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The Computer and the Universe[1]

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The reasons are briefly recalled why (1) time cannot be a primordial category in the description of nature, but secondary, approximate and derived, and (2) the laws of physics could not have been engraved for all time upon a tablet of granite, but had to come into being by a higgledy-piggledy mechanism. It is difficult to defend the view that existence is built at bottom upon particles, fields of force or space and time. Attention is called to the "elementary quantum phenomenon" as potential building element for all that is. The task of construction of physics from such elements is compared and contrasted with the problem of constructing a computer out of "yes, no" devices.

1. FROM ELEMENTS TO STRUCTURE AND FROM STRUCTURE TO ELEMENTS

An unfamiliar computer from far away stands at the center of the exhibition hall. Some of the onlookers marvel at its unprecedented power; others gather in animated knots trying, but so far in vain, to make out its philosophy, its logic, and its architecture. The central idea of the new device escapes them. The central idea of the universe escapes us.

No real computer, of course, ever springs full blown from the brow of Minerva. We start with the elements and analyze how to achieve structure. For the universe we start with the structure and try to analyze it into elements. Computer science and basic physics mark two of the frontiers of the civilization of this age. One seeks to build complexity out of simplicity. The other tries to unravel complexity into simplicity. No one, it has been said, is better at taking a puzzle apart than the person who put it together and no one is better at putting a puzzle together than the one who took it

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apart. Can it then be that there is a little of the flavor of the physics enterprise of interest for computer science? And something of use for the unraveling of the universe to be learned from the philosophy of computer design?

There is one immediate point of similarity between the two enterprises. It would be hard to find anyone fully committed to either enterprise who does not live out each day between bafflement and hope and who does not resonate to Einstein's words: "In my opinion there is *the* correct path and ... it is in our power to find it." (Einstein, 1934).

It will be helpful to compare and contrast the two enterprises in this report under four heads. First, the modern computer and the quantum universe are similar in operating on "yes, no" rather than a "how much" principle. Second, the computer and the universe differ completely in what they call on for their construction. The computer is built on the materials and forces and laws of physics. The universe has to construct particles without particles, fields without fields, space-time without space-time, and law without law. Third is a point of similarity. Calculations have to strike a compromise between accuracy and cost, and so do the measurements in the world of physics. The central point in both cases is the user's need to distinguish right result from wrong. Finally there is another contrast. What comes out of a proper computer is uniquely fixed by what goes in, while in the world of the quantum there is a battle-tested and inescapable element of unpredictability.

2. BOTH DEAL WITH "YES, NO" RATHER THAN "HOW MUCH"

The first similarity between the computer and the brain is their "yes, no" character. Who in ancient times would not have ascribed instead a "how much" character to both?

The gear-work clock of the Greeks (Price, 1974) for keeping track of the motion of the sun and moon belonged to both worlds, computer and physics, and was a "how much" device if there ever was one. An ancestor of the analog computer and of the differential analyzer of Vannevar Bush and his MIT colleagues, it was also a symbol of the "how much" kinematics of Ptolemy, Copernicus, and Kepler, of the "how much" dynamics of Galileo, Newton, and Euler and of the "how much" field theory of Faraday, Maxwell, Hertz, and Einstein.

Great Leibniz, to be sure, had a deeper vision both of computers and of physics. Goal establisher for the very different enterprises of Gödel and von Neumann, he envisaged a device that would automatically go through the "yes, no" steps of a logical proof and in that way bring the power of logic to bear on everyday problems of the greatest variety. On the physics side, "yes, no" Leibniz was inspiration to Kant, Mach, and Einstein. Kant reasoned that space and time are two essential conditions for sense perception; that they are not data given by *things* but absolute necessities of the *mind* for any possibility to make any sense whatsoever out of the data of experience. How interesting it would be if one armed with modern insights would undertake afresh the program of Kant's *Kritik* (Kant, 1781). Would he find that the very conditions for apprehending sense data force space-time upon us, not the separate space and time that Kant thought he had derived?

