NEW TECHNIQUES AND IDEAS IN QUANTUM MEASUREMENT THEORY

Editor and Conference Chairman
DANIEL M. GREENBERGER

Conference Organizing Committee
OLIVER COSTA DE BEAUREGARD, LLOYD MOTZ, ABNER SHIMONY, and ANTON ZEILINGER

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WHENCE THE NECESSITY OF THE QUANTUM?

The quantum, foundation principle of twentieth century physics, and indispensable working tool for anyone who would make reliable predictions in the world of the small, still comes to many as strange, unwelcome, forced on man from outside against his will. The necessity of the quantum in the construction of existence: out of what deeper requirement does it arise? Behind it all is surely an idea so simple, so beautiful, so compelling that when—in a decade, a century, or a millennium—we grasp it, we will all say to each other, how could it have been otherwise? How could we have been so stupid for so long?

It was not by asking always small questions that physics has achieved its astounding advances. It will surely not be by asking always small questions that the community will some day find the answer to the great question, “How come the quantum?” To ask the right question, however, one must have, as is well known, some glimmer of the answer. It is also old experience that in order to break out of blank puzzlement and into the right question-and-answer circuit, one must try and try again. One must, if necessary, make a fool of oneself many times over, thus following the example of the engine inventor, John Kris, with his familiar words about each new model—“Start her up and see why she don’t work.”

What are the features and difficulties of a recent model, “existence as meaning circuit”? First, let us look at the model, then at the problems.

THE MEANING MODEL: A PARTICIPATORY UNIVERSE

Physics gives rise, as depicted in Figure 1, to light, pressure, and sound. They provide means of communication, of the importance of which Niels Bohr notes, “...every analysis of the conditions of human knowledge must rest on considerations of the character and scope of our means of communication.” Physics is also the foundation of chemistry and biology, out of which arise communicators. Communicators plus means of communication permit the development of meaning in the sense elucidated by leading English and American schools of philosophy in recent decades, as summarized, for example, by D. Føllesdal: “Meaning is the joint product of all the evidence available to those who communicate.”

From meaning back to physics, the circuit under examination makes its way by a less apparent or underground sequence of linkages. Meaning rests on action. Action forces the choosing between complementary questions and the distinguishing of answers. Distinguishability, in the realm of complementary possibilities, demands for its measurement complex probability amplitudes. The change in the phase of a complex probability amplitude around a closed circuit not only measures the flux of field through that circuit, but can even be regarded as the definition and very essence of that field. Fields, in turn, can be viewed as the building stuff of particles; and fields plus particles generate the world of physics with which the hypothesized meaning circuit began.
look at it? Does one glance of the eye take in $10^9$ bits of information? Are we then asked to write a paragraph on what we have seen, or are we required otherwise to display the evidence upon which we act? Do we find that out of a melange so great, the brain has squeezed an amount of information—even at best—that is so small as $10^3$ or $10^6$ bits? Then, in everyday affairs, we are evidently very far away from the level of the elementary quantum phenomenon. In spite of all the mystery about how the brain accomplishes this action-oriented miracle, though, we know that every bit of information, every item of sight or touch or sound, goes back in the last analysis for its transmission to elementary quantum phenomena.

The elementary quantum phenomenon displays two characteristic features: (1) complementarity in the choice of the question and (2) statistics in the distinguishing of the answer. The split-beam experiment of FIGURE 2 illustrates both. Light arriving from the left is split at the first half-silvered mirror. It is then reflected at the upper or lower totally silvered mirror, and is detected on a photon-by-photon basis by the two counters at the right. We can ask which path does an arriving photon follow—the high road or the low road? That is one choice of question, and the photon detectors stand ready to answer it. To ask for the phase relation between the two beams is a complementary choice of question. To pose this question, we install a second half-silvered mirror at the point of crossing of the two beams and determine the relative counting rate of the two photon detectors.

Shall we install the second half-silvered mirror or shall we leave it out? We cannot do both. Not until we make that decision have we chosen what question to ask. To ask both phase and route at the same time and in the same experiment is impossible.

The choice can be delayed 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. This circumstance shows how wrong it is to say that we are finding out in the one case “which route” and in the other case the relation of phases in a “two-route mode of travel.” The world is built in such a way that it denies us the possibility to speak in any well-defined way of “what the photon is doing” in its travel from point of entry to point of reception.

