PHYS/PHIL 329 Lecture 2: Superposition

Kelvin McQueen - 2/6/2020

Announcements

- Prof. Leifer's office hours are:

Mondays and Fridays 10am-11am

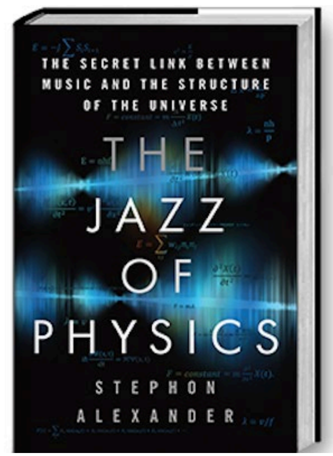
Hashinger 223

- Broken links on Canvas have been fixed.

Announcements

- Institute for Quantum Studies Public Lecture:

Reflections on Jazz and The Quantum World

Prof. Stephon Alexander (Brown University)

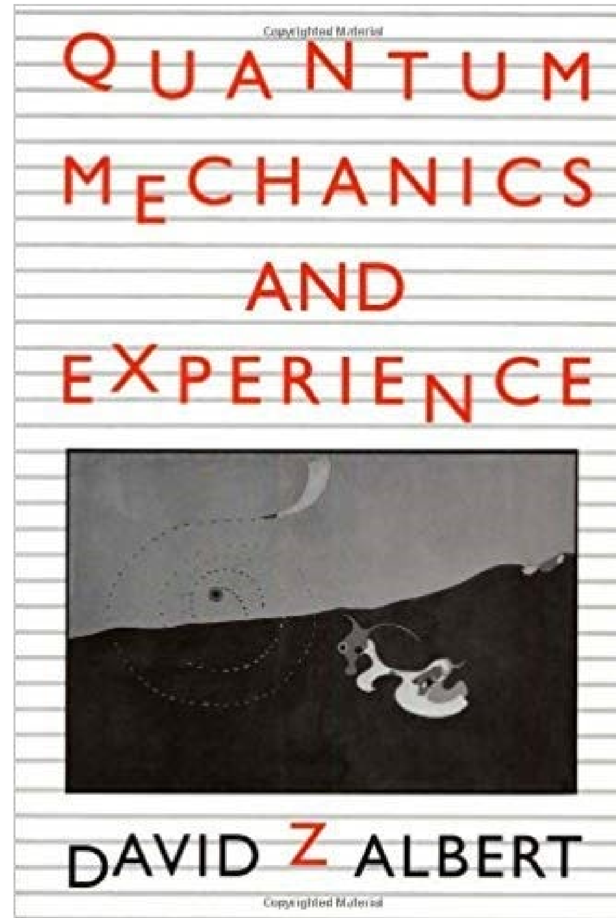
7pm, Wed. Feb. 12 in Agyros 201

Refreshments Served

Talk will be followed by a book signing. A limited number of copies of the book will be available (cash only) and there will be a door lottery to win a copy of the book.

Goals of chapter 1: “Superposition”

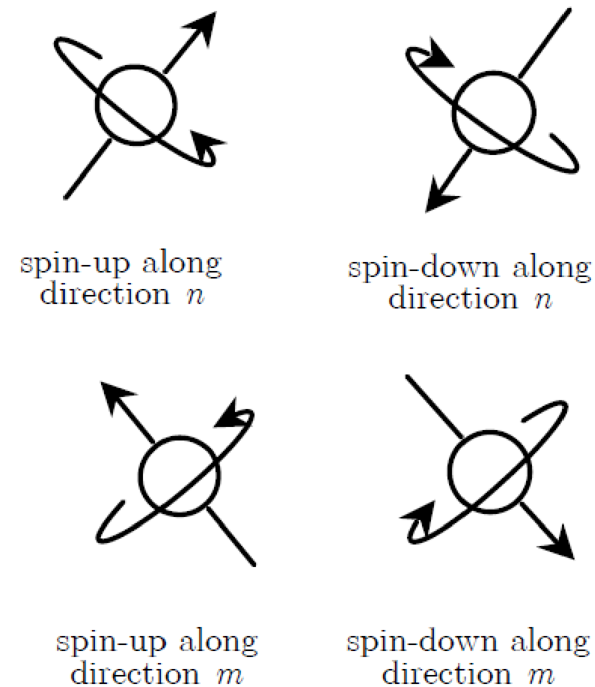
- Primary goal:
  - Albert intends the reader to abstract the concept of superposition from (idealized) real world experiments.
    - The 3-box experiment.
    - The 2-path experiments.
    - The double-slit experiment.



- Additional goals:
  - Illustrate the uncertainty principle.
  - Illustrate indeterminism.

