Philosophy 426, Philosophy of Physics: Quantum Mechanics

Spring 2021
TF 11:30-12:50
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There is no question that quantum mechanics is empirically successful. What the theory says about the nature of the world, however, remains controversial. In this class we will look at different theories of quantum mechanics and examine a range of philosophical issues that arise for them. Topics include the measurement problem; quantum nonlocality; the ontological status of the wavefunction; the fundamental ontology of the theory; the nature of probability; the compatibility of quantum mechanics with relativity; the direction of time. Throughout, special attention will be paid to the ontologies of different theories of quantum mechanics, realistically construed.

Readings

Books (available at the bookstore; ebooks on reserve at the library):

Required: David Albert, *Quantum Mechanics and Experience*

Optional: Jeffrey Barrett, *The Conceptual Foundations of Quantum Mechanics*

All other readings are available on Canvas or at an online address given below

Prerequisites

There are no official prerequisites, but we will use mathematics in the class. It is strongly recommended that you have had at least a solid high school physics class and some exposure to calculus. It is also helpful if you have had some exposure to vectors, matrices, and complex numbers, but this needn't be at your fingertips: we will review what we need during the first few classes. I will not assume any background in philosophy, although one previous course is recommended.

Requirements and grading

Attendance and participation; weekly reading. Assigned readings will not be very long, but they can be difficult. It is recommended that you read each assignment once before class and again afterward. Participation and attendance count for 10% of your final grade. Attendance is mandatory; since exam questions will be based on material covered in class, poor attendance is likely to lower your grade. Lectures will be held at the scheduled meeting time via Webex. Meeting information and a link to the meeting site is posted in an announcement on Canvas. Notes that I write up on the board during class will

be posted on Canvas after each class meeting. Note that if you miss a class it is *your responsibility* to read through the posted notes and get any additional notes and announcements from a classmate.
Exams. Two take-home midterm exams and one take-home final exam, each 30% of your final grade. Exams will comprise short-answer essay questions.

Academic integrity

Each student in this course is expected to abide by the Rutgers University Principles of Academic Integrity. Any work submitted by a student in this course for academic credit will be the student's own work. For this course, collaboration is allowed in discussing questions on exams; exams must be written up on your own. Exams submitted for credit must be entirely your own work. If you quote or use an idea from another source, *you must cite it*. More information on Rutgers' Principles of Academic Integrity is here:

`http://academicintegrity.rutgers.edu`

Course materials posted on the course website or handed out in hard copy are intellectual property belonging to the author. Students are not permitted to buy or sell any course materials without the express permission of the instructor. Such unauthorized behavior constitutes academic misconduct.

Office hours

Friday 9:30-10:30am or by appointment.

Schedule

Readings are listed by the date they will be discussed in class. Details are subject to change during the semester. Topics for the last few weeks in particular may change depending on student interest and our earlier progress. Optional readings are truly optional, containing either additional background or more advanced discussion; I will not assume that you have read them.

Jan. 19: Introduction

Overview of quantum mechanics and the departure from classical mechanics. The photoelectric effect and two-slit experiments; wave-like and particle-like behavior of light and matter; realist theories of quantum mechanics.

Reading: Feynman, "Quantum Behavior," available at
`https://www.feynmanlectures.caltech.edu/I_37.html`
Optional: Barrett ch. 1

Jan. 22: Quantum phenomena

Superposition and spin; spin boxes; spin experiments; two-path experiments; quantum-mechanical interference.

Reading: Albert ch. 1

Optional: Barrett ch. 2

Jan. 26: Mathematical formalism: preliminaries

Vectors and vector spaces; complex numbers and complex vector spaces; operations on vectors; Hilbert space; vector components and bases; expansion coefficients; operators; linear operators; matrices; Dirac notation. The mathematical formalism for spin.

Reading: Albert ch. 2 through p. 30

Optional: Barrett ch. 3; Ismael, "Quantum Mechanics," available at `https://plato.stanford.edu/entries/qm/`

Jan. 29: The standard formulation of quantum mechanics

The standard postulates and the standard way of thinking about them; representing physical states and observables using the standard formalism. Eigenvectors and eigenvalues; the eigenvalue equation. The standard way of thinking about superposition. The uncertainty principle; commutators; incompatible observables. Linearity and the dynamics; probability and the Born rule; the collapse postulate.

