Discussion 1 (June 21, 2011 - 7/7/11, DP, PRELIM version 2).

"Test of Quantum Entanglement" – Aspect Experiment:

Importance: Quantum Mechanics is strongly counter-intuitive. The Aspect Experiment of 1982 was one of the first tests to show that quantum reality is non-local (appears to involve "faster than light" communication between entangled particles) and also demonstrated "delayed choice" (detector settings being set after particle emission and during flight). It really confronted us to ask, *"HOW can Nature be like that!"* In these tests, the polarization of each photon in a pair is not determined until a detector sees it and causes an "instantaneous action at a distance with regard to the measurement of the polarization of the other member of a given pair" ("spooky action at a distance"). Entanglement and superposition are key to the new fields of quantum computation and quantum cryptography.

Entanglement Definition: Quantum entanglement or "non-local connection" of two or more objects refers to the strange non-classical "linking" of the objects of a system so that one cannot adequately describe the quantum state of a constituent without full mention of its counterparts, even if the individual objects are spatially separated. This interconnection leads to correlations between observable physical properties of remote systems, often referred to as nonlocal correlations. "Einstein famously derided entanglement as ``spukhafte Fernwirkung" or "spooky action at a distance". Schrodinger's term was 'Verschrankung' or 'cross-linking' (or `shared enclosure'). John Cramer treats entanglement as joint communications back and forth in time between particles and their source (e.g., Fig. 6 below). Photons know about their future joint detections because "they have already been there!" Even in the de Broglie/Bohm "pilot wave" case, it would seem that some back-and-forth communication is necessary merely to establish the relevant wave-function prior to using it to create a quantum potential and establish a relevant final pathway.

Most modern tests of quantum entanglement mainly use light photons and measure their polarization (e.g., up-down, or sideways). In my drawer at home, I've always had a clear calcite crystal and also a little package containing three cheap green plastic Polaroid squares (a "3P" demonstration). If two Polaroids are aligned, they transmit light; but if they are turned against each other (crossed-polarization), not much light gets through and the squares are fairly dark. If two Polaroids are crossed and the third one is added on the outside, the result is a little darker yet. What happens if the third Polaroid square is placed between the other two but at a diagonal 45° angle? It gets lighter!—more light is transmitted! This defies intuition. The electric amplitude of the light from the first Polaroid gets projected onto a 45 degree line to 70% of its value and then gets projected (i.e., cosine) again to the last crossed Polaroid to get another 70% value [cosine(45°) ~ 0.7 [15]] . For just two Polaroids at an angle θ to each other, the transmitted intensity is amplitude squared or $\mathscr{I} = (\cos\theta)^2 = \cos^2\theta$ (Malus' Law, ~ 1810). For aligned squares, $\cos^2 0° = 1 = 100\%$, and for crossed Polaroids $\cos^2(90°) = 0$ (no transmission). For two sets of 45°, the output intensity is then about 50% of 50% or near 25% transmitted. This also applies for a collection of single photons one at a time, except that what gets measured now are total quantum counts rather than variable intensity. So quantum mechanics of polarization correlation expects a Malus' Law result. The Frenchman Malus also discovered that light can be polarized by reflection from a tilted glass surface. For the new entangled photon case, two correlated photons moving in opposite directions through two separately oriented Polaroids act like one photon moving through two polaroids with different tilts.

And the calcite—well, it is "birefringent" so that different polarizations of light get bent by different amounts. A crystal on top of a printed word shows two staggered words, and a crystal on top of a printed dot shows two dots because the light from the print contains all directions of polarization at once. So all polarizations from a page of paper get altered to just two: one parallel to the crystal axis and one perpendicular (called ordinary and extra-ordinary)-- and these get bent by different amounts to give two dots. Rotate the crystal, and one dot will rotate about the other (neat!). A Polaroid on top of the dot and the crystal on top of that at just the right angle will only show one dot. Calcite can be used to detect and measure polarization.

