Faith in the Future : Quantum Spookiness

October 2000

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Class of 1992

Introduction

Thank you Jonathan Malino, Rex Adelberger, and Elwood Parker for creating this lecture series and for giving me this opportunity, and thank you friends for joining me in honoring Sheridan Simon.

Over the past few weeks, I have been reflecting on my years at Guilford, on my education, and in particular, on the ways in which Sheridan touched my life. One of the things I did was look over notes and homework from courses I had with Sheridan. I quickly learned that ten year old lecture notes, even those from the best of lectures, are not particularly interesting reading, but that some of Sheridan's comments in the margins of my homework assignments are actually quite entertaining. Here is an example, a comment on an error in usage.

> “Complementary“ means “it goes with something else “ (donuts go with coffee; pretzels complement beer). “Complimentary“ means “on account of how you're such a great guy, we're giving this to you for free “ (Complimentary BIG MAC with every Cadillac Seville you buy!).

Sheridan was a master grader. He looked for and found algebra errors buried in three page calculations. He even found pairs of errors that canceled out in calculations that gave correct results. He believed in tough love and delivered it with style and humor with a red ballpoint pen. He was also extremely patient. Teaching physics at a place very much like Guilford, I can appreciate how much of himself Sheridan put into his grading. The kind of detailed feedback he routinely gave takes tremendous investments of time and energy. I discovered as I examined his work that in many ways, I have been trying to emulate Sheridan's grading style, although my efficiency in catching errors is poorer, and my grading humor does not equal his.

Sheridan's approach to grading reflects the kind of teacher he was. As a teacher, I have experienced first hand the temptation to lower standards in response to the growing pains of my students, growing pains that are a natural part of learning. Resisting this temptation seemed to come effortlessly to Sheridan. He set clear and high standards and devoted his energy to motivating and helping students to meet them. I never saw Sheridan "lower the bar. " For example, his due dates were firm. This is as rare at Earlham as I remember it being at Guilford. Yet Sheridan magically pulled this off without alienating his students.

My last course with Sheridan was senior level Quantum Mechanics in spring of 1992. There were three seniors enrolled, and we asked Sheridan to modify his course so that it would satisfy the Interdisciplinary Studies requirement, called "IDS 401 " that all seniors had to fulfill at the time. Sheridan agreed. In addition to Sheridan's regular syllabus, we tackled various questions regarding the interpretation of quantum theory. This is a topic that I have continued to follow since then, and it seems a natural topic for this lecture, since my interest in it began in Sheridan's course. I also chose this topic, because I think it is beautiful and astonishing stuff.

I teach quantum mechanics and apply the theory in my nuclear structure research, but my experience is mainly with practical applications of the theory. I come to the more fundamental questions regarding the interpretation of the theory as a reasonably qualified amateur. With that disclaimer, I would like to a question regarding the nature of the quantum theory and the nature of nature itself. This is a question over which Albert Einstein and Niels Bohr disagreed and which has not yet been answered to everyone's satisfaction. The question is

> Do the probabilistic descriptions provided by quantum mechanics reflect a real lack of information in nature or only a lack of information in the theory?

Hereafter, I will refer to this as the Big Question. Einstein's position was that the information not provided by quantum mechanics does exist, and a theory like quantum mechanics that does not include that information is incomplete. Bohr and most other physicists at the time subscribed to the belief that the information does not exist until a measurement is made. The latter point of view was and remains the orthodox view among physicists and is known as the "Copenhagen interpretation."

Attempts to resolve this dispute span about 65 years and have been both theoretical and experimental. Being an experimentalist, I will start by describing a thought experiment, patterned after actual experiments, that will serve as a concrete illustration of the Big Question and attempts to answer it.

An Experiment

Our experiment requires three major pieces of equipment - a source that emits pairs of photons and a pair of photon detectors. Before describing the details of the experiment, I ought to give you a brief introduction to photons.

Photons and Polarization

Electromagnetic radiation, for example, visible light, X-rays, and radio waves, all consist of packets called photons. Photons consist of oscillating electric and magnetic fields that are oriented perpendicular both to one another and to the direction of travel, as shown in Figure 1. Obeying these constraints, the fields can be oriented lots of ways in the plane perpendicular to the direction of travel. This orientation is called “polarization.” For our present discussion, we do not need to understand what electric and magnetic fields are. The most important thing to carry away from this brief description is that photons have an orientation in the plane perpendicular to the direction in which they travel.

