Philosophy of Quantum Mechanics

VU University Amsterdam: W_MASP_TF013 Lecture 1: 3/2/2015

Kelvin J. McQueen

Contact info & course delivery

- My details:
  - Kelvin McQueen
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  - Please don't hesitate to contact me!
- Course details:
  - Every Tuesday and Thursday 6pm-8.45pm, HG-01A08.
    - Lectures plus discussion.
  - Additional meetings if necessary (email me).

Today's lecture

This course is based around a specific theoretical problem and philosophical problems that arise from it

And so today I shall provide a:

- Non-technical summary of the theoretical problem.
- Then, a summary of the whole course.
- Then, an explanation of what is expected of you regarding assessment.
- Finally: chapter 1 of Albert (1992): **superposition**.

The Measurement Problem

A non-technical explanation

Textbook quantum mechanics

- Textbook quantum mechanics refers to:
  - The most theoretically neutral formulation of quantum mechanics, used to teach quantum mechanics in university textbooks.
    - Originally stated in:
      - Neumann, J. von. 1955. *Mathematical Foundations of Quantum Mechanics.* Princeton University Press.
      - German original: 1932 *Die mathematischen Grundlagen der Quantenmechanik*. Berlin: Springer.
    - Modern example:
      - Phillips, A. C. 2006. *Introduction to Quantum Mechanics.* John Wiley & Sons. (esp. p51.)

- Albert (1992: chapter 2) provides a philosopher's summary of textbook quantum mechanics.
  - But he also adds a controversial interpretation, which he calls 'the orthodox Copenhagen interpretation'.
    - More on this in due course!

Textbook laws of nature

- Textbook quantum mechanics posits two laws of nature that govern the time-evolution of physical systems.
  - The Schrödinger equation
    - Describes a *deterministic* law.
  - The collapse postulate
    - Describes an *indeterministic* (i.e. probabilistic) law.

Determinism and Indeterminism

- Familiar from debates about free will.
  - Can we have free will if all our actions are fully determined by past events?
- Determinism:
  - If the state of the universe at one moment in time (e.g. the present) is completely given, together with the laws of nature, the state of the universe at any other moment can be calculated.
    - If laws of nature enable such a calculation, they are deterministic laws.
- Quantum indeterminism:
  - Given the state of the universe at one moment the collapse postulate only enables one to calculate the probability that the universe will be in one or another later state.

Are these laws compatible?

- They cannot *both* govern the fundamental evolution of physical systems *at the same time*.
- So, under what circumstances does one law and not the other apply?

- Textbook answer:
  - The Schrödinger equation applies to physical systems **when they are <u>not</u> being measure**d.
  - The collapse postulate applies to physical systems **when they <u>are</u> being measured**.

The measurement problem

- A preliminary analysis:
  - The notion of "measurement" is not well defined.
  - The process of measurement does not look like a good candidate for being a fundamental physical process.
    - What kind of process constitutes a measurement?
  - "The mechanism underlying the collapse is not understood"
    - Phillips, A. C. 2006. *Introduction to Quantum Mechanics*. John Wiley & Sons. (p51)

The measurement problem

- As we will see over the next few weeks, the measurement problem runs much deeper than this preliminary analysis.

  - In QM systems are typically in physical states that do not have definite values for a given property.
    - Systems are instead in **superpositions** of having distinct values for a given property.

  - The Schrödinger equation describes the deterministic evolution of superpositions.
  - The collapse postulate describes the indeterministic evolution of a superposition state into a more familiar definite state.

Superposition

- Particles are typically:
  - In superpositions of different positions.
  - In superpositions of different states of momentum.
  - In superpositions of being both spin-up and spin-down.
  - And so on.

- We will discuss superposition today and Thursday. Please read **chapters 1 & 2 of Albert (1992)** in preparation.

Solutions to the measurement problem

- Give up – physics can no longer describe reality
  - Anti-realist approaches
    - Briefly discussed in week 1.
- Just remove the collapse postulate…
  - Everett interpretation a.k.a many-worlds theory.
    - Discussed in weeks 3 and 4.
- Revise the collapse postulate…
  - Spontaneous collapse theories
  - Consciousness causes collapse theories
    - Discussed in week 5.
- Replace the collapse postulate, revise ontology...
  - Additional variables theories (e.g. Bohmian mechanics).
    - Briefly discussed in week 6.

Why many-worlds & collapse theories?

- A primary goal of this (6 week long!) course:
  - To introduce you to the *contemporary* philosophy of quantum mechanics literature.
- Many-Worlds is the most widely discussed solution.
  - The "Oxford Interpretation"
  - Most popular among realist physicists.
  - Does not deviate far from textbook quantum mechanics.
  - Does not conflict with other areas of physics.
  - Problems are highly philosophical (probability)
- Collapse theories are not far behind.
  - Most popular among philosophers (?) David Albert etc.
  - Does not deviate far from textbook quantum mechanics.
  - Does not conflict (much!) with other areas of physics.
  - Problems are highly philosophical (tails).
  - Central to my own research.

Basic course structure

- Part I: Quantum mechanics, quantum philosophy, and the measurement problem
  - Mathematical formalism: lectures 2 and 3.
  - Quantum philosophy: lecture 4.
  - Measurement problem: lecture 5.
    - You will be assessed on your grasp of these (40% take home exam).

- Part II: Solutions to the measurement problem
  - Following week seven you will be presented with solutions you must evaluate (at least) one.
    - You will be assessed on this (60% essay).

Assessment

- See handout!

Goals you should set yourself

- By the end of this course you will:
  - Be able to relate quantum mechanics to issues in contemporary philosophy.
  - Be competent with philosophically problematic quantum mechanical concepts.
  - Be able to formulate and clearly explain the foundational problem of quantum mechanics – the measurement problem.
  - Understand the primary solutions to the measurement problem and the costs involved in accepting them.
  - Have made a contribution towards solving the measurement problem by critically analysing existing solutions.

The mathematical formalism

- One week on the mathematical formalism of quantum mechanics… **is that even possible?**

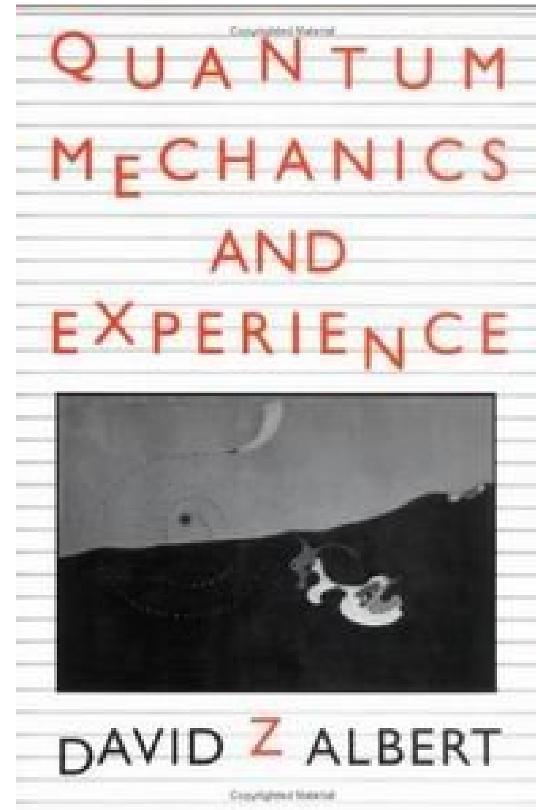
- **It is possible**, thanks to the most widely read (by far) piece in the history of the philosophy of physics.

- David Albert's *Quantum Mechanics and Experience* (1992) made courses like this possible, and is largely responsible for exponential growth of the field in the mid-to-late nineties.

- How did Albert accomplish this?

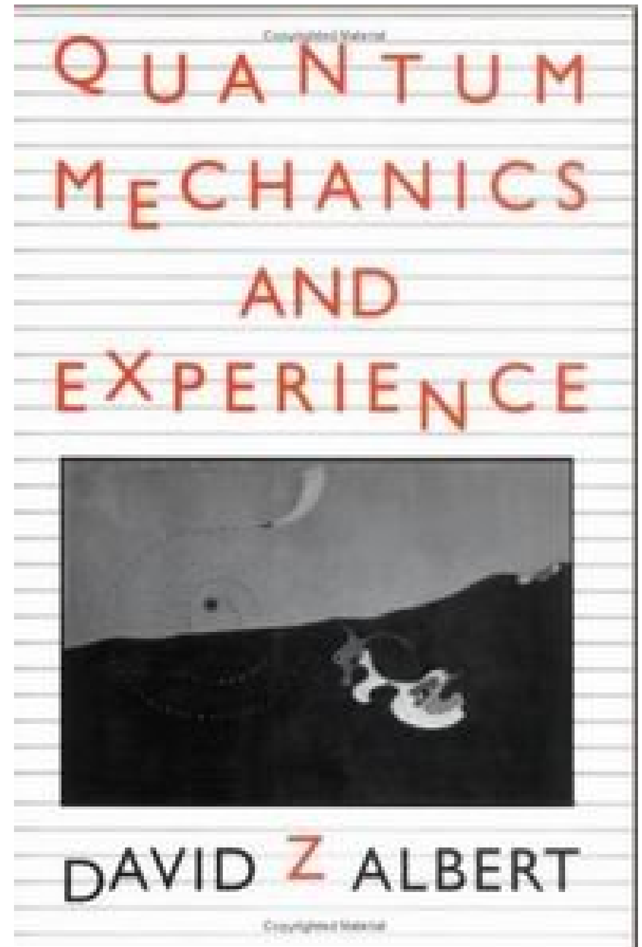
The mathematical formalism

- "At the end of reading Albert's book, one has, I think for the first time, a clear and also very deep analysis of all the solutions that have been proposed to the problem of finding a satisfactory interpretation of quantum mechanics, and a keen sense of the high price that would be involved in "buying into" any one of the proposed solutions. This is a major achievement. […] This reviewer cannot remember seeing such a remarkable combination of accuracy and readability, a combination that depends on **the most sensitive judgment as to what mathematical details need to be spelled out and which can be sketched or indicated in ordinary prose**."
  - Hilary Putnam (philosopher), Book Review of *Quantum Mechanics and Experience*
    - In *Foundations of Physics*, Vol. 24, No. 7, 1994.