Mach (1886) argued that sensations are the foundation of all concepts of the physical world, that a "law" of physics does no more than arrange sensations into convenient order as a coat rack puts coats into handy reach.

If Mach's outlook, later rejected by Einstein, was in the beginning an inspiration to Einstein and his development of general relativity (Herneck, 1979), it should be no surprise that Einstein's words "...time and space are modes by which we think and not conditions in which we live" (Forsee, 1963) echo Leibniz's statement "...space and time are orders of things and not things." (Leibniz, 1908).

The sensations, however, upon which our whole physical picture stands are not "how much" in character. Quantum theory tells us that they are "yes, no" sensations.

From a tiny dab of color on the canvas of an impressionist painting in the glance of a single second the pupil of our eye receives 50,000 photons. Each is accidental in its direction and time of arrival. The quanta in that hail of information are so numerous that they give the impression of perfect steadiness of illumination. What one of us busy mortals has the time to count them all? We rely instead on some gross and handier measure of intensity, such as the eye so aptly passes to the brain. There is no place in that message for the qualifying words, "with a root mean square fluctuation of 224 relative to an average number of 50,000." Who needs to know about quanta to know the dot of color is there? The measurement of quantities even more continuous in character than intensity, such as the position of an electron, von Neumann (1955) taught us by way of his "projection operators" to take apart into "yes, no" questions. For the world of physics as for the alphanumeric printout of the computer, the "yes, no" character[2] of what is going on may not be apparent but it is there behind the scene.

3. BUILT OF HARDWARE VERSUS BUILT OF THE INTANGIBLE

Similar in "yes, no" character, the computer and the universe differ in a central feature, their *substance*. The computer is built of hardware, whether

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[2] Especially stressed and studied by David Finkelstein.

that hardware consists of wires and transistors, magnetic bubbles, light pulses, "billiard balls," biological molecules, or smaller entities. It depends upon the laws of physics for its operation. But of what is the universe built, and by what principle of construction?

Particles, fields of force, and space-time itself are surely all intermediate entities in the construction of the universe. Beyond and above them, however, stands the quantum, the overarching principle of twentieth century physics. At its heart, in turn, stands the ultimate intangible, the elementary quantum phenomenon. The very word "phenomenon" is the hard won fruit of the twenty-eight-year dialog between Bohr and Einstein (Bohr, 1949) about the logical self-consistency of quantum theory and its implications for "reality." In today's words, "No elementary phenomenon is a phenomenon until it is a registered (observed) phenomenon." (Wheeler, 1980).

One who comes from an older time and is accustomed to the picture of the universe as a machine built out of "atoms" is not only baffled but put off when he reads Leibniz and Leibniz's conception of the ultimate building unit, the monad (Leibniz, 1962):

> 1. The Monad, of which we will speak here, is nothing else than a simple substance, which goes to make up composites; by simple, we mean without parts.
> 2. There must be simple substances because there are composites; for a composite is nothing else than a collection or *aggregation* of simple substances.
> 3. Now where there are no constituent parts there is possible neither extension, nor form, nor divisibility. These Monads are the true Atoms of nature, and, in fact, the Elements of things.
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> ⋮
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> 7. There is also no way of explaining how a Monad can be altered or changed in its inner being by any other created thing, since there is no possibility of transposition within it,... . The Monads have no windows through which anything may come in or go out....
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> ⋮
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> 9. Each Monad ... must be different from every other... ."

These words of Leibniz about the "monad" are more relevant to "quantum phenomenon" than to anything one has ever called an "atom."

