Bell's Interconnectedness Theorem

[From: Nick Herbert - "*Quantum Reality: Beyond the New Physics*"]

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John Stewart Bell

Fig. 12.6- *CERN physicist John Stewart Bell, inventor of the interconnectedness theorem, which establishes non-locality as a general feature of this world.*

Contagious magic is based upon the assumption that substances which were once joined together possess a continuing linkage; thus an act carried out upon a smaller unit will affect the larger unit even though they are physically separated.

Sir James Frazer

John Stewart Bell was born and grew up in Belfast, Northern Ireland. He is now a theoretical) physicist at CERN (a large accelerator center in Geneva financed by Western European countries) where he specializes in elementary particle physics. In 1964, while on sabbatical leave from CERN, Bell decided to investigate the quantum reality question, which had fascinated him since his undergraduate days.

Bell began by looking at von Neumann's proof, which demonstrates the impossibility of neorealism. According to von Neumann, the world cannot be made of ordinary objects, which possess dynamic attributes of their own. Bell discovered that although this proof excludes objects whose attributes combine in "reasonable ways," it does not forbid objects which can change their attributes in response to their environment. This loophole in von Neumann's proof is what allows Bohm, de Broglie, and other neorealists to build explicit ordinary-object-based models of quantum reality: all these models contain objects whose attributes are context-sensitive.

While preparing a review article on von Neumann's proof, Bell became interested in impossibility proofs in general and wondered whether a proof could be constructed which would conclusively exclude any model of reality that possessed certain physical characteristics. Bell himself managed to devise such a proof which rejects all models of reality possessing the property of "locality." This proof has since become known as *Bell's theorem.* It asserts that no local model of reality can underlie the quantum facts. Bell's theorem says that reality must be non-local.

In a letter to the author, John Bell recalls his discovery: "I had for long been fascinated by EPR. Was there a paradox or not? I was deeply impressed by Einstein's reservations about quantum mechanics and his views of it as an incomplete theory. For several reasons the time was ripe for me to tackle the problem head on. The result was the reverse of what I had hoped. But I was delighted—in a region of wooliness and obscurity to have come upon something hard and clear."

The structure of Bell's proof is as follows. For a certain class of two-quon experiments (the EPR experiment and its variations), Bell *assumes* that a local reality exists. With a bit of arithmetic he shows that this locality assumption leads directly to a certain inequality (Bell's inequality) which the experimental results must satisfy. Whenever these experiments are done, they violate Bell's inequality. Hence the local-reality assumption is mistaken. Conclusion: any reality that underlies the EPR experiment must be non-local.

WHAT IS A LOCAL INTERACTION?

The essence of a local interaction is direct contact—as basic as a punch in the nose. Body A affects body B *locally* when it either touches B or touches something else that touches B. A gear train is a typical local mechanism. Motion passes from one gear wheel to another in an unbroken chain. Break the chain by taking out a single gear and the movement cannot continue. Without something there to mediate it, a local interaction cannot cross a gap.

On the other hand, the essence of non-locality is unmediated action-at-distance. A non-local interaction jumps from body A to body B without touching anything in between. Voodoo injury is an example of a non-local interaction. When a voodoo practitioner sticks a pin in her doll, the distant target is (supposedly) instantly wounded, although nothing actually travels from doll to victim. Believers in voodoo claim that an action *here* causes an effect *there*, that's all there is to it. Without benefit of mediation, a non-local interaction effortlessly flashes across the void.

The unruly nature of unmediated action has moved physicists from Galileo to Gell-Mann to unanimously reject non-local interactions as a basis for explaining what goes on in the world. No one has so vehemently expressed physicists' distaste for non-local interactions as Sir Isaac Newton:

"That one body may act upon another at a distance through a vacuum without the mediation of anything else… is to me so great an absurdity, that I believe no man, who has in philosophical matters a competent faculty for thinking, can ever fall into."

Given his antipathy for non-local forces, Newton was somewhat embarrassed by his own theory of gravity. If a non-local force is "so great an absurdity," how does the sun's gravity manage to cross millions of miles of empty space to hold the Earth in its orbit? Concerning the actual nature of gravity, Newton wisely held his tongue. *"Hypotheses non fingo,"* he declared. "I frame no hypotheses."

Newton's faith in strictly local forces was vindicated by his successors, who explained gravity in terms of the *field concept*. The space between the sun and Earth is not empty, today's physicists say: it's filled with a gravitational field which exerts a force on any body it touches. The modern field concept allows us to regard gravity as a strictly local interaction even though it acts across vast reaches of space. The sun's mass produces a gravity field, this field pulls on the Earth and mediates the sun-Earth interaction.

Physicists today share Newton's belief that the world is tied together by strictly local connections. All presently known interactions can be explained in terms of only four fundamental forces (strong, weak, electro-magnetic, and gravitational). In every case these forces act as if they are mediated by fields. Since quantum theory has blurred the once sharp distinction between particle and field (both are quantum stuff now) we can equally well say these local forces are mediated by the exchange of *particles*. Thus the sun attracts the Earth (and vice versa) via the gravity field or via an exchange of gravitons (the particle aspect of the gravity field). In actuality gravity (as is true for the other three fundamental forces as well) is carried neither by particle or field but by something that partakes of both, an innately quantum go-between whose mediation makes every one of nature's forces strictly local.