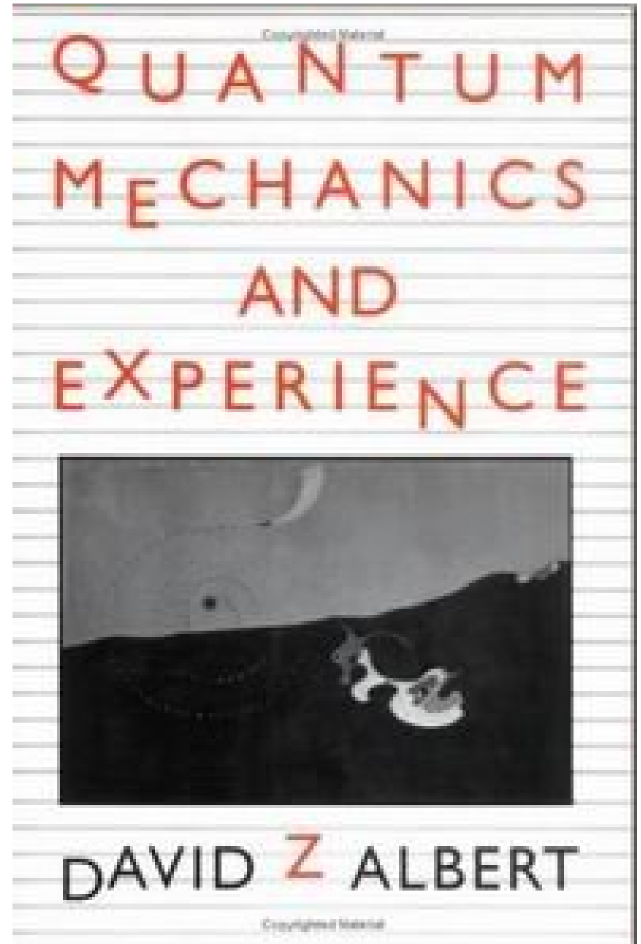
Course readings: the formalism etc.

- **Chapter 2** describes the mathematical formalism.
- A number of idealisations / simplifications are employed.
- Most importantly:
  - We want to understand what the QM *state-descriptions* are *saying about reality*.
  - The *equations* that enable us to *predict* future state-descriptions given past-descriptions are (mostly) not relevant to this project.
  - Accordingly, *dynamical equations* are not even presented in Albert, so, are not part of this course.
  - **Albert's text defines the required mathematics for this course.**



Course readings: the formalism etc.

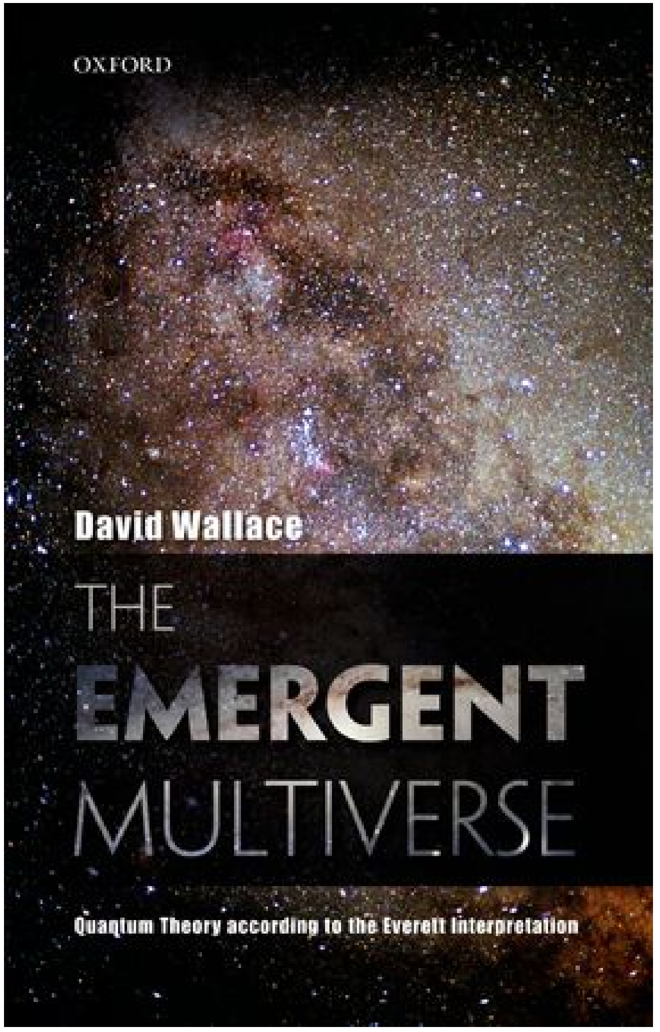
- **Chapter 3** covers nonlocality and is a basis for quantum metaphysics.
- **Chapter 4** covers the measurement problem.
- **Chapter 5** covers dynamical collapse theories.
- **Chapter 7** covers additional variables theories.
- **Chapter 6** covers many-worlds theory **but is radically out-of-date**…



Course readings: many-worlds theory

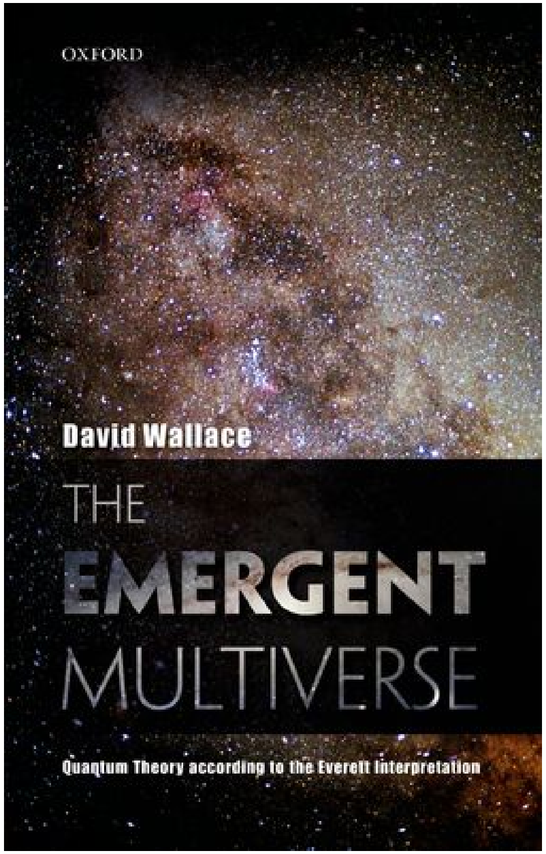
- **Chapter 2** describes many-worlds theory.
- **Chapter 4** tries to solve the probability problem.

- We will also look at other selected readings (e.g. anti-realism in ch. 1).
- Reader beware: Wallace's goals are not the same as Albert's…



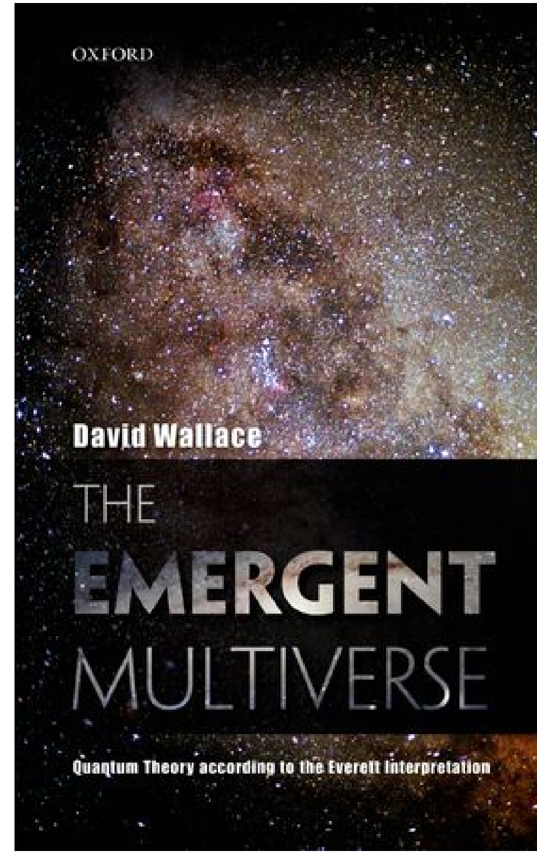
Course readings: many-worlds theory

- Lev Vaidman (physicist) Review of E.M.
  - Brit. J. Phil. Sci. 0 (2014), 1-4.
- "I appreciate the difficulty of writing a persuasive exposition of this theory. I do not think that anyone had succeeded in this before Wallace. […] However, unless the reader has an unusually strong mathematical background, he or she will have to make serious effort to see this. While Albert (1992) was afraid to scare the reader with the concept of spin and complicated his book by simulating it with colours, Wallace uses [insert jargon] and many other concepts that most physics graduates never encounter. The reader is assumed to have a significant philosophical background too, so that the book is fully accessible only to those few who, like Wallace, have doctorates in both physics and philosophy…



Course readings: many-worlds theory

- Fortunately:
- …This problem is partly solved by Wallace's clear guidance on how to read the book, advising the reader to skip technical sections. But such a reading reduces confidence. I believe that by cutting all these sophisticated parts (reducing the volume by half), Wallace could have made his book a bestseller."



- We will restrict ourselves to the 'bestseller' parts.
- For the probability problem see also the readings from Albert (2015), Greaves, Papineau and others.

Course readings: collapse theories

- Albert's (1992) chapter 5 offers an excellent description of collapse theories.
  - But his description of the tails problem is out of date!
  - His updated solution can be found in Albert (2015)

- For the tails problem our primary reading will be my:
  - Four Tails Problems for Dynamical Collapse Theories (2015).
    - Defines collapse theories (based on Albert's (1992) formalism), states the problem, and evaluates several proposed solutions (including Albert (2015)).

- For consciousness-causes-collapse we will look at my collaborative research with David Chalmers, as well as the arguments of a number of critics.

What is philosophy of physics?

And why should we study it?

What is philosophy of physics?

- Philosophy of physics is an interdisciplinary research program which:
  - Uses physics to solve problems in philosophy.
  - Uses philosophy to solve problems in physics.

Why do we need philosophy of physics?