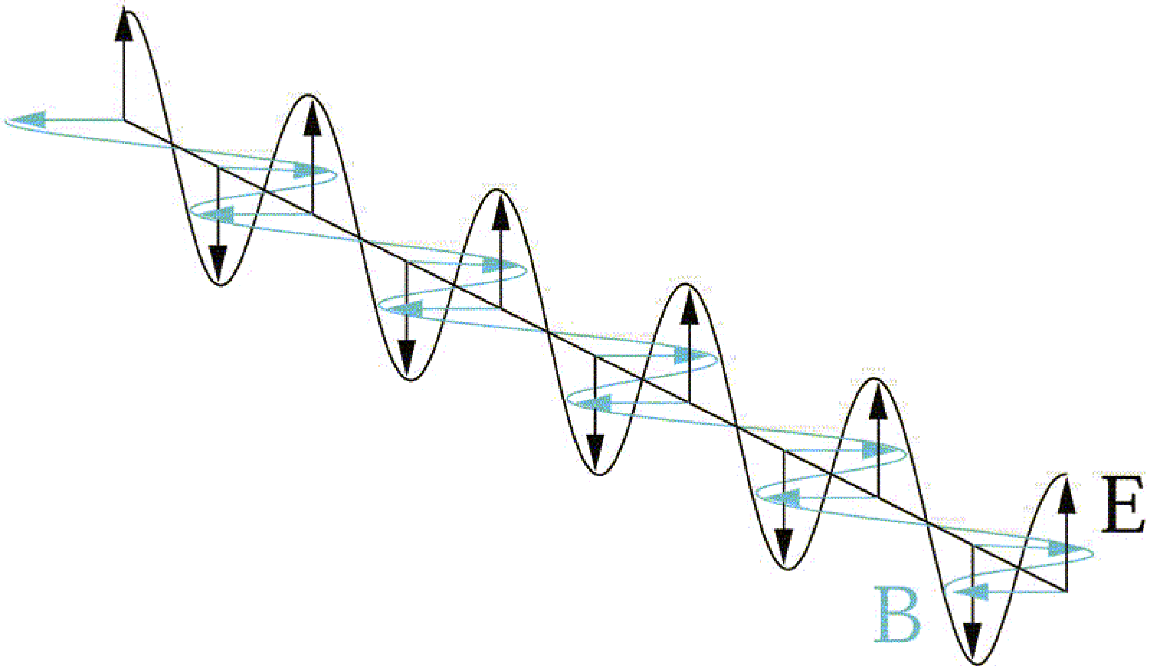

Figure 1: A schematic sketch the oscillating electric (**E**) and magnetic (**B**) fields of a photon traveling diagonally out of the page. This sketch in two dimensions is an attempt to capture a three dimensional concept. The arrows indicating the orientations of the electric and magnetic fields are meant to be perpendicular to one another, and both are also meant to be perpendicular to the direction of travel.

I can demonstrate some polarization effects with two polarizing filters and an overhead projector. On a microscopic level, each of these filters is like a picket fence allowing photons oriented in a single direction to pass through and absorbing the rest. If I place one filter atop the other, and vary their relative orientation, notice that the amount of light that passes through varies. I can align the two filters to get a maximal amount of transmission. If I then rotate one of the filters through 90 degrees, I get no transmission at all. If I cut back to a relative orientation of 45 degrees I get an intermediate amount. If we did a careful measurement, ideal filters at 45 degrees would give 50% transmission.

We are not equipped here today to observe single photons. However, if we were, we would find that with a 45 degrees relative orientation half of the photons we send in are transmitted and half are absorbed. That is, photons are not split in half by the filter.

Quantum Mechanics Says...

The quantum mechanical description of a photon that has passed through the first filter does not predict whether or not the photon will pass through the filter at 45 degrees. Instead, it describes the polarization of the photon in terms of probabilities, stating that it has a 50% chance of passing through the filter at 45 degrees and a 50% chance of being absorbed by it. Without going into detail, it is also important to know that the theory can describe the photon's chances of passing through a second filter with any other orientation.