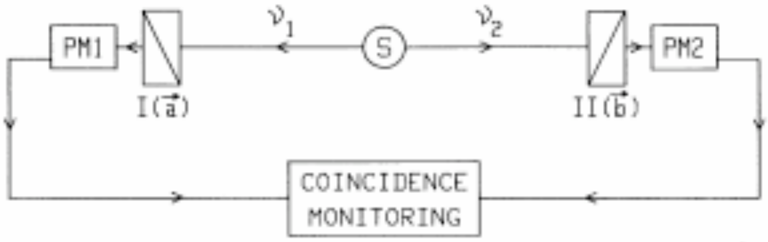

FIG. 1. Optical version of the Einstein-Podolsky-Rosen-Bohm *Gedankenexperiment*. The pair of photons ν_1 and ν_2 is analyzed by linear polarizers I and II (in orientations $\vec{a}$ and $\vec{b}$) and photomultipliers. The coincidence rate is monitored.

Figure 1 shows an idealized 'single channel' EPR test [4] modified from original Einstein ΔxΔp test to Bohm spins and now to the modern case of photon polarizations. A little more detail is supplied from the particular test by grad student Stuart Freedman and post doc John Clauser ["**FC**," 1972, 3] in Figure 3 below. This was the first application that took Bell seriously and was a partial test of Bell's ideas.

John Bell opened the window to testing quantum mechanical entanglements—but his thinking is often considered to be difficult. By assuming with Einstein that quantum mechanics ("QM") is really Local with no superluminal communications, he derived formulas that conflict with actual measurements thereby showing that QM must be non-local so that communications do not diminish with distance and act instantaneously. A few popular writers like Nick Herbert [12] offer more elementary views like Bell based on the assumption of locality. In most "Bell tests," long distance communications seem to be instantaneous and appear to violate relativity.

Herbert says, "Bell's theorem is easier to prove than the Pythagorean theorem taught in every high school." Like "Freedman and Clauser" FC-1972 and an improved Aspect 1981 version of FC, he considers visible 'blue' photons (for mercury, but violet for calcium) and light green photons emitted at the center of an apparatus and moving to the left and right through polarizers into detectors—a green detector and a blue detector ("B" and "G," -- appropriate because color filters were actually used in the Bell type experiments near the detectors). If the B and G polarizers are aligned together, then ~100% photon detection correlation can occur. A "B" photon in the B detector guarantees a G photon in the G detector. He considers calcite detectors, but photomultipliers and polarizers work too. The polarization directions can be set separately from up-alignment with angles ϕ_G and ϕ_B. Quantum mechanics ("QM") says that the output polarization correlation PC counts will only depend on the difference angle $\Delta\phi$ and not on each local setting separately. This implies that real QM detection near the polarizers know about each other's orientations so they can behave jointly. The correlation results for QM is a cosine-squared curve versus a triangular plot for local hidden variables. They give the same results at 0°, 90° and sometimes 45° -- but the QM results are enhanced in-between. So asking what happens at 22.5° or 30° would be revealing. $\text{Cos}^2(30°)$ = 75% correlation of photon detections or 25% misses. The Bell/Einstein locality supposition is that turning the Blue polarizer can only change the Blue message and not the green – a reasonable assumption, but wrong. If the blue polarizer is turned +30° and the green polarizer is turned -30° then locality would predict a 25% + 25% = 50% misses and 50% correlation. BUT, reality is $\cos^2(2\text{x}30°)$ = 25% net correlation or 75% misses. A correction to locality is that if blue is an error and green also happens to be in error, then that is a correlation again—a correction factor to the estimate. The result is then a net error rate of 50% OR LESS—an inequality, which is an example of a “Bell Inequality.” So getting 75% misses would violate the inequality and support quantum mechanics. Freedman and Clauser got 75% misses and contradicted locality. The Bell inequality is an indirect statistical measure of locality that assumes that reality is reasonable.

Bell experiments are often described as tests of Bell Inequalities. These are often shown as complex “Venn diagrams” shown on paper for overlaps of different ‘sets’ of events (settings A or A’, settings B or B’, or “other” (e.g., no polarizer present). Sometimes these are elaborately colored to keep tracks of all the overlaps [14]. The locality assumption is that all set partitions are logically independent. A setting might be A = Bell test angle of 0, 22.5°, 45°, 67.5° or 90°. Counts in each setting category are measured, and an inequality involving set-combinations is stated as a test metric.