Color and hardness idealizations

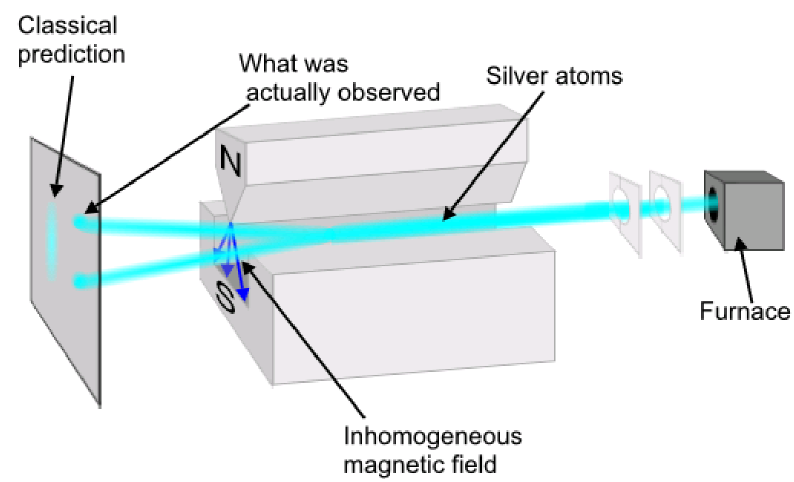
- Albert considers electrons and two "spin" properties that electrons have.
- But he idealizes away all aspects of these properties not relevant to the problem at hand (defining 'superposition' etc.).

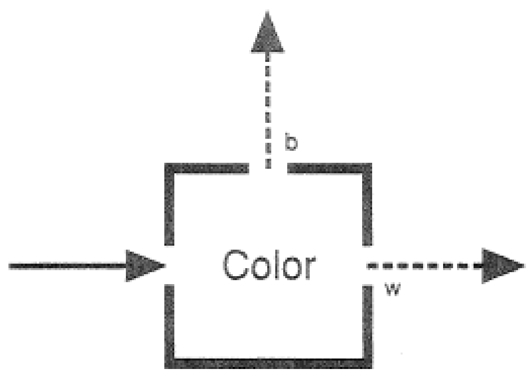


- We are left with two binary (2-valued) physical properties.
- Albert introduces arbitrary names for the two binary properties: *Color* (black vs white) and *hardness* (hard vs soft).

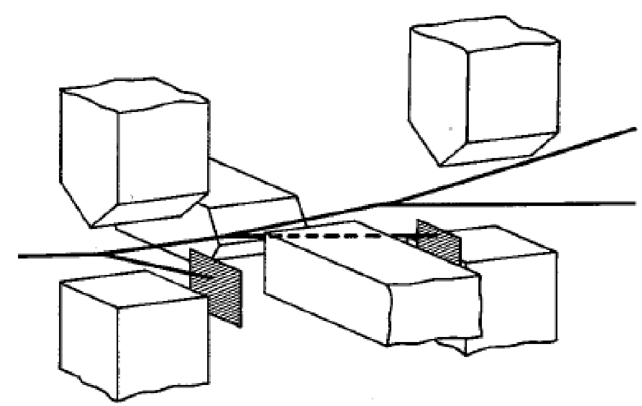
Color and hardness *box* idealizations

- The Stern-Gerlach device (top right) becomes the colour box (below).





- Optional reading: See Hughes "Introduction" for detailed discussion of the (non-idealized) "three-box experiment".

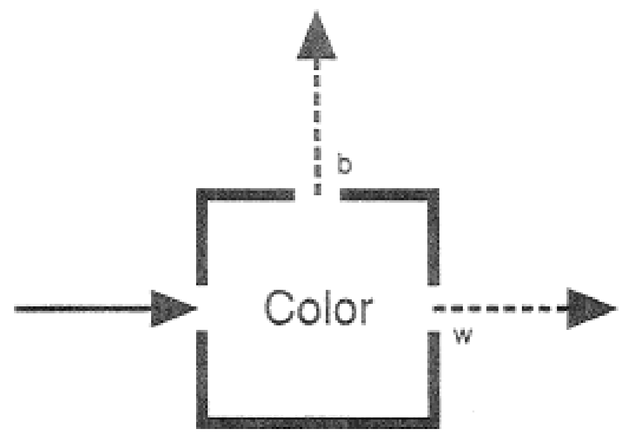


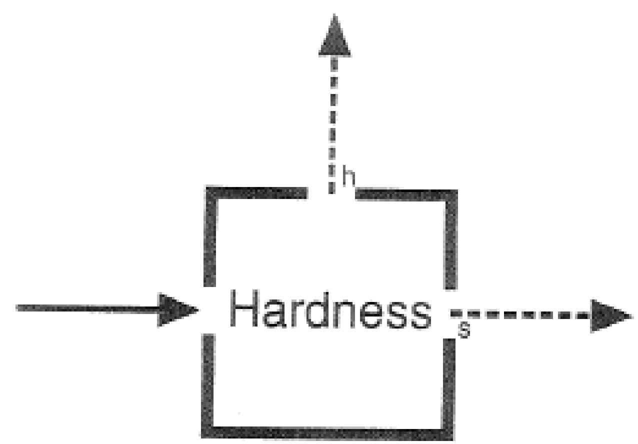
Summary of the idealized set-up

- In (idealized) quantum mechanics:
  - Electrons have two measureable physical properties called *color* and *hardness*.
  - It is an experimental fact that the color property can only assume two values: black or white.
  - It is an experimental fact that the hardness property can only assume two values: hard or soft.