Although the concept of locality docs not strictly demand it, most forces diminish in strength as you move away from their source. It is conceivable that a local force might stay constant or even increase with distance from its source (the force of a stretched spring, for instance, increases with distance). The big four forces that hold the world together happen, however, all to *decrease with distance*—gravity and electromagnetism diminish as the inverse square; the strong and weak forces fall off considerably faster.

The toughest limitation on a local interaction is how fast it can travel. When you move an object A, you stretch its attached field. This field distorts first near object A, then the field warp moves off to distant regions. Einstein's special theory of relativity restricts the velocity of this field deformation to light speed or below. According to Einstein, no material object can travel faster than light; not even the less material field warp can travel so fast.

Non-local influences, if they existed, would not be mediated by fields or by anything else. When A connects to B non-locally, nothing crosses the intervening space, hence no amount of interposed matter can shield this interaction.

Non-local influences do not diminish with distance. They are as potent at a million miles as at a millimeter.

Non-local influences act instantaneously. The speed of their transmission is not limited by the velocity of light.

A non-local interaction links up one location with another without crossing space, without decay, and without delay. A non-local interaction is, in short, *unmediated*, *unmitigated*, and *immediate*.

Despite physicists' traditional rejection of non-local interactions, despite the fact that all known forces are incontestably local, despite Einstein's prohibition against superluminal connections, and despite the fact that no experiment has ever shown a single case of unmediated faster-than-light communication, Bell maintains that the world is filled with innumerable non-local influences. Furthermore these unmediated connections are present not only in rare and exotic circumstances, but underlie all the events of everyday life. Non-local connections are ubiquitous because reality itself is non-local.

Not all physicists believe Bell's proof to be an airtight demonstration of the necessary existence of non-local connections. But the alternatives these critics offer instead seem to me to be generally obscure and/or preposterous. As we shall see in the following chapter, some physicists will go so far as to actually "deny reality itself" rather than accept Bell's audacious conclusion that quantum reality must be non-local.

How BELL PROVED REALITY CANNOT BE LOCAL

To understand the import of Bell's theorem and the arguments of his critics, it's necessary to look at Bell’s proof in some detail. Fortunately Bell's theorem is easier to prove than the Pythagorean theorem taught in every high school. The simplicity of Bell's proof opens it to everyone, not just physicists and mathematicians.

Bell's proof is based on the same EPR experiment used by Einstein, Podolsky, and Rosen to demonstrate the existence of hidden "elements of reality" which quantum theory neglects to describe. The "EPR paradox" consists of the fact that for thirty years physicists have neither been able to refute EPR's argument nor shed further light on EPR's alleged "elements of reality."

The EPR experiment involves a source of light which produces pairs of photons (Green and Blue) in the "twin state." These photons travel in opposite directions to calcite detectors (G and B) which can measure their polarization attribute $P(\phi)$ at some angle ϕ. In the twin state each beam by itself appears completely unpolarized—an unpredictably random 50-50 mixture of ups and downs at whatever angle you choose to measure.

Though separately unpolarized, each photon's polarization is perfectly correlated with its partner's. If you measure the P of both photons at the same angle (a two-photon attribute I call paired polarization), these polarizations always match.

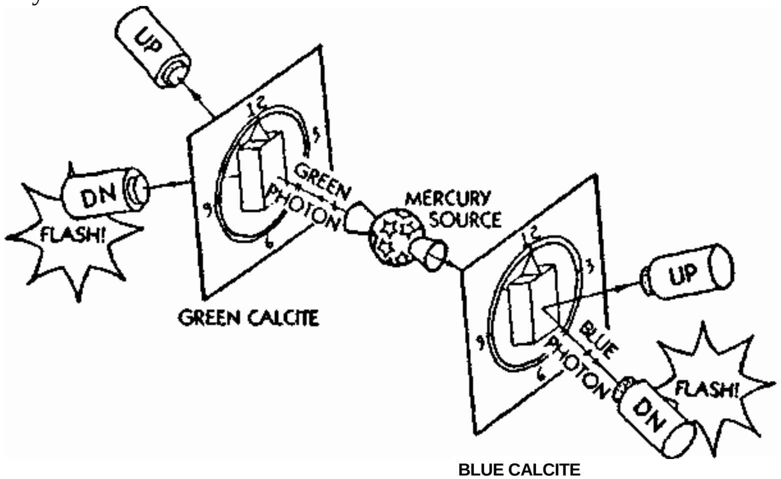

Fig. 12.1 *The EPR experiment. The central mercury source emits pairs of photons (Green and Blue) in the twin state. At Green and Blue measuring sites, the polarization $P(\phi)$ of each of these photons is recorded with a calcite-based P meter. Bell's theorem concerns the unusual strength of the polarization correlation existing between these Green and Blue photons.*

For his proof, Bell considers another two-photon attribute called polarization correlation *(PC)* which can be measured on these photons. Attribute *PC* is measured the same way as attribute *PP* except that the calcites are set not at the same but at different angles. To measure $PC(\phi)$, set Green calcite at a particular angle $\phi_{G;}$ and Blue calcite at angle ϕ_B. Now compare Green and Blue polarizations for each pair of photons. If these *Ps* are the same (both up or both down), call this a match; if opposites, call this a miss. Angle ϕ is the angle between the two calcites, namely $\phi = \phi_G - \phi_B$.