There is no simpler illustration of a quantum phenomenon than that provided by the beam splitter of Figure 1. With the final half-silvered mirror

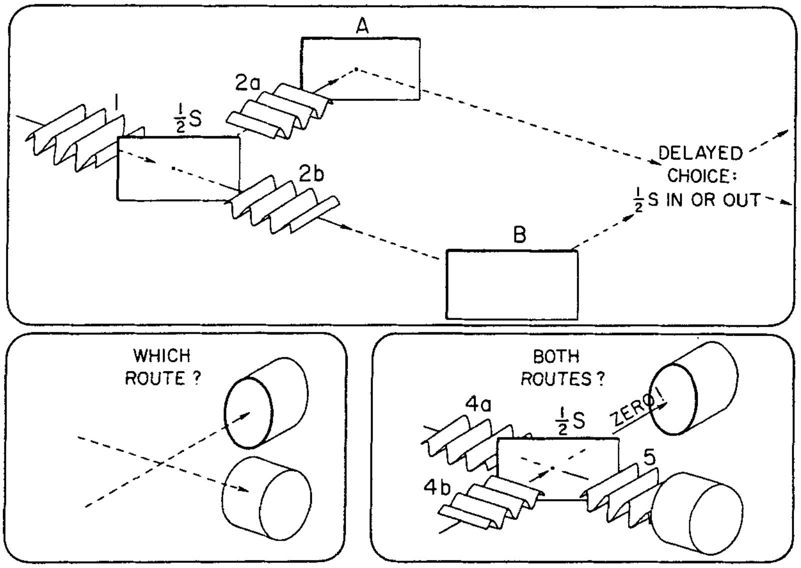

Fig. 1. Beam splitter (above) and its use in a delayed-choice experiment (below). An electromagnetic wave comes in at 1 and encounters the half-silvered mirror marked $\frac{1}{2}$S, which splits it into two beams, 2a and 2b, of equal intensity which are reflected by mirrors A and B to a crossing point at the right. Counters (lower left) located past the point of crossing tell by which route an arriving photon has come. In the alternative arrangement at the lower right, a half-silvered mirror is inserted at the point of crossing. On one side it brings beams 4a and 4b into destructive interference, so that the counter located on that side never registers anything. On the other side the beams are brought into constructive interference to reconstitute a beam, 5, of the original strength, 1. Every photon that enters at 1 is registered in that second counter in the idealized case of perfect mirrors and 100% photodetector efficiency. In the one arrangement (lower left) one finds out by *which* route the photon came. In the other arrangement (lower right) one has evidence that the arriving photon came by both routes. In the new "delayed-choice" version of the experiment one decides whether to put in the half-silvered mirror or take it out at the very last minute. Thus one decides whether the photon "shall have come by one route, or by both routes" after it has "*already done* its travel."

in place the photodetector at the lower right goes click-click as the successive photons arrive but the adjacent counter registers nothing. This is evidence of interference between beams 2a and 2b; or, in photon language, evidence that each arriving light quantum has arrived by both routes, A *and* B. In such experiments,[3] Einstein originally argued, it is unreasonable for a

[3] The center of discussion in the Bohr–Einstein dialog was more often the so-called double-slit experiment than the beam splitter depicted in Figure 1. The latter is made the focus of attention here because it presents the central point without getting into the physics of interference patterns.

single photon to travel simultaneously two routes. Remove the half-silvered mirror, as at the lower left, and one will find that the one counter goes off, or the other. Thus the photon has traveled only *one* route. It travels only one route, but it travels both routes; it travels both routes, but it travels only one route. What nonsense! How obvious it is that quantum theory is inconsistent!

Bohr emphasized that there is no inconsistency. We are dealing with two different experiments. The one with the half-silvered mirror removed tells which route. The one with the half-silvered mirror in place provides evidence that the photon traveled both routes. But it is impossible to do both experiments at once. One can observe one feature of nature, or the complementary feature of nature but not both features simultaneously. What we choose to measure has an irretrievable consequence for what we will find.

In our own day we learned to state the point even more sharply by way of a so-called delayed-choice experiment (Wheeler, 1978). There we make the decision whether to put the final half-silvered mirror in place or to take it out at the very last picosecond, after the photon has already accomplished its travel. In this sense, we have a strange inversion of the normal order of time. We, now, by moving the mirror in or out have an unavoidable effect on what we have a right to say about the *already* past history of that photon.

