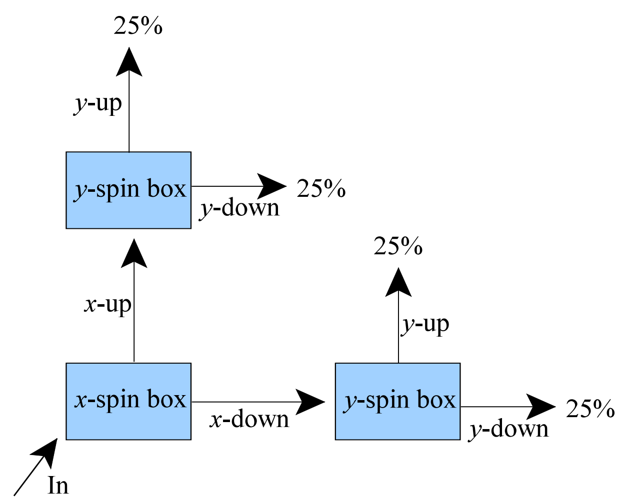
Phil. 4400
Notes #17: Quantum Mysteries

I. Electron Spin Mysteries

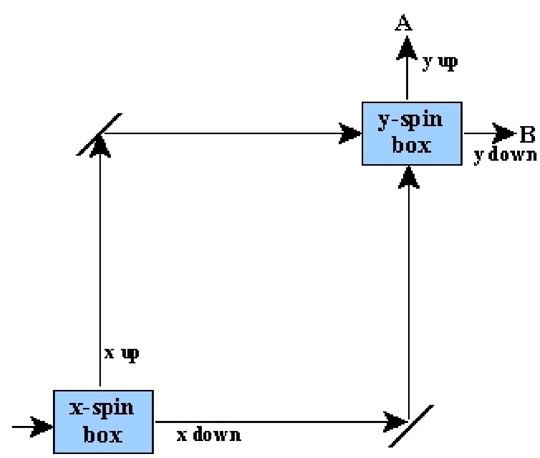
- Electrons have a property called "spin". About spin:
  - An electron has spin in any given direction, e.g., "spin in the *x* direction", "spin in the *y* direction", "spin in the *z* direction". These are distinct.
  - The spin in a given direction can take one of two values: "spin up" (spin +½) and "spin down" (spin -½).
  - Spin affects behavior in a magnetic field. Spin-up electrons are deflected up by a certain amount in a nonuniform magnetic field. Spin down electrons are deflected down by the same amount.
  - Spin in orthogonal directions is completely uncorrelated.

- Measurement:
  - An "x-spin box" is a device that measures x-spin (spin in the x direction), and sends spin up electrons out in one direction, and spin down electrons out in another direction.
  - Similarly for a "y-spin box".
  - Successive measurements of x-spin are 100% correlated. Similarly for y-spin.
  - But measuring x-spin completely *randomizes* y-spin, and vice versa (see picture at right).



- A mystery: We feed electrons with various properties into the device at right. Here's what we would expect:

What goes in	What should come out
x-spin up	50% at A, 50% at B
x-spin down	50% at A, 50% at B
y-spin up	50% at A, 50% at B
y-spin down	50% at A, 50% at B



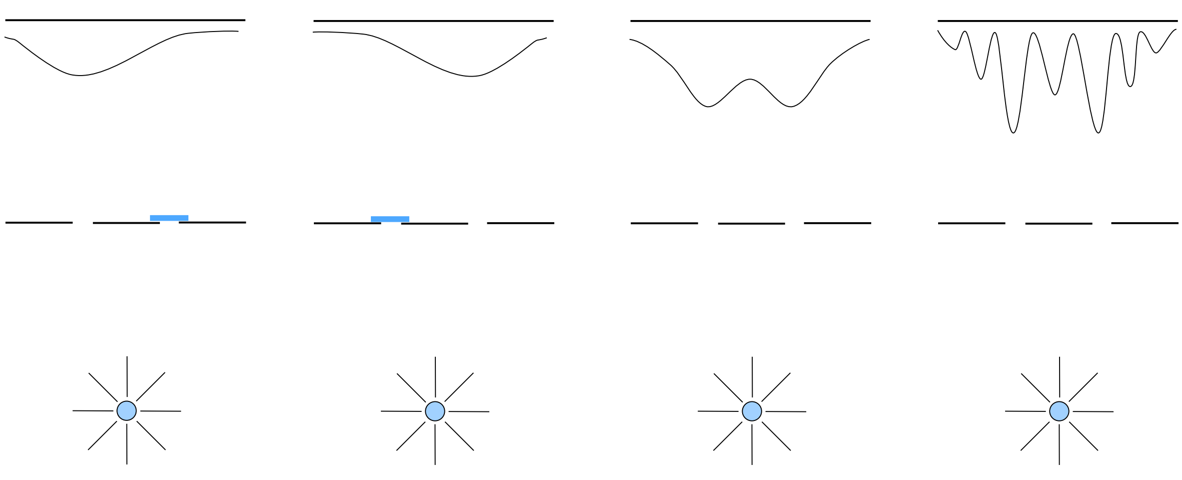
- Here's what actually happens:

