Philosophy of Physics 1b – Lecture 5

1 Introducing quantum mechanics (QM)

- Brief remarks about its history (remember Planck from Lecture 1) – for some easy to digest historical details, see *Introducing Quantum Theory,* by McEvoy & Zarate.)
- Brief remarks about the relation between QM and philosophy: it's a two-way street. (i) At least since C17, it has been clear that a very large part of our knowledge of reality comes from science, and especially from physics. So whether our 'metaphysical' interest is in reality in general, or in specific issues such as time, determinism, causation, etc., metaphysics needs an understanding of physics. And QM is a major part of modern physics, with apparent implications for some or all of these topics. (ii) It turns out that we can't just 'read off the answers' to metaphysical questions from QM. On the contrary, it is very unclear what QM is telling us about the world – very difficult to **interpret** QM, to decide what the formal mathematical theory is telling us about reality. (Application of theory works extremely well, but we don't know what it means.) And discussion of these issues is in itself a philosophical enterprise, requiring philosophical skills. Metaphysical study of QM isn't a passive exercise, a matter of simply 'reading off' the answers provided by physics. It is a matter of taking up profound questions left unanswered by physics.
- Basic aim of these lectures: to explain why the interpretation of QM is such a hard problem (what the basic issue is, what the main options concerning this basic issue are, why they are all problematic). Plus, time permitting, a brief introduction to some of the more exotic proposed solutions.

2 Complete description in classical (Newtonian) physics

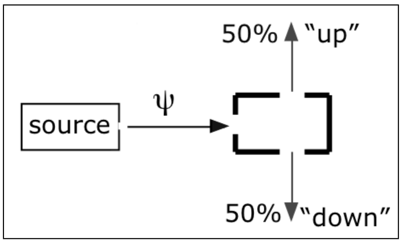
- Newtonian view of reality: small lumps of matter (particles), moving in space. The physical properties of such a system at a time are **completely described** by specifying the position and momentum (mass × velocity) of each particle. (Analogy: billiard balls on a frictionless table, with perfectly bouncy walls.)
- **Determinism** of Newtonian mechanics: if we are given a complete description at one time, we can calculate the complete description at any later or earlier time (so long as we can assume that the system is isolated – i.e. that there are no external influences to take into account).

3 How QM describes a physical system

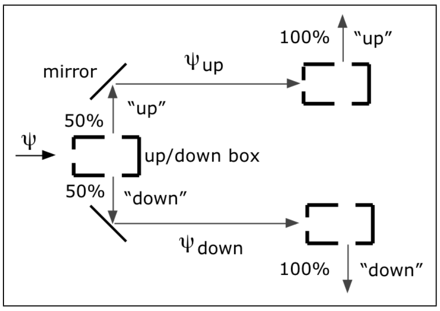
- The QM description of a physical system is summed-up in a mathematical property called the quantum state (= 'state function' = 'wave function' = 'state vector').
- **Non-essential topic:** What kind of thing the quantum state is, mathematically speaking (brief non-essential digression about vectors; example of shopping trolleys).
- **Very essential topic:** What QM says about how the quantum state changes ('evolves') over time.
- Newtonian physics is deterministic: if we know the description of a system at one time, and the system is isolated, then we can calculate its state at later (or earlier) times. **For isolated systems,** the same is true of QM: the quantum state evolves in a 'smooth', 'continuous', predictable way, in accordance with a mathematical rule called **Schrödinger's Equation.**
- The **indeterminism** (unpredictability) of QM is all associated with what happens when we make a **measurement** or **observation** on a quantum system.

4 Measurement in QM

- In Newtonian physics, a complete description predicts 'with certainty' a unique outcome for a measurement of any physical property of the system concerned.



- In QM, this is not so: in general, the quantum state does not predict a unique outcome for a measurement, but instead **assigns probabilities to a range of possible outcomes.** (Often it is an infinite range, but for simplicity we'll discuss cases with just two options, like tossing a coin.)
- Let's use 'up' and 'down' as labels for two such outcomes. The diagram here shows a source that produces particles with state ψ, and sends them to a 'measuring box' that measures for these properties. In this case, ψ predicts equal probability for the two outcomes 'up' and 'down'.
- What happens to the state of a particle when such a measurement is made? If it didn't change, then repeating the measurement would give the same indeterministic results: 50% 'up' and 50% 'down'. (Why? Because the state just is a property which predicts the probabilities of possible results of various possible measurements: if the state were the same, the probabilities would have to be the same.) But instead we get this:



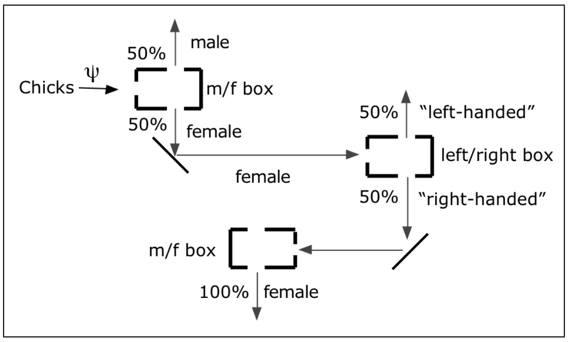
- Thus measurements are **repeatable** in QM – if we repeat a measurement immediately, we get the same result with certainty. This implies that **measurement changes the quantum state**: in the diagram above, ψ_{up} and ψ_{down} must be **different** from ψ itself. ('ψ_{up}' means the state of the particle emerging from the 'up' aperture of an up/down measurement box.)
- Similarly, ψ_{up} and ψ_{down} must be different from each other, because particles with these states behave quite differently from each other – one always gives 'up', the other always gives 'down', in the same measurement.
- The rule that specifies how the state changes on measurement is called the **measurement postulate.** The change in the state associated with measurement is often called the **collapse of the wave function**. (Why?)

5 Summary: two ways in which the QM state 'evolves' over time

1. For **isolated** systems, the quantum state evolves in a 'smooth', 'continuous', deterministic (predictable) way, in accordance with Schrödinger's Equation.
2. When a **measurement** is made, the quantum state changes ('collapses') in an abrupt, discontinuous and (in general) indeterministic way, in accordance with the **measurement postulate**.

6 The central issue in the philosophy of QM: Is measurement like sexing chickens?

- Suppose the 'particles' produced by the source are chickens, ψ means 'day old chick', and the up/down measurement box contains a chicken sexer, who sends female chicks up and male chicks down.
- Then the results shown are just what we would expect. The 'indeterminism' stems from the fact that the initial description (ψ = 'day old chick') is **incomplete** – each chicken is **already** either male or female, but the initial description ψ doesn't tell us which. And these measurements are **repeatable**, just like in QM.
- If QM is like chicken sexing, then quantum particles have definite properties before measurement, and the apparent indeterminism (the fact that (say) 50% of particles go up and 50% go down) just stems from ignorance – from the fact that we don't know all the properties in advance (because the description given to us by the quantum state is incomplete – it doesn't tell us all there is to know about the system in question).
- But most physicists think QM isn't like chicken sexing. They think: (i) the QM state is a **complete** description; (ii) the particle doesn't have a definite property up or down before measurement; (iii) all the individual particles with state ψ are the same **before** measurement; (iv) each particle becomes either ψ_{up} or ψ_{down} at the time of the measurement, and not before.
- This is analogous to thinking that chicks only become male or female when observed by a chicken sexer – a crazy view for chickens, so why not also for QM particles?
- In QM, measurement is **in some respects** very different from chicken sexing. In a case like the one shown here (2nd diagram), the second measurement somehow 'destroys the information' we got from the first measurement.
- This restriction on what it is possible to find out about the properties of quantum systems is formalised in **Heisenberg's Uncertainty Principle.** ("The more precisely the position is determined, the less precisely the momentum is known in this instant, and *vice versa.*" – Werner Heisenberg [1927])



7 The Big Issue

- Is Heisenberg's Uncertainty Principle a restriction on the 'sharpness' of reality itself, or only of what we can know about reality. ("There is a difference between a shaky or out-of-focus photograph and a snapshot of clouds and fog banks." – Erwin Schrödinger [1935])
- **In other words:** Is the quantum description complete, or are there 'hidden' aspects of reality that it doesn't describe?
- From the early days of QM there was deep disagreement. The dominant 'Copenhagen' view (e.g., Bohr & Heisenberg) was that QM is complete, that HUP is a restriction on the 'sharpness' of reality itself. This view was opposed by Einstein, Schrödinger, Born and others, who thought that QM is **incomplete**.
- **Problem:** There are serious objections to both views! (But every cloud has a silver lining: this is what makes philosophy of QM so interesting!)