- Philosophy needs physics
  - Philosophy sometimes generates problems that we need physics to solve…
    - Philosophy of science
    - Metaphysics
    - Philosophy of mind
- Physics needs philosophy
  - Physics sometimes generates problems that we need philosophy to solve…
    - We need philosophy to help *make sense* of quantum mechanics

Philosophy needs physics

- Branches of philosophy that most obviously depend on physics:
  - Philosophy of science
  - Metaphysics
  - Philosophy of mind

- Can you think of others?

Philosophy of science needs physics

- Philosophy of science
  - The study of explanation
    - Physics is the paradigmatic explainer of natural phenomena.
    - Disagreements in physics, over whether a theory explains some phenomenon are an object of study.
      - We will ask whether quantum mechanics explains the manifest world.
  - Realism versus anti-realism
    - Is there a mind-independent reality and can we describe it and have knowledge of it?
    - Does quantum mechanics suggest some form of anti-realism? (I will come back to this)

Metaphysics needs physics

- Metaphysics
  - Defined as: enquiry into the fundamental nature of reality
    - Physics describes reality at the most fundamental level. *Serious* metaphysics therefore cannot avoid physics.
  - Mereology, fundamentality, and intrinsicness
    - Classical atomism: fundamentally, it's all atoms in the void.
    - Many metaphysicians work under this assumption.
    - Quantum mechanics challenges it.
    - Many metaphysicians distinguish intrinsic from extrinsic properties.
    - But could QM undermine such an intuitive distinction?

Philosophy of mind needs physics

- Philosophy of mind
  - Physicalism (materialism) versus dualism
    - Why be a physicalist?
    - If physics requires the mind to play a fundamental dynamical role then the debate is settled in favour of mind-body dualism.
  - Veridicality of experience (i.e. how much is illusionary?)
    - Quantum mechanics may suggest that much of the structure we apparently see is illusionary.

Physics needs philosophy

- Why would physics need philosophy?
  - Philosophy offers methods that can help make sense of quantum mechanics.
  - Making sense of the theory is widely believed to be one of the deepest problems in modern physics...

Physics needs philosophy

- Five major problems of physics (Lee Smolin 2006)

- 1. The problem of quantum gravity.
- 2. The foundational problems of quantum mechanics.
  - Resolve the problems in the foundations of quantum mechanics, either by **making sense of the theory as it stands** or by inventing a new theory that does make sense.
- 3. The unification of particles and forces.
- 4. The tuning problem.
- 5. The problem of cosmological mysteries.

Physics needs philosophy

- 'Making sense of the theory as it stands'
  - Some believe QM makes sense if you just remove the collapse postulate
    - Many-worlds theory
  - Others deny that many-worlds theory makes sense…
    - Probability problem
  - …and believe that we instead need to make the collapse postulate more precise
    - Collapse theories
  - Others don't think that view makes sense either!
    - Tails problem
  - Who is right? How to decide?

Physics needs philosophy

- 'Making sense of the theory as it stands'

  - We need to make sense of key quantum mechanical concepts.
    - Superposition
    - Entanglement
    - Nonlocality
    - Measurement
    - Objective probability

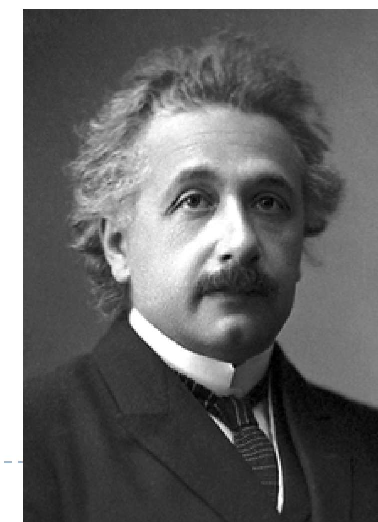
  - Once we've made sense of these concepts we can judge whether (and how) quantum mechanics needs to be supplemented.

  - Let's begin by applying some philosophy of science to the interpretation of quantum mechanics...

Anti-realism vs realism

- Making sense of quantum mechanics:

- “There is no quantum world. There is only an abstract physical description. It is wrong to think that the task of physics is to find out how nature is.”
  - Niels Bohr



- “Physics is an attempt conceptually to grasp reality as it is thought independently of its being observed.”
  - Albert Einstein

Anti-realism vs realism

- Bohr is an anti-realist
  - There is no physical reality that we can describe.
- Einstein is a realist
  - There is a physical reality that we can describe.
- Who is right?
  - Our *methodology* is to take realism about quantum mechanics as the default view and see how far we get.
  - But let's consider why philosophers of science are typically realists…

Realism versus anti-realism

- Traditional variants of antirealism:
  - Solipsisim, idealism, scepticism, positivism.
- Antirealism in the philosophy of science:
  - **Instrumentalism**: scientific theories do not describe, they merely ***predict*** experimental outcomes.
- Some have thought that QM forces instrumentalism on us:
  - "we were not led to reject a freestanding reality in the quantum world out of a predilection for positivism. We were led there because this is the overwhelming message quantum theory is trying to tell us" (Fuchs & Peres [quoted in Wallace 2012 p26].)

Wallace's four objections

- 1. Instrumentalism fails to do justice to scientific practice
  - Consider the absurdity of paleontology-instrumentalism.
  - Science also *explains*; but is that possible without description?
- 2. Makes an arbitrary division between observable/unobservable or macro/micro.
  - Aren't (observable/macro) measuring devices made of electrons? Where's the cut-off point?
- 3. Cosmology describes the universe as a whole. Can the entire universe be just a posit to help predict…?
- 4. It's not as if we can't come up with realist interpretations of quantum mechanics. The problem is that *we have too many alternatives*!
  - Instrumentalism as a "counsel of desperation".

Discussion of “Superposition”

Albert (1992: ch. 1)

Three goals of “Superposition”

- Primary goal:
  - Provide an ostensive definition ‘superposition’.
- Secondary goals:
  - Briefly illustrate the uncertainty principle.
  - Briefly illustrate the probabilistic nature of reality.

Defining theoretical terms

- Ostensive definition
  - Defines a term by pointing at features of situations where the term's referent can be detected. One then abstracts the term's meaning from these situations.
  - Chapter one uses idealised experimental set-ups to illustrate situations in which superpositions can be detected.

- Descriptive definition
  - Defines a term by reference to other (already understood) terms. (Dictionaries do this.)
  - Albert's Chapter 2 provides a descriptive definition of 'superposition' in terms of the mathematical formalism.

Ostensive definition of ‘superposition’

- Albert intends the reader to abstract the concept of superposition from examples.

- The examples are based on real world experiments.
  - The 3-box experiment.
  - The 2-path experiments.
  - The double-slit experiment.

- Albert’s description of the experiments involve substantive *idealisations*.
  - Deliberate simplification of something complicated with the objective of making it tractable.

Idealisations in science

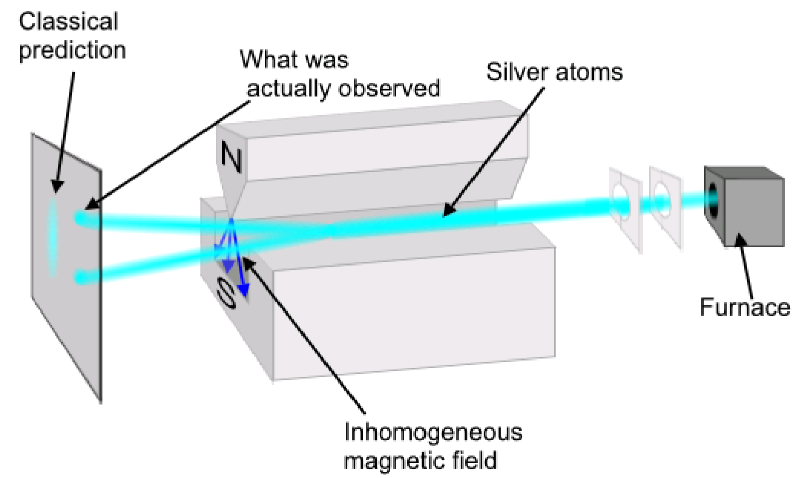
- Aristotelian idealisations
  - Strip away all properties from a concrete situation not relevant to the problem at hand.
    - **Planetary models**: planets only retain their mass and shape, every other property treated as negligible.
- Galilean idealisations
  - Introduce deliberate distortions to simplify a problem.
    - **Particle physics:** point masses moving on frictionless planes.
    - **Planetary models**: planets are ideal spheres with rotation-symmetric mass distribution.

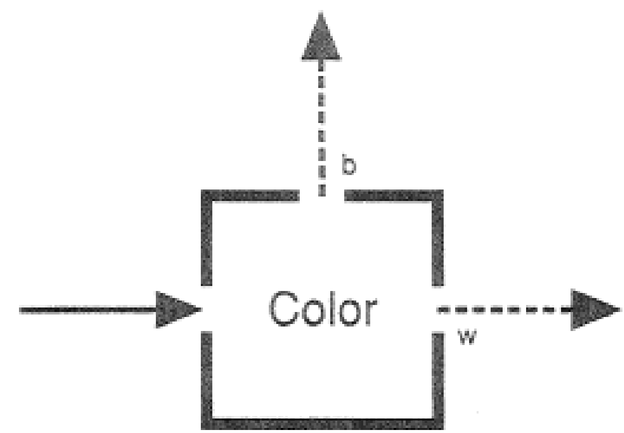
Colour and hardness idealisations

- Albert considers electrons and two types of spin that electrons can have (x-spin and y-spin).
- Albert employs (Aristotelian) idealisations and strips away all electron properties not relevant to the problem at hand (defining 'superposition' etc.).
- We are left with electrons that have positions (at times) and two binary (2-valued) physical properties.
- To emphasise that it's only the binary nature of the two properties that's important, Albert introduces arbitrary names for them: *Colour* (black vs white) and *hardness* (hard vs soft).

Colour and hardness *box* idealisations

- The Stern-Gerlach device (top right) becomes the colour box (bottom right).
- Clearly, a number of idealisations are involved.
- See Hughes (intro) for detailed discussion of the Stern-Gerlach device.