The dependence of what is observed upon the choice of experimental arrangement made Einstein unhappy. It conflicts with the view that the universe exists "out there" independent of all acts of observation. In contrast Bohr stressed that we confront here an inescapable new feature of nature, to be welcomed because of the understanding it gives us. It is wrong to speak of the "route" of the photon in the experiment of the beam splitter. It is wrong to attribute a tangibility to the photon in all its travel from the point of entry to its last instant of flight. A phenomenon is not yet a phenomenon until it has been brought to a close by an irreversible act of amplification such as the blackening of a grain of silver bromide emulsion or the triggering of a photodetector (Bohr, 1958). In broader terms, we find that nature at the quantum level is not a machine that goes its inexorable way. Instead what answer we get depends on the question we put, the experiment we arrange, the registering device we choose. We are inescapably involved in bringing about that which appears to be happening.[4]

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[4] A homely illustration of this idea is provided by the old parlor game of twenty questions in the "surprise version" described by the author in several places, most recently in *Beyond the Black Hole* (Wheeler, 1980).

The choice of question asked has a decisive consequence for[5] the elementary quantum phenomenon. For illustration it is enough to recall the inquiry of Figure 1 about the "track" of the photon, or a similar inquiry about the "path" of an electron through a beam splitter or the "motion" of an electron in an atom. In each of these examples, moreover, at least one of the available choices of question to be asked (which route for the proton or electron; or what position or momentum does the electron have in the atom) has a completely unpredictable answer. We can send a million photons through the beam splitter when it is operated in the "which route" configuration at the lower left of Figure 1. Then we can be assured half a million photons more or less (statistical variations of the order of magnitude ±500) will be recorded by each counter. However, when via the same arrangement we deal with a single photon we have not the slightest possibility to tell in advance which of the two counters it will strike.

Is there not some underground machinery beneath the working of the world which one can ferret out to secure an advance indication of the outcome? Some secret determiner, some "hidden variable"? Every attempt, theoretical or observational, to defend such a hypothesis has been struck down (for a review of relevant experiments, see Pipkin, 1978). Not the slightest hard evidence has ever been found that would throw doubt on the plain, straightforward prediction of quantum mechanics, the prediction that no prediction is possible. Probability? Yes. A definite forecast? No. Einstein could be unhappy that "God plays dice"; but Bohr could tell him jokingly, "Einstein, stop telling God what to do." (see Bronowski, 1973).

If no identifiable machinery is at hand to tell the lone photon which way to go then why not simply say of the route it actually takes, Allah willed it? And willed the outcome of every other individual quantum process?

To strike down a proposal of this kind, it has been pointed out more than once,[6] is beyond the power of logic. Instead we simply say, fatalism is not a useful approach to the choices each day offers between the paths of peril and of promise. If in the individual quantum process prediction comes to the end of the road, we do wrong to demand of science a "cause" of the individual quantum outcome.

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[5] Why not change "has a decisive consequence for ..." to "makes all the difference in the elementary quantum phenomenon"? The word "difference" is not allowable. We can do the one experiment or the other but the two experiments simply will not fit into one place at one time. We are dealing with one phenomenon, one "act of creation." The very individuality of the quantum phenomenon leaves no place for comparing what is with what might have been.

[6] For a discussion of this point I am indebted to Professor Andrew Gleason.

How did the universe come into being? Is that some strange, far-off process, beyond hope of analysis? Or is the mechanism that came into play one which all the time shows itself? Did the genius of Leibniz somehow sense the deep and secret underpinning of existence, the necessity that lies behind the strangeness of the quantum? Did he in the monad anticipate the quantum phenomenon? It does not matter.

Of all the features of the "act of creation" that is the elementary quantum phenomenon, the most startling is that seen in the delayed-choice experiment. It reaches back into the past in apparent opposition to the normal order of time. The distance of travel in a laboratory split-beam experiment might be 30 meters and the time a tenth of a microsecond, but the distance could as well have been billions of light years and the time billions of years. Thus the observing device in the here and now, according to its last minute setting one way or the other, has an irretrievable consequence for what one has the right to say about a photon that was given out long before there was any life in the universe.