Color and hardness boxes

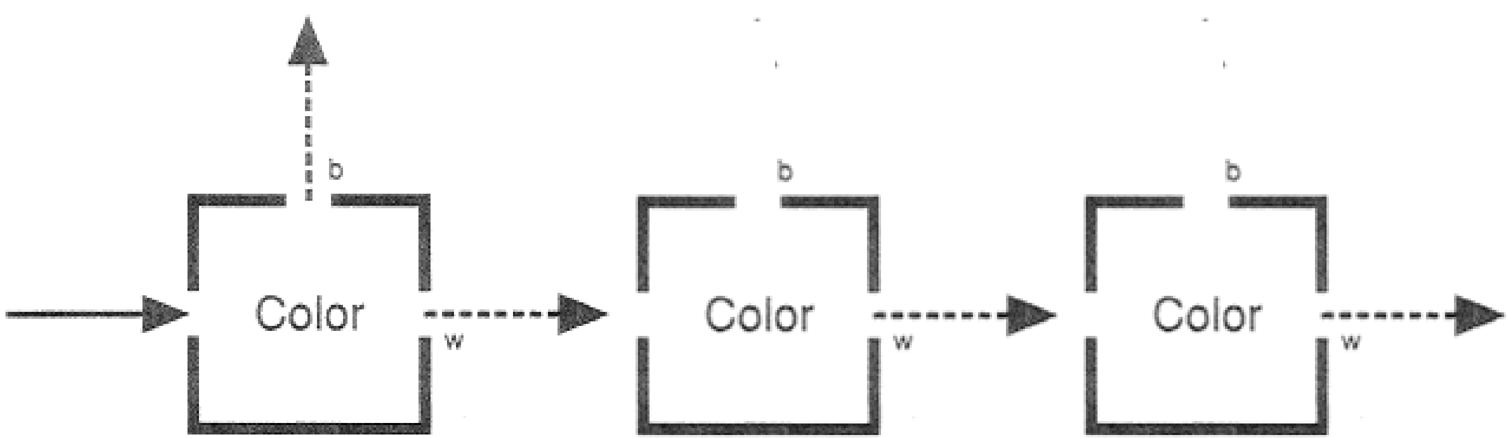
- Each box has three apertures (entry/exit points).
- We can insert electrons into the left aperture.
- The color box sends black electrons out the top aperture and white electrons out the right aperture.
- The hardness box sends hard electrons out the top aperture and soft electrons out the right aperture.





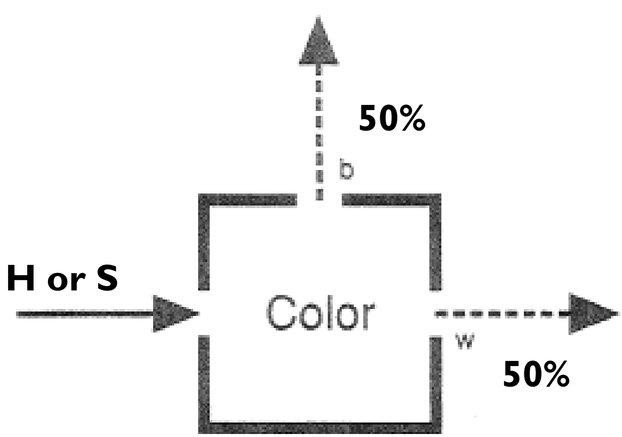
Color and hardness boxes

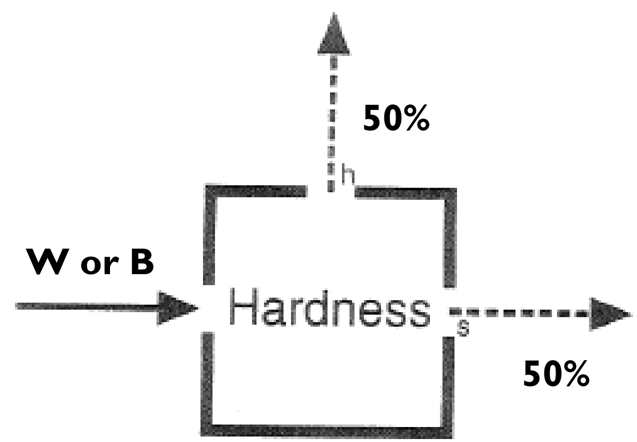
- We know the boxes are *reliable* because measurements with them are *repeatable*.
- For example, if an electron is found to be white, then provided the electron is not subsequently tampered with, another colour measurement will yield white.



Are color and hardness related?

