Chapter 6

“Interference”

Credit – Foxtrot: “Watched” (need permission)

Interference in physics is the term given for the peculiar way waves interact with each other. Waves consist of a series of peaks and troughs, or from the discourse, crests and valleys. Given two (or more) sources of waves, when the waves meet, the crests and valleys from each source interact with the others in well-established patterns. If two crests overlap, the result is an even higher crest, and if two valleys overlap, the result is an even deeper valley. But when a crest and an equally sized valley overlap, the result is flat; neither crest nor valley.

The first two cases are called constructive interference, the waves enhance each other. The latter case is called destructive interference, the waves cancel each other. But in both cases the waves are merely interacting. So why this particular choice of jargon?

- Why not call it enhancing? That accentuates the positive; crest enhances crest, valley enhances valley.
- Why not just call it interacting? That would be neutral, no judgement.
- Why then is it called interference? That accentuates the negative; valleys cancel crests.

And maybe that observation contains the explanation. How can two different ways of achieving the same thing, each successful when only one is allowed, end up preventing (interfering with) the very same thing? How can having two options, each successful when only one is allowed, suddenly fail when both are allowed?

That’s why we call it interference. It dramatizes that waves don’t merely interact; they produce a jarring, counter-intuitive abolition. Yes, they can enhance, but the jolt is that they can also *cancel*.

Let’s dig a little deeper.

Interferometer

An interferometer is an optical device that splits an incoming stream of light into two beams, only later to recombine them. The two beams follow different routes but are eventually redirected to cross each other. At the point where they cross the beams are recombined. The device used to split the beams in two and send them down the different arms of the interferometer is called a beam-splitter and is typically a half-silvered mirror. The device used to recombine them is also a beam-splitter, another half-silvered mirror.

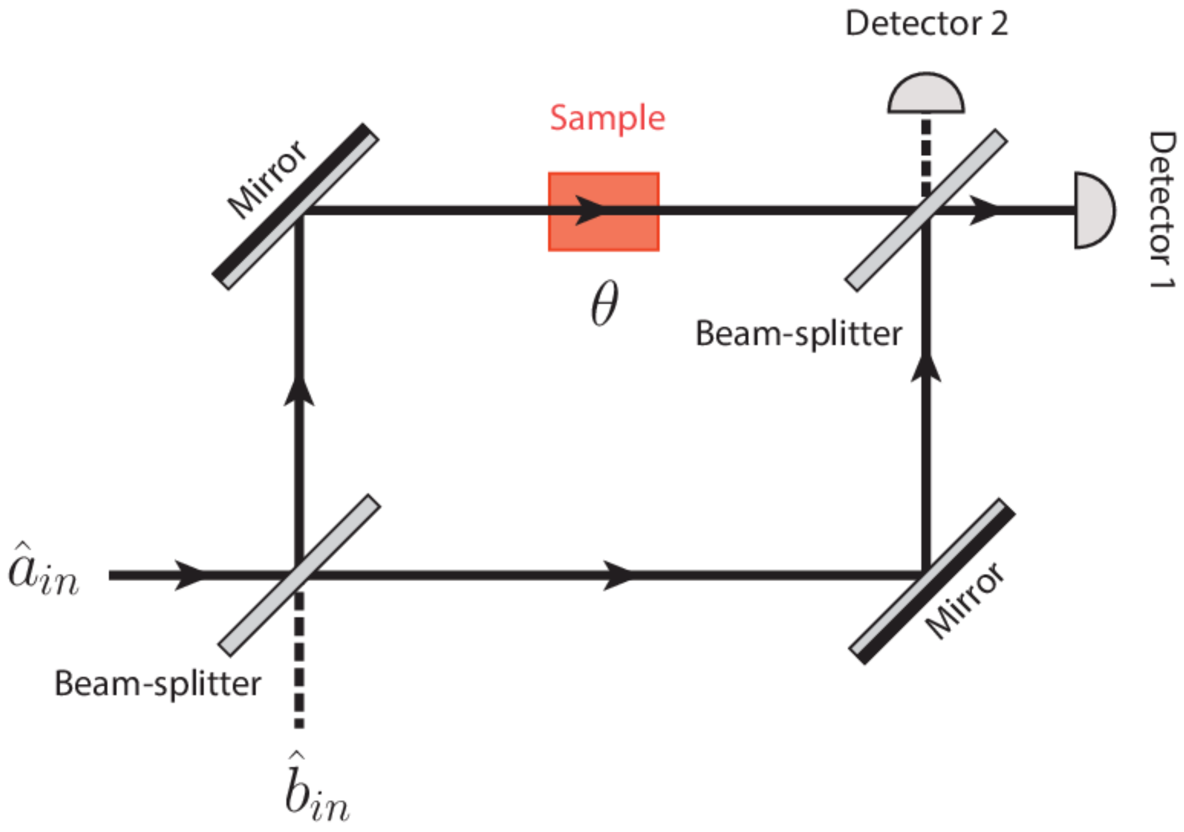

Figure 1 – **Interferometer**: A Mach–Zehnder interferometer schematic showing beam splitting, recombination, and two output detectors (source: Wikimedia Commons, CC-BY-SA 4.0).