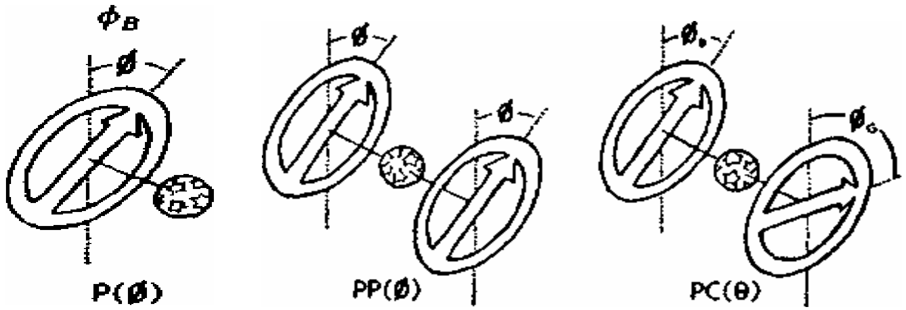

Fig. 12.2 *Three kinds of polarization measurement. A Measuring $P(\phi)$—ordinary polarization—involves counting the number of photons polarized along (up) or across (down) the calcite's optic axis oriented at angle ϕ. B. Measuring $PP(\phi)$— paired polarization—involves comparing the polarization of two photons at the same angle ϕ (miss or match). C. Measuring $PC(\phi)$—polarization correlation— involves comparing the polarization of two photons at two different angles, ϕ is the angular difference between the two calcite settings.*

For photons in the twin state, quantum theory predicts that $PC(\phi_G - \phi_B)$ depends only on the *relative angle* ϕ between calcites and is independent of the separate settings ϕ_G and ϕ_B. Thus if the angle of the Green calcite differs by 30°(in either direction) from that of the Blue calcite, the value of *PC(30)* will be the same, no matter how Green and Blue happen to be tilted. The fact that $PC(\phi)$ depends only on the *difference* between the two calcites has been amply verified by experiment.

For each angle ϕ between calcites, a *PC* measurement asks for the *fraction of matches* obtained in a long series of photon pairs. Thus *PC=1* means all matches (no misses) while *PC =0* means no matches (all misses). Bell's theorem is concerned with how this match fraction changes as we vary the angle between calcites from zero to ninety degrees.

For our previous discussion of the twin state, we already know the value of *PC* at zero and ninety degrees. At a calcite separation of zero degrees, *PC=1.* When both calcites are set at the same angle, a *PC* measurement is identical to what l've called a *PP* measurement, which for the twin state yields a 100 percent match at all angles.

At a calcite separation of ninety degrees, *PC = 0.* When a calcite is turned through a right angle, its photon-sorting operation is merely reversed: its up channel passes downs and vice versa. At ninety degrees a P meter behaves like the same P meter at zero degrees with its outputs relabeled. This calcite channel reversal plus the perfect correlation at zero degrees leads to a *perfect anti-correlation* when the calcite axes differ by ninety degrees.

At zero degrees, *PC = 1*; at ninety degrees, *PC = 0*. In between, *PC* varies between 1 and 0 as the angle between calcites swings from zero to ninety degrees. The meat of Bell’s proof is *the actual shape of this variation.*

To dramatize what's happening in this EPR experiment, imagine that Green detector is on Earth, and Blue detector is on Betelgeuse (540 light-years away) while twin-state correlated light is coming from a spaceship parked halfway in between. Although in its laboratory versions the EPR experiment spans only a room-size distance, the immense dimensions of this thought experiment remind us that, in principle, photon correlations don't depend on distance.

The spaceship acts as a kind of interstellar lighthouse directing a Green light beam to earth, a Blue light beam to Betelgeuse in the opposite direction. Forget for the moment that Green and Blue detectors are measuring something called "polarization" and regard their outputs as coded messages from the spaceship. Two synchronized binary message sequences composed of ups and downs emerge from calcite crystals 500 light-years apart. How these two messages are connected is the concern of Bell's proof.

When both calcites are set at the same angle (say, twelve o'clock), then *PC* = 1. Green polarization matches perfectly with Blue. Two typical synchronized sequences of distant P measurements might look like this:

GREEN : UDUDDUDDDUUDUDDU
BLUE : UDUDDUDDDUUDUDDU

If we construe these polarization measurements as binary message sequences, then whenever the calcites are lined up, the Blue observer on Betelgeuse gets the same message as the Green observer on Earth.

Since *PC* varies from 1 to 0 as we change the relative calcite angle, there will be some angle α at which *PC = 3/4.* At this angle, for every *four* photon pairs, the number of matches (on the average), is *three* while the number of misses is *one.* At this particular calcite separation, a sequence of *P* measurements might look like this:

*   * *   *

GREEN : UD**D**DD**UD**DDU**D**DUDDU
BLUE : UD**U**DD**DU**DDU**U**DUDDU

At angle α, the messages received by Green and Blue are not the same but contain "errors"—G's message differs from B's message by one miss in every four marks.

Now we are ready to demonstrate Bell's proof. Watch closely; this proof is so short that it goes by fast. Align the calcites at twelve o'clock. Observe that the messages are identical. Move the Green calcite by α degrees. Note that the messages are no longer the same but contain "errors"—one miss out of every four marks. Move the Green calcite back to twelve and these errors disappear, the messages are the same again. Whenever Green moves his calcite by α degrees in either direction, we see the massages differ by one character out of four. Moving the Green calcite back to twelve noon restores the identity of the two messages.