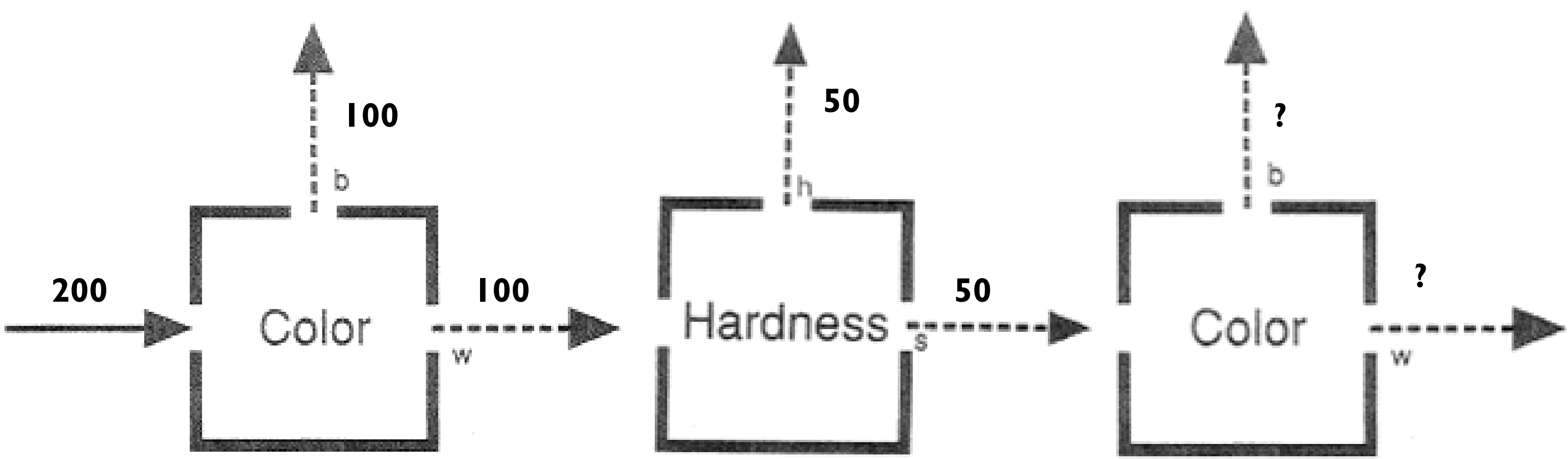
- For example, are all hard electrons black?
- Experimentation suggests no such correlation exists.
  - Of any large enough collection of, say, hard electrons, all of which are fed into a colour box, half emerge through the white aperture, half through the black aperture.
  - So color (hardness) apparently gives no information about hardness (color).





The 3-box experiment

- Send a large number of electrons (say, 200) through a colour box. Assume the first color box perfectly splits them. Then send the (100) white electrons through a hardness box. Then send the (50) soft electrons through another colour box.
- What will be the result?



The 3-box experiment - results

- Expected result:
  - 50 white 0 black.
- Reason:
  - The first color box removed the black electrons from the experiment.
- Actual result:
  - 25 white 25 black (on average).

  - In fact, if the first two boxes are set up to yield:
    - White and soft OR
    - White and hard OR
    - Black and soft OR
    - Black and hard...
  - ...then the third box will *still* yield 50% white, 50% black.

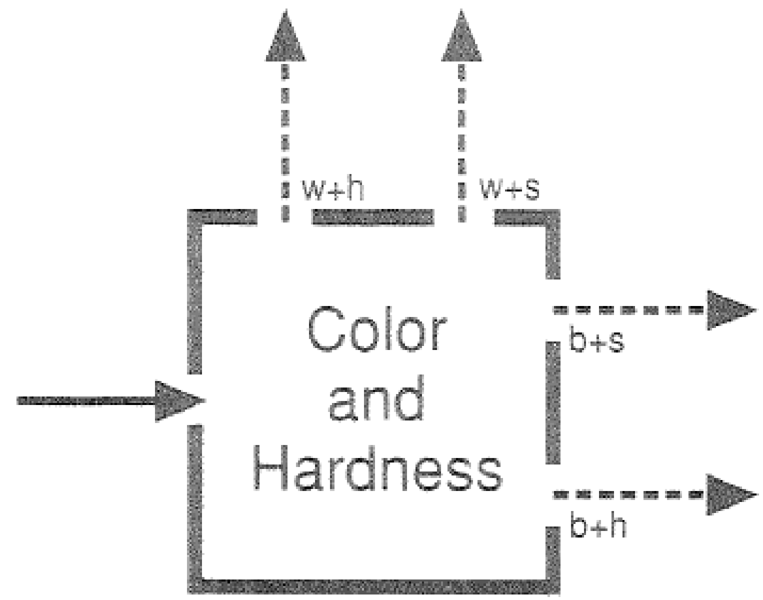
The 3-box experiment - questions

- What initial properties of the electrons determine which ones end up white, and which end up black?
  - As far as we can tell, none. There are no initial properties of the electron that explain why only some ended up white.

- Can we build (reliable) hardness boxes that don't "disrupt" color?
  - No matter what we do, we cannot move the statistics of colour disruption even so much as one millionth of one percentage point away from 50/50.

A colour-and-hardness box?

- Can we build a box that *simultaneously* determines color and hardness?
- No – we can only stack color and hardness boxes beside each other, as already seen.
- Simultaneously knowing both the color and the hardness of an electron appears to be impossible.



