Philosophy of quantum mechanics

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Today's lecture

- Recap
  - Formalism for one particle with many properties
  - Formalism for many particles with one property
    - Nonseperability & entanglement
- Nonlocality
  - Einstein's objection to quantum mechanics
  - Bell's response
- Metaphysical implications of entanglement
  - Atomism
  - Intrinsicality

Recap from previous lecture

- Formalism for one particle with many properties.
  - Particles associated with vector spaces, particle states described by vectors.
  - If a particle is associated with vector space V then every vector in V describes a possible state of the particle.
  - The combined spin-coordinate vector space describes nonseperable states.
- The formalism for many particle systems.
  - Composite systems associated with composite vector spaces.
  - Nonseperable states in composite coordinate space.
    - Entanglement in coordinate space.
    - Today: entanglement in spin space.

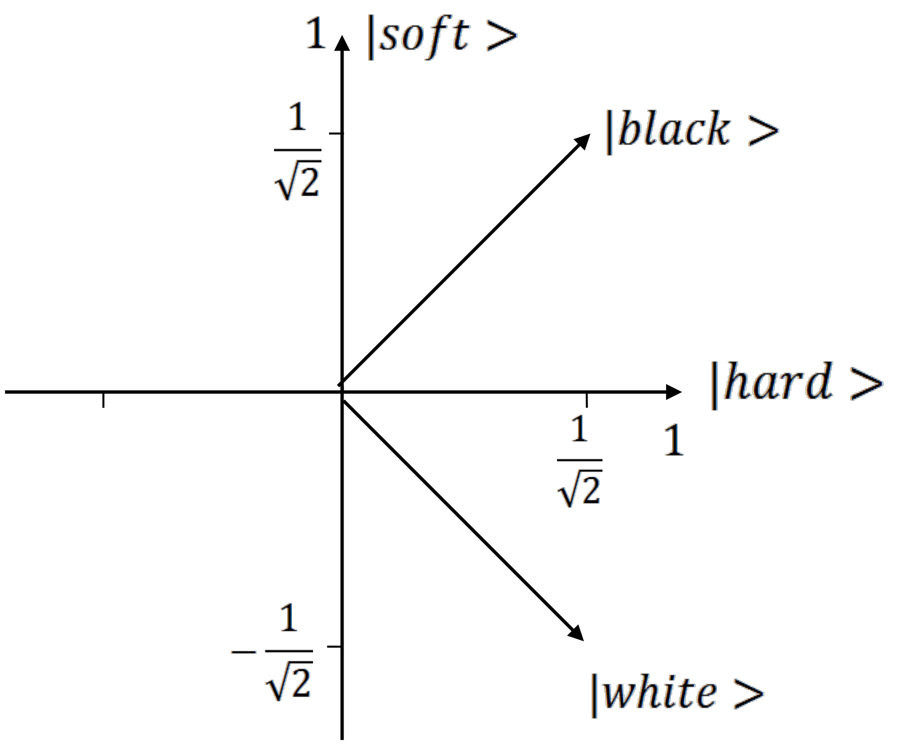
Formalism for one particle

- Experiments on the colour and hardness (etc.) of single particles suggested that:
  - Particles have both definite and superposed states.
  - Having a definite value for one property entails being in a superposition of another (incompatible) property.
  - Measuring for a property when the particle has a superposed value for that property collapses the particle's superposition.
- Formalism aims to:
  - Make these concepts mathematically precise.
  - Predict outcomes of all the experiments.

Formalism for one particle

- Vector space formalism achieves this…

- E.g. We can describe that state of being black as a weighted sum of soft and hard. The weights then yield probabilities that enable us to predict the statistical outcomes of experiments.

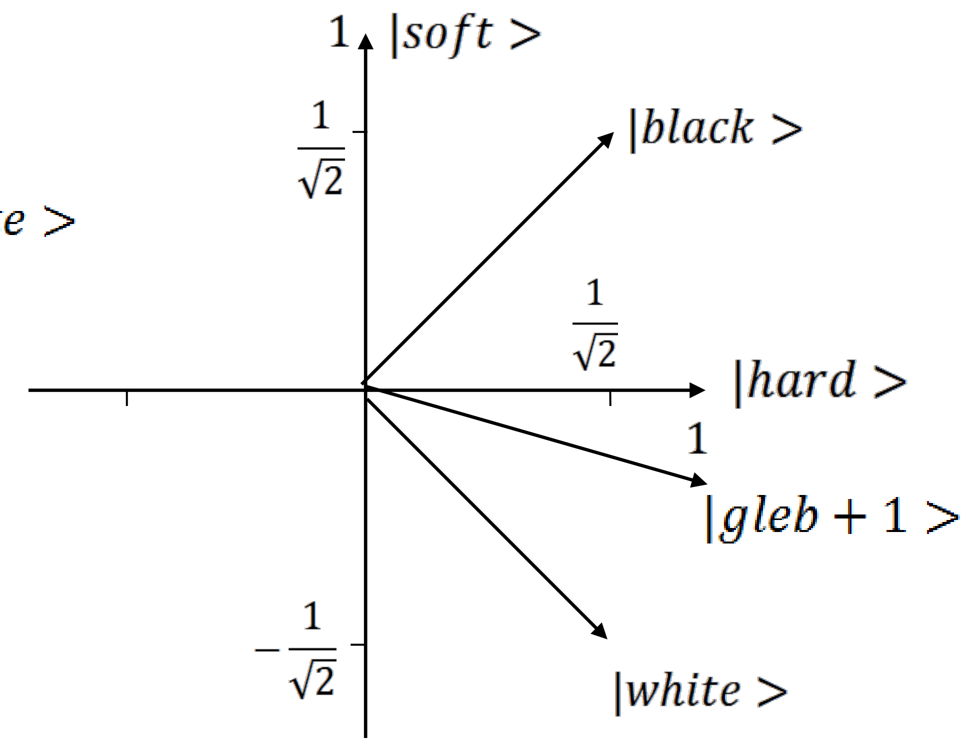


Implications

- Associating physical systems with such vector spaces enables us to infer many other possible states of the system.
- E.g. by finding vector |gleb+1> where:

$$|gleb+1> = \frac{1}{2}|black> + \frac{\sqrt{3}}{2}|white>$$

- ...we infer a new possible physical state: that state such that a colour measurement of a particle in that state yields 25/75 results.

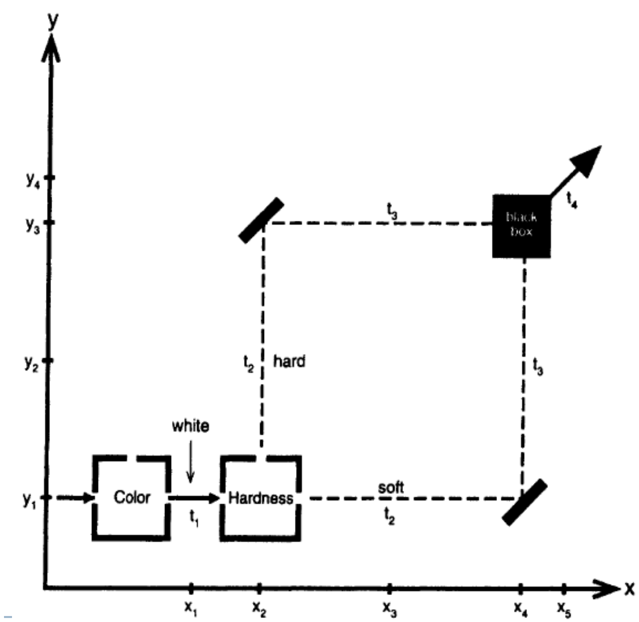


Spin space and coordinate space

- The two-dimensional vector space is that state space corresponding to colour and every property that is incompatible (to some degree) with colour.
  - All such properties are represented by operators whose eigenvectors form an orthonormal basis of that space.
- A continuous property like position cannot be represented in a 2D space.
  - Too many eigenvectors.
- Position is associated not with "spin space" but with "coordinate space".
  - But a system with both position and (e.g.) colour will be associated with the *joint* coordinate-spin vector space.
    - From which we can infer *nonseperable* physical states.

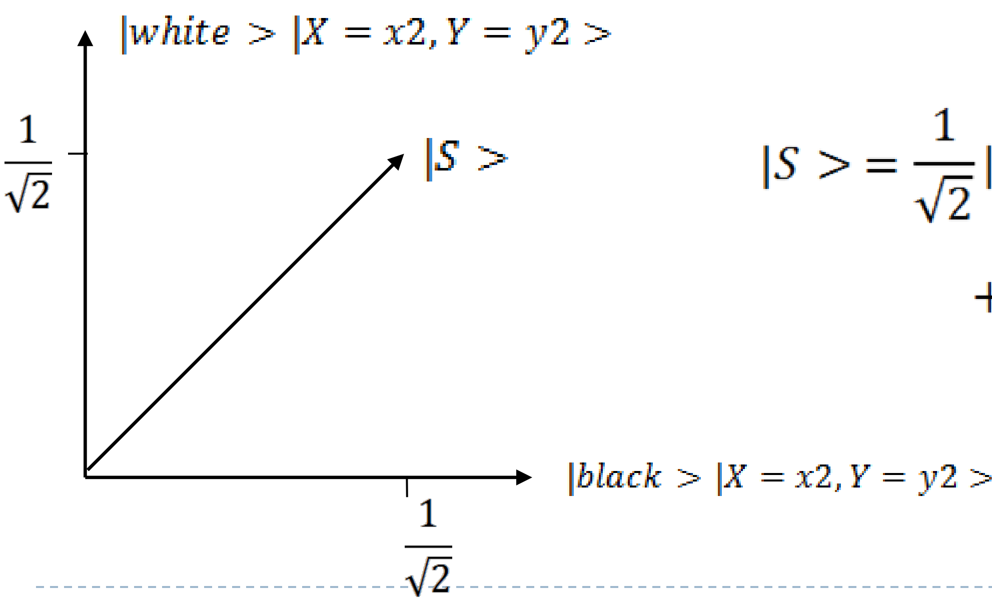
Joint coordinate-spin space

- Position state spaces are infinitely dimensional.
  - Corresponding to the infinity of possible values of position.
- But let's idealise: imagine the only possible positions states are the six coordinates Albert uses to describe the 2-path experiment:
  - (x1,y1), (x2,y2), (x3,y1),
  - (x3,y3), (x4,y2), (x5,y4).
- 6-D coordinate space.
- 12-D coordinate-spin space.