The same thing happens on Betelgeuse. With both calcites set at twelve noon, messages are identical. When Blue moves her calcite by α degrees in either direction, we see the messages differ by one part in four. Moving the Blue calcite back to twelve noon restores the identity of the two messages.

Everything described so far concerns the results of certain correlation experiments which can be verified in the laboratory. Now we make an assumption about what might actually be going on—a supposition which cannot be directly verified: the locality assumption, which is the core of Bell's proof.

We assume that *turning the Blue calcite can change only the Blue message;* likewise turning the Green calcite can change only the Green message. This is Bell's famous locality assumption. It is identical to the assumption Einstein made in his EPR paradox: that Blue observer's acts cannot affect Green observer's results. The locality assumption—that Blue's acts don't change Green's code—seems entirely reasonable: how could an action on Betelgeuse change what's happening right now on Earth? However, as we shall see, this "reasonable" assumption leads immediately to an experimental prediction which is contrary to fact. Let's see what this locality assumption forces us to conclude about the outcome of possible experiments.

With both calcites originally set at twelve noon, turn Blue calcite by α degrees, and at the same time turn Green calcite *in the apposite direction* by α degrees. Now the calcites are misaligned by 2α degrees. What is the new error rate?

Since turning Blue calcite α degrees puts one miss in the Blue sequence (for every four marks) and turning the Green calcite α degrees puts one miss in the Green sequence, we might naively guess that when we turn both calcites we will gel exactly two misses per four marks. However, this guess ignores the possibility that a "Blue error" might fall on the same mark as a "Green error"—a coincidence which produces an apparent match and restores character identity. Taking into account the possibility of such "error-correcting overlaps," we revise our error estimate and predict that whenever the calcites are misaligned by 2α degrees, the error rate will be two misses—*or less.*

This prediction is an example of a *Bell inequality.* This Bell inequality says: If the error rate at angle α is 1/4, then the error rate at twice this angle cannot be greater than 2/4.

This Bell inequality follows from the locality assumption and makes a definite prediction concerning the value of the PC attribute at a certain angle for photon pairs in the twin state. It predicts that when the calcites are misaligned by 2α degrees the difference between the Green and Blue polarization sequences will not exceed two misses out of four marks. The quantum facts, however, say otherwise. John Clauser and Stuart Freedman carried out this EPR experiment al Berkeley and showed that a calcite separation of 2α degrees gives three misses for every four marks - a quite substantial violation of the Bell inequality.

Clauser's experiment conclusively violates the Bell inequality. Hence one of the assumptions that went into its derivation must be false. But Bell's argument uses mainly facts that can be verified - photon PCs at particular angles. The only assumption not experimentally accessible is the locality assumption. Since it leads to a prediction that strongly disagrees with experimental results, this locality assumption must be wrong. To save the appearances, we must deny locality.

Denying locality means accepting the conclusion that when Blue ob server turns her calcite on Betelgeuse she instantly changes some of Green's code on Earth. In other words, locations B and G some five hundred light years apart are linked somehow by a non-local interaction. This experimental refutation of the locality assumption is the factual basis of Bell's theorem: no local reality can underlie the results of the EPR experiment.

Einstein, Podolsky, and Rosen used the locality assumption to demonstrate the existence of hidden "elements of reality" which quantum theory fails to take into account. However, if Blue and Green observers are linked by a non-local interaction, as the factual violation of the Bell inequality seems to imply, then EPR's argument is invalid by virtue of a false premise. The failure of their argument does not prove, of course, that no such "elements of reality" exist, but only that one cannot make a case for their existence by using EPR's reasoning. The logical necessity of non-local interactions resolves the EPR paradox (in Bell's words) "in the way which Einstein would have liked the least."

Reviewing the EPR paradox in his autobiography, Einstein reaffirmed his faith in locality: "On one supposition we should, in my opinion, absolutely hold fast: the real factual situation of the system (G) is independent of what is done with the system (B) which is spatially separated from the former." Einstein did not live to see Bell's proof and would certainly have been surprised by Bell's refutation of his cherished postulate. But I think he would have welcomed the strange news Bell's theorem brings us concerning the true nature of the quantum world. Bell's result vindicates Einstein's intuition that something funny is going on in quantum-correlated two particle states.

As in the case of the EPR paradox, it's important to realize what Bell did not do. He did not discover an experimental situation in which non-local interactions are directly observed. Instead he invented a simple argument based on experimental results that *indirectly demonstrates* the necessary existence of non-local connections.

The phenomena displayed by photon pairs in the twin state are entirely *local*. The only spin-space attribute accessible to Green observer is his Green photon polarization P(ϕ). This attribute is always 50-50 random (unpolarized) no matter how Blue observer sets her calcite. Because whatever Blue does, Green can detect no change in his own photon's polarization, Blue observer can send no message—superluminal or otherwise—from Betelgeuse to Earth via these correlated photons.

However, if Bell's argument is correct, then the reality behind these seemingly local phenomena not only might be, but *must be* non-local. It's not the mere fact of photon correlation that necessitates non-local connections, but the fact that twin-state photons are correlated so *strongly*.