What goes in	What comes out
x-spin up	50% at A, 50% at B
x-spin down	50% at A, 50% at B
y-spin up	100% at A
y-spin down	100% at B

- Superposition (Albert): Say we feed a y-up electron into the device. It comes out at A.
  (1) The electron doesn't (simply) take the upper path.
    - If the lower path is blocked, all the electrons coming through are x-spin up, and have a 50% chance of coming out at B.
    - Similarly if an electron detector is placed on either path to find out where the electron is.
  (2) The electron doesn't take the lower path.
    - Ditto.
  (3) It doesn't take both paths.
    - If electron detectors are placed, an electron is always found along one path or the other.
  (4) It didn't take neither path.
    - Ditto.
    - If both paths are blocked, nothing gets through.
  (5) We say the electron is in a *superposition* of both paths, and a superposition of *x*-up and *x*-down.

II. The Double Slit Experiment

- We shoot particles at a wall with 2 slits in it. Behind this wall is a fluorescent screen. We can see where the particles hit the screen.
- If just one slit is open, we get the distribution in (a).
- If the other slit is open, we get the distribution in (b).
- If both slits are open, we *expect* the distribution in (c).
- Instead, what we get is (d).
  - This is an *interference pattern*, explained by wave mechanics.
  - This occurs even if the particles are sent through one at a time.
- If any sort of detectors are placed to determine which slit the particle goes through, the distribution turns into (c).



(a) (b) (c) (d)

- Which slit does the particle go through?
  - When measured, the wave/particle acts like a particle, and goes through one slit or the other. No interference pattern.
  - When not measured (with respect to which slit it goes through), it acts like a wave. Parts of the wave from both slits interfere with each other. The "particle" is in a "superposition" of going through the left slit and going through the right slit.

Phil. 4400
Notes #18: Quantum Formalism

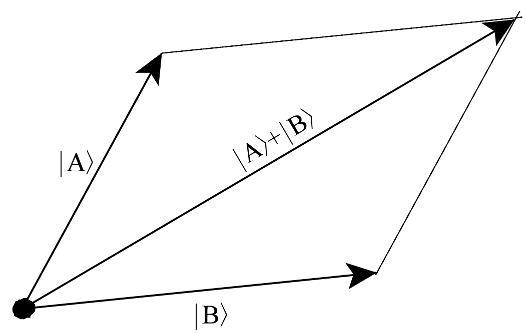
I. Vector mathematics

What are vectors?

- Vectors have: (a) magnitude/length, (b) direction.
- Can be represented as an arrow in a space (or, given an origin, as a point [see why that's the same]).
- Can also be represented by an array of numbers. (coordinates)

Some mathematical operations on vectors

- Vector × number ⇒ vector
  Multiply length by number. Same direction.
  $$c\begin{bmatrix} a_1 \\ a_2 \end{bmatrix} = \begin{bmatrix} ca_1 \\ ca_2 \end{bmatrix}$$
- Vector + vector ⇒ vector
  $$\begin{bmatrix} a_1 \\ a_2 \end{bmatrix} + \begin{bmatrix} b_1 \\ b_2 \end{bmatrix} = \begin{bmatrix} a_1 + b_1 \\ a_2 + b_2 \end{bmatrix}$$
  Parallelogram law for addition of vectors: see figure at right.



- Vector • vector ⇒ number
  - ⟨A|B⟩ = length of |A⟩ × length of |B⟩ × cosine (angle between |A⟩ and |B⟩).
    (This is the "dot product" or "inner product" or "scalar product".)
  - Product of perpendicular vectors = 0 (Cosine 90°=0).
  - Product of a vector with itself, ⟨A|A⟩, = square of the length of |A⟩. (Cosine 0°=1.)
  - This is equivalent to:
    $$\begin{bmatrix} a_1 \\ a_2 \end{bmatrix} \bullet \begin{bmatrix} b_1 \\ b_2 \end{bmatrix} = a_1 b_1 + a_2 b_2$$

Vector spaces

A vector space is a collection of vectors, such that, if |A⟩ and |B⟩ are vectors in the space, and *c* is any constant,

c|A⟩ is in the space
|A⟩ + |B⟩ is in the space

Operators

- An operator is a function that takes vectors in a vector space as inputs and returns vectors in that same space as outputs. (It is a mapping from a vector space into itself.)
- Examples:
  "Take any vector and multiply it by 5."
  "Take a vector and rotate it 45°."
  "Take any vector, and return the vector [5 -3]."