Property separability

- We can arbitrarily pick out any vector in this 12-D space and it will represent a possible physical state.
  - Just as we saw with gleb+1 in the 2D spin space.
- Let's pick out a vector that has nonzero values for only *two* of the twelve orthonormal basis vectors:



$$|S> = \frac{1}{\sqrt{2}}|white>|X=x2,Y=y2> + \frac{1}{\sqrt{2}}|black>|X=x2,Y=y2>$$

Property separability

- This way of writing down vector |S>…

$$|S> = \frac{1}{\sqrt{2}}|white>|X = x2, Y = y2> + \frac{1}{\sqrt{2}}|black>|X = x2, Y = y2>$$

- …can be rewritten by factorising out the coordinate space property:

$$|S> = \left(\frac{1}{\sqrt{2}}|white> + \frac{1}{\sqrt{2}}|black>\right)|X = x2, Y = y2>$$

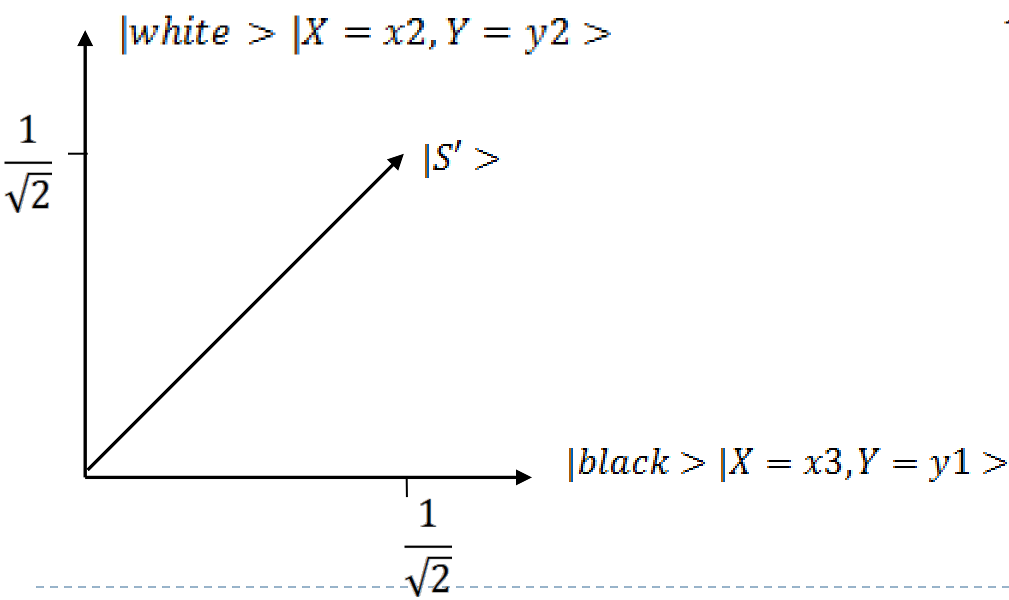
- When such factorisation is possible we say that position and colour are *separable*.
  - Note that we can also write |S> as follows:

$$|S> = |hard>|X = x2, Y = y2>$$

Property inseparability

- Now consider |S'> which represents superpositions for *both* colour *and* position:

$$|S' > = \frac{1}{\sqrt{2}}|white > |X = x2, Y = y2 > + \frac{1}{\sqrt{2}}|black > |X = x3, Y = y1 >$$



Property inseparability

- The important difference is that this expression:

$$|S' > = \frac{1}{\sqrt{2}}|white > |X = x2, Y = y2 > + \frac{1}{\sqrt{2}}|black > |X = x3, Y = y1 >$$

- ...cannot be factorised as before.

- So it cannot be interpreted as denoting a state in which the particle is in a definite hardness state.
  - This state is one where colour and position are non-separable.
- Quantum mechanics appeals to such non-separable states to explain experimental outcomes.
  - E.g. The 2-path experiments

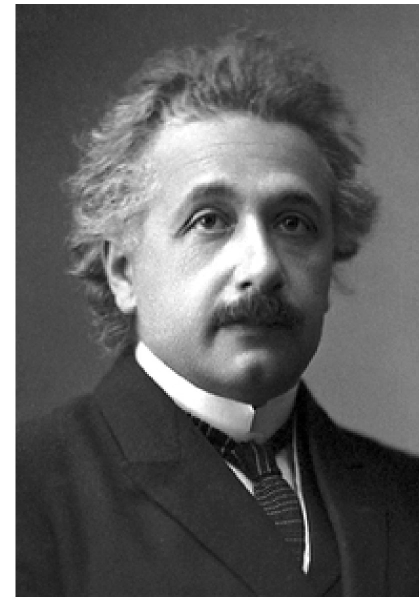
Formalism for many-particle systems

- Formalism for describing two particles with one kind of property (e.g. colour) is much like the formalism for describing one particle with two kinds of property (e.g. colour and position).
  - The dimensionality of the composite state space equals the product of the dimensionality of the component state spaces.
  - So if we only consider spin space, then the composite vector space will have 2x2=4 dimensions.
  - We can pick out vectors in that space designating states in which the colours of the two particles *are separable*.
  - We can pick out vectors in that space designating physical states in which the colours of the two particles are *nonseparable*.
    - This latter fact is at the core of Einstein's objection to quantum mechanics.

Nonlocality

Einstein versus quantum mechanics

- "Quantum mechanics is certainly imposing. But an inner voice tells me that it is not yet the real thing."
  - Albert Einstein (letter to Max Born, 1926).



- In 1935 Einstein and two research assistants (Boris Podolsky & Nathan Rosen, collectively known as *EPR*) published a metaphysical objection to quantum mechanics.