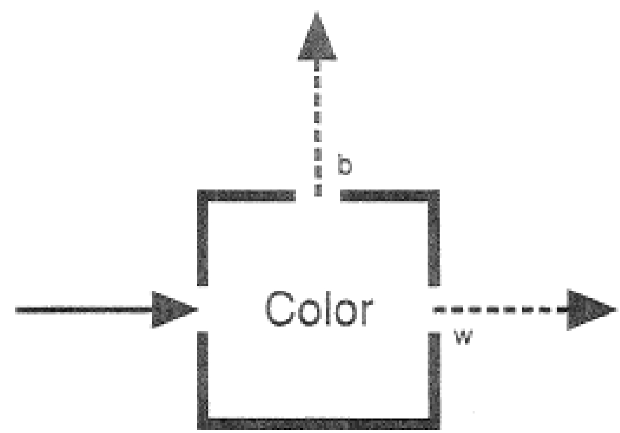


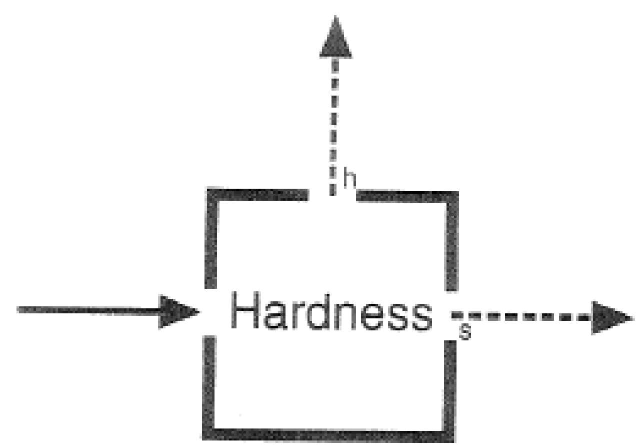
Colour and hardness

- In (idealised) quantum mechanics:
  - Electrons have two measureable physical properties called *colour* and *hardness*.
  - It is an experimental fact that the colour 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.

Colour and hardness boxes

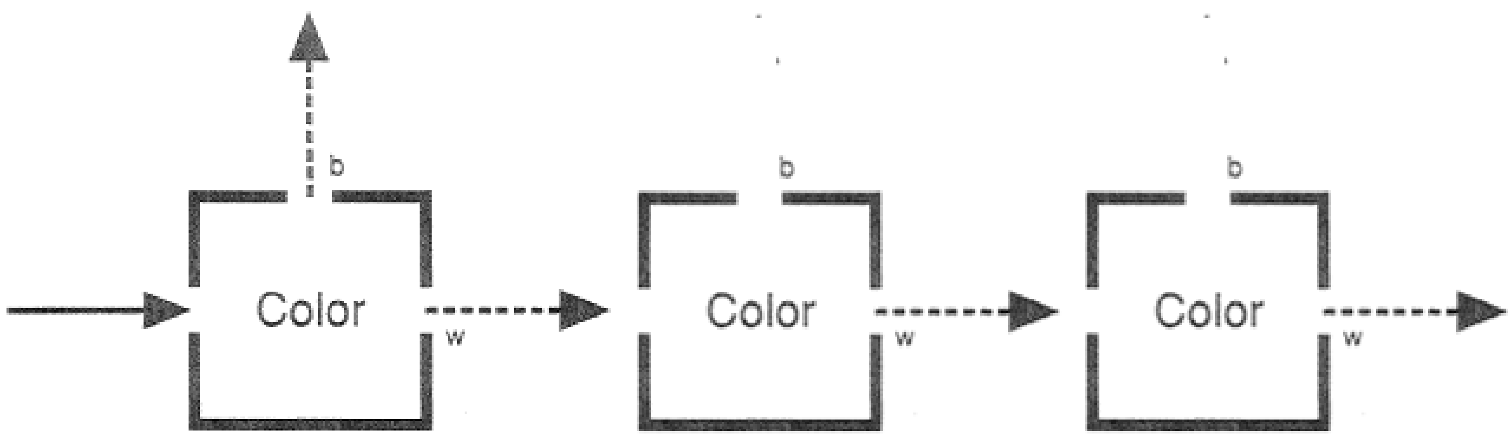
- Each box has three apertures (entry/exit points).
- We can insert electrons into the left aperture.
- The colour box sends black electrons out the top aperture and white electrons out the right aperture.
- The hardness box sends hard electrons out the top aperture and soft electrons out the right aperture.





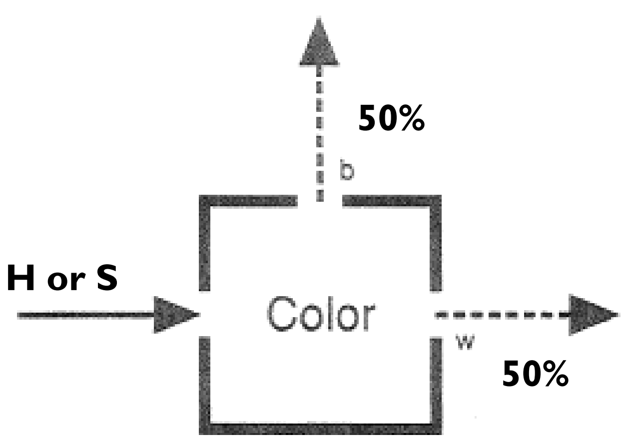
Colour and hardness boxes

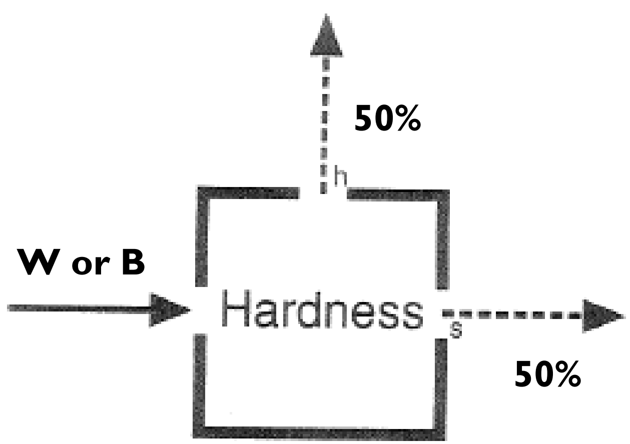
- We know that colour and hardness boxes are *reliable* because measurements with such boxes are *repeatable*.
- For example, if an electron is found to be white, then provided the electron is not subsequently tampered with, another colour measurement will yield white.



Are colour and hardness related?

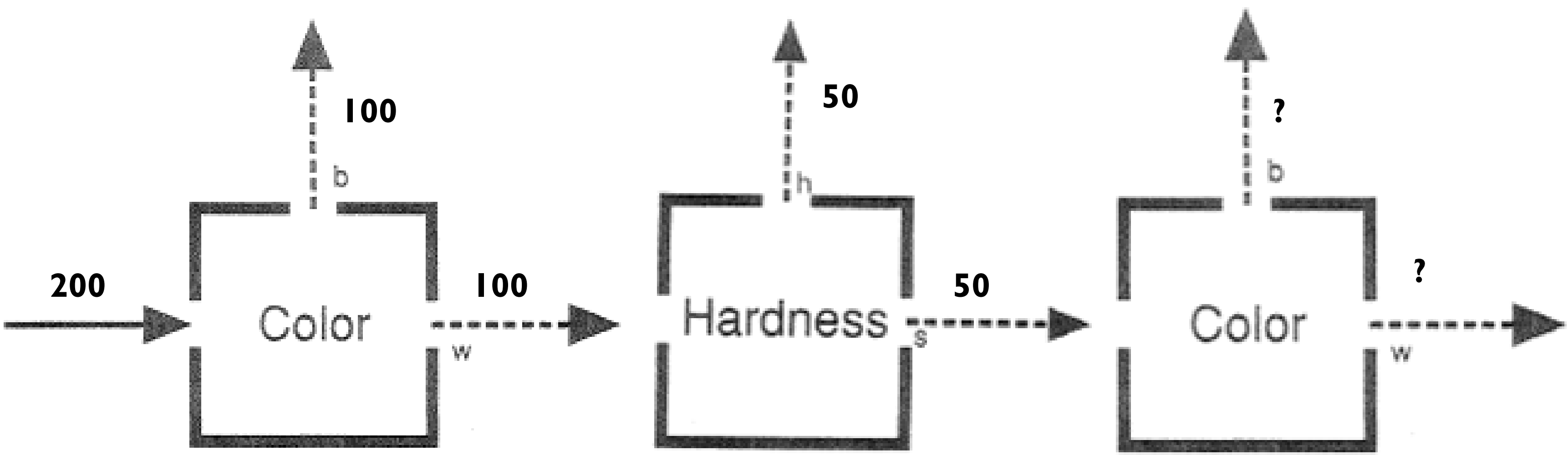
- For example, are all hard electrons black?
- Experimentation suggests no such correlation exists.
  - Of any large enough collection of, say, hard electrons, all of which are fed into a colour box, half emerge through the white aperture, half through the black aperture.
  - So colour (hardness) apparently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





The 3-box experiment

- Send a large number of electrons (say, 200) through a colour box. 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

- Expected result:
  - 50 white 0 black.
- Reason:
  - The first colour box removed the black electrons from the experiment.

The 3-box experiment

- Expected result:
  - 50 white 0 black.
- Reason:
  - The first colour box removed the black electrons from the experiment.
- Actual result:
  - 25 white 25 black.

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

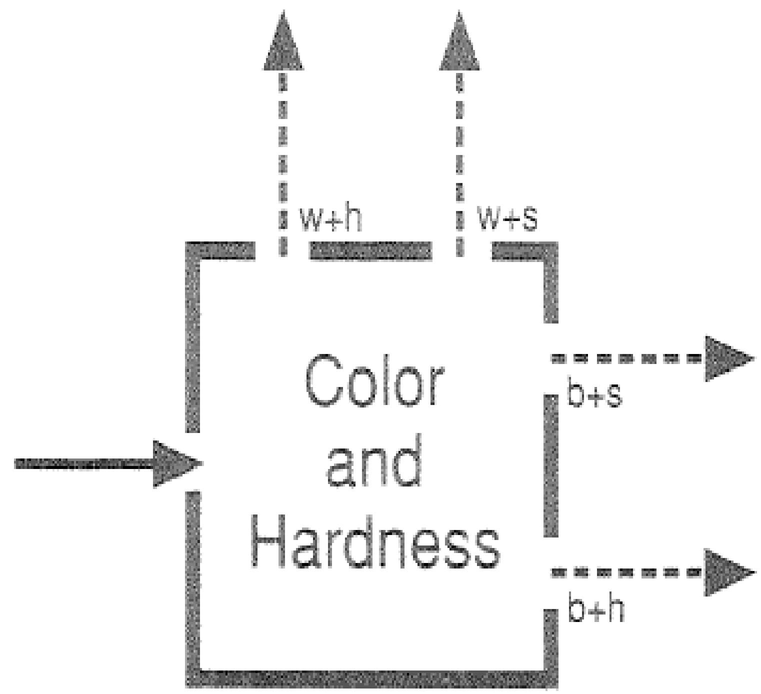
The 3-box experiment

- What 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" colour?
  - 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 colour and hardness?
- No – we can only stack colour and hardness boxes beside each other, as already seen.
- Simultaneously knowing both the colour and the hardness of an electron appears to be impossible.



