3. WHY MATTER ALONE IS NOT ENOUGH!

"Nonlocality gets more real". This is the provocative title of a bulletin in a recent issue of "Physics Today." It reports some experimental results that imply that causal influences must in some cases act over large distances faster than the speed of light. These experiments, carried out in Switzerland, are similar to many others performed over the past thirty years, but they are more spectacular because the distance involved was not just a laboratory interval of a few meters, but a geographic separation of more than ten kilometers. The results of these experiments are incompatible with the materialist conception of nature that ruled science from the time of Isaac Newton until the dawn of the twentieth century. There is a theory that perfectly describes all of these experimental results, but it is based on a non-material conception of the universe, and a new kind of mathematical law.

According to Einstein's theory of relativity, any faster-than-light action would be, from some point of view, instantaneous. But instant transfer of information is anathema to many scientists, on aesthetic and intuitive grounds. Of course, Newton's theory of gravity postulated a force that acted with no time delay over a planetary scale, and gave no hint of what was transmitting this action. His theory was severely criticized on that account, and even Newton himself was troubled by this feature. In a letter to his friend Bentley, he expressed his own skepticism about unmediated force, and by implication, I think, about any sort of instantaneous action at a distance:

",…that one body may act upon another at a distance
through a vacuum, without the mediation of anything else, by
and through which their action and force may be conveyed
from one to another, is to me so great an absurdity, that I
believe no man, who has in philosophical matters a
competent faculty of thinking, can ever fall into it. Gravity
must be caused by an agent acting constantly according to
certain laws, but whether this agent be material or immaterial
I have left to the consideration of my readers."

Newton had, in fact, made huge efforts to find a satisfactory physical explanation of this force, but failed. More than two centuries later Einstein explained gravity as being due to the warping of space-time by the presence of matter. According to this theory, the gravitational effect is indeed conveyed from point to point by a local contact interaction that transfers information no faster than the speed of light. Thus Einstein achieved what Newton had intuited, the abolition of instantaneous action at a distance. His theory of relativity implied, moreover, that *no physical influence of any kind* could act faster than the speed of light.

But why should we be concerned here with this rather esoteric question of whether faster-than-light influences exist? Our topic is human beings, and their place in the causal structure of Nature. On the time scale of biological processes in human brains and bodies the speed of light is so fast as to be essentially infinite anyway. So why worry about this seemingly irrelevant question?

There are three important reasons.

The first concerns the constitution of the world: the question of what the world is made of. Neither matter nor energy can travel faster than the speed of light. Nor could anything else in a world composed of matter and energy alone. Thus the proved existence of such influences is a compelling and easy to understand reason to abandon the tenets of materialism, and move on to the more adequate quantum framework, which is relies on a causal interplay of the idea-like and matter-like properties of nature.

The next reason pertains to size. It is often argued quantum theory concerns only very small-scale phenomena, and hence can be ignored when dealing with something as big as your brain, or even a neuron in your brain. But the faster-than-light quantum effect entailed by the Swiss experiment acts over a distance of more than ten kilometers: quantum effects are obviously not confined to small regions. Indeed, in the von Neumann formulation of quantum theory to be adopted here there is a brain-sized event associated with each of your knowings: with each of your experiential graspings of a meaning. These macroscopic brain events enter dynamically, by means of a well understood quantum process that has no classical analog, into the formation of your thoughts and actions.

The final reason concerns *understanding*. In the book *John von Neumann and the Foundations of Quantum Physics* the philosopher Wesley C. Salmon, in a contribution entitled *Scientific Understanding in the Twentieth Century* begins his section on "The Possibility of Scientific Explanation" with the following paragraph:

"Between the triumph of the atomic theory of matter early in the century and the middle of the twentieth century it would not have been incoherent to claim that we can *describe* the nature and behavior of atoms, molecules and subatomics particles, and that we can make successful predictions on the basis of such knowledge, but to deny that we have achieved anything that deserves the honorific title of explanation or understanding. To appreciate the transition from that position to our *fin de siecle* confidence in the possibility of scientific explanation and understanding, we must turn to the work of philosophers."