There are many different examples of Bell inequalities (e.g., the ‘CHSH’ inequality for Clauser’s test). One of the simplest is, “the number of objects which have parameter A but not parameter B plus the number of objects which have parameter B but not parameter C is greater to or equal to the a count of number of objects which have parameter A but not parameter C,” i.e., $N(A^+B^-) + N(B^+C^-) \geq N(A^+C^-)$. These statements are derivable using simple logic (not shown here).
An example of the categories could be A = male, B = tall, C = blue eyes – they could be any parameters. Bell was thinking mainly of particle spins for Bohm’s version of EPR. For photons, A could be “polarization up” and detector up or $\phi = 0°$, B photon up but detector at $\phi = 22.5°$, C photon up but detector at $\phi = 45°$. If an electron spin experiment discusses a test using an angle θ, a polarization test would use half that angle. There is an assumption that electrons have a spin in a given direction even if we do not measure it (but this is not true).

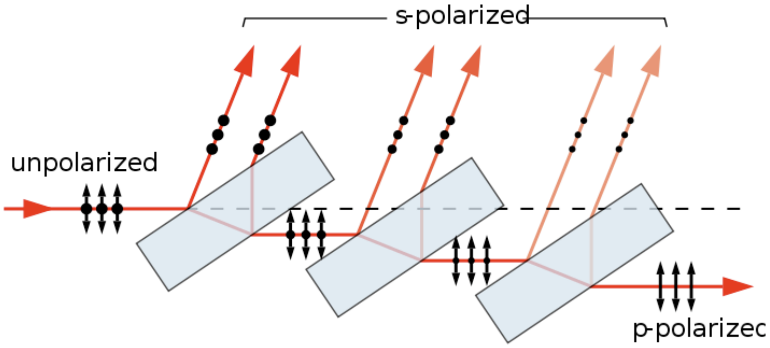

Figure 2: Stack of Plates polarizer with each plate tilted at “Brewster’s Angle”. Since the amount reflected at each glass is small, it may take 20 plates to obtain much output polarized light. [WIK]. The FC apparatus using this was a huge kludge on sawhorses. “p” means transmitted light in the **p**lane of incidence, and “s” is ⊥ .

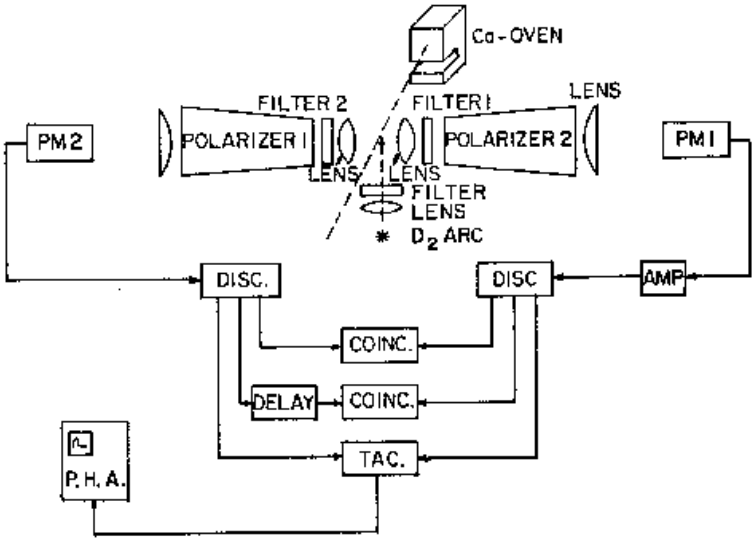

Figure 3: Freedman-Clauser (FC) test using excited state calcium-40 atoms decaying to a ground state which produces two correlated photons moving to the left and right through two differently tilted polarizers and then to photo-multipliers PM. [From reference 3]. The large polarizers are stacks of tilted glass plates. (Figure 2 above).
Then Figure 5 shows the more complicated Aspect Test [4].

Correlations between the polarizations of pairs of photons that are created in an atomic transition were studied by Clauser and Stuart Freedman in 1972 at the University of California at Berkeley. They performed measurements on the correlations and showed that Bell's inequality was violated [1] thus showing that photon pairs were entangled. Because this was a first and difficult experiment, they had several "loopholes" in this experiment such as not having a fair sample of all photons emitted by the source (the detection loophole) or possibility of un-noted causal connections (the locality loophole).