At the end of each arm of the interferometer is a detector, possibly a scintillation screen or photographic film or a CCD camera, something that records each photon. In all cases, the photon is detected as a particle, a point like event on a two-dimensional surface. The CCD camera also allows a record of the time the particle was detected, but whatever the technical solution we'll just call it a screen.

Anywhere along either arm it is possible to put a device that can detect if the photon went that way without destroying the photon. Call it a route detector. While there can be one on each arm, it suffices to monitor just one of the arms. The route detector is optional; it is the variable in the experiments to be described. All such devices do, however, have an impact on the phase of that photon, and that phase shift is random. The important consequence of that random phase shift is the dramatic effect it has on the pattern of dots recorded by the screen.

When the optional route detector is in place, each photon clearly takes one arm or the other of the interferometer. The particle view was that at the beam combiner at the entrance to the interferometer the photon had a 50/50 chance of taking either arm. If the route detector fires, then we know the photon went down that arm, if not, it went down the other arm. At the beam combiner at the exit of the interferometer, the photon again has a 50/50 chance of which way to go, and so it randomly arrives at one screen or the other.

In this case, each of the two screens slowly develops a smooth distribution of dots which peaks at the center of each respective beam and tails off. The distribution is called a diffraction pattern. In this case, each photon went only one way around the interferometer; it took one arm or the other, not both, and did so with a 50/50 probability.

However, when the route detector is removed, it is now no longer possible to determine which arm of the interferometer a photon took. The conclusion forced upon us by the equations of quantum mechanics is that each photon takes *both* arms, and the screens show not a diffraction pattern but an interference pattern. (*Ahh*, so that is why the entire apparatus is called an interferometer.) The intensity of the incoming light beams can be lowered sufficiently to permit only one photon at a time within the interferometer. The inescapable conclusion is that each photon interferes with itself. To do so, it must travel down both arms of the interferometer.

What is shocking (jarring) is that there are now places on the screens where a photon is never detected, yet before the route detector was removed, it was possible for photons to get there. These are the valleys in the interference patterns. At the screens, each photon sure looks like a particle, well localized, point like; but in the arms of the interferometer, it behaves like a wave. Yet to compute the mathematical shape of the interference pattern, we treat the photon as if it traveled a well-defined path, two paths, actually, one path down each arm of the interferometer. Taking a well-defined path is particle like behavior. The difference in the path lengths determines whether crest met crest or valley met valley (constructive interference) or crest met valley (destructive interference).

On the two screens, the two interference patterns are inverses of each other. If they are combined, their peaks and troughs cancel out. The result is indistinguishable from combining the two diffraction patterns. Every photon landed somewhere, each is accounted for, but the distributions are different.

When ones’ goals are thwarted by an adversary, that’s malicious interference. But when one interferes with one’s self, that’s called self-destructive behavior; destructive interference. Words are fascinating.

Delayed Choice

But it gets even weirder. The choice to insert the route detector or not, can be made *after* the photon has impinged on the entry beam-splitter. The classical paradigm would have us envision that an incoming photon ‘decides’ whether to go left or right at the time it encounters the beam-splitter. The quantum paradigm adds a third option; left, right, or both. Yet, the decision to use the route detector or not, can be made after ‘decision’ time, and it determines whether the photon went down only one arm, or that it went down both arms. This is the delayed choice experiment.

The present seems to have modified the past.

To give this last point full weight, consider light from a distant quasar, one that to get to earth has to pass by a massive galaxy that acts as a gravitational lens. Each photon that reaches earth had to pass by the galaxy on one side, or the other, or both. How we measure it today determines which; a decision which from the paradigm of classical physics should have happened billions of years ago, is somehow made at the last instant. Frankly, it boggles the mind. We don't understand what the math is telling us.

Mixtures versus Ensembles

To sharpen the conundrum, and deal with reasonable objections that are nonetheless naïve, it is useful to consider a variation on the above interferometer. This variation is called a Mach-Zehnder interferometer. The difference is that the beam-splitters have been replaced with polarization beam splitters. There will be two sets; one for the horizontal basis and one for the diagonal basis. Each polarization beam splitter will send photons with one polarization down one arm, and the photons with the other polarization down the other arm.

