Part 1: What is Quantum Mechanics?
- The equation is Linear: If $\Psi$ and $\Psi'$ describe possible physical states at a given time $t$, also $\Psi + \Psi'$ does.
  - State: all you need to specify in order to completely describe the system
  - $\Psi$:
    - If the nucleus does not decay, nothing happens and the cat stays alive
    - $\Psi_1 = \int |\Psi_1|^2 d\Psi_1$
  - $\Psi'$:
    - If the nucleus decays, the device is activated, the poison is released into the box and the cat dies
    - $\Psi_2 = \int |\Psi_2|^2 d\Psi_2$

Part 1: Impossible cats
- Now, reflect on what this state might mean:
  - $\Psi_{\text{total}} = \Psi_{\text{decayed}} + \Psi_{\text{undecayed}}$
  - It is the sum of the state describing a nucleus having not decayed and the cat staying alive and the state describing a nucleus having decayed and the cat getting killed.

Part 1: What is Quantum Mechanics?
- A fundamental physical theory
- The fundamental object of the theory is something called the wave function $\Psi$: it completely describes the state of a physical system.
  - The wave function lives in a space with dimension $2^d$.
  - The wave function evolves in time according to an equation called Schrödinger's equation.

Part 2: solutions to the measurement problem
- Deny claim 1 (the wave function provides a complete description)
  - Add the observer (Quantum Theory with the Observer)
  - Add macroscopic variables (Copenhagen Interpretation, CI)

Part 2: Problems with Solution 1
- How do I precisely characterize what is an observation?
  - What makes me so special to change the state just by looking at the object?
    - Is it only me, or any human? (If you say it is only me who can do it, you should explain why...)
    - Is it only humans, or even animals? (If you say animals cannot do it, you should explain why...)
    - Does consciousness play any role in physics?
Part 2: Quantum Theory with the Observer vs Quantum Theory without the Observer

- Quantum Theory with the observer:
  - The observer plays an important role in the theory
- Quantum theory without the observer:
  - Is it possible to construct a Quantum Theory in the formulation of which the observer is not crucial?

Part 2: Quantum Theories without the Observer - BM

- ROUTE 1: THE WAVE FUNCTION DOES NOT PROVIDE A COMPLETE DESCRIPTION
  - Bohmian Mechanics (BM):
    - State: the wave function + the particles’ positions
    - Temporal Evolution of the state:
      - the wave function evolves according to Schrödinger’s equation
      - the particles’ positions evolve according to an equation determined by the wave function

Part 2: BM and the Measurement Problem

- live cat
dead cat

Actual position of the cat

Part 2: Quantum Theories without the Observer - GRW

- ROUTE 2: THE WAVE FUNCTION DOES NOT EVOLVE ACCORDING TO SCHRODINGER’S EQUATION
  - Spontaneous Localization theory or Ghirardi- Rimini-Weber theory (GRW)
  - State: the wave function
  - Temporal Evolution of the state:
    - the wave function evolves linearly almost always but sometimes it spontaneously collapses

Part 2: GRW and the Measurement Problem

- For macroscopic objects, after a very small time, the wave function spontaneously collapses to one of the terms of the superposition

Part 2: Quantum Theories without the Observer - MW

- ROUTE 3: MEASUREMENTS DO NOT HAVE RESULTS
  - Many worlds
  - State: the wave function
  - Temporal Evolution of the state:
    - the wave function evolves linearly according to Schrödinger’s equation
    - Every result realizes in a different world (everything that can happen, does happen... somewhere)

Part 2: Quantum Theory without Observers

- I will focus my attention only on BM and GRW
  - I want to focus on the common structure of Quantum Theories without Observers and BM and GRW are the clearest examples
  - I do not want to enter into a discussion of the MW theory
  - There are too many “interpretations” of MW
  - And maybe too many issues to be discussed about it

Part 3: from the cat to the mat

- The discussion in terms of Schrödinger’s cat is somewhat misleading:
  - It is just a symptom, not the cause of all the troubles with Quantum Mechanics
  - The real problem is the absence of a clear ontology for Quantum Mechanics
  - In the following part, I will try to clarify this

Part 3: the common structure of BM and GRW

- In the literature, they are considered as dichotomical:
  - They choose different horns of Bell’s alternative: “Either the wave function, as given by the Schrödinger equation, is not everything, or it is not right”
  - I will claim that, instead, they share a common structure: They are mathematical structures grounded on a primitive ontology (PO)
  - Rest of the talk:
    - Discuss the need for a clear ontology and the notion of PO
    - Discuss the role of the wave function
    - Discuss the common structure between BM and GRW

Part 3: the need for a clear ontology

- If one wants to be a REALIST w.r.t. a Fundamental Physical Theory, then it must be clear what the theory is about:
  - What are the entities that are ‘out there’ in the world and what is their mathematical representation?
  - If we do not specify the ontology, the theory is only empty mathematics