He goes on to say that "According to an old doctrine, going back at least to Aristotle, we seek to know, not only *what*, but also *why*."

Salmon is contrasting here to two different ideas of science. One claims science is only about *knowledge*, *description,* and *prediction*; whereas the other says science can provide also *understanding*.

During the first fifty years of the twentieth century the ascendant position of philosophers of science was the first view, but now, according to Salmon, philosophers are coming back to the old idea that science can provide also understanding. That shift supports, philosophically, the aim of this book, which is to provide not merely a description of the quantum world, but also an understanding of it.

It is probably not coincidental that the ascendant views of philosophers during that first half of the century dovetailed with those of the quantum physicists. The essential core of Bohr's message was precisely that scientists should focus on *knowledge*, *description*, and *prediction*, and forego the endeavor to *understand* in terms of traditional concepts and categories.

But why should scientists, of all people, have abandoned the effort to understand nature?

The reason is clear: Quantum theory, as a mathematical structure, is built on the idea of non-microscopic events and instantaneous actions. Yet the scientist were reluctant to admit that such things could actually exist: they preferred abandoning understanding, to abandoning locality However, if understanding is ever to be achieved, non-locality must surely be acknowledged.

No reasonable person should accept on hearsay a revolutionary new idea of reality that overturns everything that has been believed for generations, and is, moreover, wildly counter-intuitive: might not the physicists who are setting forth this "craziness" be carried away by enthusiasm, or be so beguiled by the power of their mathematical tools that they lose touch with reality. This abrogation of the formerly well established science has such far-reaching consequences that serious thinkers need to understand for themselves the empirical evidence and its logical implications. I shall therefore describe here the experiment performed in Switzerland by members of the Applied Physics Group of the University of Geneva, and then explain how their results contradict the basic idea that Nature is built of matter and energy alone.

The general idea of the Swiss experiment is this: A sequence of pairs of photons is generated in Geneva, and one member of each pair is sent by optical fiber to the village of Bellevue, and the other is sent to Bernex. In each village a random choice is made to perform one or the other of two alternative possible experiments. Each performed experiment gives a result Yes or No. But the operations are all carried out so fast that the information about which random choice is made in a village cannot, even by traveling at the speed of light, get to the other village before the result appears there.

It needs to be emphasize is that the experiment does not demonstrate a direct "mechanical" influence of the choice made in one regions upon the result appearing in the other. The situation is more subtle than that. A "mechanical" influence would be one such that, for an *actually performed* sequence of measurements in the two villages, the answer Yes or No appearing in one village is correlated to the choice made in the other village. (For example, each time the "first" possibility is chosen in one region the result "Yes" appears in the other region, and each time the "second" choice is made the result "No" appears.) Such a correlation, if it existed, could be used to send a telegraph message from one village to the other faster than light. But the possibility of sending such messages faster-than-light is strictly excluded by quantum theory. Correspondingly, the existence of such a "mechanical" faster-than-light influence is not what this experiment demonstrates!

Classical physical theory imposes, however, also a stronger no-faster-than-light condition. Because all casual connections are carried by matter or energy the theory allows no influence of the choice made in one village on the outcome of *either one of the two experiments that could be chosen in the other village.* It is this stronger condition that is incompatible with the predictions of quantum theory confirmed (to within the limits imposed by the experimental exigencies) by the Swiss experiment.

I turn now to a more detailed description of the Swiss experiment, and to the proof of the violation of this no-faster-than-light condition. Readers more interested in general ideas than in detailed proofs can skip at any time to the last paragraph of this chapter without loss of continuity.

The initial phase of the Swiss experiment occurs at a lab in downtown Geneva. A pair of associated twin photons is born there. This birthing is achieved by directing a laser beam at a crystal. Most of the laser light goes through the crystal, but each laser photon in a small subset is split into a pair of photons, with each member of the pair carrying about half the energy of its laser-photon parent.