EPR's objection to quantum mechanics

- EPR considered possible quantum states like this:

$$|A> = \frac{1}{\sqrt{2}}|black>_1\,|white>_2 - \frac{1}{\sqrt{2}}|white>_1\,|black>_2$$

- Particle 1 and particle 2 are in a combined colour superposition.
- EPR noticed that the collapse postulate entails something odd:
  - If you measure particle 1 and collapse it to |black> you thereby collapse particle 2 to |white>.
    - No matter how far apart the particles are.

The completeness of a physical theory

- EPR argued that quantum mechanics cannot be *complete*.
  - A physical description is complete if it describes every element of reality.
  - A sufficient condition on being an element of reality is obeying the principle of *locality*.

- The principle of locality:
  - If, without disturbing a system, we can predict with certainty the value of a physical quantity, then there exists an element of reality corresponding to this physical quantity.

Principle of locality

- Principle of locality:
  - If, without disturbing a system, we can predict with certainty the value of a physical quantity, then there exists an element of reality corresponding to this physical quantity.
- An example:
  - If, without disturbing an electron, we can predict its colour (with probability = 1) then it really has that colour.
  - Note: measurements can count as disturbances.
  - Hence 3-box experiment is consistent with the principle of locality.

Principle of locality

- Principle of locality:
  - If, without disturbing a system, we can predict with certainty the value of a physical quantity, then there exists an element of reality corresponding to this physical quantity.
- Why believe this principle?
  - It's highly intuitive!
  - If you can predict (with certainty) what the outcome of a measurement on particle P will be white, but the means by which you make this prediction does not involve you disturbing (e.g. measuring) P, then there must already be some definite fact about P that entails that it will be white.
    - Either: P is already white;
    - Or: P has some property that *determines* that P will be white at the time of measurement.

EPR's objection to quantum mechanics

- Imagine the state of a 2-particle composite to be...

$$|A> = \frac{1}{\sqrt{2}}|black>_1 \, |white>_2 - \frac{1}{\sqrt{2}}|white>_1 \, |black>_2$$

- ...and we measure the colour of particle 1 and get black.
- Since we can *then* infer that particle 2 will be white, EPR reasoned that 2 must have *already been white* prior to the measurement on particle 1.
  - Or at least, 2 must have already had some property that entails this.
- This follows from the principle of locality.
- But |A> does not encapsulate *this* information.
- So |A> is an *incomplete* description of reality.
  - So *quantum mechanics* is incomplete.

EPR's objection to quantum mechanics

- The objection runs deeper since this state:

$$|A> = \frac{1}{\sqrt{2}}|black>_1 |white>_2 - \frac{1}{\sqrt{2}}|white>_1 |black>_2$$

- ...is equivalent to this state:

$$|A> = \frac{1}{\sqrt{2}}|soft>_1 |hard>_2 - \frac{1}{\sqrt{2}}|hard>_1 |soft>_2$$

- EPR's argument applies equally well:
  - If measuring particle 1's hardness yields soft then the description fails to account for particle 2 being hard.
    - Note: we can also run the argument for gleb, scrad and every spin space property.
- But then particle 2 is white *and* hard which *contradicts the incompatibility relations*.

Bell's response

- In 1964 Bell demonstrated that:
  - The principle of locality yields testable predictions in certain situations.
  - Those predictions contradict the predictions of quantum mechanics.
- So we can test these situations to see if quantum mechanics is incomplete or if the principle of locality is false.

The set-up

- Consider the entangled state of particles 1 and 2:

$$|A> = \frac{1}{\sqrt{2}}|black>_1 |white>_2 - \frac{1}{\sqrt{2}}|white>_1 |black>_2$$

- Consider any three spin space properties.
  - Following Albert let's use colour, gleb, and scrad...

Bell's response

- Bell realised that if locality is true then given |A> the particles are in one of eight possible states:

$$\begin{bmatrix}(C_+S_+G_+)_{p1}\\(C_-S_-G_-)_{p2}\end{bmatrix}_I \begin{bmatrix}(C_+S_+G_-)_{p1}\\(C_-S_-G_+)_{p2}\end{bmatrix}_{II}$$

$$\begin{bmatrix}(C_-S_-G_-)_{p1}\\(C_+S_+G_+)_{p2}\end{bmatrix}_{III} \begin{bmatrix}(C_-S_-G_+)_{p1}\\(C_+S_+G_-)_{p2}\end{bmatrix}_{IV} \begin{bmatrix}(C_-S_+G_+)_{p1}\\(C_+S_-G_-)_{p2}\end{bmatrix}_{V}$$

$$\begin{bmatrix}(C_+S_-G_-)_{p1}\\(C_-S_+G_+)_{p2}\end{bmatrix}_{VI} \begin{bmatrix}(C_+S_-G_+)_{p1}\\(C_-S_+G_-)_{p2}\end{bmatrix}_{VII} \begin{bmatrix}(C_-S_+G_-)_{p1}\\(C_+S_-G_+)_{p2}\end{bmatrix}_{VIII}$$

- Note: + and – derived from eigenvalues e.g. state of particle 1 in VII is:
  - (|Colour=+1>, |Scrad>=-1>, |Gleb=+1>)

Bell's response

- Let "p1(C) ≠ p2(G)" mean that the eigenvalue of particle 1's colour is the opposite eigenvalue to particle 2's gleb.
- From the eight possible states one can infer that for any collection of pairs of such electrons, each pair is such that:
  - p1(C) ≠ p2(G) – see I, III, VII, VIII.
- Or:
  - p1(C) ≠ p2(S) – see I, II, III, IV.
- Or:
  - p1(G) ≠ p2(S) – see I, III, V, VI.