Linear operators

- A linear operator is a special kind of operator. It's an operator that satisfies (a) and (b):
  a) $cO|A\rangle = Oc|A\rangle$ (where c is any constant. That is, it doesn't matter if you operate on a vector first, then multiply by a number, or multiply first then operate.)
  b) $O(|A\rangle + |B\rangle) = O|A\rangle + O|B\rangle$ (It doesn't matter if you operate on two vectors first, then add them together, or add the vectors first and then operate.)
- Any linear operator (in a 2-dimensional space) is equivalent to multiplying by a 2×2 matrix. I.e., O can be represented by a matrix, $\begin{bmatrix} O_{11} & O_{12} \\ O_{21} & O_{22} \end{bmatrix}$, such that for any vector $|A\rangle$,

$$O\,|\,A\rangle = \begin{bmatrix} O_{11} & O_{12} \\ O_{21} & O_{22} \end{bmatrix} \times \begin{bmatrix} a_1 \\ a_2 \end{bmatrix} = \begin{bmatrix} O_{11}a_1 + O_{12}a_2 \\ O_{21}a_1 + O_{22}a_2 \end{bmatrix}.$$

  Note that the result on the right hand side of the above equation is a 2×1 matrix.

Eigenvectors

- Sometimes an operator has a special relation to a particular vector: when applied to that vector it doesn't change the direction (but it may change the length). In that case, that vector is an *eigenvector of* that operator. I.e., if

$$O|A\rangle = e|A\rangle$$

  (for some constant e) then A is an "eigenvector of O".
- Also, e is called the "eigenvalue" for that eigenvector.
- For most operators, most vectors are not eigenvectors. Only a few special ones are.
- Some examples:
  - What are the eigenvectors & eigenvalues for the unit operator ("multiply every vector by 1")?
  - What about "multiply every vector by 5"?
  - What about "rotate any vector 75° about the vector $|C\rangle$"?
  - What about the operator $\begin{bmatrix} 3 & 0 \\ 0 & 3 \end{bmatrix}$?

II. The Quantum Mechanical Algorithm

A. Physical states:

Represented by vectors of length 1. These are called *state vectors.*

Note: "states" vs. "properties":

- Properties can take on any of multiple values. (Ex.: "position", "spin in the x-direction")
- States are specific values of those properties (or collections of such values, for a system). (Ex.: "Boulder, Colo.", "spin up in the x direction")

B. Observables (measurable properties):

Represented by linear operators. The operators must relate to the state vectors as follows:

a) If O represents an observable property, then the state vectors that correspond to definite values of that property are the *eigenvectors* of O.

b) When a physical object's state vector is an eigenvector of O with eigenvalue a, then a is the value of the property.

Examples:

$$x\text{-spin} = \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}. \quad |\text{x-up}\rangle = \begin{bmatrix} 1 \\ 0 \end{bmatrix}. \quad |\text{x-down}\rangle = \begin{bmatrix} 0 \\ 1 \end{bmatrix}.$$

$$y\text{-spin} = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}. \quad |\text{y-up}\rangle = \begin{bmatrix} 1/\sqrt{2} \\ 1/\sqrt{2} \end{bmatrix}. \quad |\text{y-down}\rangle = \begin{bmatrix} 1/\sqrt{2} \\ -1/\sqrt{2} \end{bmatrix}.$$

You can verify that these definitions satisfy (a) and (b).

Picture below shows the spin space. (*Do not confuse with physical space!*)

Also notice that:

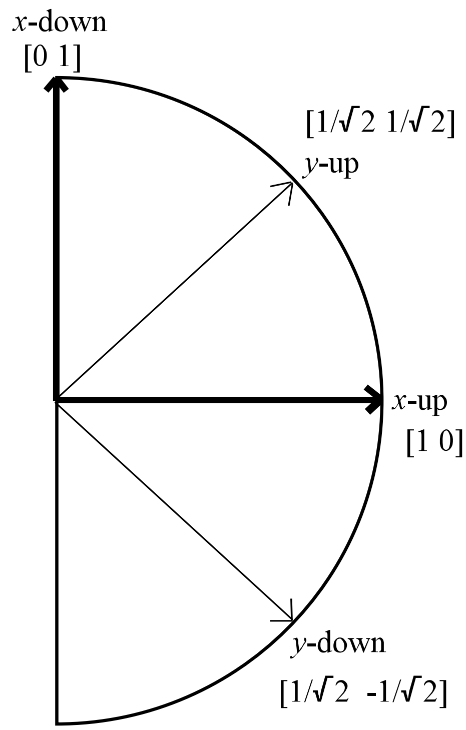
$$|x-up\rangle = \frac{1}{\sqrt{2}}|y-up\rangle + \frac{1}{\sqrt{2}}|y-down\rangle$$

$$|x-down\rangle = \frac{1}{\sqrt{2}}|y-up\rangle - \frac{1}{\sqrt{2}}|y-down\rangle$$

$$|y-up\rangle = \frac{1}{\sqrt{2}}|x-up\rangle + \frac{1}{\sqrt{2}}|x-down\rangle$$

$$|y-down\rangle = \frac{1}{\sqrt{2}}|x-up\rangle - \frac{1}{\sqrt{2}}|x-down\rangle$$

reflecting the fact that |x-up⟩ is a superposition of |y-up⟩ and |y-down⟩, etc.