To use other language, we are dealing with an elementary act of creation. It reaches into the present from billions of years in the past. It is wrong to think of that past as "already existing" in all detail. The "past" is theory. The past has no existence except as it is recorded in the present. By deciding what questions our quantum registering equipment shall put in the present we have an undeniable choice in what we have the right to say about the past.

What we call reality consists of a few iron posts of observation between which we fill in by an elaborate papier-mache construction of imagination and theory (Gombrich, 1961).

Useful as it is under everyday circumstances to say that the world exists "out there" independent of us, that view can no longer be upheld. There is a strange sense in which this is a "participatory universe."

Are billions upon billions of acts of observer participancy the foundation of everything? We are about as far as we can be today from knowing enough about the deeper machinery of the universe to answer this question. Increasing knowledge about detail has brought an increasing ignorance about plan. The very fact that we can ask such a strange question shows how uncertain we are about the deeper foundations of the quantum and its ultimate implications.

To encounter the quantum is to feel like an explorer from a faraway land who has come for the first time upon an automobile. It is obviously meant for use, and an important use, but what use? One opens the door, cranks the window up and down, flashes the lights on and off, and perhaps even turns over the starter, all the time without knowing the central point of the thing. The quantum is the automobile. We use the quantum in a transistor to control machinery, in a molecule to design an anesthetic, in a superconductor to make a magnet. Could it be that all the time we have been missing the central point, the use of the quantum phenomenon in the construction of the universe itself? We have turned over the starter. We haven't got the engine going.

Three features of nature more than any others provide the compulsion to analyze this large-number question.

First, the more we learn about the laws of physics, the more we learn how little we have learned. Electromagnetism, gravitation, and the Yang–Mills theory of the quark binding field (Yang and Mills, 1954), the yield of decades of research, hundreds of investigators, and thousands of experiments, turn out to be derivable from principles of almost trivial simplicity. One is the principle that the boundary of a boundary is zero (Misner et al., 1973). The other is the "principle of embeddability" of Hojman et al. (1973) —the requirement that fields and their momenta on a future timelike hypersurface must calculate out to the same value whatever the order of operations in pushing forward many-fingered time from the orginal hypersurface. The very simplicity of such "symmetry" considerations conceals the mechanism behind the laws of physics.

Second, the universe came into being in a big bang, before which, Einstein's theory instructs us, there was no before. Not only particles and fields of force had to come into being at the big bang, but the laws of physics themselves, and this by a process as higgledy-piggledy as genetic mutation or the second law of thermodynamics. There was no tablet of granite with the laws chiselled on it in advance!

There is a third reason why the ultimate building unit of existence—call it elementary quantum phenomenon or call it monad or call it what one will —has to be of an intangible and other-worldly character. That building unit and the building process itself have to transcend the category of time. In Einstein's 1915, still standard, battle-tested general relativity space-time is the classical history of space geometry undergoing its dynamical evolution with time. In quantum gravity (Misner et al., 1973, chaps. 43 and 44), however, the 3-geometry and its time rate of change are dynamically conjugate quantities. The uncertainty principle deprives one of any means whatsoever to attribute precise values to both quantities on the same spacelike hypersurface. Space-time, one comes to realize, is the classical theory of space evolving deterministically in time. Space-time as the history of a geometry can be compared with world line as the history of a particle. Both are classical idealizations. Both, quantum theory tells us, are wrong and no more so than at small distances and at small times. When one deals with regions of the order of magnitude of the Planck length, $L=(\hbar G/c^3)^{1/2}$ $=1.6\times10^{-33}$ cm, quantum theory says, the very ideas of before and after lose all meaning and application. Time is not a primary category in the description of nature. It is secondary, approximate, and derived.

So far as we can see today, no account of existence that presupposes the concept of time can ever account for either time or existence. Of all reasons for supposing that the elementary quantum phenomenon is indeed the proper building unit to consider, one of the most striking is the circumstance, as seen in delayed-choice experiments, that it reaches across time.