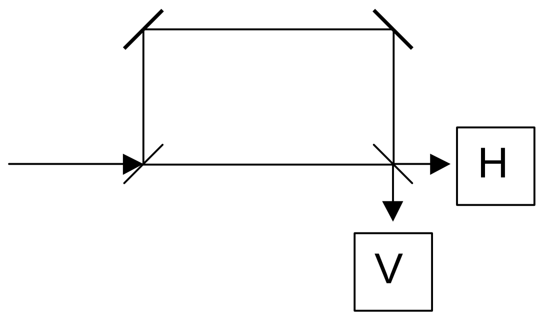
For some of these pairs one partner is sent by optical fiber to a lab in the village of Bellevue, while the other partner is sent to a lab in the town of Bernex. These two labs lie more than ten kilometers apart.

At each lab the arriving twin is sent into an "interferometer".

Interferometers are, themselves, very interesting devices, and they need to be understood if the experiment is to be made clear.

There are different kinds of interferometers. To simplify the explanation without altering the principle I shall consider one that is slightly different from what was used in the Swiss experiment.

This interferometer involves two ordinary (i.e., fully silvered) mirrors, each of which reflects all the light falling on it, and two half-silvered mirrors. In half-silvered mirrors the layer of silver is so thin that it reflects (like a mirror) only half the light incident upon it, and transmits (like a plate of clear glass) the other half.



AN INTERFEROMETER

[*The light enters the device horizontally, and eventually exits either horizontally, or vertically downward. Photon detectors H and V signal the emergence of the photon in the horizontal and vertical exit beams, respectively. The two 45 degree slanted lines on the lower side of the rectangle represent half-silvered mirrors, the two upper 45 degree slanted lines represent fully silvered mirrors. Thus half the light takes the short direct path between the two half-silvered mirrors, whereas the other half takes the longer roundabout path. Each detector, H or V, gets half of its light via the direct path and half via the roundabout path*.]

Experiments with an interferometer of this kind reveal an interesting "interference" phenomena: the fraction of the photons detected in detector H depends upon the *difference between the lengths of the two alternative paths available to the photon;* i.e., on the *difference* of the lengths of short (direct) and the long (roundabout) paths between the two half-silvered mirrors. This fraction can easily be computed by imagining the photon to be a wave, like the wave on the surface of a pond. This wave divides at the first half-silvered mirror into two parts, which move along the two different paths to the second half-silvered mirror. At the second half-silvered mirror the direct and roundabout parts of the wave are reassembled, and one reconstituted combination is sent to H, and the other reconstituted combination is sent to V.

The wave consists of a long regular sequence of crests and troughs, and the "wavelength" of the light is distance between successive crests. The key point is that the laws of wave optics say that the process of reflection off of a slanted 45 degree (half-silvered or fully-silvered) mirror *shifts the crest* of the reflected wave *backward by one quarter of a wave length*, relative to the geometric distance traveled by the wave. *Transmission* through the half-silvered mirror generates no such shift.

The wave in, say, the horizontal exit beam will be the sum of a part coming via the direct path and a part coming via the roundabout path. Suppose that the difference in the lengths of these two paths is an integral (i.e., whole) number of wave lengths. Then, *without the quarter-wave-length shifts associated with the reflections*, the crests of the waves in this exit beams that come via the direct and roundabout routes will exactly coincide: the extra distance traveled by the light that takes the roundabout path would not produce any *net shift* in the position of the crests, relative to the wave that takes the short path, because a shift by an integral number of wave lengths just shifts each crest into coincidence with another crest. Thus the contributions from the long and short routes would, after being recombined at the second half-silvered mirror, be exactly "in phase." The same would be true in the vertical exit beam.