This is a truly strange kind of description. Our experience of the macroscopic world leads us to expect that we ought to be able to know the actual polarization of the photon, not just the probabilities of observing the two possible outcomes. I claim that most people are naturally predisposed to stand with Einstein in finding this probabilistic description wanting.

Back to the Experiment

With some background on photons and the quantum mechanics of polarization, we are ready for a more detailed description of our thought experiment. Recall that we have a photon source and two detectors. Each of our detectors is actually a fancy filter coupled to two photon detectors. The filter has a specific orientation, and sends photons polarized parallel to this direction into one detector, while sending photons polarized perpendicular to this direction into the other detector. Hence, we get a positive reading for both outcomes. Our photon source generates pairs of photons that travel in opposite directions and that are polarized in the same direction. Due to this shared orientation we will call these “correlated pairs” of photons.

If we orient the detectors in the same direction, and collect correlated photon pairs, we always find that the detectors give identical results. That is, either both detectors register parallel polarizations or both register perpendicular polarizations. This simply reflects the fact that our photons have the same orientation. If the detectors do not have the same orientation, then we expect mixed results. Without going into detail, in these cases, we find that the data is distributed in excellent agreement with (probabilistic) quantum mechanical predictions.

We can now reframe the Big Question in terms of our thought experiment as follows.

Does a photon carry information regarding the direction of its polarization relative to any filter with which it may interact, or is that information determined only when it interacts with an actual filter?

To make sure we have all survived the reframing of the question with our understanding of it intact, how would Einstein and Bohr have answered this new question? (Einstein would have taken the former position, and Bohr would have taken the latter.)

Quantum Spookiness : The EPR Paradox

Now that we have set up our thought experiment and taken some data, we are ready for the spooky part of the story. Einstein's position that photons ought to have well defined polarizations even before they interact with a detector is known as “local realism. “ In 1935, Einstein, along with Boris Podolsky and Nathan Rosen, published an argument [1] for local realism. Their argument has come to be called the “EPR paradox.” I will give their argument in terms of our thought experiment. Einstein will require some refinements of the experiment, and we will be happy to oblige. Thoughts experiments are relatively cheap to reconfigure.

Imagine our source emits a pair of correlated photons, moving away from each other toward two distant polarization detectors. Einstein has asked that we place the detectors far enough apart that our two photons and detectors cannot influence the outcomes of their respective measurements by any known means. Further, he asks that we vary the orientations of our detectors randomly and independently while the photons are in flight. With Einstein's refinements, our data still show that whenever our detectors happen to be aligned, we get agreement. Our data also still agree extremely well with quantum mechanics for all relative orientations of the detectors.

The paradox that EPR presented is that either we have to accept that, in order to give polarizations that agree, the photons communicate by some means faster than the speed of light, thus violating another extremely successful theory called relativity, or we have to accept local realism, that is, that the photons' polarizations are well determined at the source. According to EPR, the latter is the only reasonable conclusion. Einstein referred to the possibility of signals traveling faster than the speed of light as spukhafte Fernwirkungen or “spooky actions at a distance“ [2]. The argument continues that if we accept local realism, then quantum mechanics is incomplete. That is, our photons have properties that quantum mechanics does not describe.

In the 1930s, it was not clear how to resolve this disagreement between EPR and the proponents of the Copenhagen interpretation. Keep in mind that the EPR conclusion that quantum mechanics is incomplete did not call into question the results it could produce. The quantum theory was and continued to be extremely successful in practice. EPR was not a “show stopper, “ but rather left us with a vague sense of unease about the theory. In fact, physicists happily continued to apply the theory for about three decades before a major step was made toward resolving the issue.

Bell's Theorem and Experimental Tests

In 1964, John Bell published a paper [3] outlining an answer to the EPR paradox involving a thought experiment and a relatively simple calculation. It is no accident that our thought experiment resembles very much the one Bell proposed. Starting with an assumption of local realism, that is, assuming that our particles have well determined characteristics all along, he was able to derive a simple mathematical relationship that is violated by quantum mechanics. In the literature this result is called “Bell's theorem. “ His conclusion was that quantum mechanics and local realism are incompatible. Bell's theorem provides, at least in principle, a means of resolving the Big Question experimentally.