Contrast indeed there is between the building materials and the building plans of the computer and the universe.

4. DISTINGUISHABILITY AS A CENTRAL OPERATING PRINCIPLE OF THE COMPUTER AND OF THE UNIVERSE

A computer would be thrown out of a business office if it did not have enough precision to distinguish between a gain and a loss; and the very concept of "universe" would be impossible if there were not clearly distinguishable physical effects. "Distinguishability" is the without-which-nothing principle of computer design. Can distinguishability also be the central requirement for a comprehensible universe and, in some strange, unrealized way, the wellspring of the quantum principle? This question is not the central point of the fascinating doctoral thesis of Wootters (1980) but it is a motivation for his work and is alluded to there.

In Figure 2 (taken with permission from Wootters), the laser at the left is the tool of the sentry to signal to defense headquarters, via the two indicated counters miles to the right, the direction of arrival of the enemy. Inside the laser, "corked up," are a thousand photons of identical and adjustable linear polarization. The sentry turns the laser to the proper orientation and pulls the cork the instant he sees the direction of arrival.

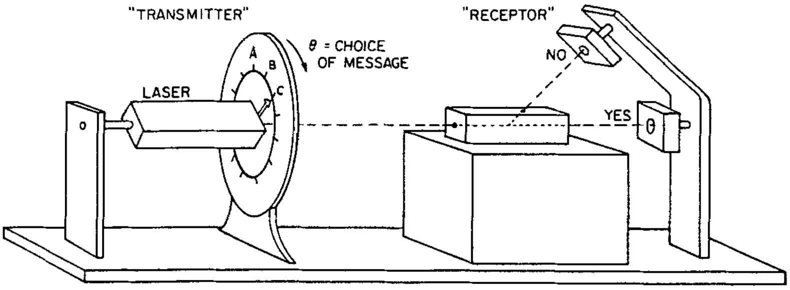

Fig. 2. Determining direction of polarization by measuring the relative number of "yes" and "no" counts (from W. K. Wootters).

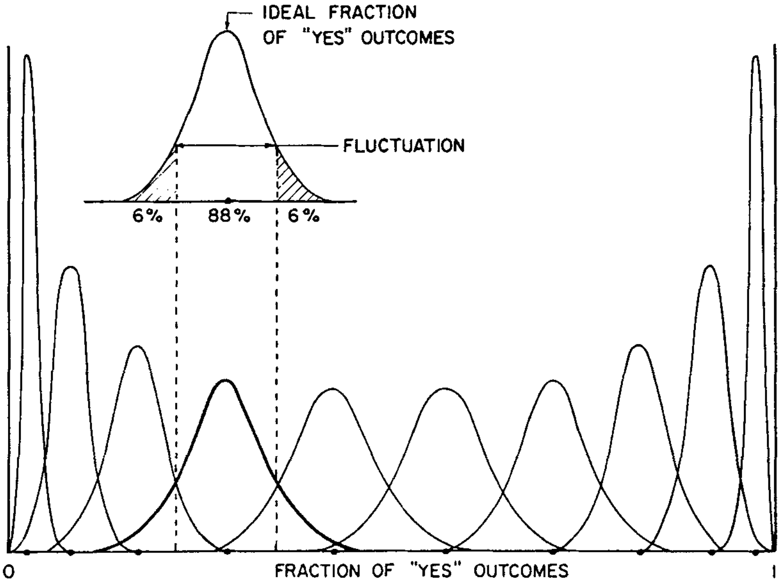

Fig. 3. Probability of this, that or the other number of "yes" counts for selected settings of the polarization of the photons from the laser in Figure 2 (from W. K. Wootters).

Photons on arriving at the Nichol prism, go to the "yes" counter and the "no" counter in the proportion of 600:400 if actuality follows expectation. Ordinarily it does not. There is a root mean square departure from ideality —in a large number of repetitions in a defense exercise—given by $(600\times 400/1000)^{1/2}=15.49$. This number tells how different the expectation value of the "yes" counts must be for another orientation of the laser if the two directions are to be distinguished reliably.