C. Dynamics of the state vector (unobserved):

When not observed: evolves according to Schrödinger Equation.

- This equation is deterministic.
- It is also linear: If

  |A⟩ evolves into |A'⟩, and
  |B⟩ evolves into |B'⟩

  then

  a|A⟩ + b|B⟩ evolves into a|A'⟩ + b|B'⟩.

D. Results of measurements:

Suppose a system is in a state (represented by) |A⟩, and you measure some observable (represented by) O. Then:

- If |A⟩ is an eigenvector of O, then you will, with certainty, find the system to be in the state corresponding to that eigenvector. The state is not disturbed by the measurement.
- If |A⟩ is *not* an eigenvector of O, then two things will happen:
  1) The system will immediately *jump to* a randomly selected eigenvector of O. The probability of its jumping to any given eigenvector |E⟩ is given by $|\langle A|E\rangle|^2$.
  2) You will thereupon observe the system to be in that state.

- Step (1) above is where chance enters QM.
  - Called “State vector collapse” / “wave function collapse”
  - The claim that wave-function collapses occur is “the collapse postulate”.

III. The Copenhagen Interpretation

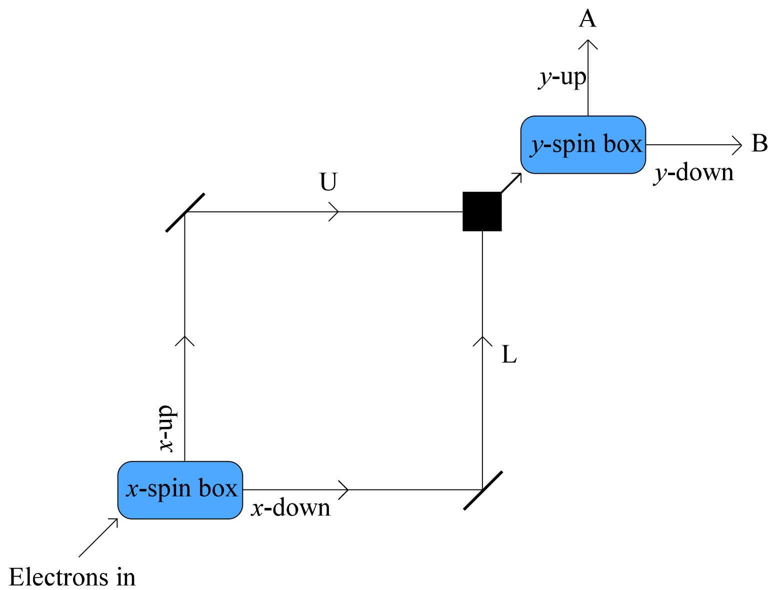
- When an object is in a superposition of two states, it has no definite state. This is not a matter of ignorance.
- Observers (or “measurements”) cause things to go into definite states.
  - Corollary: Observers (or measuring devices) are governed by different laws from the rest of the universe.
- What constitutes a measurement/observation?
  - When there is a conscious being?
  - When there is an interaction with a “macroscopic” object? How large?
- Gives rise to the Shrodinger’s Cat example. Is the cat enough to collapse the wave function?

IV. 'Explanation' of the Quantum Mysteries

In the device at right, we feed in electrons with $|y\text{-up}\rangle$, say.

U and L are points on the upper and lower paths, respectively.

E is the point where the electrons end up when the two paths recombine.



What will happen?

(1) $|y-up\rangle = \frac{1}{\sqrt{2}}|x-up\rangle + \frac{1}{\sqrt{2}}|x-down\rangle$ (as discussed earlier).

(2) An electron with $|x\text{-up}\rangle$ would evolve into $|x\text{-up}\rangle|E\rangle$. (That's the state where it still has spin up in the x direction, and it's located at point E.)

(3) Similarly, an electron with $|x\text{-down}\rangle$ would evolve into $|x\text{-down}\rangle|E\rangle$.

(4) Therefore (due to linearity), an electron with $\frac{1}{\sqrt{2}}|x-up\rangle + \frac{1}{\sqrt{2}}|x-down\rangle$ would evolve into $\frac{1}{\sqrt{2}}|x-up\rangle|E\rangle + \frac{1}{\sqrt{2}}|x-down\rangle|E\rangle$. (From 2, 3.)

(5) This state is equal to:

$$|E\rangle\left(\frac{1}{\sqrt{2}}|x-up\rangle + \frac{1}{\sqrt{2}}|x-down\rangle\right) = |E\rangle\left(\frac{1}{\sqrt{2}}\begin{bmatrix}1\\0\end{bmatrix} + \frac{1}{\sqrt{2}}\begin{bmatrix}0\\1\end{bmatrix}\right) = |E\rangle\begin{bmatrix}1/\sqrt{2}\\1/\sqrt{2}\end{bmatrix} = |E\rangle|y-up\rangle.$$

Hence, the electron will emerge as a y-spin up electron.

