An Unsettling Story

Heres an unsettling story about something that can happen to electrons
(One of the most unsettling stories in the history of science)

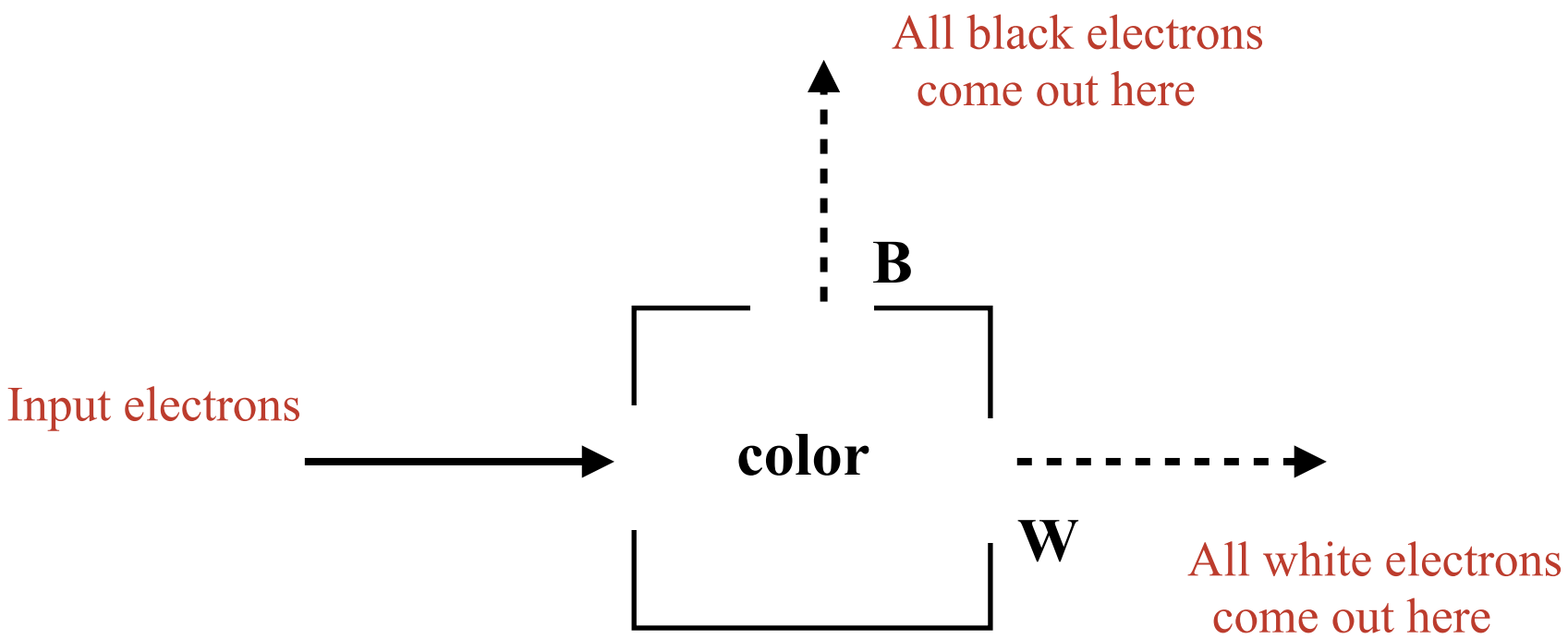
Concerns two particular physical properties of electrons which we can measure with great accuracy. *(Details not important for the moment)*

Lets call them: **color** and **hardness**

Turns out:
- color of an electron can only be one of two values:
  Black (B) or White (W)
- electron hardness can only either be
  Hard (H) or Soft (S)