Part 3: the notion of Primitive Ontology

- By the primitive ontology of the theory I mean what the theory is fundamentally about
  - The PO is the stuff things are made of
  - Closely related to the notion of “local beables” introduced by Bell, 1976
  - Instead of talking about the state of a system (as we do when we discuss Schrödinger’s cat) it is better to talk about the PO
  - (More on state vs PO later)

Part 3: Local Beables

- Beables: be-ables
  - “the mathematical counterparts in the theory to real events at definite places and times in the real world (as distinct from the many purely mathematical constructions that occur in the working out of physical theories, as distinct from things which may be real but not localized, and as distinct from the ‘observables’ of other formulations of quantum mechanics, for which we have no use here.)” (Bell, 1976)

Part 3: the notion of Primitive Ontology

- Consider, for example, Classical Mechanics:
  - Other mathematical entities (in addition to x, the position of the particles) enter into the theory
  - However, all properties of the system are determined by the history of the positions of the particles x=x(t) is fixed
  - The position is, in this sense, “primitive”
  - Particles form the primitive ontology (PO) of Classical Mechanics
Part 3: the dynamics of the PO

It is not sufficient, to defining a Fundamental Physical Theory, to specify only what is the PO: we also need to specify how it "behaves".

What is the law of motion for the PO?

- The variables describing the PO must be distinguished from the other "auxiliary" (or nomological) variables that allow for the implementation of a dynamical law for the primitive variables.

Part 3: PO vs Nomological Variables

- PO=output
- Nomological variables: algorithm to generate the output
- Different algorithms can produce the very same output
- Each: different sorting algorithms
  - Selection sort: find the smallest value in the list, swap it with the value in the first position, repeat the steps for rest of the list
  - Bubble sort: stepping through the list to be sorted, comparing two items at a time and swapping them if in the wrong order
- Theories with the same output are physically equivalent
- (two theories are physically if they lead to the same histories for the PO)

Part 3: the PO and its dynamics

Fundamental physical theory=
(what there is) & (how it behaves)

(Primitive) & (nomological) variables

In Classical Mechanics: the PO is that of particles while the potential and the other variables are nomological in Quantum Mechanics ...

Part 3: No Clear Ontology for Quantum Mechanics

- It is not clear what Quantum Mechanics is about:
  - 1 About atoms, molecules, electrons...
  - 2 About the wave-function?
  - 3 About the observer?
  - 4 About the results of measurements?

Depending on the answer to this question we have different formulations of Quantum Mechanics
- (some more satisfactory than others, some less and others not at all...)

Part 3: CI and primitive ontology

3: So Quantum Mechanics might be about the observers (Von Neumann)

- But then we have to include consciousness into physics (something that we might not want to do)

4: Or, Quantum Mechanics can be about the results of measurement (Bohm's CI):

- 2 (measurement results) are what the theory is fundamentally about (MACROSCOPIC PO)
- The wave function expresses the law which governs the behavior of the PO in a simple and natural way (nomological variables)
- (PO, auxiliary or nomological variables) = (Z; Ψ)

Part 3: PO and the Positivists

- Positivists understood the importance of basing a theory on something secure
- In particular, they recognized experience to be this kind of undeniable, safe, secure thing on which we could base our theories. That is, they wanted scientific theories to be based on a sort of macroscopic ontology
- In this sense positivism has provided an important step toward a realistic interpretation of Quantum Mechanics

Part 3: Metaphysics and Bohmian Mechanics

- Two ways of interpreting what matter is made of in BM:
  - Option 1: things are made of the wave function and one single particle in a very big space (Albert, Loewer)
  - Option 2: things are made of particles moving in 3-space (myself, Goldstein, Ducrr, Tumulka, Zangh, Monton, ...)

Part 3: Metaphysics and Ghirardi-Rimini-Weber Theory

- Two different ways of interpreting GRW:
  - Option 1: things are made of the wave function (Albert, Loewer, P. Lewis, Rimini, ...)
  - Option 2:
    - GRW1 (Ghirardi): things are made of a mass density field in 3-space
    - GRW2 (Bell, Tumulka): things are made of flashes (spacetime events at the wave function collapses)

Part 3: Option 1 vs Option 2

- The wave function lives in a space with a very large number of dimensions (~10^25)
  - In Option 1, 3-space is just an illusion: we need to explain our perceptions of 3-space, ...
  - There is reductionism and reductionism:
    - For the PO in 3-space, "everything" is determined: this seems to be OK
    - For fixed the wave function, "everything" is determined: this seems too extreme
  - Need of consciousness again to explain perception of 3-d?
  - If yes, what is the advantage of this theory vs. Quantum Theory with Observer?