The strange effect of measurement:

- If route L is blocked, then step (3) fails.
- If a measuring device is placed to determine which route the electron takes, then
  - wave function collapses into *either* $|x-up\rangle|U\rangle$ *or* $|x-down\rangle|L\rangle$ (each 50% likely).
  - If the first happens, then the electron winds up at $|x-up\rangle|E\rangle$ and subsequently has a 50% chance of coming out at A and a 50% chance of coming out at B.
  - If the second happens, then the electron winds up at $|x-down\rangle|E\rangle$ and subsequently has a 50% chance of coming out at A and a 50% chance of coming out at B.

Phil. 4400
Notes #19: Quantum Nonlocality

I. The EPR Argument

This is due to Einstein, Podolsky, and Rosen (EPR).

• Consider a pair of electrons in the state $|A\rangle$,

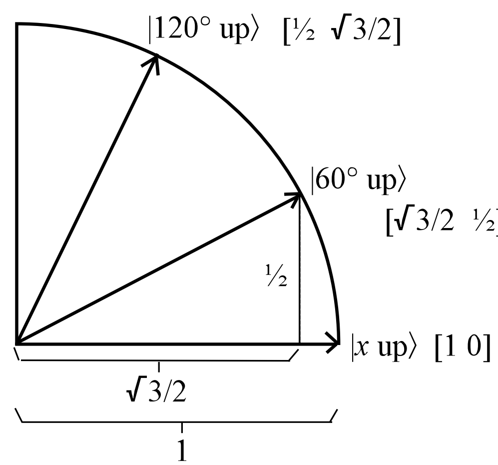
$$|A\rangle = \frac{1}{\sqrt{2}}|\text{x-up}\rangle_1|\text{x-down}\rangle_2 - \frac{1}{\sqrt{2}}|\text{x-down}\rangle_1|\text{x-up}\rangle_2$$
$$= \frac{1}{\sqrt{2}}|\text{y-up}\rangle_1|\text{y-down}\rangle_2 - \frac{1}{\sqrt{2}}|\text{y-down}\rangle_1|\text{y-up}\rangle_2$$

In this state, neither electron has a definite spin, *but* they have opposite spin.

• Imagine the two electrons sent far apart, and then spin of electron 1 is measured. Spin of electron 2 subsequently guaranteed to be opposite.

1. If it is possible to predict, with certainty, the outcome of a measurement on an object without disturbing the object, then there exists an element of reality corresponding to that outcome (i.e., the object already has that property).
2. It's possible to measure the x-spin of electron 1, when the system is in state $|A\rangle$, without disturbing electron 2.
   Key Assumption: **Locality:** Events at spacelike separation cannot affect each other.
3. If this is done, the x-spin of electron 2 can be predicted with certainty.
4. So, when the pair is in state $|A\rangle$, electron 2 already has a definite x-spin. (From 1-3)
5. By similar reasoning, electron 2 has a definite y-spin. (*Note:* Same reasoning applies to spin in *any* direction.)
6. So objects can have definite values of "incompatible" properties simultaneously. (From 4,5)
7. State $|A\rangle$ does not represent the x-spin of electron 2.
8. So qm is incomplete. (From 4, 7)

II. Bell's Theorem



• EPR propose that the particles have a determinate value for spin in each direction.
Suppose we measure spin in one of the following 3 directions:

0° (the x direction), 60° (in the x-y plane), or 120° (in the x-y plane)

for each particle. (So there are 9 combinations of measurements.)

• Suppose we measure 60°-spin on electron 1, and x-spin on electron 2.
  - Result of 1st measurement: P(spin up) = .5
    P(spin down) = .5

- Result of 2nd measurement:

  |Spin up in the 60° direction⟩ = |60° up⟩ = $\begin{bmatrix} \sqrt{3}/2 \\ 1/2 \end{bmatrix}$

  If 1st measurement was x-spin up, then for 2nd measurement:

  P(spin up, 60°) = |⟨60°up|x up⟩|² = $\left(\begin{bmatrix} \sqrt{3}/2 \\ 1/2 \end{bmatrix} \cdot \begin{bmatrix} 1 \\ 0 \end{bmatrix}\right)^2 = \left[\left(\frac{\sqrt{3}}{2}\right)(1) + \left(\frac{1}{2}\right)(0)\right]^2 = \left(\frac{\sqrt{3}}{2}\right)^2 = \frac{3}{4}$

  P(spin down, 60°) = $1 - P(spin - up) = 1 - \frac{3}{4} = \frac{1}{4}$.

- So, probability of *agreement* (both results come out "spin up" or both come out "spin down") = 3/4. Probability of *disagreement* = 1/4.

• Similarly, we can calculate the probabilities for all the results of each of the nine possible combinations of measurements. Results shown below.

QM predicts:

Spin Property Measured		Probability of
Electron 1	Electron 2	*dis*agreement
0°	0°	1
0°	60°	¼
0°	120°	¼
60°	0°	¼
60°	60°	1
60°	120°	¼
120°	0°	¼
120°	60°	¼
120°	120°	1

Question:

Is it *mathematically possible* to achieve these statistical results, by assigning definite values to spin in each of the three directions, for each electron?