Measuring Color

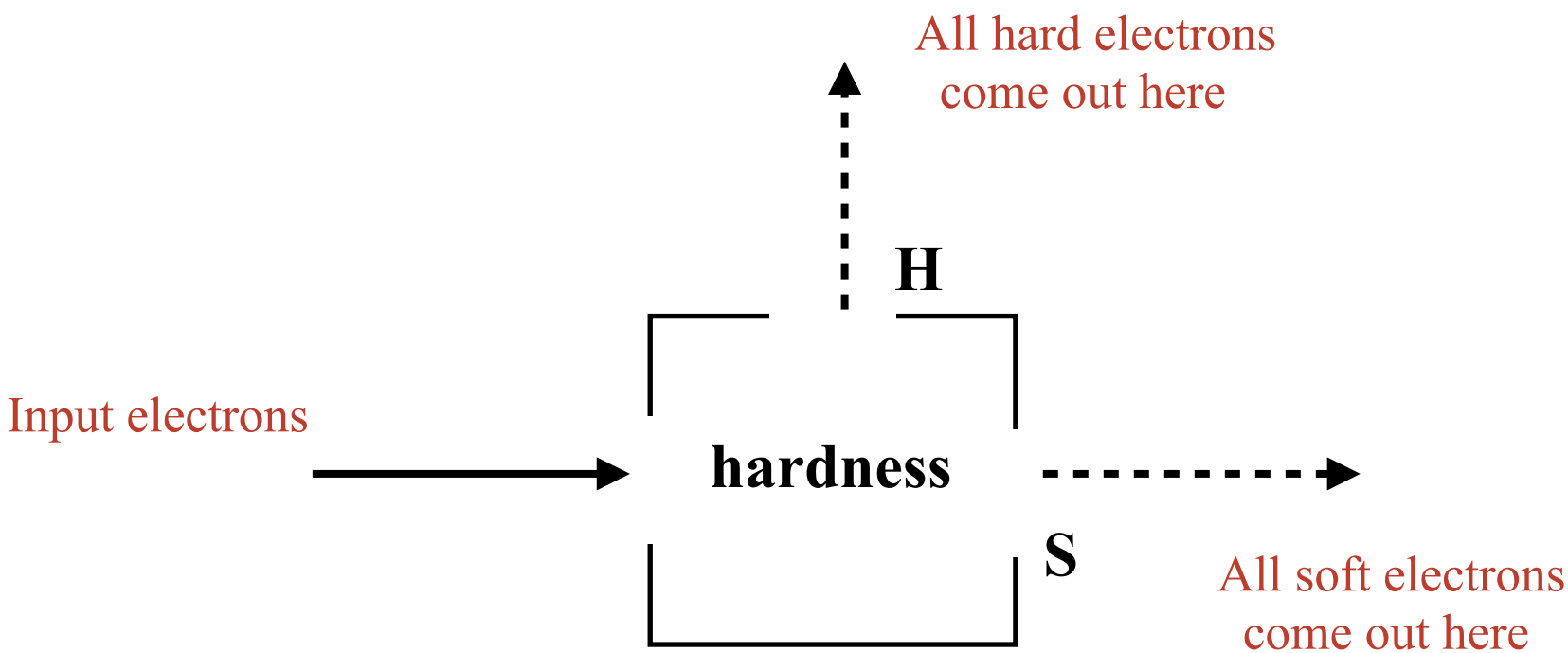
Can build measuring device: “color box”