Part 3: Metaphysics and Bohmian Mechanics Option 2

- It is a theory about point like particles in 3-dimensional space
- The microscopic description of reality is discrete (particle-like)

Part 3: Metaphysics and GRWm

- It is a theory about a field in 3-dimensional space (mass density field)
- The microscopic description of reality is not particle-like but continuous

Part 3: Metaphysics and GRWf

- It is a theory about a set of "events" in spacetime, the flashes (their location in it can be read off from the history of the wave function)
- "the world is a galaxy of such events"
- The microscopic picture of this theory is discrete in space-time.

Part 3: The common structure

- They all have a Primitive Ontology
- Bohmian Mechanics:
  - PO: positions of particles
  - GRW theory:
    - PO: flashes (random events in space-time)
    - GRWm: 3-d density of mass field
    - Different choices of PO define different physical theories

Part 3: The common structure

Dynamics: the wave function
- Bohmian Mechanics:
  - Deterministic evolution for Ψ (Schrödinger's equation)
  - The wave function induces a law for the PO (the guiding law)
- GRW theory:
  - The wave function evolves randomly
  - The wave function induces a law for the PO (either the mass density or the flashes)
Part 3: The common structure

- Dual structure: $(X; \Psi)$
  - $X = \{p, q\}$: "observation" of space-time
  - $\Psi$: governing $X$

Part 3: The role of the wave function

- Human view of laws:
  - The simplest and most informative way of expressing our best theory of the world
- Non-Human view of laws (This is my view):
  - "The wave function is a law"
  - It summarizes the laws of classical mechanics
  - The functions are not laws, but rather the knowledge of the laws

Part 3: PO and Ontological Commitment

- PO: what you need to postulate as existing in the world if the theory is true
- Nomological variables: you can be metaphysically neutral w.r.t. to them, you need not be committed to their existence in order to formulate the theory

Part 3: Common Structure and Revolutions

- BM, GRW, GRWm, CI: They all have a clear PO and the role of the wave function is to govern its evolution
- This structure is also common to Classical Mechanics: PO=particles; Nomological variables = potential, ...
- So it seems that rather than having a discontinuity between the view of the world provided by Classical Mechanics and those provided by Quantum Mechanics, we have a continuity (at least in some respects):
- All of those theories are mathematical structures grounded on a clear PO

Part 3: State, PO and Supervenience

- Metaphysical vs Natural supervenience: $Y=f(X)$
  - $Y$ metaphysically (or logically) supervenes on $X$
  - $Y$ is nothing in $Y$ that cannot be found in $X$, $Y$ is exhausted by $X$
  - Ex: water=$H_2O$, heat=molecular motion
- $Y$ naturally (or nomically) supervenes on $X$
  - $Y$ cannot be $Y$ without $X$ but $Y$ is more than what is in $X$
  - Ex: The PO in GRW naturally (but not metaphysically) supervenes on $\Psi$

Part 3: PO and Relativity

- What about relativistic Quantum Theories without Observers?
  - In order to answer this question it is necessary to make a choice of the PO: Relativistic Invariance (like any other symmetry) is a 'property' of the law which governs the dynamics of the PO
  - Different PO may lead to different symmetries
  - Example: GRW can be made relativistically invariant (Tumulka)
  - GRWm is not relativistically invariant

Part 3: Differences between BM and GRW

- The empirical predictions of BM agree exactly and always with those of Quantum Mechanics while those of GRW do not (only approximately and in most cases)
- One can empirically distinguish between BM and GRW
- Usually, the empirical disagreement is explained by appealing to the fact that in one theory (BM) the wave function evolves according to Schrödinger's equation while in the other (GRW) it doesn't. However...

Part 3: The flexible wave function

- ...we showed (quant-ph/0603027) that it is possible to reformulate:
  - GRW in terms of a wave function that obeys Schrödinger's equation
  - BM in terms of a wave function that does collapse !!!

Part 3: Empirical equivalence

- But then, where is the empirical disagreement between the two theories coming from?
  - Observation:
    - the empirical equivalence of two theories basically amounts to the assertion that the two worlds, governed by the two theories, share the same macroscopic appearance
    - the macroscopic appearance is a function of the PO, not directly a function of the wave function:
      - the position $z$ of a pointer at t is a function of the PO $z=Z(PO)$

Part 3: Empirical equivalence

- Empirical equivalence with Quantum Mechanics:
  - the probability of the event $z=2$ agrees with the distribution predicted by QM (obtained by integrating $|\Psi|^2$ over all configurations in which the pointer points to 2)
  - "effective $|\Psi|^2$"-distribution w.r.t. to the Schrödinger evolution:
    - BM has this property
    - GRW doesn't
  - This is the source of the empirical disagreement between the two theories

Conclusion

- What is the structure of Quantum theories without Observers?
  - There is a clear primitive ontology, and it describes matter in space and time
  - There is a state vector $\Psi$ that evolves either according to Schrödinger's equation or for a long time approximately so
  - The state vector $\Psi$ governs the behavior of the PO by means of (possibly nondeterministic) laws

“Thanks, Folks!”