Reading: Albert ch. 2 pp. 30–38

Optional: Barrett ch. 4

Feb. 2: More on the mathematical formalism

Hermitian operators; position and momentum; the wavefunction; systems with more than one degree of freedom; nonseparable states; entanglement.

Reading: Albert ch. 2 pp. 39–53

Feb. 5: Two-path experiments

Describing two-path experiments with the standard theory. The standard way of thinking about these experiments and about superposition.

Reading: Albert ch. 2 pp. 53–60

Optional: Barrett ch. 5

Feb. 9 and Feb. 12: Quantum nonlocality

Multi-particle systems; entanglement; the singlet state. The EPR argument; completeness and reality; quantum nonlocality. The lessons of Bell's theorem. Quantum mechanics and relativity.

Reading: Albert ch. 3

Optional: Barrett ch. 6; Einstein, Podolsky, and Rosen, "Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?"; Aspect, "Bell's Inequality Test: More Ideal than Ever"

Feb. 16: The measurement problem

Measurement and collapse; the linearity of the dynamics; the measurement problem and the orthodox view of quantum mechanics; Schrödinger's cat.

Reading: Albert ch. 4

Optional: Barrett ch. 7

Feb. 19: Collapse theories

Collapse theories in general, GRW in particular. The wavefunction; position, momentum, energy; physical space and configuration space. The possibility of experimental evidence of collapse; energy conservation.

Reading: Albert ch. 5, pp. 80–99

Optional: Bell, "Against Measurement"

Feb. 23 and Feb. 26: Problems for collapse theories

Midterm 1 posted Feb. 23; due Mar. 2

The possibility of measurements that don't get recorded in macroscopic position states; the possibility of belief states that remain in superpositions; the preferred basis problem; the tails problem; compatibility with relativity. The wavefunction, particles, and macroscopic objects in collapse theories. The ontology of quantum mechanics; wavefunction realism; physical ontology and experience. Different versions of the GRW theory.

Reading: Albert ch. 5, pp. 100–111; Barrett, "The Collapse of the Quantum State" (ch. 8 of *The Conceptual Foundations of Quantum Mechanics*)

Optional: Albert and Loewer, "Tails of Schrödinger's Cat"

Mar. 2: No class

Midterm 1 due by the end of the class period.

Mar. 5: Bare theory; many minds

What it feels like to be in a superposition; the dynamics with nothing added; the bare theory. Single minds and many minds. Empirical adequacy; making sense of probability in quantum mechanics.

Reading: Albert ch. 6

Optional: Barrett ch. 9, ch. 10.5

Mar. 9 and Mar. 12: Many worlds

Everettian or many-worlds theories of quantum mechanics; making sense of probability in many-worlds theories; the question of a preferred basis; fundamental and nonfundamental ontology and structure.

Reading: Lewis, "Uncertainty and Probability for Branching Selves"; Wallace, "A Prolegomenon to the Ontology of the Everett Interpretation" secs. 3 and 4.3

Optional: Barrett ch. 10; Wallace, "Everett and Structure"

Mar. 23 and 26: Bohm's theory

Bohmian mechanics; hidden variables; the guidance equation; the conditional wavefunction; effective collapse; the nature of probability in deterministic theories in general and Bohm's theory in particular. The nature of particles and the wavefunction in Bohm's theory; compatibility with relativity; different conceptions of the physical ontology of the theory.

Reading: Albert ch. 7

Optional: Barrett ch. 11; Goldstein, "Bohmian Mechanics," available at `https://plato.stanford.edu/entries/qm-bohm/`

Mar. 30: Wavefunction realism

Midterm 2 posted; due Apr. 6

The ontological status of the wavefunction; considerations in favor of realism about the wavefunction; finding the ordinary world in the wavefunction; the status of configuration space and of ordinary space.

Reading: Albert, "Elementary Quantum Metaphysics" and "Wavefunction Realism"

Optional: Albert, "Quantum Mechanics and Everyday Life" (ch. 6 of *After Physics*)

Apr. 2: Against wavefunction realism
Considerations against realism about the wavefunction; informational completeness and ontological completeness; local beables; accounting for empirical evidence and ordinary experience.

Reading: Maudlin, "Completeness, Supervenience, and Ontology" pp. 3151–top of p. 3162

Optional: Maudlin, "Can the World be Only Wavefunction?" especially pp. 121–125

Apr. 6: No class

Midterm 2 due by the end of the class period.