Bell's response

- So locality entails that *every* such electron pair satisfies:
  - $p1(C) \neq p2(G) \vee p1(C) \neq p2(S) \vee p1(G) \neq p2(S)$.
- But *quantum mechanics* entails that only certain fractions of pairs satisfies each disjunct:
  - $p1(C) \neq p2(G) = 1/4$.
  - $p1(C) \neq p2(S) = 1/4$.
  - $p1(G) \neq p2(S)) = 1/4$.
- And therefore that only ¾ (at most) satisfies:
  - $p1(C) \neq p2(G) \vee p1(C) \neq p2(S) \vee p1(G) \neq p2(S)$.
- So locality and quantum mechanics make *different predictions*.

Bell's response

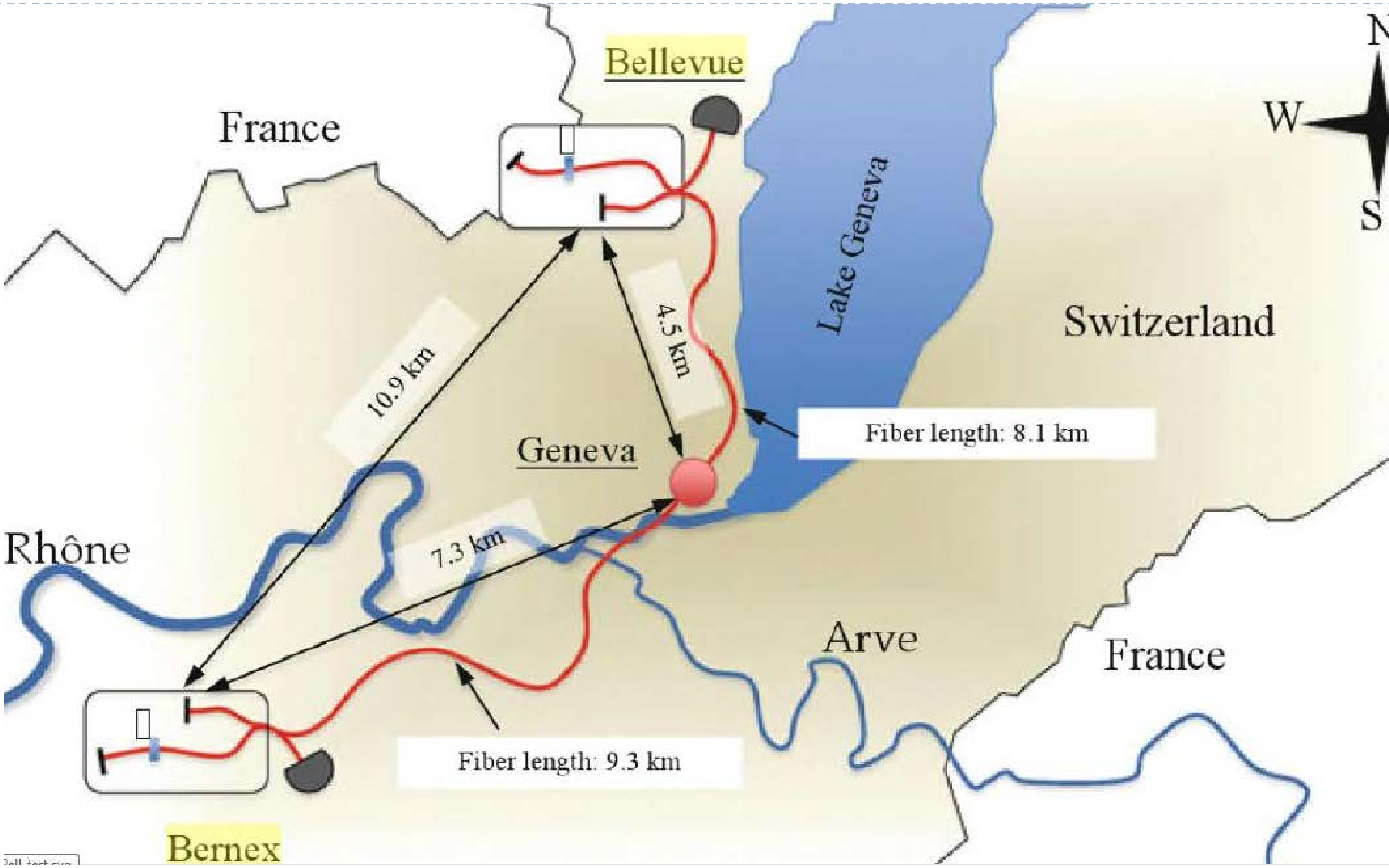
- Experiments have been done on such pairs of particles.

- The locality predictions are wrong.
- The predictions of quantum mechanics are right.
  - http://en.wikipedia.org/wiki/Bell_test_experiments

- So the principle of locality is false and (the completeness of) quantum mechanics is confirmed.

  - (Note: Bohr accepted both locality and QM "completeness" but rejected realism: so Bell showed that local, realist, additional variable interpretations, are impossible).

Distance is not a factor



- Tittel, W. et al. (1998), "Violation of Bell inequalities by photons more than 10 km apart", *Physical Review Letters* 81: 3563-6,.

What is nonlocality?

- The statistics of the outcomes of measurements on electron 2 depend nonlocally on the outcomes of measurements on electron 1 (and vice versa) no matter how far apart they are.