But when the shifts at the 45 degree reflections are taken into account the situation is more interesting. Consider first the light that goes to the detector H. The light that travels the roundabout route to the detector H is reflected four times and hence will have its crests shifted by four quarter wave lengths (which add up to one full wave length). The light that travels the short direct route is not shifted at all. Since a shift by a full wave length keeps the crests aligned, the part going to H via the roundabout route will be completely in phase with the light going to H via the short (direct) route. Thus there will be *complete constructive interference* between the two parts of the wave that go to H.

But consider next the two parts that go to V. The wave going via the roundabout path to V is shifted backward by three quarters of a wave length, whereas the wave that goes via the short path to V gets shifted backward by one quarter of a wave length (because it is *reflected* only once.) Therefore the relative shift is seven quarter wave lengths minus one quarter wave length. This is six quarter wave lengths, or one and a half wave lengths, which is equivalent to a half wave length, since a shift by a full wave length keeps the crests aligned. But a half wave length shift moves each crest of one part onto a trough of the other part, and the two waves will cancel each other out. Thus there will be complete destructive interference: no light will go to V. This "wave optics" calculation matches the empirical facts.

Thus if the difference in the lengths the long and short path lengths is an integral number of wave lengths of the light, then *all of the photons* will get detected in H, and none in V. But if, say, the roundabout path is now lengthened by a half wave length the situation will be reversed and all of the light will go to V and none to H.

These wave optics calculations are easy to do, and to understand, and they give predictions about the fractions of the light going to H and to V, respectively, that are in full accord with experiment. These results demonstrate clearly the wave nature of light. This wave nature persists undiminished even when the beam is attenuated so strongly that two photons are never (or at least hardly ever) in transit at the same time.

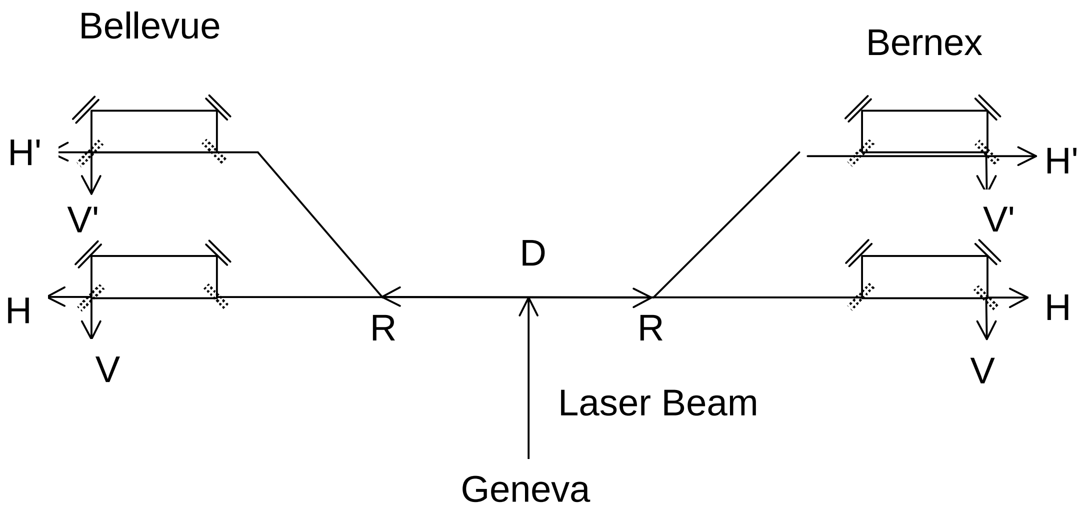
Having thus establishing the wave nature of the light we arrive at an interesting puzzle! If one places detectors in the two paths just *before* they reach the second half-silvered mirror, then for each photon that enters the interferometer *only one or the other* of the two detectors will fire, never both. This seems to show clearly that the photon travels *along one path or the other*, not both.

But how can one reconcile this particle-type (single-path) behavior with the empirically validated wave-like behavior just described, which depends upon the interference between the light that travels the two paths?