Can measure the color of an input electron by seeing where it comes out

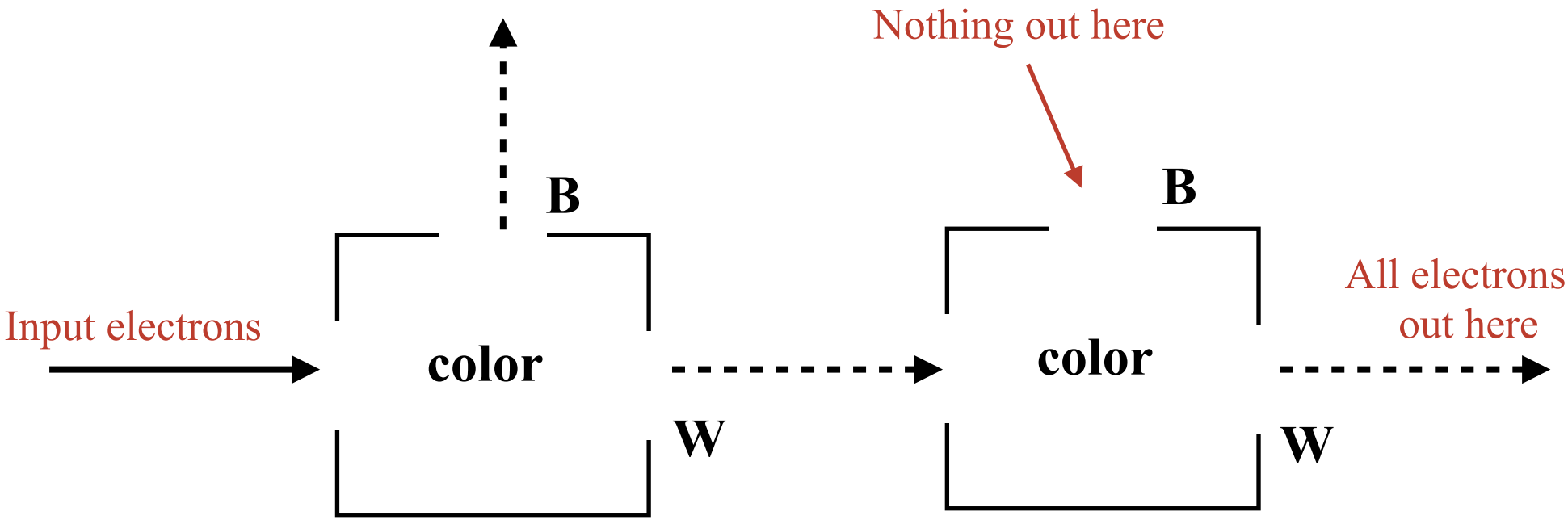
Measuring Hardness

Can build measuring device: “hardness box”



Can measure the hardness of an input electron by seeing where it comes out

Color/Hardness "good" physical variables



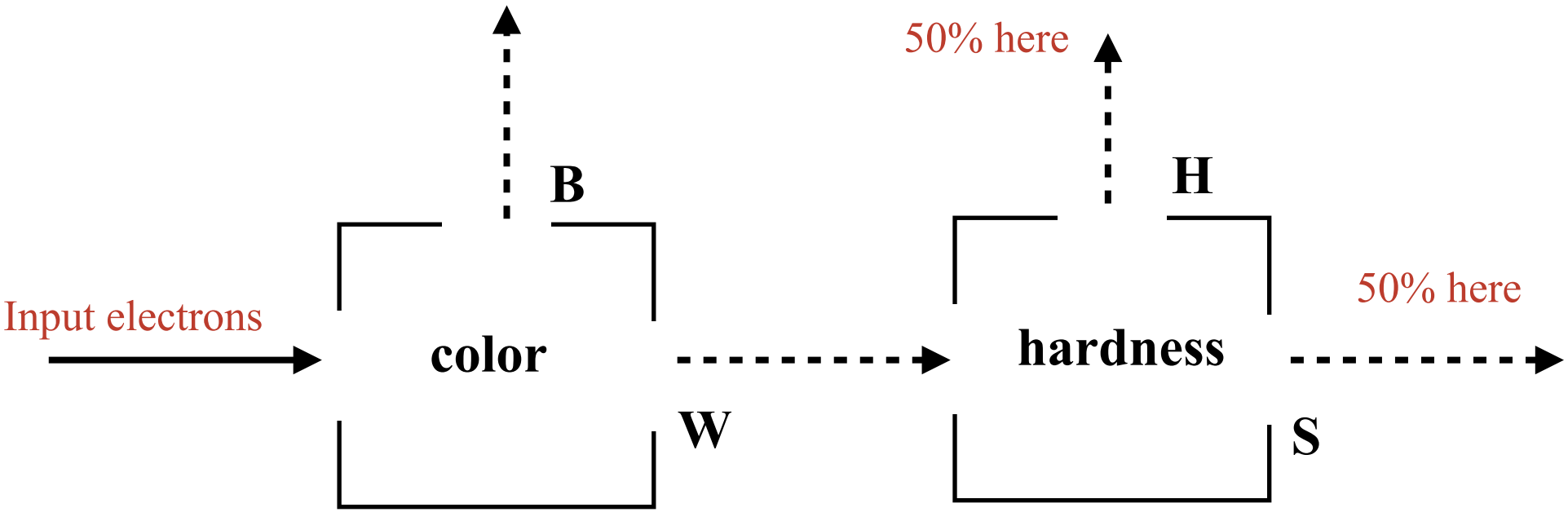
Measurements are repeatable.
Same when:

- selecting **B** w/color box then measuring color
- selecting **H** w/hardness box them measuring hardness
- selecting **S** w/hardness box them measuring hardness

Color/Hardness Correlations

Are color and hardness somehow related?