- What must physical reality be like to explain this?
  - Before we answer this, let's consider two interesting ways nonlocality connects to Einstein's theory of relativity.

Communication and relativity theory

- The outcomes of measurements sometimes depend nonlocally on the outcomes of other distant measurements; but the outcomes of measurements never depend nonlocally on *whether* other distant measurements were carried out.
  - While my collapsing your particle determined your measurement outcome, my collapsing your particle did not alter what outcome you should have otherwise expected.
- For this reason, entanglement cannot be exploited to send messages.
  - Sufficient for consistency with special relativity?

A relativistic curiosity

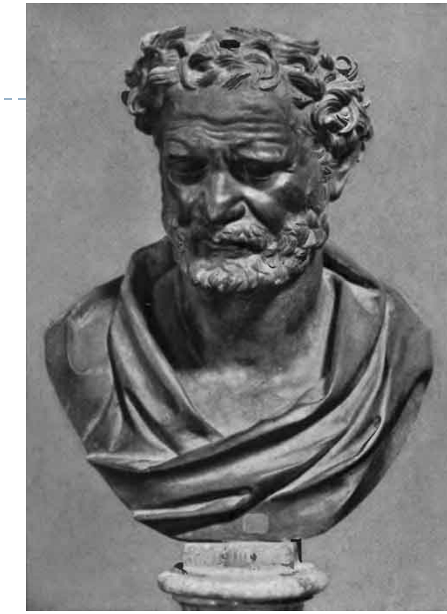
- The parts of a whole are parts that all exist at *the same time*.
  - Classically, *simultaneity* is absolute so no problem.
  - But in relativity, there's no unique way of decomposing extended spatiotemporal objects into specific parts.
- Consider state |A>. Imagine we measure the colour of particle 1.
  - Particle's 1 and 2 collapse simultaneously in one reference frame.
  - There will be a point P on 2's worldline such that in one reference frame, P occurs before 1 is measured, in another, P occurs after 1 is measured.
    - So now what is the state of particle 2 at point P?

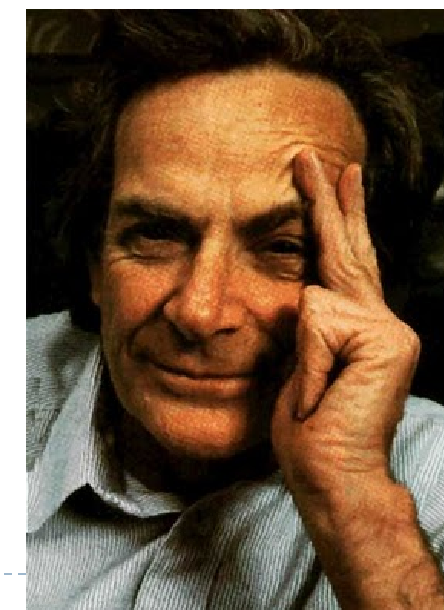
Atomism

Atomism

- "Nothing exists except atoms and empty space, everything else is opinion."
  - Democritus (460BC -370BC).

- "If all scientific knowledge were to be destroyed, and only one sentence passed on, what statement would contain the most information in the fewest words? I believe it is the atomic hypothesis."
  - Richard Feynman (1918-1988)





Atomism clarified

- Methodological atomism:
  - The aim of physics is to understand wholes in terms of their parts.
- Epistemological atomism:
  - From facts about elementary parts we can deduce and explain all facts.
- Metaphysical atomism:
  - The atomic facts are metaphysical fundamentally. Non-atomic facts are nothing over and above atomic facts.
    - I'll mostly speak in these terms...

Atomism clarified

- How can non-atomic facts be "nothing over and above" atomic facts?

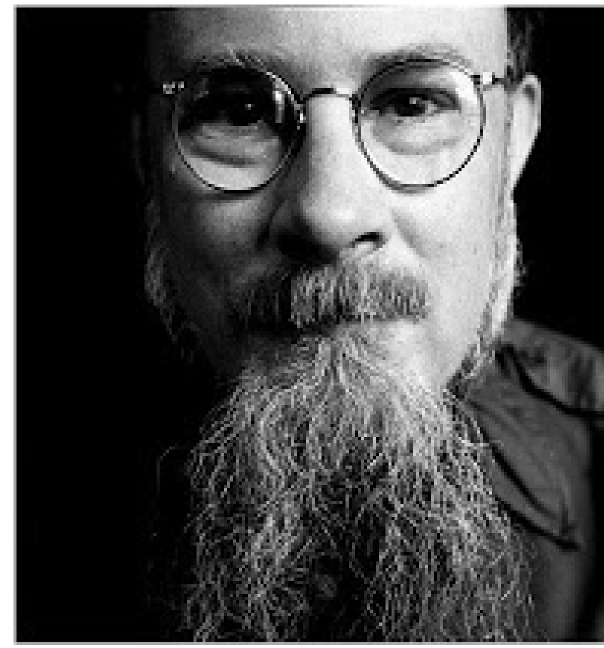
- The idea is that wholes are nothing but the sums of their parts.
  - But this suggests that if the parts exist then the whole must exist.
  - Simple counterexample: the parts of my android will remain even if I destroy the android.
    - So the android has properties that are determined (and explained) by more than just the parts.

Atomism clarified

- Atomist solution:
  - Although destroying the android may not change the *intrinsic* properties of its parts, it changes their *relational* properties.
- Now we have:
  - The android is the sum of its parts if and only if all of the facts about the android are determined by the intrinsic properties of the parts and the relations between those parts.
- The view is becoming clearer, but we need constraints on the "relations".
  - Otherwise any composite property thought to oppose atomism could be treated as a "relation" among parts.