Our thought experiment is based on the most successful set of experimental tests to date. The first set of tests was developed in the early 1970s [4,5,6] and used standard polarization filters. The experiment was further refined in the early 1980s [7,8,9] to include polarization detectors giving positive results for both parallel and perpendicular polarizations and also to include rapid variation of detector orientations. The most recent refinement came in 1998, with a measurement [10] with detectors placed far enough apart to rule out communication between them via any signal traveling at or below the speed of light.

These measurements show excellent agreement with quantum mechanics and disagree with Bell's theorem by as many as 30 standard deviations. We now appear to have a collection of experimental answers to the Big Question. We are led by these results to conclude that both quantum mechanics and nature are nonlocal. The photons in our thought experiment do not carry precise polarization information. Instead their polarizations are only determined when they reach the detectors, even though the detectors are hundreds to thousands of meters apart.

I feel I should admit that have a hard time grasping what nonlocality really means. At this point in developing my understanding of all of this, I end up thinking of one of our correlated pairs of photons in flight as a single object rather than two distinct photons. The outcomes of two distant measurements of these photons are tied together. In this sense, they are not separate. Correlated pairs like these are often referred to as “entangled“ in the literature.

Loopholes and Skeptics

Let us not get too carried away with the idea that we have an answer to the Big Question. This issue remains unresolved for some. There are reasonable physicists who do not believe that the current evidence rules out local realism. Until 1998, there was a loophole in the experimental evidence due to the fact that detectors were too close together. This allowed the possibility of relativistically legal communication between detectors regarding the outcomes of measurements. That loophole has been closed with recent experiments [10,11]. There is a remaining loophole regarding the efficiencies of the detectors. Modern experiments of this type currently catch only about 5% of the photon pairs produced by the source [10]. Although it is not clear why we should consider that 5% to be an unrepresentative sample, a true skeptic does not have to be convinced by the existing evidence. I expect further developments in this area.

Applications

I would like to consider two potential applications that might come out of experimental tests of Bell's theorem, one that could work and one that cannot. One recent experiment in Switzerland involved the transmission of photons through fiber optic cables over several kilometers [11]. Perhaps we can use this “spooky action at a distance“ for instantaneous long distance communication, using the orientation of one detector to send signals to the other. Unfortunately, this idea is a complete flop. The data collected by each detector is randomly distributed, regardless of anything we do with the orientations of the detectors. The correlations we see in the polarizations are only evident if we compare the data from both detectors after the fact.

However, the Swiss group [11] suggests another application that could work in principle. If the detectors are aligned, then we get identical streams of random data at both ends. We could use this random data for encryption of secure information. A person at one detector could use the data to encrypt a message, while the person at the other detector could write down the same data and use it to decrypt the message later. This method provides an interesting security feature. Someone trying to intercept the data would disturb correlated pairs. That would show up as missing data in one of the detectors. This design could certainly be realized, but whether it will turn out to be a practical, cost effective encryption method remains to be seen.

Closing

In closing, I want to address a second Big Question. Actually, it is more of a charge than a question. Quoting the brief description that accompanies print copies of these lectures, part of the task Sheridan set for me is “to reflect on the significance and impact of [my] Guilford education. “ My answer to that charge will likely vary over the years, but at this point in my life and career, the aspect of my Guilford education that has meant the most to me is my transformation from a reasonably good student to an independent learner. Sheridan and his colleagues were engaged in stretching me beyond what I believed I could achieve, with the goal in mind of leaving me with the ability to do that for myself. It has been eight years since I left Guilford, and I have forgotten much of the particulars of what I did here. Unrefreshed facts have a fairly short half life in my brain. What I carried away with me when I graduated and what has carried me the farthest since, are the independent learning skills I began to develop here. Sharing with you here some of what I have learned since leaving Guilford about a topic that I love is a demonstration of what those skills have meant to me.

The teaching I found here helped to empower me in my life beyond graduation, but it also impressed me as a fulfilling career. While the faculty seemed exhausted by the work at times, most of them also seemed to be truly happy. This made an impression on me, because even then I knew that happiness is not always easy to find. In interacting with the faculty at Guilford and at Earlham, I have the feeling that, while we generally feel we deserve better compensation, many of us are secretly amazed that we are paid anything at all to do what we love to do. I feel fortunate to have found my way to Guilford, into the study of Physics, and now into a teaching career, and I feel a debt of gratitude to the Guilford faculty members who helped me to steer this course.

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