Distinguish from what? “There is no such thing as a fact,” it has been said; “there is only a fact for a purpose.” Exaggerated as this statement may be, it nevertheless points to the why of distinguishability: action. Answer A advises one action; a distinct answer, B, advises a very different action. Sometimes the statistics do not suffice to distinguish with the requisite certainty which is the answer. Then more measurements, and more certainty. Sometimes there is not enough time to secure those points to the why of distinguishability: action. Answer A advises one action; a distinct answer, B, advises a very different action. Sometimes the statistics do not suffice to distinguish with the requisite certainty which is the answer. Then more measurements, and more certainty. Sometimes there is not enough time to secure those extra counts. Then the upcoming decision of how to act has to be taken with an unacceptable risk. In brief, it is difficult to see how distinguishability can have any possible point except against a background of action.
A PROBABILITY AMPLITUDE AND ONE THAT IS COMPLEX: HOW COME?

For the quantitative determination of distinguishability, the statistician and geneticist, R. A. Fisher, taught us as long ago as 1922 that the wrong number is the probability of a yes or a no in an example like ours, or the probability of blue eyes, grey eyes, or brown eyes in a population-characterizing example like his. The right number, he showed, is the square root of the probability of this, that, or the other outcome, or is, in today's words, the probability amplitude of the specified answer. As descriptor of a run of counts, Fisher thus gave us a point (with all its Cartesian coordinates positive) on the surface of the unit sphere in the space of real numbers—a point in a real Hilbert space. The dimensionality of this space is equal to the number of distinct outcomes for the individual count: two for the split-beam experiment, and three for the illustrative example of the eye colors.

According to 1980 extension of Fisher's results by the quantum physicist, William K. Wootters, the potential distinguishability of two nearly identical sets of experimental results, or between one of results and a nearly identical ideal set of results that might serve as a signal to action, is measured by the angle, θ, in Hilbert space between the two probability-amplitude vectors. Here, the "potential distinguishability" is the quantity that has to be divided by the familiar factor, the square root, N/\sqrt{2}, of the total counts, N, so as to obtain the actual distinguishability parameter, θ = θ\sqrt{N}. This parameter (by way of the Gauss function) tells us, for example, that we run odds of 1,680,675 to 1 of being wrong if, when having observed 800 yes counts and 600 no counts in the split-beam experiment, we nevertheless proceed to bet on a phase-shift between the two beams of 90 degrees rather than 81.79 degrees.

How come is it that quantum mechanics, reaching as it does beyond Fisher's genetic concerns, gives us probability amplitudes that are not real, but complex? No one put his finger earlier on the decisive point than E. C. G. Stueckelberg.14 Probability amplitudes that are exclusively real are incompatible, he showed, with Heisenberg's principle of indeterminism, or, in our translation, with Bohr's principle of complementarity: namely, the freedom to choose, and the necessity to choose, which question we will put to nature.

So much for the sense in which the double demand of complementarity and distinguishability leads to the heart of quantum theory, the complex probability amplitude.

THE CHANGE IN THE PHASE OF A PROBABILITY AMPLITUDE AROUND A CLOSED CIRCUIT AS THE ULTIMATE DEFINER AND ESSENCE OF FIELDS AND SPACE-TIME GEOMETRY

The difference in phase of an electron's probability amplitude around a closed circuit (brought about by a flux of magnetic field through the area bounded by that circuit) shows up in the shift of the pattern of double-slit interference fringes. The idea and the experiment were proposed in 1959 by Y. Aharonov and D. Bohm.17 This AB effect is by now observationally well established. Likewise, for gravity and for every other gauge field, we have reason to believe18 that the phase difference in the relevant probability amplitude around a closed circuit provides a way to define and measure that field. The meaning-circuit model translates this conclusion to a new and stronger proposition: Neither field nor geometry has any existence or significance except insofar as it is defined, directly or indirectly, by such phase differences.

The Closure of the Meaning Circuit

With particles owing their definition and existence to fields, with fields owing their definition and existence to distinguishability and complementarity, and with these features of nature going back for their origin to the demand for meaning, we have exposed to view (at least in broad outline) the main features of the underground portion of the model of existence as a meaning circuit closed by observer-participancy.