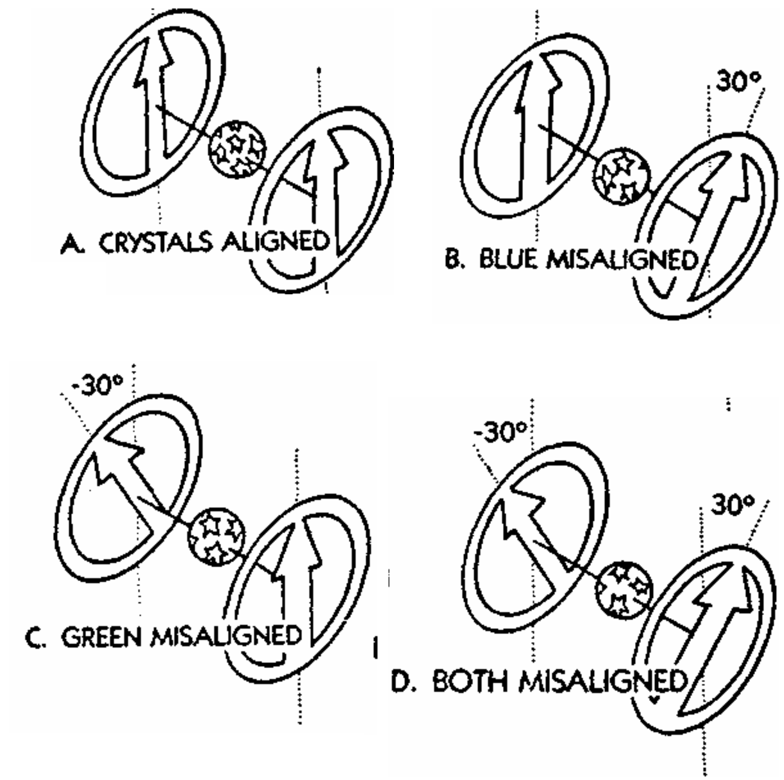

Fig. 12.3 Simple proof of Bell's theorem. A. Both calcites aligned: errors = zero. B. Blue crystal tilted by 30^o: errors = 1 in four marks. C. Green crystal tilted by - 30°: errors = / in four marks. D. Both Green and Blue crystals tilted by 30°: what's the new error? If we assume locality (Green's move cannot chance Blue's mark), this new error cannot be greater than 2 in four marks. However, for EPR photon the PC measurement at 60° gives 3 errors in four marks. Therefore locality assumption is false.

Many situations can be envisioned which show perfect correlation at $\theta = 0°$ and perfect anti-correlation at $\theta = 90°$, but whose in-between correlation varies so as actually to *satisfy* Bell's inequality. A few examples of such weakly correlated systems are shown in Fig. 12.5. Weak correlations can always be explained by strictly local interactions. On the other hand, strongly-correlated systems (such as Fig. 12.4) violate the Bell inequality; their parts are more synchronized than they have any right to be. To explain such highly cooperative behaviour, no local model of reality will suffice.

Bell's theorem gives those who share Newton's belief that non-local influences are "a great absurdity" an opportunity to put their convictions to the test. For folks loyal to locality, the argument of Bell which purports to demonstrate the existence of hidden faster-than-light connections must be mistaken. Those convinced beforehand of Bell's error should be highly motivated to discover the fallacy in his reasoning. Later we will look at some recent attempts to invalidate Bell's argument and to recover a strictly local world. On the other hand, if Bell's reasoning is correct invisible non-local connections must truly exist. Can we then devise means of making these connections directly evident instead of relying on Bell's indirect argument? The possibility of practical superluminal communication via the quantum connection will be discussed in the next chapter.

Bell proved his theorem for a particular two-photon system. What justification exists for extending his conclusion (the reality underlying the EPR experiment must be non-local) to the general case of everyday experience (the reality underlying *everything* must be non-local)? To expand the scope of Bell's argument we turn to quantum theory.

In quantum theory's formalism, what accounts for strong photon correlation in the twin state *is phase entanglement.* Whenever quantum system A meets quantum system B, their phases get mixed up. Part of A's proxy wave goes off with B's wave and vice versa. Phase entanglement thereafter instantly connects any two quons which have once interacted. Before Bell's discovery, this strong quantum connection had been recognized (especially by Schrödinger, who considered it quantum theory's most distinctive feature) but regarded by physicists as a kind of mathematical fiction with no roots in reality. Since Bell's theorem demands a superluminal connection and quantum theory provides one—in the form of ubiquitous but presumably "fictitious" phase connections—perhaps these quantum connections are not as fictitious as was once believed.

Since there is nothing that is not ultimately a quantum system, if the quantum phase connection is "real," then it links *all systems that have once interacted at some time in the past*—not just twin-state photons— into a single waveform whose remotest parts are joined in a manner un-mediated. unmitigated, and immediate.