Humean Supervenience

- "Humean Supervenience says that the fundamental relations are exactly the spatiotemporal relations: distance relations, both spacelike and timelike. And it says that the fundamental properties are local qualities: perfectly natural intrinsic properties of points, or of point-sized occupants of points."
  - David K. Lewis (in "Humean Supervenience Debugged" (1994)).



Humean supervenience

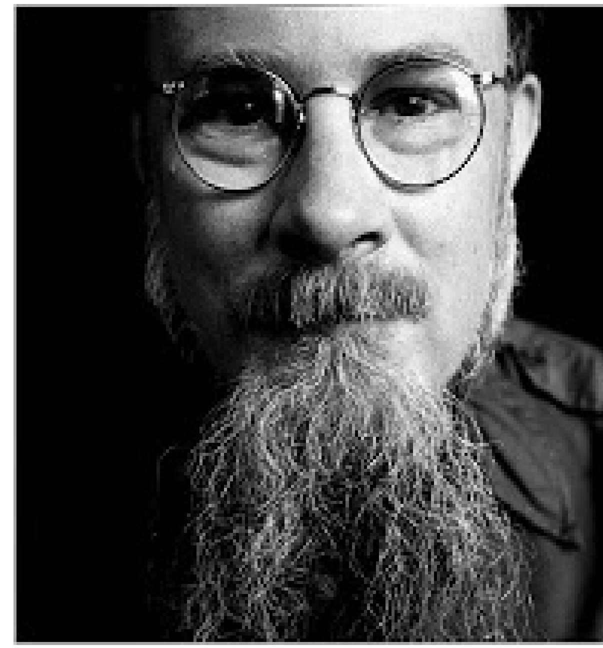
- Humean Supervenience says that the fundamental relations…
  - Non-fundamental relations supervene on fundamental reality, fundamental relations do not supervene on anything (they are "basic").
- …are exactly the spatiotemporal relations: distance relations, both spacelike and timelike. And it says that the fundamental properties…
  - Same for non-fundamental / fundamental *properties*.
- …are local qualities: perfectly natural intrinsic properties of points, or of point-sized occupants of points.
  - Intrinsic properties are not relational, they are in some sense "properties of the object that only depend on the object itself, and not on the existence of other objects".
    - I'll come back to intrinsicality.

Atomism as Humean Supervenience

- Now atomism has determinate content.
- We can now ask whether atomism conflicts with quantum mechanics…
- Note: atomism so defined is *very* influential in contemporary metaphysics.
  - It is simply a working assumption for many metaphysicians.
    - What do they think of quantum mechanics?
    - Many are sympathetic with Lewis' dismissal…

Atomism and entanglement/nonlocality

- "I am not ready to take lessons in ontology from quantum physics as it is now. First I must see how it looks when it is purified of instrumentalist frivolity, and dares to say something not just about pointer readings but about the constitution of the world; and when it is purified of doublethinking deviant logic; and – most of all – when it is purified of supernatural tales about the observant mind to make things jump. If, after all that, it still teaches nonlocality, I shall submit willingly to the best of authority."
  - David K. Lewis, In Philosophical Papers (1983),V2, intro XI.



Atomism and entanglement

- Can the physical state of a system be completely specified by the attribution of physical states to the spatial parts of the system, together with their spatiotemporal relations?
- Consider a system described by:

$$|A> = \frac{1}{\sqrt{2}}|black>_1 \; |white>_2 - \frac{1}{\sqrt{2}}|white>_1 \; |black>_2$$

- What can we say about the state of particle 1?
  - It has no spin state.
  - Position? But this could equally well be entangled...

Atomism and entanglement

- Perhaps all we can say about particle 1, given state |A>:

$$|A> = \frac{1}{\sqrt{2}}|black>_1 |white>_2 - \frac{1}{\sqrt{2}}|white>_1 |black>_2$$

- ...is that the spin state of particle 1 is just that given by |A>.
  - Then it appears that the physical states of particle 1 cannot be specified without reference to particle 2.
  - Seems inconsistent with atomism.

Atomism and entanglement

- It seems that atomism can only account for separable (factorisable) states:

$$|B> = \frac{1}{\sqrt{2}}|hard>_1 |hard>_2 - \frac{1}{\sqrt{2}}|soft>_1 |hard>_2$$

$$= \left(\frac{1}{\sqrt{2}}|hard>_1 - \frac{1}{\sqrt{2}}|soft>_1\right)|hard>_2$$

$$= |white>_1 |hard>_2$$

- But cannot handle entangled states:

$$|A> = \frac{1}{\sqrt{2}}|black>_1 |white>_2 - \frac{1}{\sqrt{2}}|white>_1 |black>_2$$

Prevalence of entanglement

- "There is reason to think that the universe is one vast entangled system. The universe begins in the explosion of the primordial atom (the Big Bang), and such interaction suffices for entanglement. […] The world turns out to be nonseparable into individual and independent objects."
  - Jonathan Schaffer In "From Nihilism to Monism" (2007, p168).

