruction: Postulate an inexplicable something on which to build? That would shatter a central principle of Western thought: Every mystery can be unraveled. Or postulate under each level of structure another, and under that yet another, in a never-ending sequence? That would be equally disastrous. No way offers itself to navigate a course between these rocks of ruin except to believe that the world of existences synthesizes itself after the pattern of a closed circuit.

Life, mind, communication count for nothing in the scheme of existence? Everything!

An elementary quantum phenomenon put to use to establish meaning: There's the rub. How can we reconcile such a life-and-mind-centered notion with the traditional spirit of physics? Einstein speaks of the inspiration of his youth, "Out yonder there was this huge world, which exists independently of us human beings and which stands before us like a great, eternal riddle ...." Marie Sklodowska Curie tells us, "Physics deals with things, not people." David Hume asks, "What peculiar privilege has this little agitation of the brain which we call thought, that we must thus make it the model of the whole universe?"

Are life and mind indeed unimportant in the workings of existence? Is life never to inherit the vastness of space because today its dominion is so small? Or is not rather life destined to take possession of all the out-there because the time available for conquest is so large? How easy it is to be overimpressed by the remoteness of the quasars; how tempting to discount as anthropocentric any purported place for life and mind in the construction of the world. Is it not even more anthropocentric to take man's migration by foot and ferry in fifty thousand years as the gauge of where life will get in fifty billion years?

The fight against here-centeredness began with the 1543 *De revolutionibus orbium coelestium* of Copernicus. The time-bridging power of the elementary quantum phenomenon warns us today to battle against now-centeredness.

Life and mind: For how much can they be conceived to count in the scheme of existence? Nothing, say the billions of light years of space that lie around us. Everything, say the billions of years of time that lie ahead of us.

It cannot matter that man in time to come will have been supplanted by, or will have evolved into, intelligent life of quite other forms. What counts—in the idea view being explored in this paper—is the rate of asking questions and obtaining answers by elementary quantum phenomena, acts of observer-participancy, exchanges of information. If space is closed, if—following on the present phase of expansion—the system of galaxies contracts, if temperatures rise, all in line with the best known Friedmann cosmology, and if life wins all, then the number of bits of information being exchanged per second can be expected to rise enormously compared to that number rate today. The total count of bits: How great will it be before the counting has to cease because space is within a Planck time of total crunch? And how great must that future total be—tally as it is of times past—to furnish enough iron posts of observation to bear the smooth plaster which we of today call existence?

Bits needed. Bits available. Calculate each. Compare. This double undertaking, if and when it becomes feasible, will mark the passage from clues about existence to testable theory of existence.

No ensemble, no factory for making universes. Observer-participancy the whole source of the "out there" plus *life, mind, communication*

Counting bits is one test of theory for the future; accounting for the reciprocal fine-structure constant, $\hbar c/e^2 = 137.036\ldots$, and the famous large-number dimensionless constants of physics is another. Those constants must have nearly the values they do, Robert H. Dicke, Brandon Carter, and others point out, if life is ever to be possible—not merely life as we know it, but life of almost any conceivable form. This observation has led some investigators to the idea of an ensemble of universes, one differing from another in the values of the dimensionless constants—a latter-day version of those words of David Hume from two centuries ago: "Many worlds might have been botched and bungled, throughout an eternity, ere this system was struck out: much labor lost: many fruitless trials made, and a slow, but continued improvement carried

on during infinite ages in the art of world-making." There operates on such an ensemble of universes, Charles Pantin argued in 1951, something "analogous to the principle of Natural Selection, that only in certain Universes, which happen to include ours, are the conditions suitable for the existence of life, and unless that condition is fulfilled there will be no observers to note the fact." This ensemble concept is common to many of today's versions of the cosmological anthropic principle, reviewed in the comprehensive book of John D. Barrow and Frank J. Tipler [*The Anthropic Cosmological Principle*, Clarendon Press, Oxford, 1986].

The contrast between the two views could hardly be greater: selection-from-an-ensemble and observer-participancy. The one not only adopts the concept of universe, and this universe as machine, it also has to postulate, explicitly or implicitly, a supermachine, a scheme, a device, a miracle, which will turn out universes in infinite variety and infinite number. The other takes as foundation notion a higgledy-piggledy multitude of existences, each characterized, directly or indirectly, by the soliciting and receiving of answers to yes-no questions, and linked by exchange of information.

Solipsism, no; communication, yes

Solipsism? Solipsism in the dictionary sense of "the theory or view that the self is the only reality"? Not so! We can even question whether two often-quoted thinkers of the past ever meant anything at all like solipsism in this sense by their well-known statements: Parmenides declaring that "What is ... is identical with the thought that recognizes it," and George Berkeley teaching that "*Esse est percipi*": To be is to be perceived. The heart of the matter is the word *self*. What is to be understood by the word self we are perhaps beginning to understand today as well as some of the ancients did. We know that in the last analysis there is no such thing as self. There is not a word we speak, a concept we use, a thought we think which does not arise, directly or indirectly, from our membership in the larger community. On that community the mind is as dependent as is the computer. A computer with no programming is no computer. A mind with no programming is no mind. Impressive as is the greatest computer program that man has ever written and run, that program is as nothing compared to the programming by parents and community that makes a mind a mind.

The heart of mind is programming, and the heart of programming is communication. In no respect does the observer-participancy view of the world separate itself more sharply from universe-as-machine than in its emphasis on information transfer.

The great question

Will we ever succeed in stripping off the continuum, in comprehending the why of the quantum, in achieving a physics of total austerity, in deriving—without time—the essence of time? And all this by interpreting the world as a self-synthesizing system of existences built on observer-participancy? In assessing this enterprise, we have the advice of Niels Bohr that "... every analysis of the conditions of human knowledge must rest on considerations of the character and scope of our means of communication."

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Note

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