The1982 French 'Aspect experiment' improved on 'Clauser and Freedman's experiment by using a two-channel detection scheme to avoid making assumptions about photons that were detected. They also varied the orientation of the polarizing filters during their measurements – and in both cases Bell's inequality was violated [9]." "The locality loophole was closed in 1998 by Zeilinger and colleagues at the University of Innsbruck, who used two fully independent quantum random-number generators to set the directions of the photon measurements."

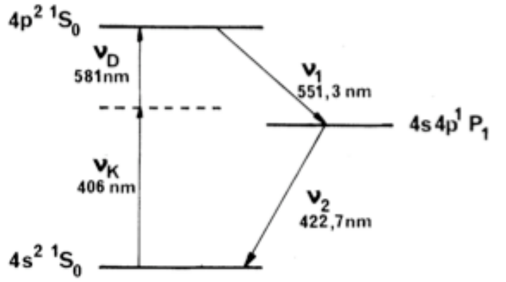

Figure 4: Excited energy state diagram for the **Two photon cascade:** Pump an Atomic beam of calcium atoms up to an electron excited state which then emits a cascade green and (almost

immediately) a violet photon with correlated polarizations. This was used by Aspect and by Freedman & Clauser [who in turn borrowed the idea and apparatus from Kocher and Commins] but with two-photon absorption from a Kr and Dye laser. The polarizers observing these photons are ‘pile of plates’ [Aspect 1981 PRL 47 p460]. {The names of the states above refer to principle and orbital quantum numbers and their occupation by electrons. Going from net spin zero to zero requires two photons carrying away one unit of angular momentum each}.

<u>**Figure 5:**</u> Aspect’s ‘delayed choice’ EPR test modified from Figure 1 above. This picture is mainly complicated by showing the quick switching devices for the left and right photon paths . (Fig 2 in Aspect’s Article).

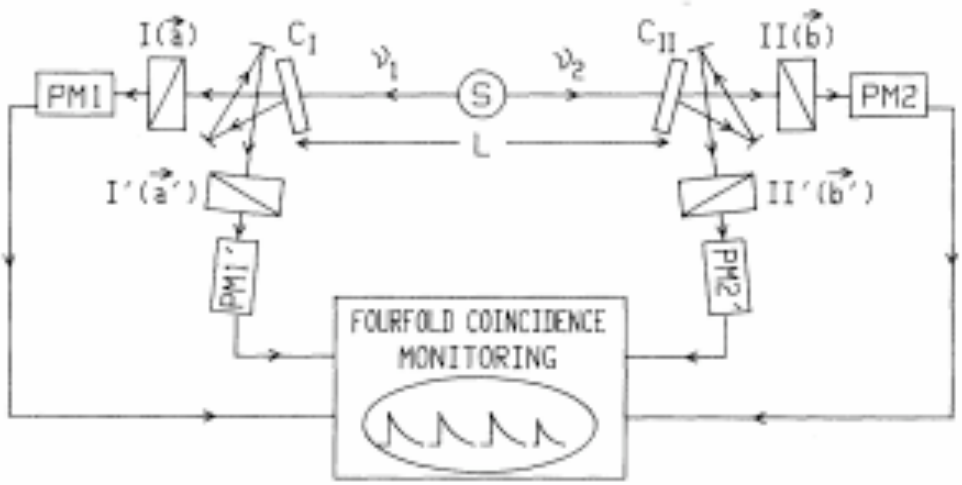

FIG. 2. Timing experiment with optical switches. Each switching device (C_I, C_{II}) is followed by two polarizers in two different orientations. Each combination is equivalent to a polarizer switched fast between two orientations.

<u>**Relevant History**</u>:
<u>**1935: Einstein, Podolsky, Rosen Classic paper “EPR”.**</u> This represented Einstein’s ‘local and real’ thinking about entanglement, but he didn’t know about the paper being submitted in his name. He believed the Copenhagen interpretation of quantum mechanics to be incomplete. That is, QM differs from the ‘obviously true’ local realism and hence must be incomplete and have unrecognized ‘hidden’ variables. It was believed that Einstein lost his debates to Niels Bohr so that EPR ideas were not generally accepted at that time, and world-wide quantum introspection ceased for decades.