Apr. 9: Primitive ontology
Further considerations against wavefunction realism. Primitive ontology as an approach to the metaphysics of quantum mechanics in particular and physics in general; how to figure out the physical ontology of a theory; the scientific and manifest images of the world; the wavefunction as nomological in character.

Reading: Allori, "Primitive Ontology and the Structure of Fundamental Physical Theories"

Optional: Belot, "Quantum States for Primitive Ontologists"

Apr. 13: Additional considerations
Further considerations in the wavefunction ontology debate; the idea of a separable and local fundamental metaphysics; entanglement phenomena as evidence for wavefunction realism.

Reading: Ney, "Separability, Locality, and Higher Dimensions in Quantum Mechanics"; Ismael, "Space, Quantum Mechanics, and Bohm's Fish Tank" pp. 131–the end of sec. 7.1 and sec. 7.7

Optional: the rest of Ismael

Apr. 16 and Apr. 20: The direction of time
The problem of the direction of time; statistical mechanics and thermodynamics; phase space; entropy; the past hypothesis. Albert's argument that the GRW theory of quantum mechanics can solve the problem.

Reading: Greene, "Chance and the Arrow" (ch. 6 of *The Fabric of the Cosmos*); Albert, "Quantum Mechanics" (ch. 7 of *Time and Chance*)

Apr. 23 and Apr. 27: Quantum mechanics and scientific realism
What should the realist say about the different theories of quantum mechanics? Scientific realism in the face of quantum mechanics; empirical adequacy and scientific explanation; competing theoretical aims and virtues; different senses of the equivalence of scientific theories.

Reading: Jones, "Realism About What?" secs. 1, 2, 4; Ruetsche, "Getting Real about Quantum Mechanics" secs. 2 and 3.D; Saatsi, "Scientific Realism Meets Metaphysics of Quantum Mechanics" secs. 1, 2, 4; North, "On the Equivalence of Physical Theories" sec. 1; sec. 2 through p. 7; sec. 3 through p. 14; sec. 4.

Optional: Barrett ch. 12; the rest of Ruetsche; the rest of North

Apr. 30: Catch-up and review
This day is left open to catch up, discuss a different topic, and/or review any material from the semester, according to student preference.

Final exam posted Apr. 30; due 1:00 pm May 7.

May 7, 1:00 pm: Final exam due

Student wellness services

Just In Case Web App. `http://codu.co/cee05e`. Access helpful mental health information and resources for yourself or a friend in a mental health crisis on your smartphone or tablet and easily contact CAPS or RUPD.

Counseling, ADAP & Psychiatric Services. (848) 932-7884, 17 Senior Street, New Brunswick, NJ 08901, `www.rhscaps.rutgers.edu/`. CAPS is a University mental health support service that includes counseling, alcohol and other drug assistance, and psychiatric services staffed by a team of professional within Rutgers Health services to support students' efforts to succeed at Rutgers University. CAPS offers a variety of services that include: individual therapy, group therapy and workshops, crisis intervention, referral to specialists in the community and consultation and collaboration with campus partners.

Violence Prevention & Victim Assistance. (848) 932-1181, 3 Bartlett Street, New Brunswick, NJ 08901, `www.vpva.rutgers.edu/`. The Office for Violence Prevention and Victim Assistance provides confidential crisis intervention, counseling and advocacy for victims of sexual and relationship violence and stalking to students, staff and faculty. To reach staff during office hours

when the university is open or to reach an advocate after hours, call 848-932-1181.

Disability Services. (848) 445-6800, https://ods.rutgers.edu/, Lucy Stone Hall, Suite A145, Livingston Campus, 54 Joyce Kilmer Avenue, Piscataway, NJ 08854. Rutgers University welcomes students with disabilities into all of the University's educational programs. In order to receive consideration for reasonable accommodations, a student with a disability must contact the appropriate disability services office at the campus where you are officially enrolled, participate in an intake interview, and provide documentation: https://ods.rutgers.edu/students/documentation-guidelines.

If the documentation supports your request for reasonable accommodations, your campus' disability services office will provide you with a Letter of Accommodations. Please share this letter with your instructors and discuss the accommodations with them as early in your courses as possible. To begin this process, please complete the Registration form on the ODS web site at: https://ods.rutgers.edu/students/registration-form.

Scarlet Listeners. (732) 247-5555, http://www.scarletlisteners.com/. Free and confidential peer counseling and referral hotline, providing a comforting and supportive safe space.