Before this would-be model can ever rise to the status of a proper model and be subject to quantitative analysis, some questions and difficulties require clarification: (1) What reality does the model ascribe to the physical world before the advent of any meaning-making community? (2) In what respect does it differ totally from the familiar anthropic principle on the issue of why the dimensionless constants of nature have the values they do? (3) What are we to understand by such a term as the community character of meaning? (4) What is the status of an elementary quantum phenomenon that is not put to use in the establishment of meaning? (5) How are we to reconcile the continuum of the world of physics with the discrete yes-or-no character of elementary quantum phenomena? (6) How can we ever hope to quantify meaning? Finally, (7) why a meaning circuit? Why any closed loop at all?

It is appropriate now to take a closer look at these seven questions, of which every one has been suggested by our original query, "How come the quantum?"

Millennia without Meaning before the Advent of the Meaning Makers?

Question one: If life and mind and meaning are so important in the scheme of things, then what is the status of the past? Do the early revolutions of the Milky Way, the building of the elements, and the formation of the elementary particles—all before the advent of life—rank lower in reality than today's wind, snow, and shiver? No. Through the photons that reach the telescope, we see more clearly a quasar event of six billion years ago (before there was any life anywhere) than we can perceive the three-encyclopedia-long sequence of bits in our own DNA, in the here and now.

Does the past exist (and exist only) in the records of the present? If so, then the past ranks no lower and no higher than the rest of what we call existence. In the words of Torgny Segerstedt, "reality is theory."

The quantum brings a new insight, however, to this old conclusion. What is the polarization of that photon that reaches the eye today from a quasar flash of six billion years ago? Is it north-south? Or is it NE-SW? Not until we have set the analyzer to the one orientation or the other have we asked the question. Not until the one or the other of the appropriately paired photodetectors (the yes-counter and the no-counter) clicks have we distinguished an answer. Not until then do we have the right to attribute a polarization to the received photon. This is the respect in which we ask, or do, in
the present has an inescapable consequence for what we have the right to say about the
past—even a past long before life. This is the sense in which (through the quantum-
level questions we put to nature) we are participators in the making of what we call
reality.

To turn from the past to the future is to encounter deeper issues. What is the status
of a quantum event so far away that the asking of a question about it and the
distinguishing of an answer take place only one hundred million years from now when
man has been supplanted by, or has evolved into, intelligent life of quite another form?
To attribute a reality to that event now would seem to be premature.

Shall we compare space-time to a great sheet of sandpaper? Shall each glittering
glued-down grain represent an event deterministically fixed in space, fixed in time, and
fixed in character? What a misleading model of existence! How contradictory to
existence, or what we call reality. Those make-believe universes totally devoid of life
cannot be observed, but because there is no way to make them.

Why Are the Dimensionless Constants of Nature Such as to Permit Life?

Question two: How does it come about that the universe ever makes a home for life,
mind, and meaning? Many upholders of the anthropic principle propose one answer,
which is based on selection. The concept of observer-participancy suggests quite
another, which is founded on construction. Both analyses note that life as we know it
(not only human life, but any carbon-based life) would be forever impossible in a
universe (if such a universe can be imagined) in which one or another of the basic
dimensionless constants of physics differs by a few percent either way from its value
here. Both take as a starting point the 1957 postulate of Robert H. Dicke that the
Weyl-Eddington-Dirac coincidences between the large dimensionless constants of
physics [cf. reference 19, chapter 4] “were not random, but conditioned by biological
factors.” The one account envisages an infinite ensemble of universes, one differing
from another in the dimensionless constants of physics, with life totally impossible in
the overwhelming majority of these systems. Life, mind, and meaning have only a
peripheral and accidental place in the scheme of things in this view. In the other view,
they are central. Only by their agency is it even possible to construct the universe or
existence, or what we call reality. Those make-believe universes totally devoid of life
are (according to this view) totally devoid of physical sense not merely because they
cannot be observed, but because there is no way to make them.

The Community Character of Knowledge

Question three: Are there then as many pasts, as many presents, and as many
futures as there are observer-participants? A proposal so extravagant overlooks the
community character of everything we call knowledge. Already at the quantum level,
Niels Bohr warns us of the folly of trying to construct a “quantum language.” He
emphasizes that no measurement is truly a measurement unless the result can be
communicated from one person to another “in plain language.” In a wider context, we
know that meaning itself would be impossible without communication. There is not a
word we speak, a concept we possess, or an idea we conceive that is not rooted in the
larger community.