1964: John Bell’s theoretical papers showing that ideas on entanglement and locality could actually be measured! This is sometimes called “the most profound discovery of science.” He revived de Broglie/Bohm views versus the Copenhagen interpretation. Note that Bohm theory has nonlocal hidden variables (position and velocity) and is viable. Bell's theorem or Bell's inequality “is a no-go theorem, loosely stating that no physical theory of local hidden variables can reproduce all of the predictions of quantum mechanics.” It is important to note that Bell’s statements involve logic only and have nothing directly to do with quantum mechanics. The failure of Bell inequalities means that reality doesn't follow what we might call conventional assumptions and logic.

1972: Freedman and Clauser ("FC") succeeded for the first time in preparing two particles that exhibited the strange condition predicted by quantum theory called 'entanglement'. This FC test was improved in a 1981 Aspect test (without delayed choice). [They used a photon cascade from calcium but later experiments use 'down conversion'].

1978: John Wheeler's version of a delayed choice thought experiment in which the method of detection can be changed in flight after the photon passes the double slit and force the photon to decide if it is a particle with path or a wave with interference (verified by Aspect in 2007).

1982: **Aspect's** test based on Freedman and Clauser's test but with better precision, fewer loopholes, and delayed choice of detector polarization orientation. This test finally forced the world to take entanglement seriously and started a rebirth of quantum debating.

Aspect Test:

Alain Aspect was an early convert to the possibilities of John Bell's theorem. He wanted to show that non-locality was indeed an essential element of quantum mechanics and that Einstein's belief in locality was misplaced. His first goal was to replicate previous tests for one and two channels but with more accuracy and fewer loopholes. And then he wished to perform the Wheeler random delayed choice test evolved further by Bohm, Aharonov, and Bell. Testing quantum mechanics was academically-politically risky, so he got a blessing from Bell, "You must be a very courageous graduate student" [13].

In Paris, Aspect used a long distance between detection stations of about 12 meters allowing for a long transit time for light of 40 nanoseconds. There are rapid switches near each detection station that decide one of two alternative measurements to make. They are very clever 'electro-optical-acoustical' transducers, driven in phase, creating ultrasonic standing waves in a slab of water through which the relevant photon must pass using a frequency of about 25 MHz (the frequency is different for the two stations). The periodic density variation in the wave acts as a diffraction grating: If a photon is pictured as a localized 'wave packet' (length in time ~5 nanoseconds) that arrives at say station-1 when the wave has a node in-between its peaks, it is transmitted straight through the slab and enters a polarizer set in direction 'a'. If on the other hand it arrives at an antinode (periodic density peaks of counts or probability), then it undergoes Bragg diffraction and is directed into a polarizer set at a' (as sketched in Figure 5 above). Light quantum Photons incident at intermediate phases of the wave are deflected into neither polarizer and are thus missed in the counting. This experimental idea is just amazing to me. The period of switching between the alternative choices (a quarter period of the transducers) is about 10 nsec., short compared to the transit time of light between the stations. To the extent, then, that one can regard the switching as a "random" process, the locality loophole is blocked. The data obtained in ref. [4] violate the Bell predictions by many standard deviations. Truly random choices were conducted much later.

How is it possible for the two polarizers to 'know about each other' and know about recent changes in testing instantaneously? This appears not only to violate common sense but also relativity limited by the speed of light, c . One possible explanation was proposed by John Cramer in 1986 [6,7,8]. He has a view of quantum mechanics called the "Transactional Interpretation." The math of quantum mechanics is straightforward, but there are many different interpretations of what the math represents in the physical world. Cramer essentially says that a photon is it own antiparticle and can travel backwards in time as well as forwards. Feynman also considers any antiparticle as a particle **traveling backwards in time (fig 6)**. When an emitter wants to emit a photon, it first sends an offer wave forwards in time. An absorber then sends a confirmation wave backwards in time to the emitter. The communication process continues until a completed transaction occurs and the proper quantum numbers are delivered to the absorber. The emitter knows what kinds of tests it is going to encounter in the future because its wave function ‘has already been there.’ In quantum mechanics, the offer wave is called ‘psi’ and the confirmation wave is ‘psi-star’ (ψ, ψ^*-- complex conjugation represents time reversal). The probability of the transaction is then very naturally the product $P = \psi^*\psi = |\psi|^2$. This forward-backward propagation also represents normal electromagnetic wave propagation as ‘half-advanced half-retarded’ electric fields going forward and backward in time (R and A waves—the Wheeler-Feynman electrodynamics).