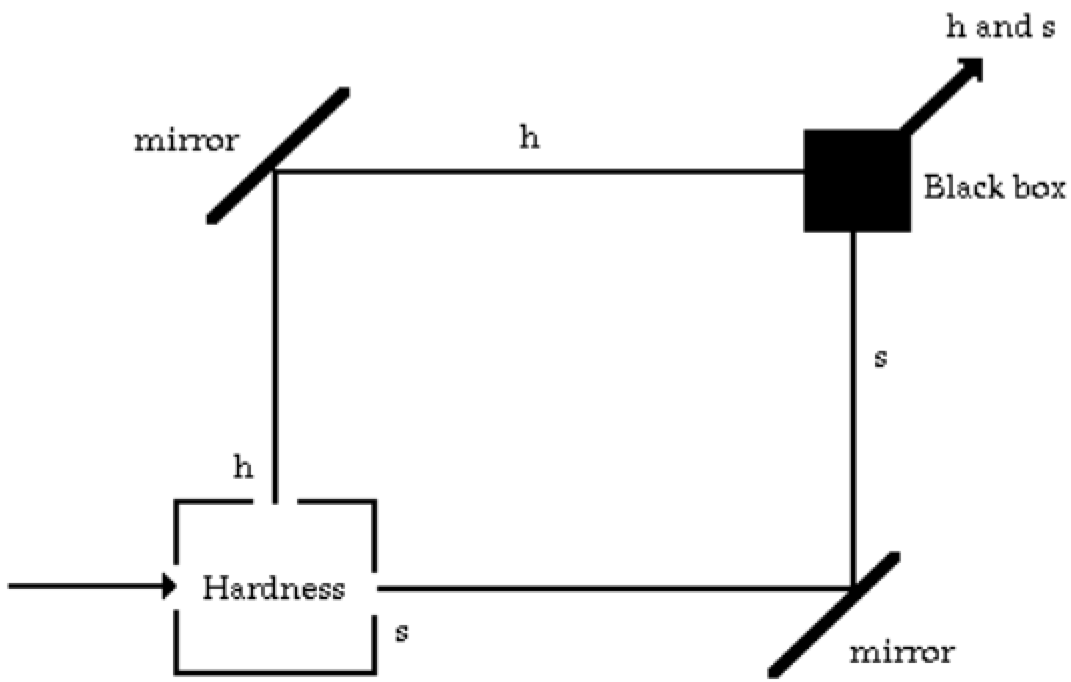
The 3-box experiment - summary

- Hardness boxes randomise the colour of electrons.
- Colour boxes randomise 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 beams of electrons into a hardness box. Hard and soft electrons are then deflected off distinct mirrors into a "black box" that recombines the electrons into a single beam.

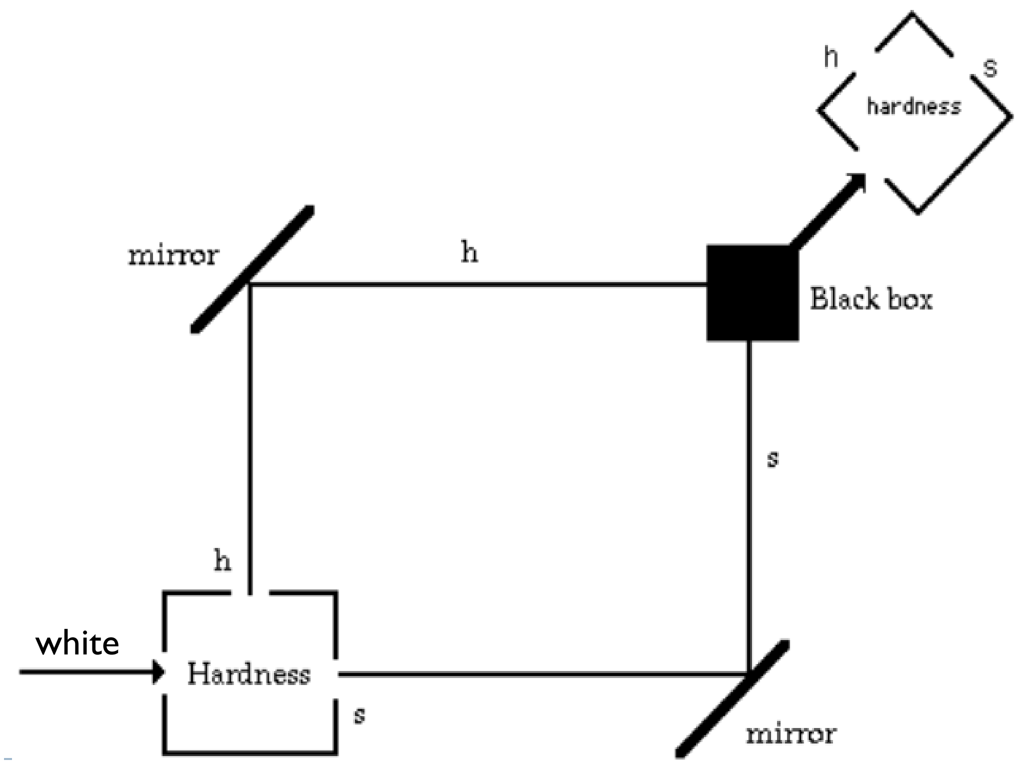


The 2-path experiments

- **2-path experiment 1:**

  Send white electrons through and then measure their hardness.

- **Expected result:**

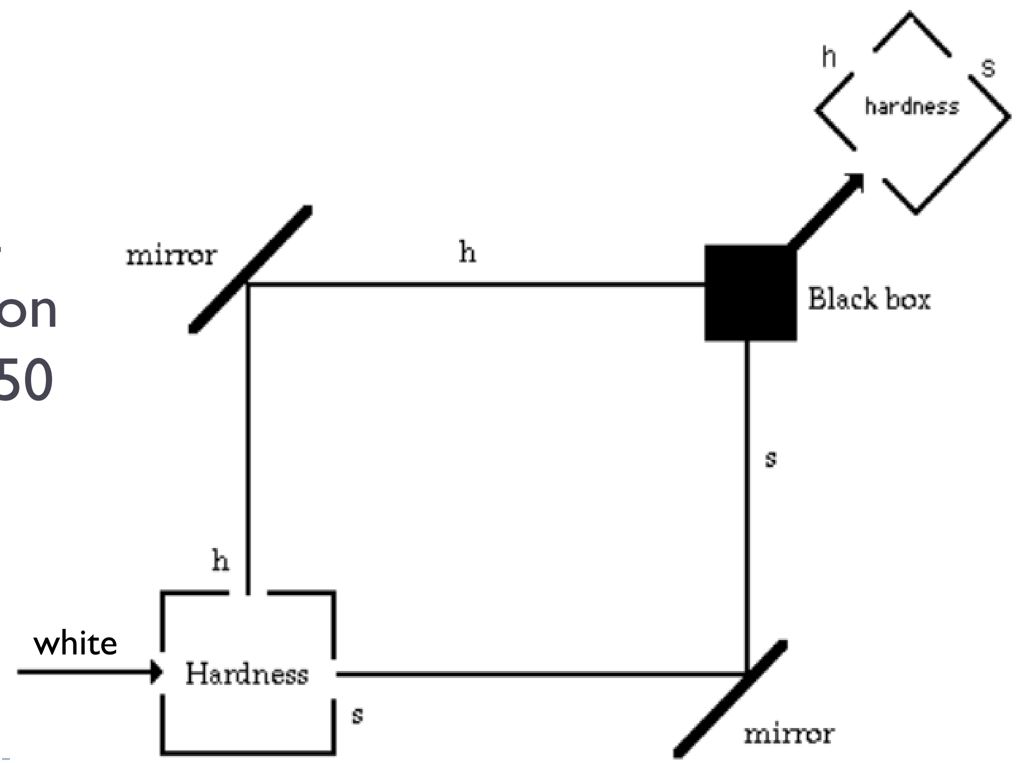


The 2-path experiments

- **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.

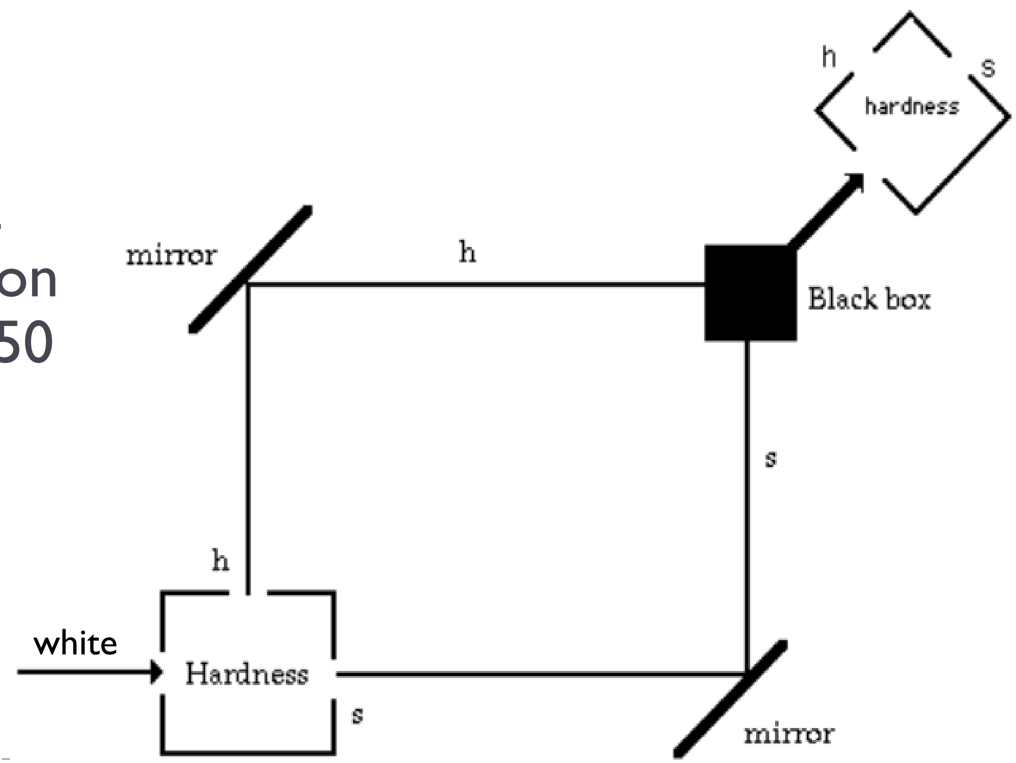


The 2-path experiments

- 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...

