PHYS 190: Quantum Entanglement

“Spooky Action at a Distance” and Experiments That Contradict Common Sense

> “Science is for everyone.... We are all natural explorers.”
>
> —Wanda Diaz-Merced
>
> “I don’t demand that a theory corresponds to reality because I don’t know what it is. Reality is not a quality you can test with litmus paper. All I am concerned with is that the theory should predict the results of measurements.”
>
> —Stephen Hawking

Quantum entanglement is a rigorous mystery, although Einstein disparaged it as “spooky action at a distance.” We need only logic and arithmetic to prove an astonishing fact: our everyday assumptions are contradicted by measurements of entangled particles. Our everyday assumption is this: objects have properties that exist regardless of whether anyone is observing them, and the measurement of one object can’t affect a distant object. We will carefully study the evidence and the reasoning that compel us to abandon this everyday assumption. The mysterious implications are a subject of perennial debate among physicists and philosophers. This course is an evidence-focused seminar, which is part of Emory’s initiative to elucidate “The Nature of Evidence: How Do You Know?”

The goals of the course are the following:

Distinguish uses of evidence in the foundations of physics

- What is the role of irrefutable mathematical and logical truths?
- What is the role of experimental data?
- How do these two types of evidence combine to contradict our everyday assumptions?

Evaluate and analyze evidence

- What is the mathematical evidence for this claim: everyday assumptions impose constraints on measurable quantities?
- What kind of experimental evidence is gathered to test these constraints?
- How confident should we be in the evidence and its implications?
- Does experimental evidence support or contradict our everyday assumptions?

Build arguments based on evidence and assess the arguments of others

- What does the evidence imply about the fundamental nature of reality?
- Why is there no consensus among physicists?
- What are the loopholes that limit the significance of some experiments, and how do other experiments close the loopholes?
- Does evidence from macroscopic instruments imply the existence of a microscopic reality?
- Is it valid to construct narratives about objects too tiny to see, or is quantum physics just a set of predictions of results from our macroscopic instruments?

Grades will be computed as follows:

- 50% (2% per class starting Sept. 9): Synopsis of the use of evidence in each assigned reading. Submit a minimum of five sentences by the beginning each class. If there are multiple readings, at least one sentence must address each reading. How did the author(s) use evidence to support their arguments? What kind(s) of evidence did they use: experimental evidence, mathematical/logical evidence (irrefutable mathematical or logical truths), or something else? Was it clear or confusing? Persuasive or dubious?
- Staged assignment: The evidence against local realism.
  - 20%: Analysis of an argument. Choose a "proof" that local realism is incompatible with real or hypothetical experimental evidence: quantum triplets, Ball's PR box, Bub and Bub's super quantum entangler, Becker's quantum roulette, or any other proof of some variation of Bell's theorem. Does the proof rely more on experimental evidence or mathematical/logical evidence? Is it confusing? Does it make sense? Can it be clearer? Does it have any relevance to real life? Carefully restate every step in the author's argument (especially the steps that are implicit or omitted). How clear is each step, and how compelling is the evidence to support it? Your paper should be at least 500 words and may be much longer.
    - Rough draft due Oct. 28. I'll return it within a week.
    - Final draft due Nov. 11.
  - 30%: Extension of the argument. Build upon your understanding of the author's argument in one or more the following ways: clarify any muddled points; challenge or rectify any weaknesses or loopholes in the argument; create a new analogy to an entangled system; discuss the implications for one or more philosophical interpretations of quantum physics (local realism, Copenhagen, nonlocal realism, many worlds, QBism, etc.). How strong is the evidence against local realism? Are you advocating a particular interpretation of the evidence, or are you summarizing alternative positions? Your paper should coherently interweave various ideas studied over the semester. Dissect and elaborate on any subtleties. **There's a market for clear writing about quantum mysteries.** The last word has not been written. What do you want to explain to the global community? Your paper should be at least 1500 words and may reuse sentences from the earlier assignment. Due Dec. 17. A rough draft is optional but recommended and may be submitted any time. Please give me at least a week to read it.