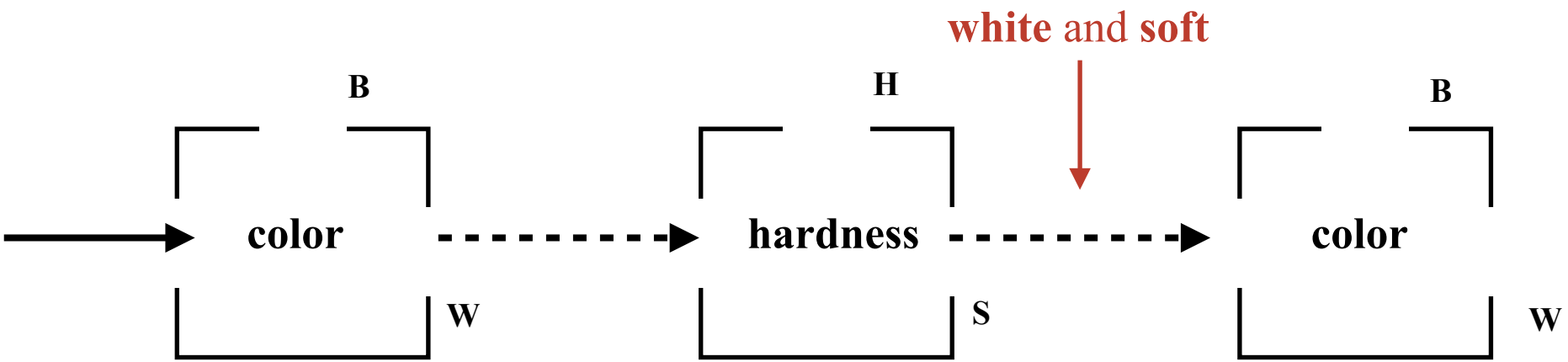
Easy to check for correlations using our boxes.



We find no correlations exist.

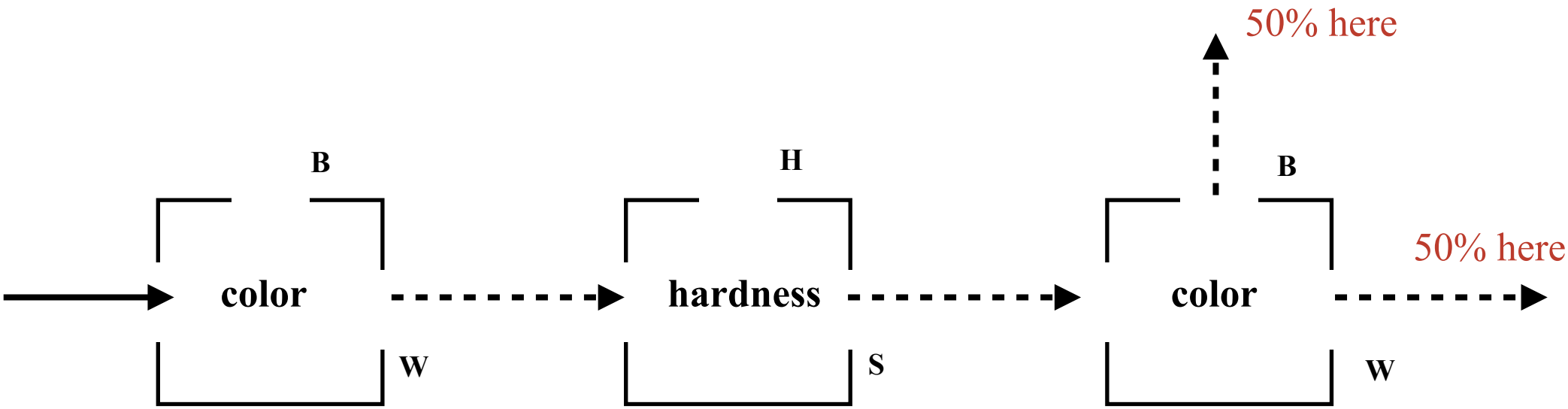
- 50% of **white** electrons measured to be **hard**, 50% measured to be **soft.**
- Same with **black** electrons.
- 50% of **hard** electrons measured to be **white**, 50% measured to be **black.**
- Same with **soft** electrons.