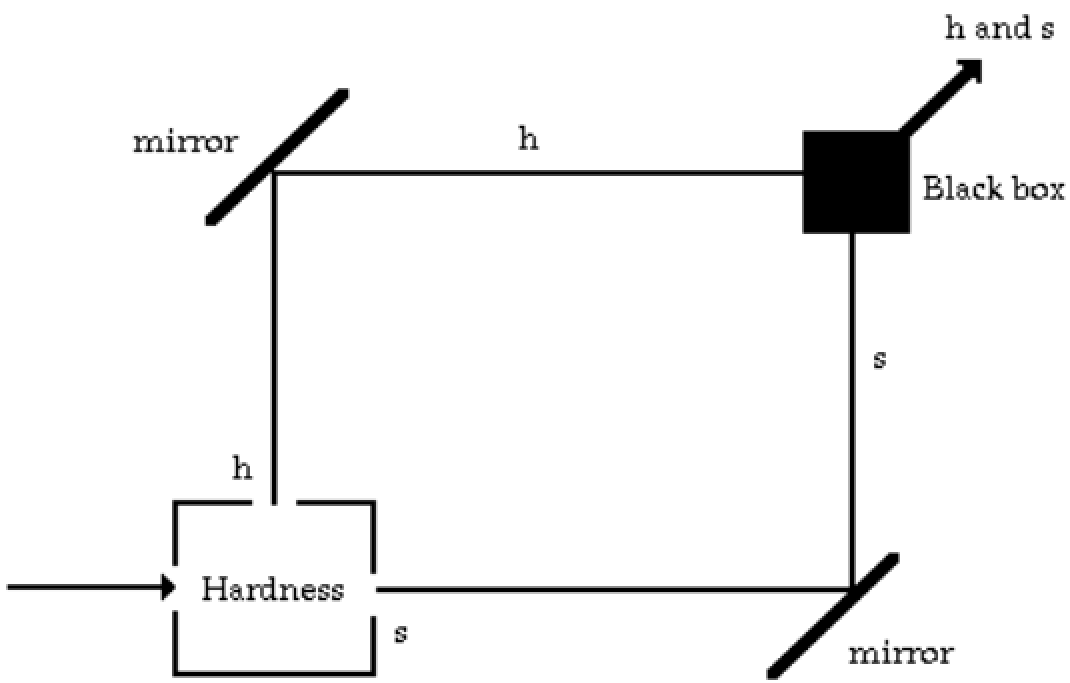
The 3-box experiment - summary

- Hardness boxes randomize the color of electrons.
- Color boxes randomize the hardness of electrons.

- This is confusing but doesn't yet call for a conceptual revolution, so let's try some further experiments to find out what's happening...

The 2-path experiments

- Basic set up:
  - Send electrons into a hardness box. Hard and soft electrons are then deflected off mirrors into a “black box” that recombines the electrons into a single beam.

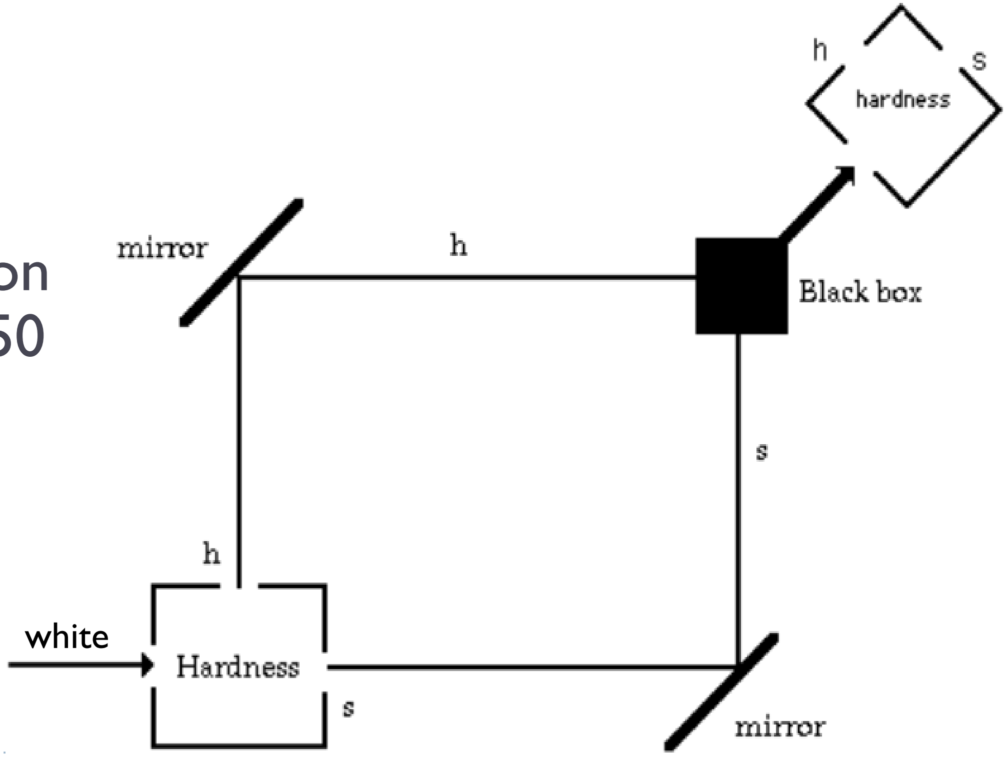


The 2-path experiments

- 2-path experiment 1:

  Send white electrons through and then measure their hardness.