Alternatives to Humean Supervenience

- Consider some apparently obvious metaphysical claims:
  - (1) Objects (e.g. particles) exist.
  - (2) If objects exist then objects are "something in themselves" in that they have intrinsic properties.
  - (3) Relations exist.
  - (4) If relations exist then there exist "relata" i.e. objects related by the relations.
- Alternatives can be categorized in terms of which claims they reject.
  - **Epistemic structuralism** accepts all four.
  - **Ontic structuralism** denies (1) and (4), accepts (2) and (3).
  - **Esfeld's view** denies (2), accepts (1), (3) and (4).
  - **Monism** accepts (1) and (2), rejects (3), neutral on (4).

Epistemic structuralism

- Differs from Humean Supervenience by:
  - Treating entanglement relations as fundamental relations.
    - For Lewis, only spacetime relations are fundamental.
  - Treating intrinsic properties of entanglement relata as *unknowable*.
- As David Mermin (1998: 762-4) writes:
  - "the correlata that underlie those [entanglement] correlations lie beyond the descriptive powers of physical science […] in our description of nature the purpose is not to disclose the real essence of the phenomena."
    - 'What is quantum mechanics trying to tell us?' *American Journal of Physics*, 66, 753-767.
- We can only describe relations or collections of relations (structure). Hence: 'epistemic structural realism'.

Ontic structuralism

- Differs from epistemic structuralism by denying the need to postulate unknowable intrinsic properties.
- But nonetheless accepts:
  - (2) If objects exist then objects are "something in themselves" in that they have intrinsic properties.
- And therefore denies:
  - (1) Objects (e.g. particles) exist.
- So what exists? Relations! (and structures made from them). So the view also denies:
  - (4) If relations exist then there exist "relata" i.e. objects related by the relations.
- This view is advocated by:
  - Ladyman, J. (1998) What is Structural Realism? *SHPMS*, 29, 409-424.
  - French & Ladyman (2003) Remodelling structural realism. *Synthese*, 136, 31-56.

Esfeld's view (for lack of a better name)

- Differs (primarily) from ontic structuralism by denying:
  - (2) If objects exist then objects are "something in themselves" in that they have intrinsic properties.
- And by accepting:
  - (4) If relations exist then there exist "relata" i.e. objects related by the relations.
- Esfeld writes:
  - "By contrast to a radical metaphysics of relations, the position set out in this paper recognizes things that stand in the relations, but claims that, as far as the relations are concerned, there is no need for these things to have qualitative intrinsic properties underlying the relations. This position opposes a metaphysics of individual things that are characterized by intrinsic properties. A problem with the latter position is that it seems that we cannot gain any knowledge of these properties insofar as they are intrinsic. Against this background, the rationale behind a metaphysics of relations is to avoid a gap between epistemology and metaphysics."
    - See lecture 4 folder.

Monism

- Monism accepts:
  - (1) Objects (e.g. particles) exist.
  - (2) If objects exist then objects are "something in themselves" in that they have intrinsic properties.
- But denies:
  - (3) Relations exist.
- How is that possible?
  - Because there is only ONE object.
  - It's intrinsic properties are described by the wave-function of the universe.
- Against Esfeld's view Schaffer writes:
  - "If one treats entangled systems holistically, then one accords them basic intrinsic spin properties, and crucially one can attribute the very same property to different systems with different numbers of components. For instance, a single electron, and various systems, might each have the same spin property. But if one treats entangled systems via parts in entanglement relations, then one cannot attribute the same relation with different numbers of components. This represents a loss of empirically important unity."
    - See section 2.2. of: www.jonathanschaffer.org/monism.pdf

Intrinsicality

What is Intrinsicality?

- Esfeld says:
  - "Intrinsic [properties] are all and only those qualitative properties that a thing has irrespective of whether or not there are other contingent things; all other qualitative properties are extrinsic or relational. That is to say: having or lacking an intrinsic property is independent of accompaniment or loneliness." (2004: p602)
- Arguably, the first sentence is not overly helpful.
  - How do we know if a property satisfies that definition?
- The second sentence appeals to a "test for intrinsicness" defined by David Lewis.

The Loneliness test for intrinsicness

- Property P of object o is intrinsic to o if and only if o would retain P were o to be made lonely.
  - Two different ways of thinking about "being made lonely".
    - Delete every object in the world except for o.
    - Take o from the actual world and put o in an empty possible world.
- Does this help?
  - In "Tests for Intrinsicness Tested" (see lecture 4 folder) René and I consider some problem cases, e.g.
    - The Queen's *wearing a golden ring*.
      - Intrinsic or extrinsic?
    - Depends on whether we remove the ring before making the Queen lonely!

The Loneliness test for intrinsicness

- The example suggests that we must isolate the *components* of any object before making the object lonely.
- But it's not clear that this idea makes sense in light of quantum mechanics.
- For example, let particle 1 be a component of the Queen and let particle 2 be a noncomponent:

$$|A> = \frac{1}{\sqrt{2}}|black>_1 |white>_2 - \frac{1}{\sqrt{2}}|white>_1 |black>_2$$

- How do we make particle 1 lonely (or lonely relative to particle 2) if they are entangled in any way?

Essay options

Philosophical categories	Essay questions
Philosophy of science	(i) Does quantum mechanics introduce novel reasons for accepting scientific anti-realism? (ii) What is the dimensionality of space according to (non-relativistic) quantum mechanics? 3 or 3ND?
Philosophy of mind	(i) Is there any reason to think that the mind-body problem and the measurement problem are connected? (ii) What are the implications of quantum mechanics for the causal closure argument for physicalism?
Metaphysics	(i) What are the implications of quantum mechanics for atomism? (ii) What are the implications of quantum mechanics for intrinsicality?