The following space-time diagram shows how two well-spaced detections can have instantaneous quantum communication using forward-backward communications.

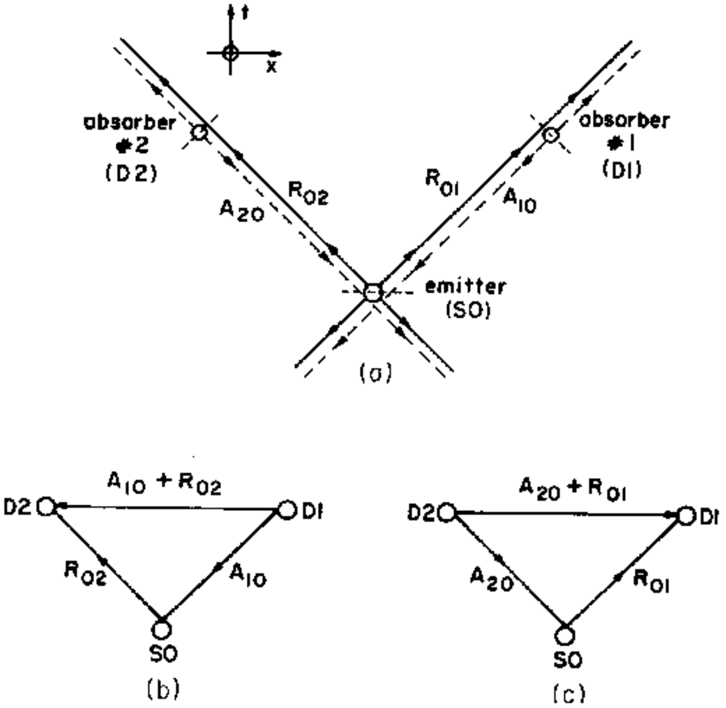

Figure 6 : John Cramer’s picture of allowed communication between two observers (absorbers or detectors) in terms of ‘Minkowski’ space-time diagrams for the case of the ‘Freedman-Clauser’ experiment. The 45° lines are light-like (at the speed of light on the light-cone) for ‘advanced’ and retarded waves (arrows down and arrows upwards). Nonlocal enforcement of polarization correlations can occur between D1 and D2 as 4-vector sums connecting them (b,c). The joint transaction occurs along all the lines together and is ‘atemporal’. [Cramer, 6]

In spite of the apparent faster than light transfers of quantum information, it is believed that exploitation of nonlocality for controllable signaling is impossible for classical observers (“no signaling proofs”).

Following these entanglement (Bell/EPR) tests, Aspect performed a test for the original Wheeler view of a delayed choice experiment. The essence of this test is shown below (e.g., figure 7).