Wootters asks: How must the probability of a "yes" count depend upon angle, θ, of polarization if the defense system is to have the benefit of the maximum number of distinguishable directions? He formulates and solves this problem of the calculus of variations. The answer is simple. In a world with the maximum number of distinguishable possibilities the counting rate must vary as $\cos^2 n\theta$. Amazingly, nature is built just this way, with $n=\frac{1}{2}$ for electrons and neutrinos, $n=1$ for photons, and $n=2$ for gravitons. It is not clear *why* nature should want to provide the maximum number of distinguishable possibilities. It is only remarkable that this simple "distinguishability postulate" gives a standard result of quantum theory without ever once appealing to quantum theory.

Another issue of distinguishability for vividness can likewise be put into a defense context. I am the battalion commander. My general tells me that it is very important to know whether the enemy tribe that we face is the Thors (who are hopelessly committed to the opposing alliance) or the Eddas (who we stand a good chance of being able to win over by persuasion to our cause). None of us understands the language of either tribe. To distinguish them we have only the different proportion between blue and gray eyes in the two tribes (Figure 4). The general orders me to conduct a raid and bring back enough captives to tell him which tribe we face and tell him this with a dozen-to-one certainty. If I make a mistake I will be shot by the general, so I must take enough prisoners in the raid. But if I take too many my losses in the action will be great. A simple statistical analysis shows, according to Wootters, that I must take 16 prisoners.

The problem of distinguishing the Aeolians and the Boreans (again Figure 4), were they the enemy tribes, at first sight looks much more difficult because the difference between the two is much less than that between the Thors and the Eddas in the upper, linear, diagram where the axes are the probabilities p_1, p_2, and p_3 of gray eyes, blue eyes, and brown

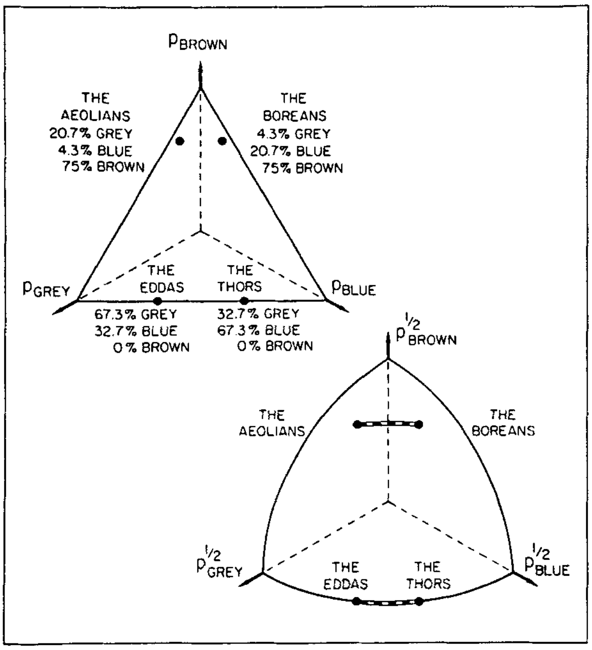

Fig. 4. Triangle above: probabilities of gray, blue, and brown eyes for tribes plotted in three-dimensional probability space. Quarter-sphere below: same information with axes measuring "probability amplitudes" (from W. K. Wootters).

eyes, respectively. In actuality, however, the same number of captives will suffice for the task.

When one replots the same statistical information about the tribes with axes that measure $p_1^{1/2}$, $p_2^{1/2}$, and $p_3^{1/2}$, what had been a plane triangle becomes a quarter of a sphere and the distinguishing separations measure out essentially to equality. In other words, the proper tool for the analyzing of distinguishability in this new context is probability amplitude, not probability itself—again a feature of quantum theory, without quantum theory.

More than half a century ago Fisher (1922), analyzing population genetics, discovered the simplicities to be achieved by describing the genetic make-up of a population in a space where the axes are square roots of probabilities rather than probabilities themselves. Wootters recognized the analogy to the Hilbert space of quantum mechanics. He went on to derive a result new to quantum theory: *distance in Hilbert space measures distinguishability* (Wootters, 1981).