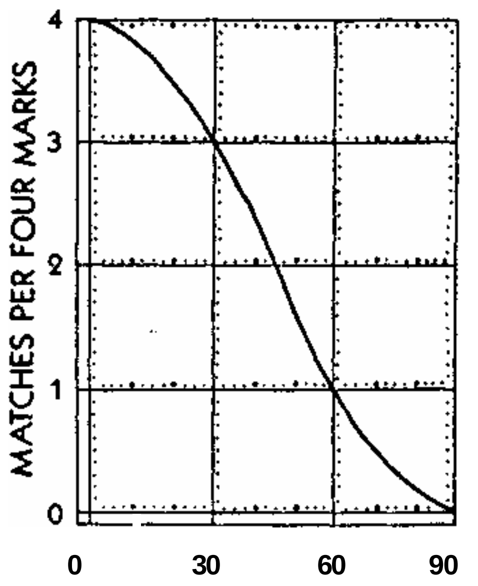

Fig. 12.4 *Quantum theory's prediction* /or *PC (θ) of twin-state mercury tight. This result violates Bell's inequality, hence argues against locality. In 1972 this prediction became a matter of fact (measured by Clauser at Berkeley); now the quantum facts say locality is false.*

The mechanism for this instant connectedness is not some invisible field that stretches from one part to the next, but the fact that a bit of each part's "being" is lodged, in the other. Each quon leaves some of its "phase" in the other's care, and this phase exchange connects them forever after. What phase entanglement really is we may never know but Bell's theorem tells us that it is no limp mathematical fiction but a reality to be reckoned with.

CLAUSER'S EXPERIMENT

In 1964, when Bell derived his inequality, no twin-state PC measurements existed against which it could be tested. However, the *calculation* of twin-state polarization is an elementary exercise in quantum theory. This calculation predicts that $PC(\theta) = cos^2\theta$, a correlation plotted as Fig. 12.4. The angle α at which misses = 1/4 for $cos^2\theta$ is 30°. Bell's inequality consequently demands that the number of misses at 2α (60° in this case) shall be no greater than 2/4.

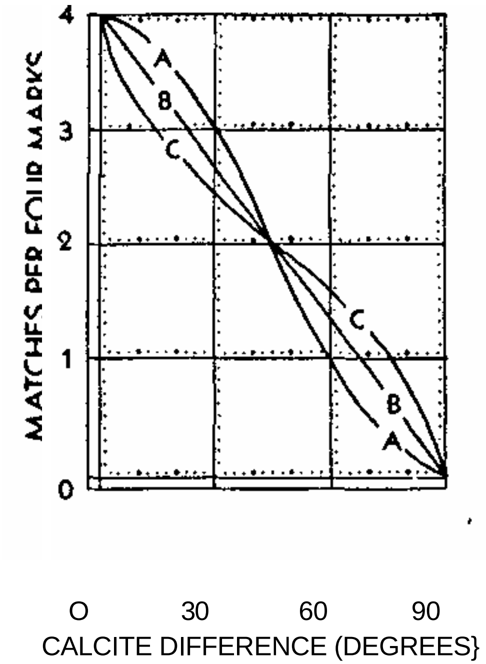

FIG. 12.5 Some *polarization correlations which do not violate Bell's inequality. Curve A is the strongly correlated mercury tight pictured in Fig. 12.4. The straight line B satisfies Bell's inequality; so does the dished-in curve C. Both curves B and C can be simulated by local mechanisms; they are weakly correlated. Curve A cannot be simulated by any local mechanism. These curves illustrate on just how small a quantitative difference Bell's important theorem rests.*

However, at 60° this expression gives a miss fraction of ¾ . Since ¾ is considerably greater than 2/4 , the theoretical expression $PC = cos^2\theta$ violates Bell's inequality. This violation marks the twin state as a *strongly* correlated system—a pair of entities linked tighter than any local reality can explain.

The fact that this calculated result violates Bell's inequality implies that *any system which obeys these quantum-theoretical predictions cannot be explained by a local reality*. Before Bell's discovery, one could still imagine that a local reality lurked beneath the experimental facts, after 1964, one could blissfully believe in a strictly local world only by hoping that *quantum theory was wrong* in its predictions concerning photons in the twin state.

Since it challenges one of physicists' most cherished beliefs—that the world is fundamentally local—one might have expected Bell's proof to explode like a bombshell in the corridors of science. Instead, Bell's proof, published in an obscure little journal, was largely ignored even by those physicists who managed to find out about it.

Most physicists are not impressed by Bell's proof because it deals with *reality*, not *phenomena*. The majority of physicists are phenomenalists— whose professional world is circumscribed by phenomena and mathematics. A phenomenalist perceives science as advancing in two directions: 1. new experiments uncover novel phenomena; 2. new mathematics explain or predict phenomena in original ways. Since it proposes no new experiments and derives no new phenomena-relevant mathematics, but merely puts certain constraints on an invisible reality, Bell's proof lies outside the fashionable formula for success in science and is generally dismissed by scientists as "mere philosophy."

Physicists' cool reception of Bell's proof is reminiscent of David Hume's famous prescription for separating truth from nonsense: "Does it contain any abstract reasoning concerning quantity or number? *No*. Does it contain any experimental reasoning concerning matter of fact and existence? *No*. Commit it then to the flames: for it can contain nothing but sophistry and illusion."In the midst of this climate of indifference toward theories of reality, John Clauser, a young Ph.D. from Columbia, proposed actually to measure twin-state photons to see whether their polarization correlation attribute satisfied Bell's inequality (world is local; quantum theory wrong) or not (world is non-local; quantum theory right). Clauser received no support al Columbia for his proposal to put Bell's inequality to experimental test, and moved to Berkeley where apparatus already existed which he knew he could modify to measure twin-state photons.