This problem is, of course, the famous "wave-particle duality" puzzle.

The simplest answer is to assume that there is both a "particle of light", the photon, *and* a wave. The wave obeys the laws of wave optics, but also *guides* the photon to places where the waves interfere constructively, and away from places where the waves interfere destructively. So there is no really serious problem at this one-photon level. It is only when one considers *two paired photons* that a real puzzle arises.

So let us return to the Swiss experiment. In that case there are two interferometers in each village, and hence four altogether.



THE EXPERIMENTAL SET UP.

[*The laser beam is split at D. The two R's indicate the two random processes, each of which randomly sends the photon that arrives in its laboratory to either the "upper" or the "lower" of the two interferometers in that village. H and V label the photon detectors in the horizontal and vertical exit channels, respectively. There are four alternative possible cases. In Case One the two selected interferometers are the two lower ones, one in Bellevue and one in Bernex. In Case Four the two selected interferometers are the two upper ones. The two lower interferometers are mirror images of each other, and the two upper interferometers are mirror images of each other. All four of the short paths (between the two half-silvered mirrors in an interferometer) have the same length, but the roundabout paths are slightly longer in the upper two interferometers than in the lower two. In the lower two interferometers the difference between the long and short paths is an integral numbers of wavelengths.]*

Some of the photons get lost along the way and do not reach a detector. But there are many pairs whose two members both reach detectors, one in Bellevue, the other in Bernex. Signals from those detectors are sent back by ordinary wires to a central processor in Geneva.

Consider first Case One. In this case the two selected interferometers are the two lower ones in the diagram. These two interferometers are mirror images of each other. This means, in particular, that the length of the short path in the Bellevue device is the same as the length of the short path in the Bernex device. Likewise, the lengths of the two long paths are the same.

Each pair of photons is created at an event in Geneva. One member goes to Bellevue the other member goes to Bernex, and then each generates a signal that goes back to Geneva. Bellevue and Bernex do not lie at the same distance from Geneva. Thus the signals from these two villages will not arrive in Geneva simultaneously: there will be a *time lag.* This delay depends upon whether the photons traverse the short or the roundabout routes inside the interferometers. However, if both photons, one in each village, take the short route then this time lag will be the same as when both take the long route. (This is because the *difference* between the lengths of the long and short routes is the same for the two photons, and hence the *difference in transit times* is the same.) But if one photon of the pair takes a roundabout route whereas the other takes the direct route then the time lag between signals from Bellevue and Bernex will be either longer or shorter than the common lag time for the cases in which both photons traverse the direct route or both traverse the roundabout route.

This difference in lag times allows the experimenters keep only those pairs of photons such that both members take the long path or by take the short path. The slight lengthening of the long paths in the upper two interferometers (in our diagram) is too small to upset this restriction of the data to the contributions in which both of the two siblings take the roundabout route or both take the direct route.

When *coincidences* of detection events, one in each village, are considered it is the *sum of the two phases* that is pertinent. In Case One the long path in each interferometer is longer than the short path by an integral (i.e., whole) number of wavelengths. Consequently, there will be constructive interference if both photons are detected in the H detectors, or if both are detected in the V detectors, but destructive interference if one photon is detected by a V detector, but the other is detected by an H detector.

(These result are easy to deduce. Note that in the case where both photons are detected in an H detector the contribution from the two long paths gives a total shift of eight quarter wave lengths (there are altogether eight 45 degree reflections on the path to the two detectors H) and the two short paths give no shift. Thus we get a two-wave-length shift, and hence complete *constructive* interference. In the case of two V's the two long paths give a backward shift of six quarters (three reflections in each village) whereas the two short paths give a total backward shift of two quarters, for a net difference of one full wavelength, and hence, again, complete constructive interference. In the case of H in one region but V in the other, the contribution from the two long paths will be shifted back by seven quarters, whereas the contribution from the two short paths will be shifted back by only one quarter of a wave length, for a net difference of one and a half wave lengths. Thus the crests coming from the long paths will coincide with the troughs coming from the short paths, which means complete destructive interference.)