- Expected result:
  - 50% hard 50% soft.
  - Reason: we've learnt that hardness measurements on white electrons yield 50/50 results.
- Actual result:
  - 50% hard 50% soft.
  - No surprises…

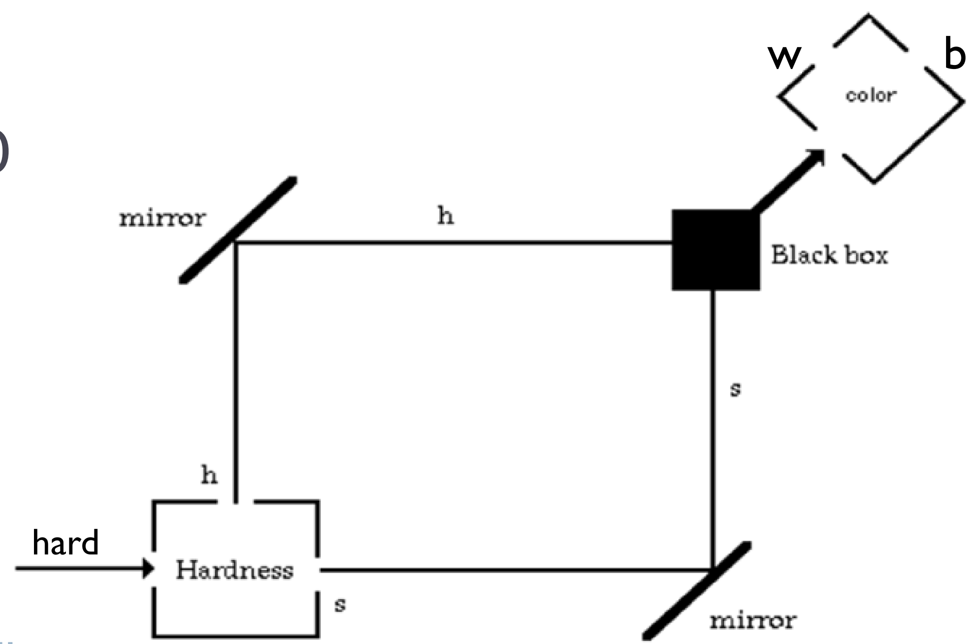


The 2-path experiments

- 2-path experiment 2:

  Send hard electrons through and then measure their color.

- Expected result:
  - 50% white 50% black.
  - Reason: we've learnt that color measurements on hard electrons yield 50/50 results.
- Actual result:
  - 50% hard 50% soft.
  - No surprises…