Many kinds of excited atoms emit pairs of twin-state photons as they return to their ground slate. Most experiments carried out to test Bell's inequality have used either mercury atoms excited by electron impact or calcium atoms excited by laser light. Clauser's Berkeley mercury source operates like a mercury-vapor streetlamp—both emit Blue and Green twin-state light—but Clauser's source was smaller and more intense than the lamps which nightly flood Telegraph Avenue with photons in the twin state.

Because real photon detectors are not 100 percent efficient—they count only about 10 percent of the photons which strike their phosphor faceplates—one cannot simply compare Bell's inequality to experimental results. Adapting Bell's original reasoning to existing experimental realities, Clauser and his colleagues derived a version of Bell's inequality (called the "CHSH inequality" after John F. Clauser, Michael A. Horne, Abner Shimony, and Richard A. Holt) which is testable with low-efficiency detectors.

Clauser was motivated to test the Bell inequality by his strong faith that the world was ultimately local. If quantum theory predicts a result which conflicts (via Bell's proof) with locality, so much the worse for quantum theory. Clauser anticipated that his experiment would prove quantum theory wrong at least in this matter of twin-state polarization. The results proved otherwise. In 1972 Clauser announced that quantum theory had passed his test. Bell's inequality had been experimentally violated by Blue and Green photons at Berkeley. Now not merely quantum theory but quantum fact contradict the hypothesis that the world is linked up by strictly local lines.

Clauser's pioneer test of the Bell inequality contains a loophole through which a desperate logician might still derive a local world. To pinpoint this loophole, let's return to our imaginary EPR experiment in space.

Clauser's mercury source sent Blue and Green light to opposite corners of a room. Our spaceship lighthouse shoots photons to Betelgeuse and Earth five hundred light-years apart.

Clauser switched the orientation of his P meters every 100 seconds. Clauser's switching time, translated to cosmic lighthouse scale, corresponds to keeping the P meters on Earth and Betelgeuse fixed *for more than a billion years.* Such leisurely P measurements would permit information on how distant P meters were set to leak between Earth and Betelgeuse at sublight speed (carried perhaps in the gossip of interstellar tourists)—information which could allow most of the photons to simulate strong correlations by strictly local means. To block the possibility of subluminal security leaks during long P-meter rests, the experimenter must be able to change the P meters while the photons are in flight. To change a calcite this fast in the lab means switching its orientation in a few billionths of a second.

Unfortunately, mere matter just can't move that fast. However, physicist Alain Aspect at the University of Paris devised an experiment to test Bell's inequality which uses two acousto-optical switches to deflect each photon beam to one or the other of two preset calcite detectors. Instead of rapidly moving his calcites, Aspect moves his light beams.

With his ultrafast switches, Aspect can measure a different polarization every 10 billionth of a second, fast enough to eliminate subluminal security leaks between Blue and Green P meters. If Aspect's twin-state photons violate Bell's inequality, the reality that underlies their strong correlation must connect Green and Blue measurement stations at a speed exceeding the velocity of light. Aspect completed his experiment in 1982, verifying the strongly correlated quantum theoretical predictions, hence violating Bell's inequality and supporting his contention that our phenomenally local world is in actuality supported by an invisible reality which is unmediated, unmitigated, and faster than light.

Although Bell's theorem arose in the context of quantum theory, Bell's result does not depend on the truth of quantum theory. The Clauser-Aspect experiments show that Bell's inequality is violated by the facts. This means that even if quantum theory should someday fall, its successor theory must likewise violate Bell's inequality when it comes to explaining the twin state. Physics theories are not eternal. When quantum theory joins the ranks of phlogiston, caloric, and the luminiferous ether in the physics junkyard, Bell's theorem will still be valid. Because it's based on facts, Bell's theorem is here to stay.

Bell's theorem is an important tool for reality research because it enables folks who create imaginary worlds confidently to reject millions of impossible worlds at a single glance. Bell's theorem tells you right away: "If it's local, it's hokum."

One of the worlds soundly obliterated by Bell's proof is the "disturbance model" of quantum reality. In this model—a species of neorealism —quantum entities actually possess attributes of their own whether measured or not, but the measuring device changes these attributes in an unpredictable and incontrollable way. The inevitable disturbance of the quantum system by the device which measures it gives rise, in this model of reality, to quantum randomness, to the uncertainty principle and all the other quantum oddities.

As a picture of how the quantum world might actually operate, many physicists who have not given much thought to the matter take refuge in some vague disturbance model of reality. For several years I avoided thinking about the quantum reality question by supposing that a disturbance model of some kind was sufficient to account for the strange quantum facts.

Such a disturbance model would explain, for instance, the observed polarization of the Green photon in the EPR experiment as a result of the Green calcite's "uncontrollable disturbance" of some intrinsic Green photon attribute. In other words, this model explains Green's observer's results by appealing to a hypothetical mechanism which involves only the Green photon and the Green calcite. Bell's theorem shows that any such local mechanism, no matter how ingenious, simply fails to fit the quantum facts: Bell's proof knocks out the disturbance model because it's local.

Facile popular expositions often invoke the disturbance model of measurement to justify Heisenberg's uncertainty principle: we cannot know a quantum entity as it is because we must inevitably disturb whatever we observe. Bell's result shows this notion of quantum measurement as local disturbance to be as outdated as the obsolete picture of the atom as miniature solar System.