The second difference is that finer control is offered over the source of the photons that enter the Mach-Zehnder interferometer. It has 6 settings, best presented as a bulleted list:

- Horizontally polarized photons only.
- Vertically polarized photons only.
- Diagonal polarized photons only.
- Slant polarized photons only.
- Random horizontally or vertically polarized photons.
- Random diagonal or slant polarized photons.

The route detector will not be needed.

Obviously, there are many variations now; many different experiments that could be run. Let's start by having the polarizing beam splitters for the horizontal basis installed in the interferometer. When the source is only generating horizontally polarized photons, they all go down the |H> arm. One screen has a nice diffraction pattern on it, the other is blank. When the source is generating only vertically polarized photons, they all go down the |V> arm. Now the first screen is blank, and the other one has a nice diffraction pattern on it. Obviously, when the source is randomly generating either horizontal or vertically polarized photons, both screens have a nice diffraction pattern on them.

Now for the interesting result. When the source is generating only diagonally polarized photons, each photon is in a superposition of horizontal and vertical polarization, thus, each photon goes down both arms. The result is that both screens now display interference patterns. One of them has a crest at the center of the beam, the other has a valley. If combined, they exactly reproduce the diffraction pattern of either the pure horizontal or pure vertical polarization sources.

If the source is switched to generating only slant polarized photons, each photon is again in a superposition of horizontal and vertical polarization, put with a phase difference of 180 degrees. In the language of the discourse, they are half vertical, half horizontal, whereas in the previous case, they were half horizontal, half vertical. As before, each photon goes down both arms, and as before each screen shows an interference pattern, but now, the interference patterns have been swapped. The interference pattern with a crest at the center of the beam is now on the screen that had a valley at the center of the beam, and vice-a-versa.

If the source is now switched to its last option, spewing forth a beam of photons that are randomly either of diagonal or slant polarization, then all photons still go down both arms, but both screens show only a diffraction pattern. Why? Because the sum of the inverted interference patterns is a diffraction pattern.

The point is this. When the source is generating photons with random polarizations in the horizontal basis, the incoming photons are a *mixture* of polarizations. From the point of view of the interferometer they are not in a superposition; mixture not ensemble. Each photon goes down only one arm. When the source is generating photons with either diagonal only or slant only polarization, the incoming photons are an *ensemble* of polarizations. From the point of view of the interferometer they are in a superposition; ensemble not mixture.

In the first case the photons are randomly going down one arm *or* the other, but in the second case they are going down *both*. That's why that second case results in interference patterns. If the route detector is reinserted, the photons will in fact randomly go down only one arm or the other, but then the interference patterns go away to be replaced with the diffraction patterns.

While an ensemble leads to interference, and a mixture does not, a mixture of ensembles won't either. It is thus not possible for an interferometer to distinguish between a mixture of horizontally and vertically polarized photons or a mixture of diagonally and slant polarized photons. But in the first case, every photon is going down only one arm, while in the latter, every photon is going down both arms.

Obviously, equivalent results are obtained if diagonal polarizing beam splitters are used instead; just invert the roles of the polarization sources.

Decoherence

Superposition is sensitive to the weights and phases of the various uncertain states. As an isolated quantum system interacts with its environment, superposition leaks out into the larger macro system and the quantum system begins to behave more and more in a classical manner. While decoherence may not actually lead to collapse (physicists are divided on this), it does seem like a precursor to it.

The Measurement Problem

The final fundamental issue to wrestle with before tackling entanglement is called the measurement problem. We never observe an object in a superposition. Whenever a measurement is performed, we get a single value. However, in order to correctly predict experimental outcomes, the object has to be regarded as having been in a superposition prior to the measurement.

Here's the rub; we don't have objective criteria for determining when the measurement occurred. We are in the position of the art critic who is asked to define good art; he can't, but he “knows it when he sees it.” The math allows us to claim a measurement at almost any point. Was it the path through the cloud chamber, when the water droplets formed, is that when the wave function collapsed, and a measurement made? Or was it when the camera photographed the cloud chamber? Or when the grad student looked at the film? Or when the professor reviewed the grad student’s notes?

This problem has gone unsolved, at the time of this writing, for almost 100 years, defying expectations. That a problem this fundamental to the field of quantum mechanics has proven so intractable is a primary piece of evidence that the field is ready for a paradigm shift.

Now, finally, we are ready to tackle entanglement.