• Suppose a large number of electron pairs in state |A⟩ are produced.
  - Each pair is sent in opposite directions, then measurements of spin in the 0°, 60°, or 120° direction is measured on each.
  - We do each of the 9 possible combinations of spin measurements many times, to verify the statistics.
  - Which spin measurements are done each time is *random* (so the electrons can't "know" what spin measurements they're going to encounter).
  - On each occasion, the electrons must have one of the following 8 sets of properties:
    (*Example*: In profile (a1), the first particle is spin up in the 0° direction, spin up in the 60° direction, and spin up in the 120° direction. The second particle is the opposite on all three.)

Possible sets of spin properties for the 2 EPR electrons

	Profile (a1)		Profile (b1)		Profile (c1)		Profile (d1)	
	Elect. 1	Elect. 2	Elect. 1	Elect. 2	Elect. 1	Elect. 2	Elect. 1	Elect. 2
0° spin	↑	⇨	↑	⇨	↑	⇨	⇨	↑
60° spin	↑	⇨	↑	⇨	⇨	↑	↑	⇨
120° spin	↑	⇨	⇨	↑	↑	⇨	↑	⇨
	Profile (a2)		**Profile (b2)**		**Profile (c2)**		**Profile (d2)**	
	Elect. 1	Elect. 2	Elect. 1	Elect. 2	Elect. 1	Elect. 2	Elect. 1	Elect. 2
0° spin	⇨	↑	⇨	↑	⇨	↑	↑	⇨
60° spin	⇨	↑	⇨	↑	↑	⇨	⇨	↑
120° spin	⇨	↑	↑	⇨	⇨	↑	⇨	↑

- *Observations:*
  - In each profile, Electron 2 has the opposite spin properties from Electron 1. This is because, when the *same* spin property is measured on Electron 1 and Electron 2, the probability of disagreement is 100%.
  - Profile (a1) is equivalent to (a2) except that the roles of Electron 1 and 2 have been interchanged. So they're equivalent as far as disagreement goes.
  - Similarly for (b1) and (b2), for (c1) and (c2), and for (d1) and (d2).
  - These 8 profiles are exhaustive.

- *Terminology:*

  a = the frequency with which (profile (a1) or profile (a2)) occurs.
  b = the frequency with which (profile (b1) or profile (b2)) occurs.
  c = the frequency with which (profile (c1) or profile (c2)) occurs.
  d = the frequency with which (profile (d1) or profile (d2)) occurs.

- *Equations:*

$$a+b+c+d = 1 \qquad \textbf{(1)}$$ Because the 8 alternatives are logically exhaustive.

$$a+b = \frac{1}{4} \qquad \textbf{(2)}$$ Because when 0 and 60 are measured, P(disagreement) = ¼.

$$a+c = \frac{1}{4} \qquad \textbf{(3)}$$ Because when 0 and 120 are measured, P(disagreement) = ¼.

$$a+d = \frac{1}{4} \qquad \textbf{(4)}$$ Because when 60 and 120 are measured, P(disagreement) = ¼.

- *The Impossibility:*
  Adding equations **(2)**, **(3)**, and **(4)**:

$$3a + b + c + d = \frac{3}{4} \qquad \textbf{(5)}$$

  Now, subtracting equation **(1)** from equation **(5)**:

$$2a = -\frac{1}{4} \rightarrow a = -\frac{1}{8} \qquad \textbf{(6)}$$

  Note: This is not possible. Profile (a1) or (a2) cannot occur -1/8 of the time.

- The predictions of QM have been experimentally verified. (Alain Aspect's experiment)

Conclusion

- EPR's theory is wrong.
- In fact, *Locality* is false.
  - There is superluminal action. (Influences between events outside each other's light cones.)
  - This may be incompatible with Special Relativity.
  - This is independent of one's interpretation of QM, or even the QM algorithm: The *experimental results* are incompatible with Locality.

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Notes #20: Bohm's Interpretation of QM

I. Basic postulates

(a) A physical system consists of particles *and* a pilot wave.
(b) The wave always evolves in accordance with the Schrödinger Equation. No collapse.

$$i\hbar\frac{\partial\Psi}{\partial t} = -\frac{\hbar^2}{2m}\nabla^2\Psi + V\Psi$$

(c) Particle has a determinate but unknown initial position. The (epistemic) probability of its being at a location is proportional to the square of the amplitude of the wave function at that location. $\rho = |\Psi|^2$
(d) The wave causes the particle to move in a specific way. The particle gets carried along with the flow of the amplitude of the wave function, according to the equation below. (It moves in the direction of the gradient of the wave function.) The equation of motion:

$$\frac{dQ_k}{dt} = \frac{\hbar}{m_k}\mathrm{Im}\frac{\Psi^*\nabla_k\Psi}{\Psi^*\Psi}(Q_1,\cdots,Q_N)$$

(e) For a system of many particles, there is a *single* wave, occupying a many-dimensional *configuration space*. The equation in (d) determines the change in the position of the system in configuration space.