The rate at which the pairs are detected is slow enough so that each pair of particles, one detected in Bellevue the other in Bernex, can be distinguished from all the other pairs by fast electronics. A pair is classified as "matched" if both members are detected in a horizontal exit channel or both are detected in a vertical channel. They are "unmatched" if one partner is detected in a horizontal exit channel and its mate is detected in a vertical exit channel.

Quantum theory predicts, and the empirical results confirm (to within the limits imposed by experimental exigencies) that the fraction of the pairs that are unmatched will be the *sine squared* of L/2 minus S/2, where L is the *sum* of the two long paths, one in each village, and S is the *sum* of the two short paths. The sine-squared function oscillates smoothly between zero and one, and touches zero each time L/2 minus S/2 reaches some half-integral multiple of the wave length of the light. This agrees with the result in Case One that was just described.

For ease of explanation, I shall use just one simple property of this formula: if for some original value of L/2 minus S/2 none of the pairs are unmatched then for small shifts of L/2 minus S/2 away from this original value the number of unmatched pairs *will grow like the square of this small shift.* In particular, if for some small value of this shift in L/2 minus S/2 the value of this fraction of mismatches is f, then a doubling of this small shift will multiply the fraction of mismatches by about 4: the fraction of mismatches will *more than double!*

What is so astonishing about that?

What is puzzling and interesting is this. The experiment is done with very high speed equipment. The speed is so high that the information about which of the two interferometer is randomly chosen for the photon in one village cannot get to the other village before its twin photon is detected there, without that information traveling faster than light. Under these conditions the principles of classical physics ensure that the random choice *of what is done to a twin in one village* can have no influence on the behavior of its faraway sibling. But this condition of no faster-than-light influence cannot be reconciled with the quantum results just described.

How is this remarkable result proved?

Case Two is the same as Case One up until the moment that the two random choices are made, but the random choice in Bellevue goes the other way: the upper interferometer is picked by the random process there, but nothing is changed in Bernex. Now a small fraction f of the pairs will be "unmatched". Since nothing has changed in Bernex, this small fraction f of unmatched events must arise from a switching of this fraction f of the events in Bellevue from what they were in Case One. That is, if in Case One the sequence of detection events is, say (H, V, V, H, H, H, V, H, etc.) in both Bellevue and Bernex then in Case Two the fraction f, say 1%, of these values will be reversed from their Case One values in Bellevue, *but none will be reversed in Bernex*. This is the first key consequence of the no-faster-than-light-influence condition: it ensures that the random choice made in Bellevue does not disturb the outcomes in Bernex.

Case Three is the same as Case One in Bellevue, but the upper interferometer is chosen in Bernex instead of the lower one. Hence the same fraction f of the detection events, but now in Bernex, must be opposite to what they were in Case One.

In Case Four the changes that were made in Bellevue in Case Two, and in Bernex in Case Three are now made simultaneously in both Bellevue and Bernex. Hence in this final case the changes that occur in Bellevue must be the same as the changes made there in Case Two, since no influence of the choice made in Bernex can be present in Bellevue. Similarly, in this Case Four, the changes made in Bernex must be the same as the changes that were made there in Case Three.

But then the total number of mismatches in Case Four can be no greater than the sum of the number of mismatches in Cases Two and Case Three. Thus the fraction f* of mismatches in Case Four can be no larger than 2f. But this contradicts the empirically verified prediction of quantum theory that f* is roughly 4f.

This large-scale failure of the core causality idea of relativistic classical physics suggests that we must be prepared for a profound revision of our conception of the nature of the physical world. Bohr, Heisenberg, Pauli, and the other founders of quantum theory partially achieved this by bringing conscious human observers into basic physical theory in a way that permits the idea-like aspects of reality to be more deeply involved in the causal structure of the Nature than classical ideas allow. So let us look now more closely at what they did.