Please submit all assignments by email.

Office hours:

I'm often in my office (Math & Science Center N308), and you're welcome to drop by any time. If my office is out of the way, please make an appointment to make sure I'm there.

Statement from the Department of Physics:

We are all here in this class for the same reason: to learn physics. It is unacceptable to judge your fellow students by gender, race, or anything else. Please treat your classmates with respect both in and out of the classroom. If you have any concerns please talk with the teacher or the department chair.

The meaning of quantum physics has been debated for decades and remains a subject of contemporary interest. We will read three books, all published in 2018:

> Philip Ball. *Beyond Weird: Why Everything You Thought You Knew About Quantum Physics Is Different*. (ebook available through Emory library)
>
> Adam Becker. *What Is Real? The Unfinished Quest for the Meaning of Quantum Physics*.
>
> Tanya Bub and Jeffrey Bub. *Totally Random: Why Nobody Understands Quantum Mechanics (A Serious Comic on Entanglement)*.

Readings to be completed by the beginning of the indicated class:

Introduction to Quantum Physics

Aug. 28. No readings.

Sept. 4. Becker (Introduction and Prologue, pp. 1-10). Ball ("By way of introduction…" and "No one can say what quantum mechanics means," pp. 1-21).

Sept. 9. Ball ("Quantum mechanics is not really about the quantum," pp. 22-34).

Sept. 11. Becker (Chapter 1, pp. 11-20). Ball ("Quantum objects are neither wave nor particle," pp. 35-57).

Sept. 16. Becker (Chapter 2, pp. 21-41). Ball ("Not everything is knowable at once," pp. 144-156).

Super Entanglement

Sept. 18. Ball ("Things could be even more quantum than they are," pp. 306-319).

Sept. 23. Bub and Bub ("Part I," pp. 1-71).

Einstein's View: Local Realism

Sept. 25. Bub and Bub (pp. 72- 81). Becker (Chapter 3, pp. 34-60).

The Double Slit

Sept. 30. Becker (Chapter 5, pp. 87-116).

Oct. 2. Ball ("Quantum particles aren't in two states at once," pp. 58-75).

Interpretations of Quantum Physics

Oct. 7. Ball ("What 'happens' depends on what we find out about it," pp. 76-101). Becker (Appendix, pp. 289-294).

Oct. 9. Ball ("There are many ways of interpreting quantum theory," pp. 102-125). Bub and Bub (pp. 82-125).

Oct. 16. Becker (Chapter 4, pp. 61-85). Bub and Bub (pp. 126-157).

Oct. 21. Becker (Chapter 8, pp. 163-189).

Bell's Theorem: Evidence Can Overrule Common Sense

Oct. 23. Becker (Chapter 7, pp. 141-162).

Oct. 28. Ball ("Whatever the question, the answer is 'Yes,'" pp. 126-143).

Oct. 30. Ball ("The properties of quantum objects don't have to be contained within the objects," pp. 157- 177).

Nov. 4. Ball ("There is no 'spooky action at a distance,'" pp. 178- 195).

Nov. 6. Becker (Chapter 9, pp. 193-218).

Nov. 11. Becker (Chapter 10, pp. 219-241).

Quantum Decoherence

Nov. 13. Ball ("The everyday world is what quantum becomes on human scales," pp. 196-216).

Nov. 18. Ball ("Everything you experience is a (partial) copy of what causes it" and "Schrodinger's cat has had kittens," pp. 217-251).

The Many-Worlds Interpretation

Nov. 20. Becker (Chapter 6, pp. 117-139).

Nov. 25. Becker (Chapter 11, pp. 243-265).

Applications

Dec. 2. Ball ("Quantum mechanics can be harnessed for technology" and "Quantum computers don't necessary perform 'many calculations at once,'" pp. 252-285).

Conclusions?

Dec. 4. Becker (Chapter 12, pp. 267-288).

Dec. 9. Ball ("The fundamental laws of quantum mechanics might be simpler than we imagine" and "Can we ever get to the bottom of it?" pp. 320-354).