Another type of impossible world is the "classical style" reality symbolized by Newton's apple. Apples, and everything else in such a world, are truly ordinary objects which possess attributes all their own even when not being measured. When measured, whether by man, woman, or machine, a classical apple merely reveals some attributes which it previously possessed.

Such an apple world (which experts call a "local non-contextual reality") is not inconceivable or illogical. But, according to Bell's theorem, apple world is impossible because it can't possibly fit the facts. As a model for the world we actually live in, apple world and all its local non-contextual cousins are, by virtue of their locality, sheer fantasy worlds.

We obviously need to be more sophisticated in our choice of possible worlds. Let’s imagine, for instance, a *relational reality* patterned after the notions of Niels Bohr. The entities that make up such a world are like rainbows: they do not possess definite attributes except under definite measurement conditions. Upon measurement, attributes do emerge but they are a joint possession of entity and M device. In such a rainbow reality (called "local contextual"), attributes are not innate to an entity but change when the conditions of observation change. The only restriction we place upon such observer-induced changes is that distant M devices cannot change an entity's condition if such an influence would require a faster-than-light signal. In such a contextual, but local reality, only nearby observers take part in the determination of an entity's apparent attributes.

Like apple world, rainbow world is neither inconceivable nor illogical. It is simply, on account of its locality, not the sort of world we happen to live in.

Bell's theorem rejects apple worlds; it also rejects rainbow worlds. What kinds of worlds does Bell's theorem allow?

A POSSIBLE WORLD

Imagine Joe Green, an inhabitant of a *non-local* contextual world. Up in his sky, Joe sees a rainbow made up of a glistening pattern of colored dots. Unlike the regular dots in a photographic halftone, Joe's rainbow's dots form a random array.

On the other side of the same sun lies a counter-Earth, where Suzie Blue watches another rainbow in her counter-sky. Suzie's rainbow is likewise composed of a random array of colored dots. When Joe Green moves his chair, his rainbow moves too (a rainbow's position attribute is contextual, not innate), but Suzie's rainbow stands still. However, when Joe moves his chair Suzie's random array 200 million miles away instantly changes into a different (but equally random) array of colored dots. Suzie is not aware of this change—one random array looks pretty much like any other—but this change actually happens whether she notices it or not.

The *phenomenon* in this hypothetical world, whether the rainbow moves or not, is completely local: Suzie's rainbow doesn't move when Joe changes places. However, this world's *reality*—the array of little dots that make up both rainbows—is non-local: Suzie's dots change instantly whenever Joe moves his chair. Such a non-local contextual world, in which stable rainbows are woven upon a faster-than-light fabric, is an example of the kind of world permitted by Bell's theorem. A universe that displays *local phenomena* built upon a *nonlocal reality* is the only sort of world consistent with known facts and Bell's proof. Superluminal rainbow world could be the kind of world we live in.

During the past twenty years Bell's theorem has been proved in many ways, some of which refer to photon attributes and some which don't. My version of Bell's proof makes no essential use of the concept of a photon or its attributes. Although Green and Blue photons and their polarization attributes are mentioned to familiarize you with the details of the EPR experiment, when it comes to the proof of Bell's theorem my argument is formulated entirely in terms of a pair of binary messages printed by particular macroscopic objects. I prove Bell's theorem here in terms of moves (orientations of calcite crystals) and marks (ups and downs on a data tape).

Bell's theorem as a relation between moves and marks takes non-locality out of the inaccessible microworld and situates it squarely in the familiar world of cats and bathtubs. Expressed in thoroughly macroscopic language, Bell's theorem says: *In reality, Green's move must change Blues mark non-locally.* From arguments based on phenomena alone (no appeal to hidden attributes) we conclude that clicks in a certain counter must be instantly connected to the movement of a distant crystal of calcite.

For anyone interested in reality, Bell's theorem is a remarkable intellectual achievement. Starting with fact plus a bit of arithmetic, Bell goes beyond the facts to describe the contours of reality itself. Although no one has ever seen or suspected a single non-local phenomenon, Bell proves conclusively that the world behind phenomena must be non-local.

If all the world's phenomena are strictly local, what need is there to support local phenomena with a non-local fabric? Here we confront an alien design sense bizarre by human standards: the world seems strangely overbuilt. In addition the world's superluminal underpinning is almost completely concealed—non-locality would have been discovered long ago if it were more evident; it leaves its mark only indirectly through the impossibly strong correlations of certain obscure quantum systems.

In his celebrated theorem, Bell does not merely suggest or hint that reality is non-local, he actually proves it, invoking the clarity and power of mathematical reasoning. This compulsory feature of Bell's proof particularly irks physicists whose taste in realities is strictly local.

Bell's important proof has caused a furor in reality research comparable to the Einstein-Podolsky-Rosen scandal of 1935. On the one hand, Bell's theorem proves the existence of an invisible non-local reality. Those who prefer their realities to be local have so far not been able to refute Bell's argument. The fact that Bell's proof is remarkably clear and brief has not hastened its refutation.

On the other hand, although Bell's theorem *indirectly* necessitates a deep non-locality, no one has come up with a way to *directly* display this purported non-locality, such as a faster-than-light communication scheme based on these deep quantum connections. If reality research's bottom line is "Reality has consequences," then this Bell-mandated deep reality has so far failed to make a showing. What the future holds for Bell's instantly connected but as yet inaccessible deep reality is anyone's guess.