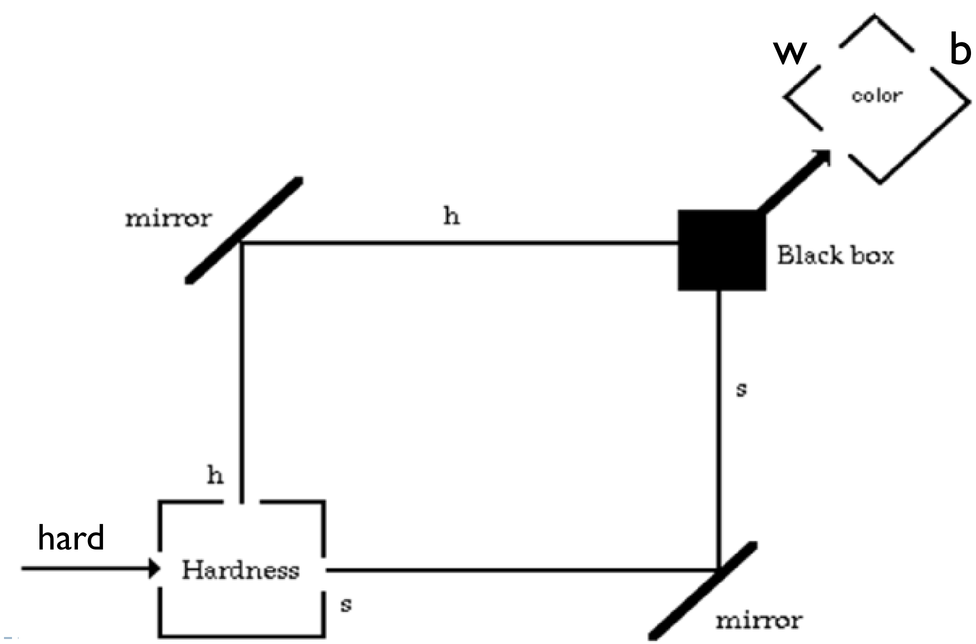


The 2-path experiments

- **2-path experiment 2:**

  Send hard electrons through and then measure their colour.

- **Expected result:**

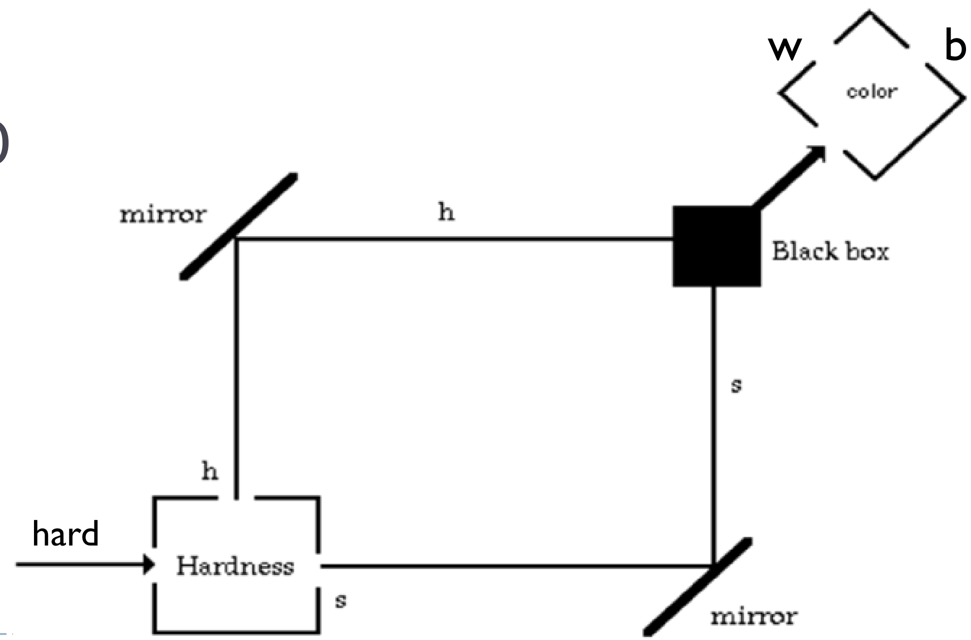


The 2-path experiments

- 2-path experiment 2:

  Send hard electrons through and then measure their colour.

- Expected result:
  - 50% white 50% black.
  - Reason: we've learnt that colour measurements on hard electrons yield 50/50 results.

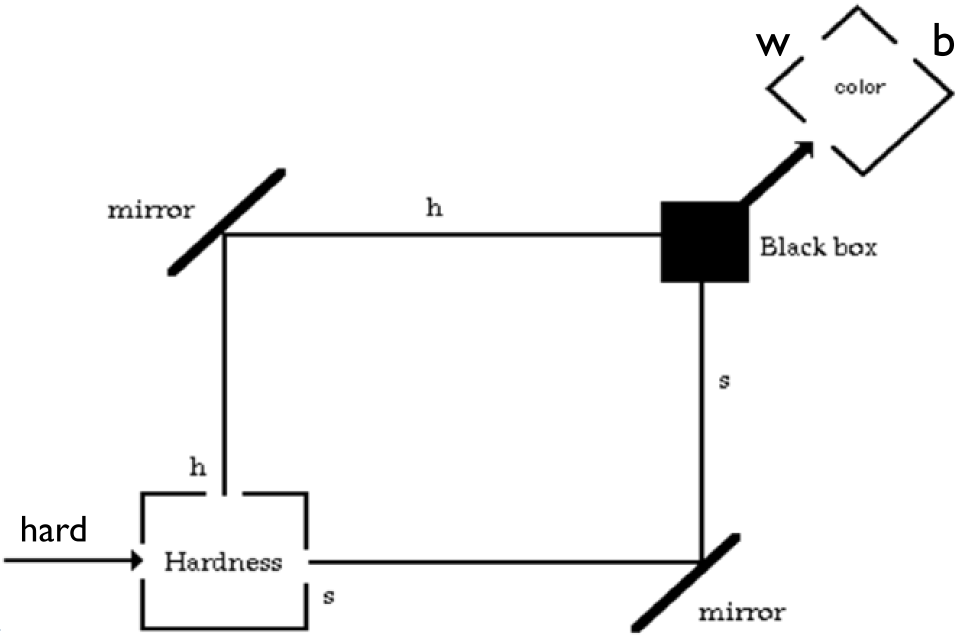


The 2-path experiments

- 2-path experiment 2:

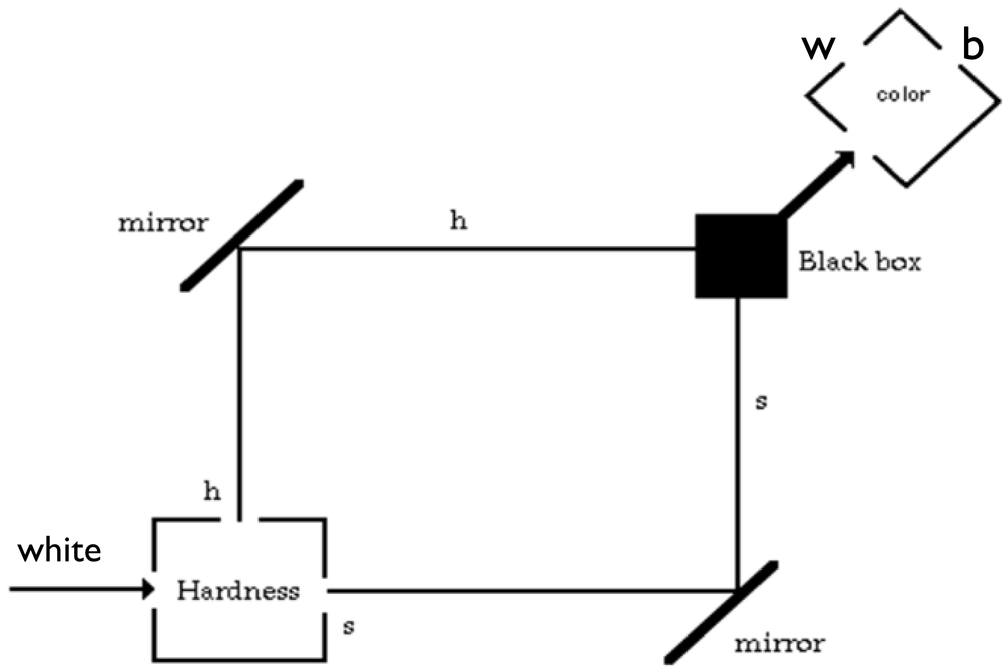
  Send hard electrons through and then measure their colour.