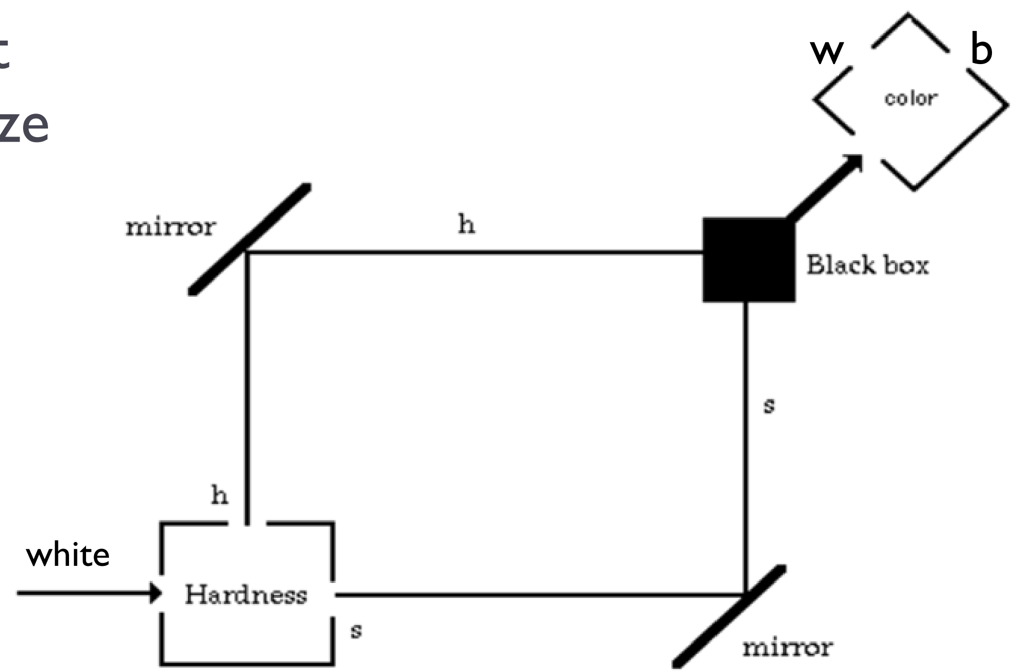


The 2-path experiments

- **2-path experiment 3:**

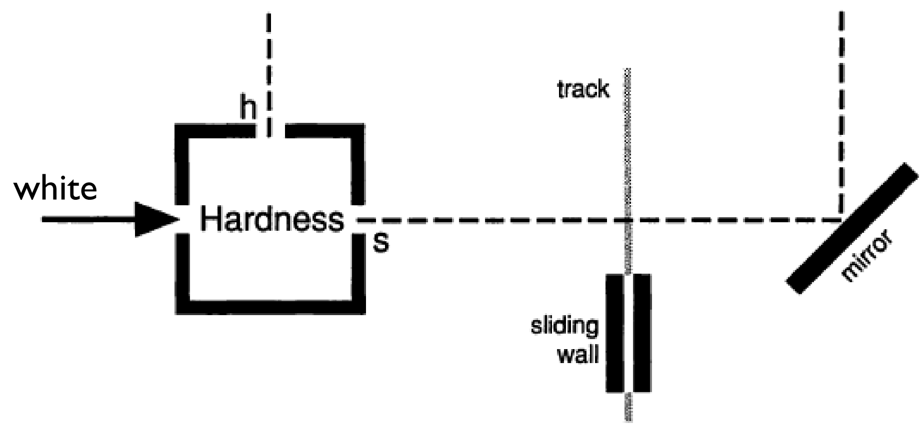
  Send white electrons through and then measure their color.

- **Expected result:**
  - 50% white 50% black.
  - Reason: we've learnt that hardness boxes randomize color, the colour box should confirm this.
- **Actual result:**
  - 100% white!



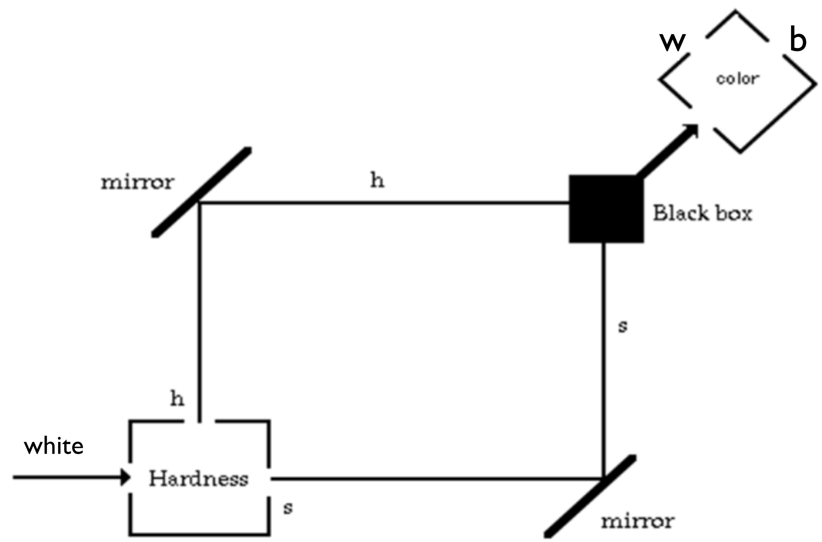
The 2-path experiments

- 2-path experiment 4:
  - Repeat experiment 3 (i.e. send white electrons through and then measure their color) but insert a stopping wall on the s-path.
- Expected result:
  - 50% less electrons, 100% will be white.
  - Reason: same experiment as 3, but we are blocking half the electrons?
- Actual result:
  - 50% less electrons, 50% white, 50% black.
  - What is going on!?



The 2-path experiments

- In experiment 3 (which yields 100% white) which path are the electrons taking?
  - H-path?
    - No: this would yield 50% white as experiment 4 demonstrates.
  - S-path?
    - No: putting the wall on the h-path also gives 50% white.
  - Both paths?
    - No: when we measure which path they are on we always get a definite result.
  - Neither path?
    - No: if we wall up both paths nothing gets through.
- This defies all pre-quantum concepts. We need *new* concepts to describe what is happening!



Superposition

- "What can such electrons be doing? They must be doing something which has simply never been dreamt of before. Electrons seem to have modes of being available to them which are quite unlike what we know how to think about. The name of that new mode (which is just a name for something we don't understand) is *superposition*." (Albert p11.)

- The electron is *in a superposition* of going down both the h-path and the s-path.
- The electron is therefore *in a superposition* of being both hard and soft.

- Let's consider one more example...