Configuration space:
- A mathematical "space" that a system occupies, with three dimensions for each particle.
- The system occupies a point in that space. The location of the system in the configuration space reflects the locations of all the particles in physical space.
- Example: Consider two particles, A [located at (1, 3, -4)] and B [located at (-1, 2, 0)]. The 2-particle system occupies the point (1, 3, -4, -1, 2, 0) in the 6-dimensional configuration space.

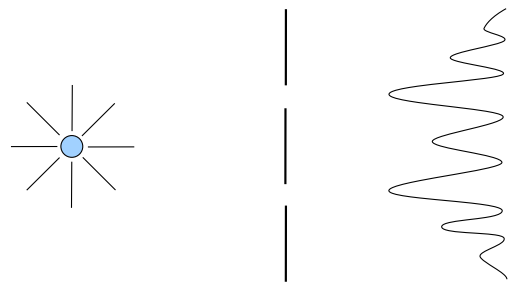
II. Interesting features

- Postulates (c) and (d) entail that the probability distribution for particle positions at any *later* time will *also* be proportional to Ψ^2. (The equation of motion is specifically cooked up to achieve this result.)
- The theory is deterministic. But indeterministic variants can be developed. (As suggested by Bohm & Hiley in *The Undivided Universe*.)
- The theory gives the standard empirical predictions of quantum mechanics.
  - One exception: If a sufficiently precise collapse theory is given, it is possible in theory (but extremely difficult) to test for wave function collapses. Bohm predicts that no such collapse will be found.
- The theory is nonlocal. Instantaneous action at a distance is possible. Bohm says everything is interconnected.
- All properties other than position are "contextual".
  Contextual properties: Properties that depend on a relationship of the object to its environment (esp. the experimental apparatus used for "measuring" them).
  - Ex.: Outcome of a spin measurement depends on orientation of the measuring device.

III. How does the theory deliver QM phenomena?

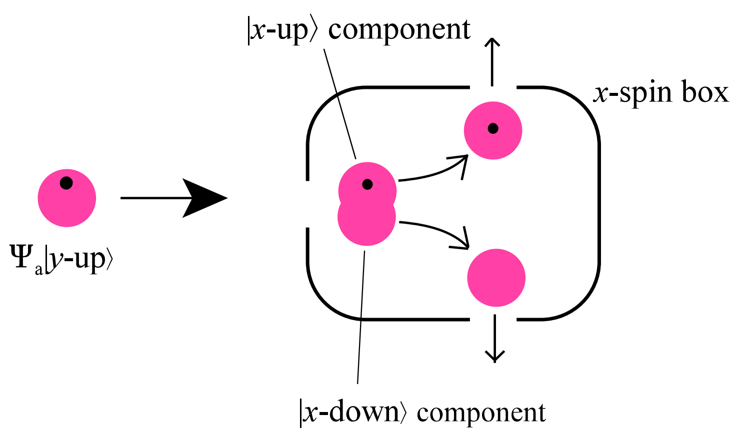
A) The double slit experiment

- Pilot wave goes through both slits, producing interference.
- Particle goes through one slit or the other, depending on its initial position.
- The equation of motion [(d) above] implies that the particle will be carried away from areas where the amplitude of the wave is lowest. Hence the observed interference pattern.
- If one slit is blocked, the pilot wave only goes through the other. No interference.



B) A spin measurement

- Electron starts out with |y-up⟩ wave function, is fed into x-spin box.
- The wave function evolves: The |x-up⟩ component of the wave function moves towards the aperture indicating "spin up", while the |x-down⟩ component moves the opposite way.
- Electron carried along with the wave function. Suppose electron starts in upper half of the wave. Then it will move up.
  - As the "x-up" and "x-down" components move apart, the electron winds up in a region where the "x-down" component is absent *first*.
  - It is subsequently carried along by the "x-up" part of the wave function.