- Expected result:
  - 50% white 50% black.
  - Reason: we've learnt that colour 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 colour.
- **Expected result:**

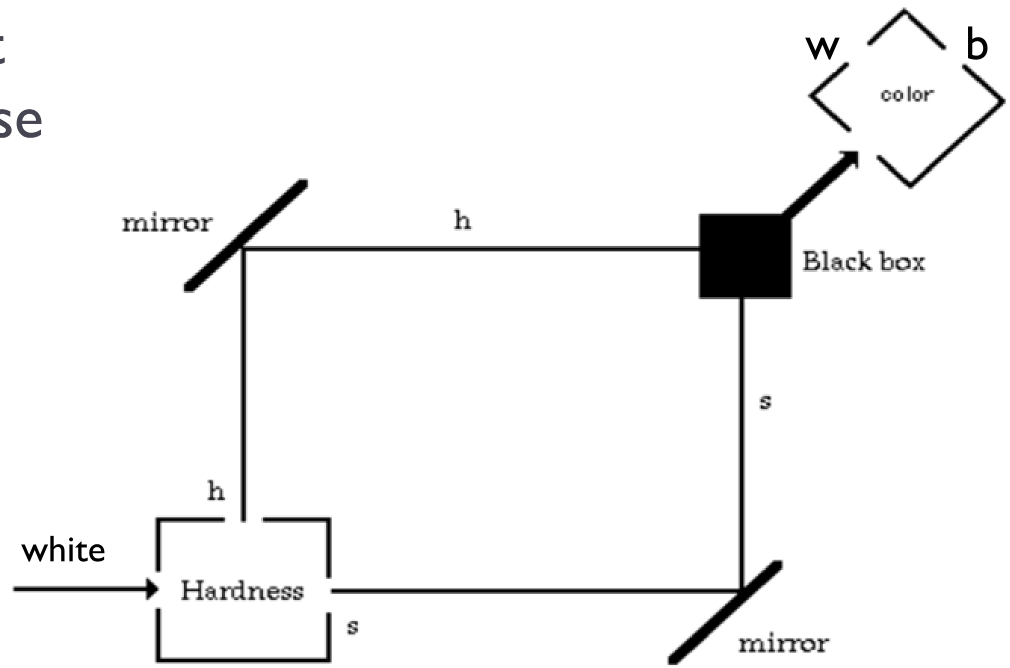


The 2-path experiments

- **2-path experiment 3:**

  Send white electrons through and then measure their colour.

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

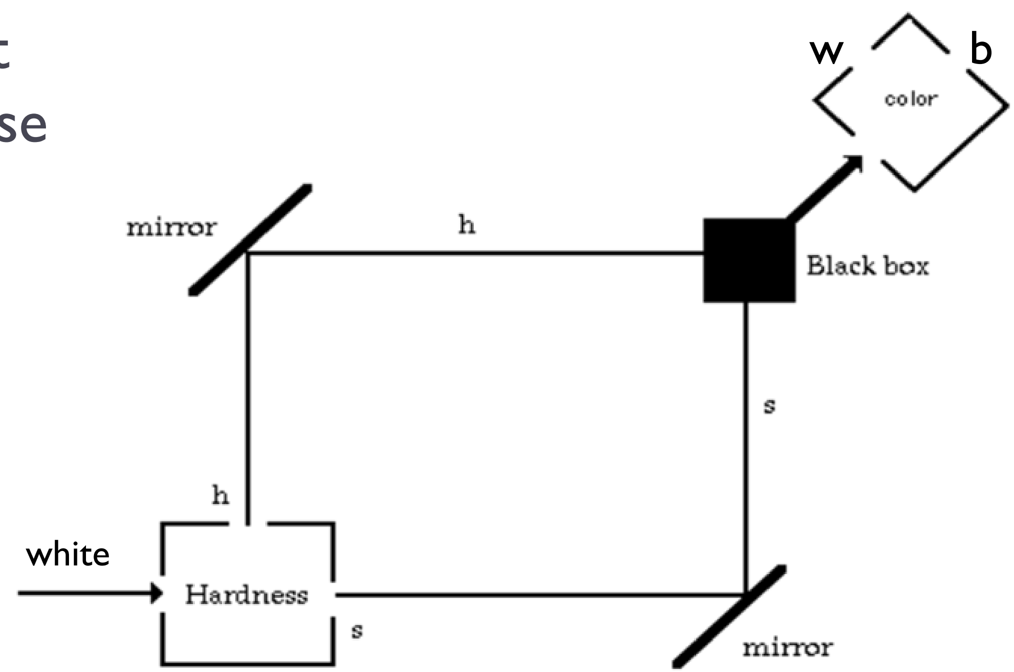


The 2-path experiments

- 2-path experiment 3:

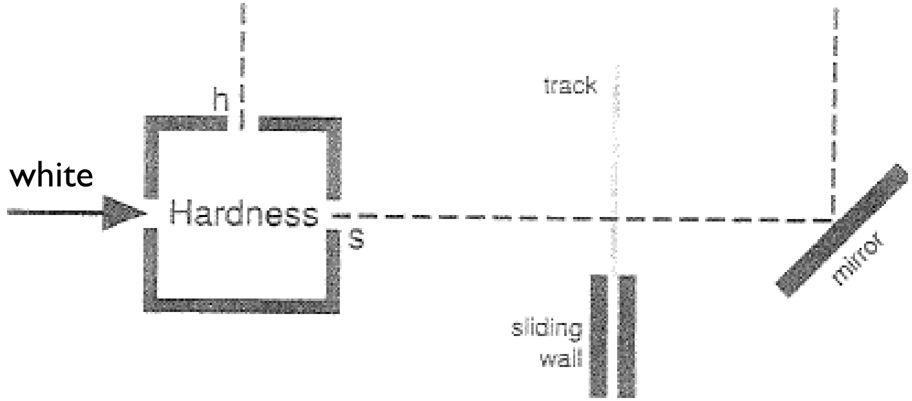
  Send white electrons through and then measure their colour.

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



The 2-path experiments

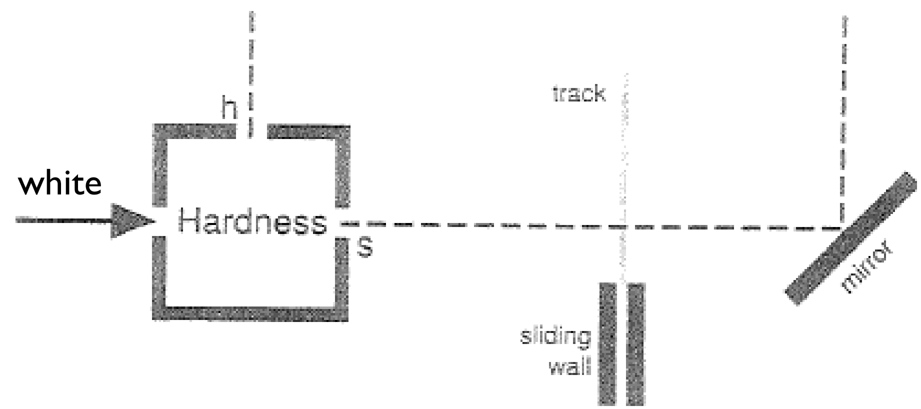
- 2-path experiment 4:
  - Repeat experiment 3 (i.e. send white electrons through and then measure their colour) but insert a stopping wall on the s-path.
- Expected result:



The 2-path experiments

- 2-path experiment 4:
  - Repeat experiment 3 (i.e. send white electrons through and then measure their colour) 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?



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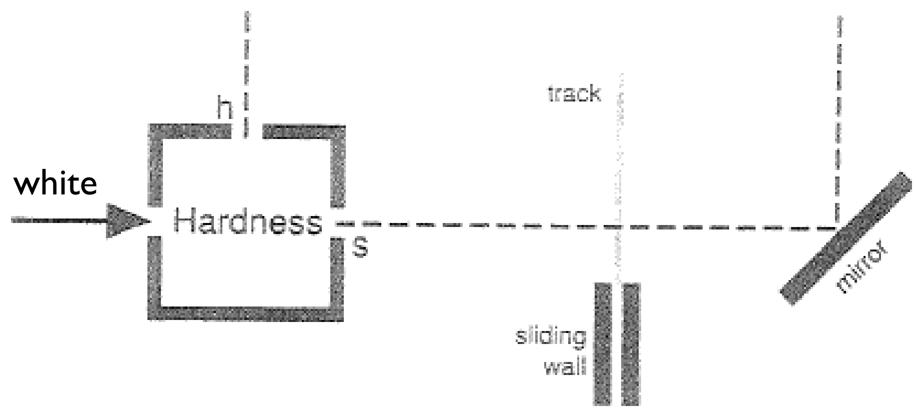
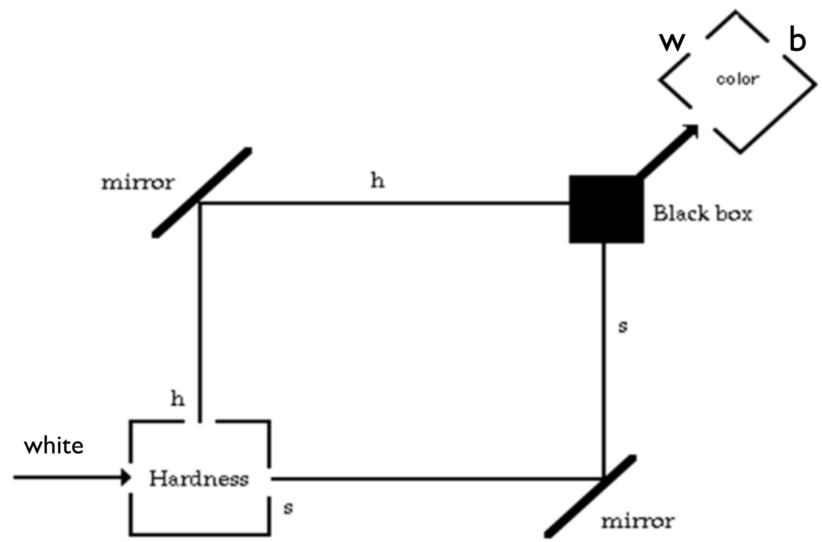
  - Reason: same experiment as 3, but we are blocking half the electrons?
- Actual result:
  - 50% less electrons, 50% white, 50% black.
  - What is going on!?



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.