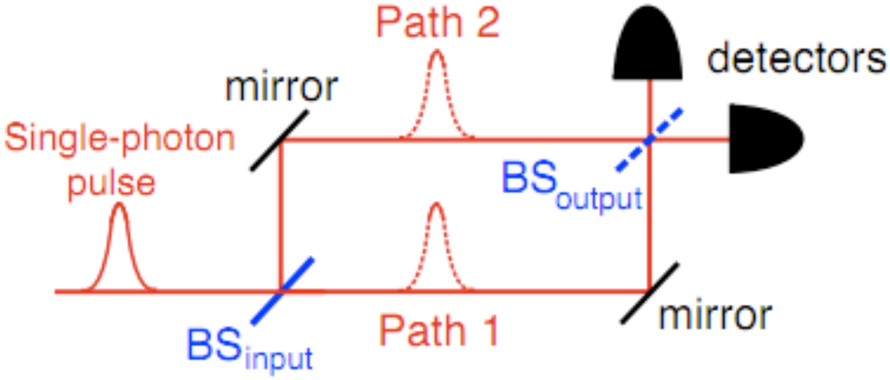

Figure 7: "Wheeler's delayed-choice Gedanken Experiment with a single-photon pulse in a **Mach-Zehnder** interferometer. The output beam splitter BS-output of the interferometer can be introduced or removed (closed or open configuration) at will." The 2006 Aspect realization [5] used a **48 meter** pathway with movable BS output. "The choice between measuring either the open or closed configuration is made by a quantum random number generator, and is space-like separated — in the relativistic sense — from the entering of the photon into the interferometer. Measurements in the closed configuration show interference with a visibility of 94%, while measurements in the open configuration allow us to determine the followed path with an error probability lower than 1% [6]." The traditional initial and final beam splitters have opposite orientations for different phase shifts of reflected and transmitted light so that one detector will usually see just destructive interference (no nominal output).

Feynman referred to the usual two-slit quantum superposition interference experiment for photons or electrons as containing the central mystery of quantum mechanics. However, having two slits close together restricts the types of experiment modifications that can be performed. The Mach-Zehnder interferometer with a large rectangular pathway enables a lot of room between the two interfering paths so that many experiment can be done. Each path can be separately affected by electric fields, magnetic fields, and gravitational fields to vary the phase of that path. This device is increasingly used for modern QM tests. One result is to show that for single particles, particle traits such as charge, magnetic moment, mass, spin, appear to be carried along both paths at the same time.
Later Bell tests include: Geneva 1998 test of entanglement over several kilometers distance. Tests guaranteeing pure randomness for delayed choices. Three particle entanglements. Trapped entangled atomic-ions (Boulder 2001). 2008 18 kilometer detection. Superconducting qubits. Many Zeilinger tests in Austria. As of 2011, physicists have now been able to entangle 8 photons together in a very complicated apparatus on a light table! (the latest record [11]).
Perhaps the most interesting interferometer is a specially carved single silicon crystal that breaks an incoming neutron beam (from a nuclear reactor) into an upper and lower beam and then recombines them again to get interference. This one can see that gravity slows down the phases of the lower beam. A special device can also be inserted into the lower beam so that it responds to the presence of a separate magnetic field that precesses the neutron's magnetic moment and causes a shift in the output interference. The particle property of magnetic moment appears to exist in each path even for just one neutron at a time going through the system. There is interference between the possible upper and lower path-- it really boggles the mind.

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APPENDIX:

Question: Plane polarized photons? Figure 4 shows the cascade from a spin zero state to spin one and then spin zero again. A photon is a spin one particle which carries away the change in angular momentum of the electron states. A spin one photon is either right circularly polarized state $|R\rangle$ or left circularly polarized $|L\rangle$ so that the electric field corkscrews through space in the direction of motion. But the experiments use plane polarized detectors. Any direction of polarization can be written as a combination or "superposition" in the $|x\rangle$ plane direction or the $|y\rangle$ direction [15], and a y-direction plane polarized photon is: $|y\rangle = (|R\rangle + |L\rangle)/\sqrt{2}$. Similarly, a right polarized photon can be written as $|R\rangle = (|x\rangle + i\,|y\rangle)/\sqrt{2}$. If $|R\rangle \rightarrow |y\rangle$, where does the angular momentum go—it has to be conserved. [Ans: probably into the polaroid crystal].

How to visualize the "simplest Bell example" $N(A^+B^-) + N(B^+C^-) \geq N(A^+C^-)$.
Draw a 2x2 square array (2 rows x 2 columns) where the rows are A+ and A- (top to bottom) and the columns are B+ and B- (meaning 'not B' – like in [14]). At the center, draw a circle or center a diamond so that the inside is C- and the outside is C+. Label all little areas from upper right as a "counter-clock-wise" b, c, d for the outer C+ and then repeat around another circle for the inner C- d,e,f,g. Then the above inequality is area "e + a + f + g" >" f + e" – obviously true. If counts are proportional to the appropriate partition of areas, then counts also follow. But it assumes independence (a tall boy doesn't bias towards having blue eyes).
The Scientific American Picture uses: $N(A^+C^-) + N(A^-C^+) + N(B^+C^-) + N(B^-C^+) \geq N(A^+B^-) + N(A^-B^+)$.
Or: "f + e + c + d + f + g + a + d" ≥ "a + e + c + g" , or after canceling, just $2(f + d) \geq 0$. Again, obviously true.