In one of her many wonderful writings, Marie Sklodowska Curie tells us that
physics deals with things only—not people. Today, the quantum forces on us a
different outlook. It tells us that existence is not a deterministic machine grinding away
out there. It is senseless for the uninvolved to try to speak in abstracto of what is
happening out there at the microscopic level. Involvement is essential: observer-
participancy. Not until a choice has been made and not until one or another
complementary question has been posed can there be an answer.

The Elementary Quantum Phenomenon That Is Not Put to Use: Does It Count?

Question four: What significance, if any, are we to attribute to an elementary
quantum phenomenon that is not put to use to establish evidence and meaning? Despite
all that we know about measurement theory in the realm of the quantum, nothing is more
puzzling than the linkage between the counter’s click and the community that makes meaning. An example will illustrate the problem. A detector, by its irreversible act of amplification, its pulse of current, and the registration of that
pulse, brings to a close an elementary quantum phenomenon. However, the apparatus
is mounted on a space probe traversing the rings of Saturn. A moment later, before the
equipment can beam its message back to earth, a boulder smashes it to atoms. All
opportunity vanishes for the quantum process to contribute to the establishment of
meaning. An event has taken place, but not an event that is put to use.

As a second example, consider a crystal of zinc sulfide thrown up by nature on the
back side of the moon. It stops a cosmic-ray proton. Ten million photons emerge, which
is an irreversible act of amplification if there ever was one. The signal, however,
dissipates out into space. No use is made of it.

In both examples of quantum events not put to use, the amplifying device consists
of some 10^{22}—10^{23} particles coupled by a complex of electromagnetic interactions. Why
should we attribute to those unused elementary quantum phenomena any special
significance whatsoever? Surely all over the universe, in regions out of sight, interactions are going on all the time and between particles that are stupendous in
number compared to the count in our two examples. Amidst that tumult, there is many
a concatenation that on anyone’s bookkeeping must count as an elementary quantum
phenomenon that was brought to a close by an irreversible act of amplification. Not
one of these collective electromagnetic twitches is deprived of the status of “phenome-
non” through its lack of all of the credentials of today’s laboratory equipment: no
copper wire, no manufacturer’s trademark, no silicon chip.

There is no irreversible act of amplification that may not later be erased. Not
unless it is put to use in the establishment of meaning does the elementary quantum
phenomenon win any special status. To attribute a unique importance to those
elementary quantum phenomena that happen to be observed appears, however,
unbelievably anthropomorphic, totally anti-Copernican, and utterly in contradiction to
the spirit of physics. Does it diminish the objection to recall that the population of
Africa increases by a million every three weeks? Or to reflect that the number of
observer-participants a millennium from now may well be orders of magnitude greater
than it is today? Or to count on numbers of intercommunicating observer-participants
billions of years in the future still greater by many orders of magnitude? Or to
recognize the role of the elementary quantum phenomena that they observe in establishing what we call the reality of the here and now?

To say that this concept of a participatory universe, built on a meaning circuit, is anti-Copernican is not of much help in arriving at a rational judgement of it. It is more to the point to recognize its difficulties and incompleteness. To speak of difficulty is to come to the problem of the continuum.

The Continuum as an Elaborate Construction of Imagination and Theory That We Build by Surfacing-Over the World of Elementary Quantum Phenomena

Question five: How can we possibly imagine building the continuous world of physics on the yes-or-no of quantum phenomena, no matter how numerous they are? Physics, after all, presents to us a continuous infinity of locations for particles, a continuous infinity of field strengths, and a continuous infinity of degrees of freedom of dynamic space geometry. To construct all that out of the discrete is totally impossible.

It is one of the great achievements of the mathematics (and mathematical logic) of recent decades to destroy belief in the existential character of the continuum of natural numbers. It is an illusion. It is an idealization. It is a dream. With numbers of ever increasing mathematical sophistication, we can approach that limit ever more closely; however, we commit a folly if we think we can ever get there. This lesson of the mathematics of our time carries for physics an inescapable consequence. What we think of at the bottom as a world of the continuous simply is not there.

The concept of the participatory universe replaces the continuum. For the "R" of what we call reality, it gives us a few iron posts of observation, built on elementary quantum phenomena, between which we ourselves troll in a continuum of paper-mâché and of plaster of Paris, an elaborate construction compounded of imagination and theory. In no other way do we know how to reconcile the continuum of everyday impressions (and of long-established physics) with the discreteness of the means by which alone, in the last analysis, we acquire our knowledge. How else can the appearance of a continuum arise except by our own surfacing-over the discrete?