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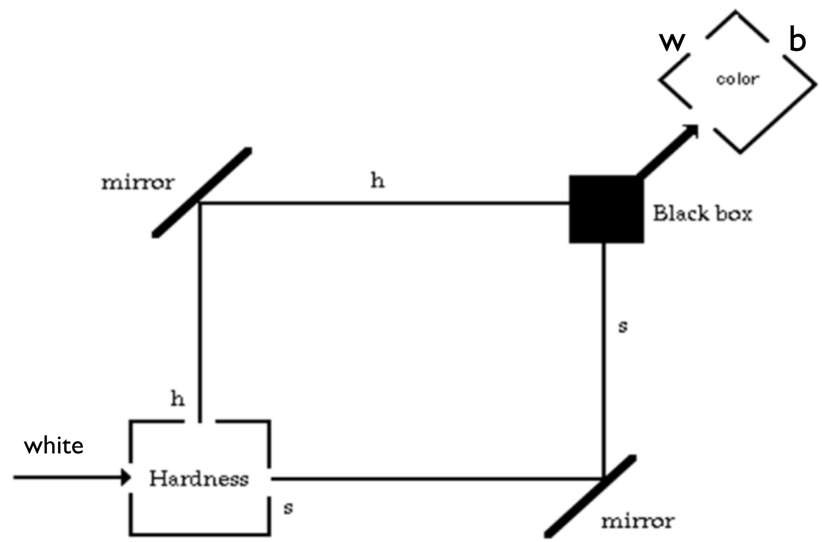

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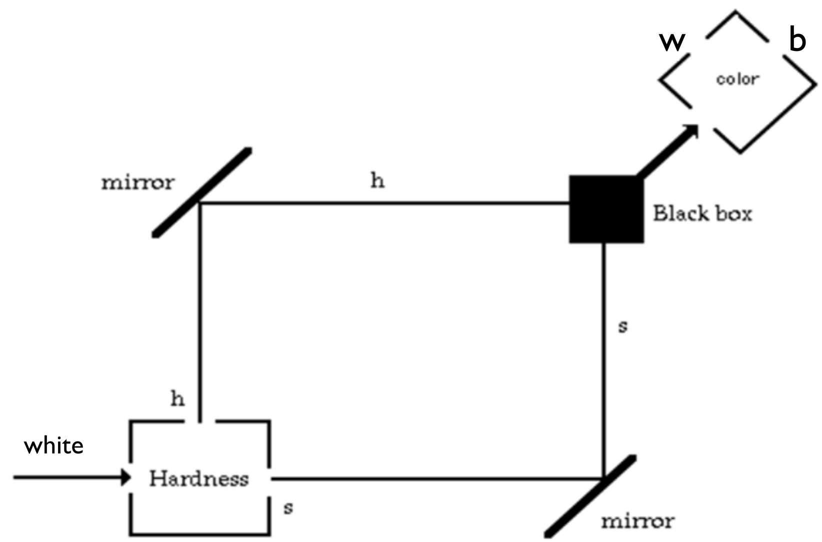

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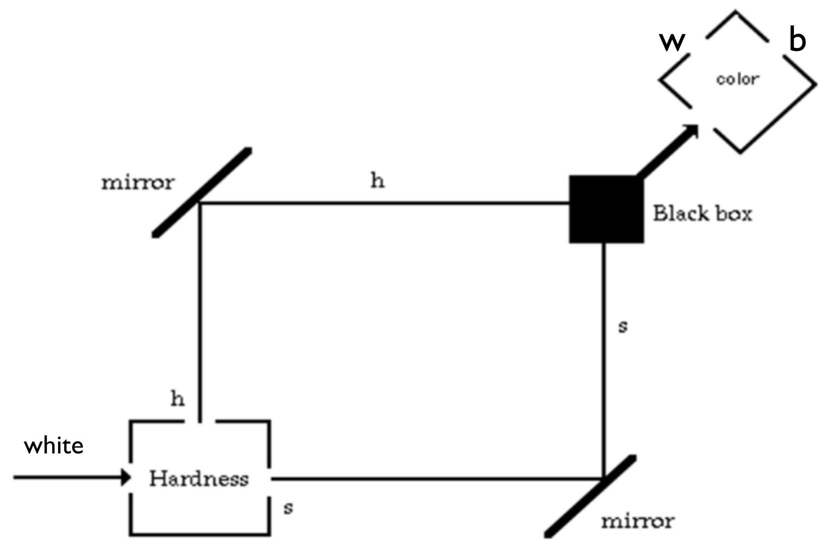
  - Neither path?
    - No: if we wall up both paths nothing gets through.



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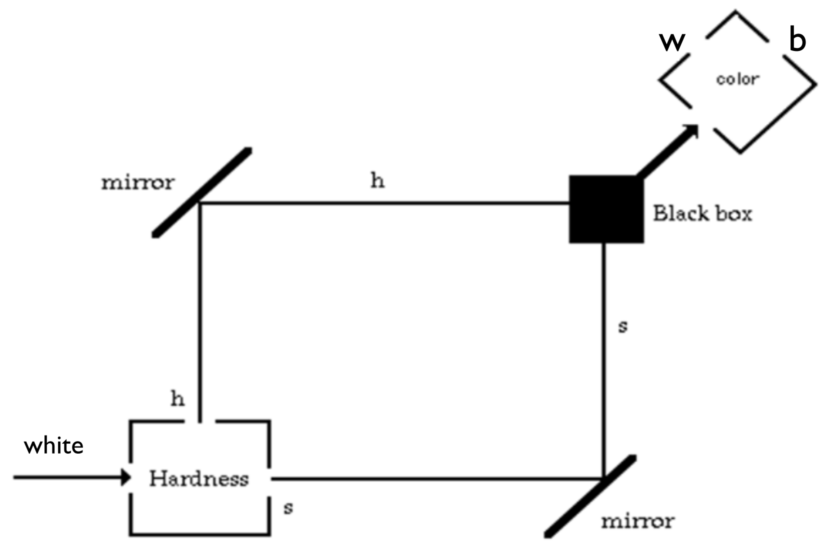
    - No: when we measure which path they are on we always get a definite result.
  - Neither path?
    - No: if we wall up both paths nothing gets through.
- This defies all pre-quantum conceptual resources. We need new concepts to describe what is happening.



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.)

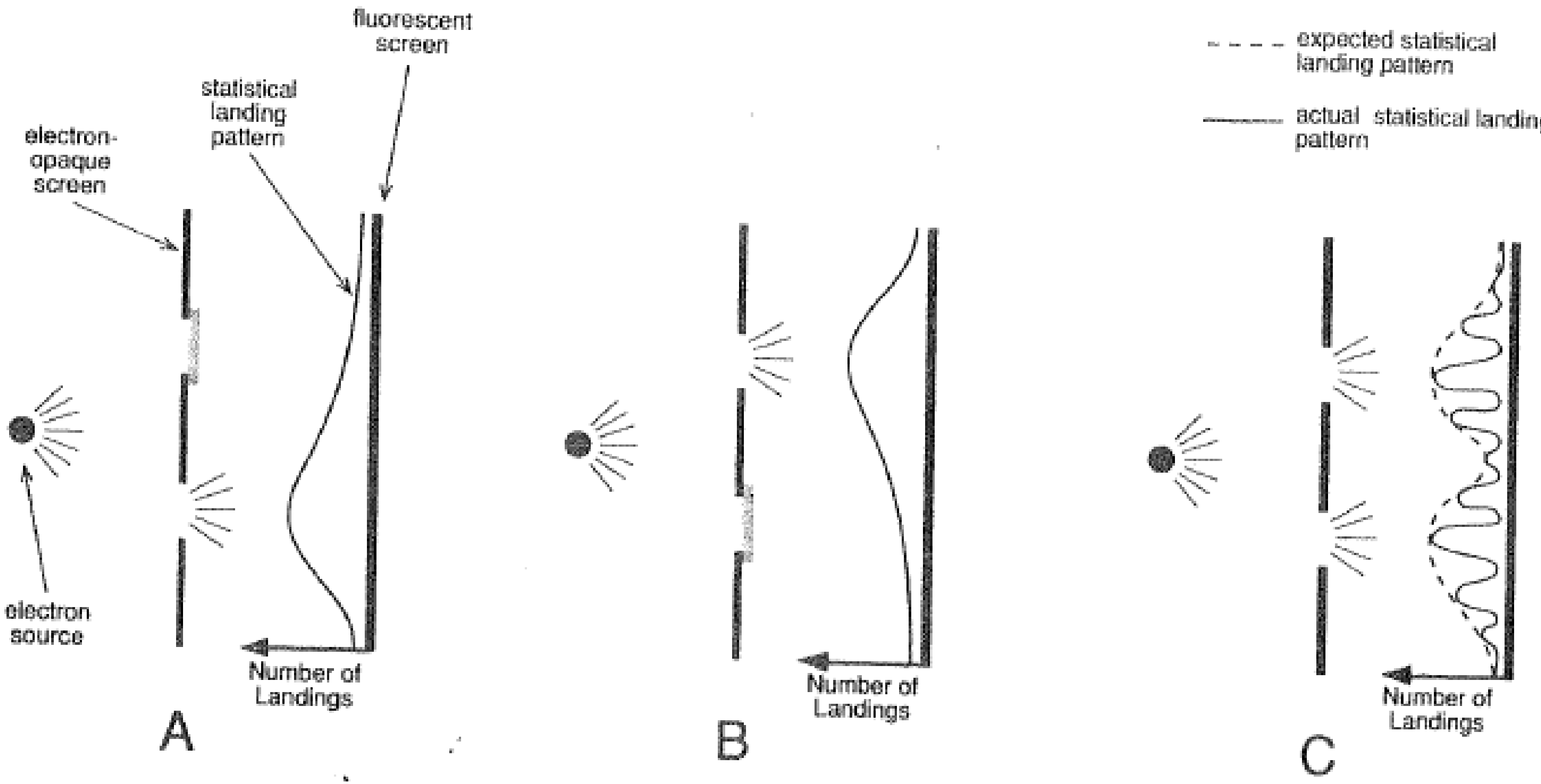
- The electron is in a superposition of going down both the h-path and the s-path.
- The electron is therefore in a superposition of being both hard and soft.

- 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
      - Although in doing so, we get an A/B type of pattern).
  - Neither slit?
    - No: when we block both slits we get not landing pattern.
- The electrons are each in a superposition of going through both slits.

- For an animated presentation see:
  - http://www.youtube.com/watch?v=DfPeprQ7oGc

Superposition - recap

- We've seen several examples of superposition states.
  - In the situations where we cannot say that the particle is going though slit one or slit two nor both nor neither, we say that the particle is in a superposition of going through both.
  - In the situations where we cannot say that the particle is hard or soft nor both nor neither, we say that the particle is 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.

Uncertainty principle

- We noted earlier that we cannot simultaneously measure colour and hardness (slide 55).
- 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 colour and hardness of an electron simultaneously.
  - So "uncertainty principle" is an unfortunate label.
- Having a definite colour entails not having a definite hardness.
  - So "incompatibility principle" would be more accurate.
  - Others call it the "indeterminacy principal".

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 descriptive 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.