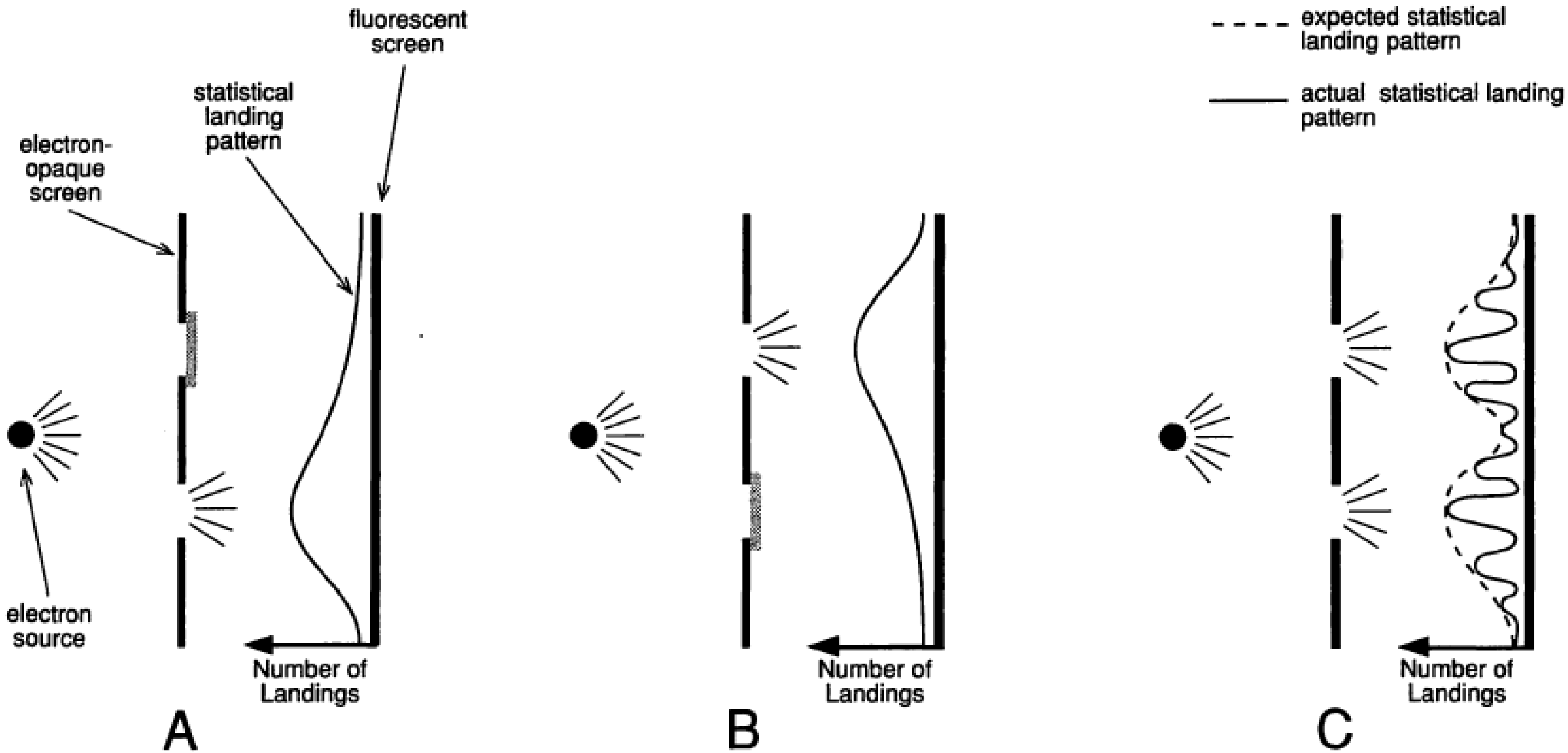
The double-slit experiment

- Fire electrons at a florescent screen. When an electron hits a spot on the screen that spot flashes, we can then detect where the electron landed.

- Place a wall in between the electron gun and the screen. The wall has two slits, which can be blocked up.

- Depicted on next slide…
  - Note: larger numbers of landings on an area of the screen are depicted by larger peaks…

The double-slit experiment



The double-slit experiment

- In experiment C, which slit do the electrons go through?
  - Just one of the two slits?
    - No: this would give a pattern that is the sum of the patterns in experiments A and B.
  - Both slits?
    - No: when we measure which slit they are going thought we find they are going through one.
  - Neither slit?
    - No: when we block both slits we get no landing pattern.
- The electrons are each in a superposition of going through both slits.

- Helpful animated presentation of the double-slit experiment:
  - The Quantum Experiment that Broke Reality | PBS Space Time

Superposition - recap

- We've seen several examples of superpositions.
  - Going though neither slit one nor slit two nor both nor neither, means being in a superposition of going through both.
  - Being neither hard nor soft nor both nor neither, means being in a superposition of hard and soft.
- These are the types of states we need to get a better understanding of!
- The formalism of chapter two will be immensely helpful, and will enable you to *predict* all the strange behaviour we have just seen.

Uncertainty principle

- We noted earlier that we cannot simultaneously measure color and hardness.
- We've also seen that putting a white electron through a hardness box means the electron is neither hard nor soft nor both nor neither.
- So it's not that we cannot know the color and hardness of an electron simultaneously.
  - So "uncertainty principle" is perhaps an unfortunate label.
- Having a definite color entails *not having* a definite hardness.
  - So "incompatibility principle" or "indeterminacy principle" may be a more accurate label.

Indeterministic collapse

- Measurements would be deterministic processes if a hardness measurement on a white electron yielded a particular hardness with certainty.
- But that would require the white electron to actually *be* a particular hardness (which it isn't).
- And when we do the measurements we find particular hardness values only with certain probabilities (e.g. 0.5).

- The transition from superposition states to definite states is therefore a matter of *objective probability*.

Towards a formal def. of superposition

- A superposition is (represented in the formalism by) *a weighted sum of ordinary physical states*.

- [black] = #[hard] + #[soft]
- [white] = #[hard] - #[soft]
- [hard] = #[black] + #[white]
- [soft] = #[black] - #[white]

- As we shall see, the numbers (#) will concern the objective probability that we will find the particle to be in the associated state, on measurement.
- The formalism of chapter 2 will allow us to get much more precise about this.