How Are We to Quantify Meaning?

Question six: How can we possibly use the concept of "meaning" in any well-defined way in the world of physics when the world of philosophy gives us for that term a definition totally deprived of any quantitative handle? Bit? We know what that is. Information capacity of a communication channel? That, too, we know how to define and measure. But meaning? Neither a physics-minded definition nor a way of measurement is available.

If the motto is correct that every difficulty is an opportunity, then there is no better place to apply it than "meaning." Happily for such an enterprise, we know that the view of science that used to say, "define your terms before you proceed," is totally out of date. Nowadays, we recognize that all the laws and theories of physics have this deep and subtle character, that they both define for us the needful concepts, and that they make statements about these concepts. Contrariwise, the absence of some body of

Why a Circuit Rather than a Foundation?

Question seven: Why speak of a circuit? Why not seek instead for a foundation? There is an old legend about the foundation that supports the world: Our globe rests on the back of a great elephant. The elephant stands on the back of a giant tortoise. A lady in the audience, listening to the speaker's account of this idea, asks, "On what does the tortoise stand?" "On the back of a still larger tortoise," she is told. "And what does it stand on?" she inquires. The lecturer's reply is famous: "Tortoises, madam; on and on and on, nothing but tortoises."

How different is the account we give today of the foundation of existence? Matter is built on molecules. The molecule is built on atoms. The atom has a nucleus. The nucleus is built on nucleons. The nucleon is built on quarks. The quark is built on fields. The field is built on geometry of one or another dimension. At each stage of the unfolding story, at each clear view of one turtle, we have had to look for the next turtle. Is there ever to be an end? How can there be an end if we ask always for foundation of foundation of foundation...? No escape is evident from this view of worlds without end—or tortoises without end—except in a line of influence that closes on itself, that forms a loop, that makes a circuit. No model for such a loop is available to us today except one of information-theoretic character, the model of existence as a meaning circuit.

SURVEY OF THE DIFFICULTIES OF THE MEANING-CIRCUIT MODEL

The model under analysis here accepts that the meaning-creating community of observer-participants, past, present, and future, is brought into being by the machinery of the world. However, it goes on to interpret this very world of past, present, and future, and of space, time, and fields, to be (despite all its apparent continuity, immensity, and independence from us) a construction of imagination and theory troweled and plastered in over countably many elementary quantum phenomena, surfaced over the iron posts of discrete acts of observer-participancy, the anti-like but magnificent labor of a community stretching from far in the past to even farther in the future.

The worst model of existence that we possess today is surely one so oriented as this to observer-participancy, information, and meaning. It is the worst, except we possess no other model that puts in central place the quantum and the question of "how come the quantum?".

Is spacetime an illusion? Time itself not primordial, precise, and supplied from outside physics, but secondary, approximate, and derived (as elasticity is in today's bookkeeping)? Repelled we may be in the beginning by the thought of giving up the
The central principle of algebraic geometry, that identity which states that the
smoky dragon whose tail is sharply defined, whose bite is also well marked, but which
in between cannot be followed? What better reason is there to say that something
cannot be followed than to recognize that there is nothing there to follow? And thus to
ascribe to multitudes of elementary quantum phenomena those null intervals that tie
existence together so tightly?)

No continuum (and mathematical logic denies the concept of the continuum)
means no dimensionality; neither four nor ten nor any higher number. Moreover, only the
feature of a description of nature that could be worse than no dimensionality at all
would be a dimensionality.27 To confront a number, to ask why this number rather than
another number, is to be forced to seek a foundation, after which comes another
foundation question, and then yet another, and so on and on: nothing but turtles.
Can we formulate the laws of physics without recourse to the continuum? We do
not know how. That is perhaps the most conspicuous difficulty of the meaning model.
1. Is the problem soluble? There is one favorable indication. The laws of electrodynamics,
the quantum. In confronting that challenge, we can perhaps gain a little courage from
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the famous adage of Philip W. Anderson: "More is different."


22. To Frank Tangherlini, Physics Department, Holy Cross College, Worcester, Massachusetts, the author is indebted for a look at the extensive bibliography he has collected on the changing views over the years as to why the world has 3 (+1) dimensions.