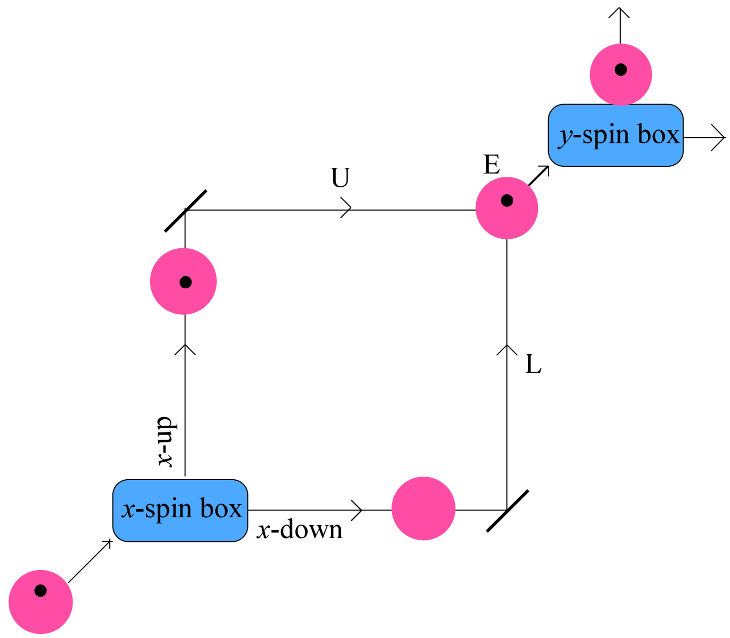


- *Note:* No collapse. The |x-down⟩ part of the wave function still exists.
- Why will electron subsequently be measured as *x*-up, with 100% probability?
  - |x-down⟩ component is no longer in the region where the electron is located.
  - Electron's motion determined by the wave function at its current location.
  - This explains the *apparent* collapse.
- But if the x-down component is somehow brought back to where the electron is, it can then affect the electron's behavior.

C) The mysterious two-path experiment

- Electron takes one path or the other.
- The wave splits in two and takes both paths.
  - The |x-up⟩ component takes the U path.
  - The |x-down⟩ component takes the L path.

- The wave components recombine at point E, creating a |y-up⟩ wave function once again. (See diagram.)



D) "Effective" collapses

- Measurement brings about "effective collapse": the wave function does not actually collapse, but system acts as if it did.
  - Components of the wave function corresponding to different possible measurement outcomes (outcomes that would have occurred had the initial position been different) still exist.
  - But these components separate into different places in configuration space.
  - Only the wave function components in the vicinity of *the system's current position* affect its motion.
- The non-existence of collapses is *in principle* detectable. After a measurement:
  - Different components of the wave function (corresponding to different possible measurement outcomes) must be recombined in configuration space.
  - An 'interference effect' (as in the double slit experiment, or the 2-path experiment above) would occur, according to Bohm.
  - Collapse theories predict no interference effect.
- This is *in practice* unfeasible. Why:
  - Recombination of wave function components implies:

    The system is at a place in configuration space, such that it would have been at that same place, if one of the other measurement outcomes had occurred.

  - That means: *Every particle* in the system is where it would have been (in physical space), had another measurement outcome occurred.
  - That means: Every trace of the measurement outcome, in the position of any particle, has been erased.

IV. Advantages of Bohm

1. Uniform dynamics:
   - Wave function always evolves in the same way. (The collapse postulate is bogus.)
   - Measuring devices/observers governed by same laws as the rest of physical reality.
2. Logical coherence:
   - Cats are either alive or dead, not in a 'superposition' of alive and dead.
3. Precision: Copenhagen interpretation requires a vague concept of "measurement," or "macroscopic" objects.
4. Determinism, if you consider that an advantage.

V. Objections to Bohm

1. Conflicts with Special Relativity.
   - Bohm's theory is *blatantly* nonlocal:
     - In the EPR experiment, outcome can depend on order in which measurements are done.
     - Anyway, because motion of system depends on the wave function at the system's location in configuration space, the location of particle 1 can affect the motion of particle 2 (even if particles 1 and 2 are far apart).
   - That means: it requires a preferred reference frame.
     - But we can *not* use the nonlocality to send signals.
     - We also cannot *identify* the preferred reference frame.
2. A positivist objection: Bohm's theory entails the existence of undetectable facts (as just noted).
3. Copenhagen got here first. Bohm's theory lacks novel predictions.
4. Another conspiracy of silence objection: Isn't it bizarre how the world conspires to prevent us from detecting (a) the preferred reference frame, (b) the truth of determinism, (c) the lack of collapses? I.e., things are set up exactly to make it look like orthodox QM is true?
5. The probabilistic postulate, $\rho = |\Psi|^2$, is ad hoc. Why should the epistemic probability be that?
6. *Technical objection:* Difficult to come up with a Bohmian version of relativistic quantum field theory.

Phil. 4400
Review of Unit 4

Know these concepts:
vector, state vector
superpositions
  Including, how they're different from mere ignorance
wave interference effects
operator
linearity (incl.: linear dynamics)
eigenvector
observables
wave function collapse
  & why it's supposedly needed
locality / non-locality
configuration space
effective collapse

Know these examples, & what happens in them:
Double slit experiment
Ordinary spin measurements
  & Copenhagen account of them
  & Bohmian account
The two-path experiment
  & how Copenhagen Interp. explains it
  & how Bohm explains it
EPR example
  & what it was intended to show

Know these principles:
Evolution of wave function (unobserved)
Bell's theorem & what it shows
In Bohm's interpretation:
  His view of wave-particle duality
  His view of collapse, "measurement", and such
  The motion of particles
  Determinism
  Non-locality
  'Effective' collapses: when they happen
Copenhagen Interpretation, including:
  Collapse postulate
  what's determinate / indeterminate
  views of 'measurement'

Know these arguments:
Objections to Copenhagen Interp:
  Logical incoherence
  Special role for observers
Objections to Bohm:
  How it conflicts w/ Relativity
  The conspiracy of silence