Go further and *derive* quantum theory from considerations of distinguishability? No one sees how. No one even sees how to account for nature's use of complex-valued probability amplitudes rather than real ones or quaternions. However, unpublished work of Wootters reveals one tantalizing distinction between Hilbert spaces based on number systems of the three kinds. Consider a very large number of quantum states, dotted over the Hilbert space sphere with uniform density. To each quantum state corresponds one point on triangle in the probability space p_1, p_2, p_3 of Figure 4 or an appropriate simplex if the Hilbert space has a higher dimensionality. The distribution of points over this simplex is uniform if the number system is complex [Wootters relates this result to a finding of Sýkora (1974)], but for a real number system it is concentrated toward the borders of the simplex, and for quaternions toward its center. In other words, the number system of quantum mechanics is such—Wootters shows—that complete randomness over the Hilbert sphere gives complete randomness in the probability simplex.

Distinguishability has another feature; it implies measurement. Measurement—for an elementary quantum process—has only then been accomplished when, in Bohr's words (Bohr, 1958), the phenomenon has been "brought to a close" by an act of "irreversible amplification." Only then does the possibility exist to communicate the finding to another in "plain language" (Bohr, 1963).

Communication, in turn, is a precondition for the establishment of meaning [see, for example, Føllesdal (1975)].

It is impossible to give a meaning to the term *path of the photon* in the split-beam experiment of Figure 1 short of the registration of the photon by one or the other of the two counters. Moreover, that bringing of the phenomenon to a close could have been postponed by moving the counters further to the right and putting many more mirrors along the way. Similar postponement is possible in multiplexed Stern–Gerlach atomic-beam experiments on the orientation of a magnetic moment but in either case eventually there has to be an irreversible act if there is to be any meaningful result. In this respect this quantum world shows a striking analogy to the computer. As Bennett (1973) has shown [see also the precursor conclusion of Keyes and Landauer (1970)], it too in principle can be designed to be as close to reversibility as one desires. Again, however, the information wandering reversibly back and forth inside is devoid of meaning until it is captured at the end by an irreversible process. Evidently we must have an irreversible world if we are to have a world of distinguishability and meaning.

5. MORE IS DIFFERENT

Steady enlargement of number-processing capacity, from the abacus to today's computer, has brought a stepwise evolution of computer architecture. It has also forced a specialization in function within the computer—forseen by von Neumann (1958)—that recalls the limbs, sensors, and organs of an animal or particles, fields, and space-time of the universe. "More is different"[7] has long been a guiding theme of many-body physics. It is spectacularly appropriate for any complex form of life and any complex computer. Is it also the key to the structure of the world? There billions upon billions of "elementary quantum phenomena" or "elementary acts of observer participancy" come into play. Does the very monstrousness of these numbers force the specialization of structure and function that we call "physics"?

It is one thing to state these questions, but quite another to find a way to analyze them. In every other large-number problem we have entities that we can touch and rules for moving them around and a preexisting framework in which to do the moving. Here, however, we start with an almost terrifying austerity: no time, no space, and no law. The building element is the elementary "yes, no" quantum phenomenon. It is an abstract entity. It is not localized in space and time. Its interior is inscrutable, untouchable. The combinatorics of such entities is a new and rich problem. In considering this problem it is an encouragement to tell over one by one the fields of knowledge where other entities come into play in large numbers; but among

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[7] P. W. Anderson is thanked for this phrase.

them all it is difficult to name one with more relevant insights than the theory of computers and of information generally. Will we not sustain the tradition of Leibniz, Kant, Mach, Gödel, and von Neumann if we suppose that we will someday understand "physics as information"[8]?

Planck's discovery of the quantum in 1900 drove a crack in the armor that still covers the deep and secret principle of existence. In the exploitation of that opening we are at the beginning, not the end.

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[8] This phrase used by E. Fredkin at the conference where this paper was given.

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