Consider Three Boxes



Expect only **white** electrons to come out of the last color box…

Consider Three Boxes



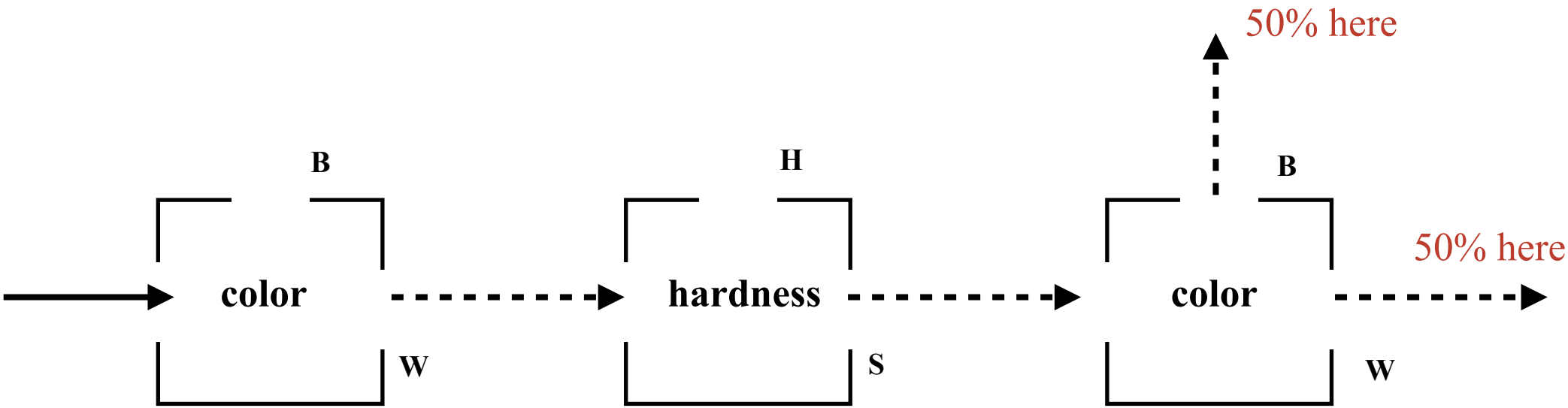
Expect only **white** electrons to come out of the last color box…not whats observed.

- Precisely 50% **black** and 50% **white**
- Same for any other color/hardness pair.
- Same if we measure hardness, color, then hardness

Hardness measurement, apparently, disturbs the color property.

eg: w/o the hardness box, 100% of electrons would come out **white** on the right

Consider Three Boxes



Maybe the hardness box is crudely built.

Two questions about the hardness box:

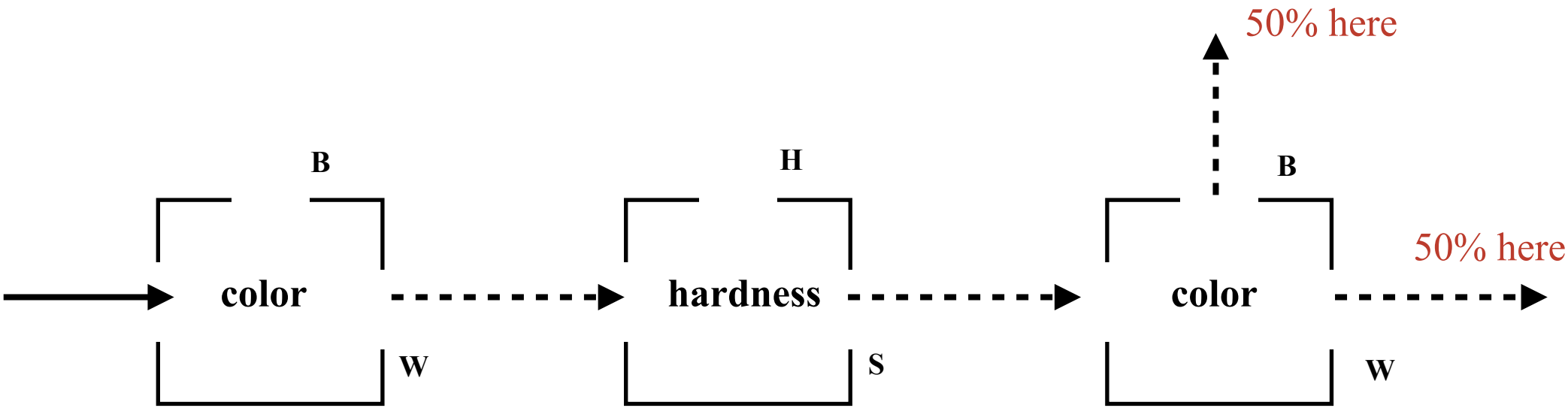
- What determines which electrons have their colors changed and which don't ?

  Cannot find any correlations between electron input properties and which color whey are measured. As far as we know, no answer.

- Can we build hardness box with out disturbing color ?

  Can build hardness boxes many different ways, all produce the same statistics. Always exactly 50/50, unable to change in anyway

Consider Three Boxes



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d and which don't ?

Example of *Uncertainty Principle*

- color and hardness said to be "incompatible"
- measuring one will always disrupt the other
- cannot say: "color is X and hardness Y"

operties and

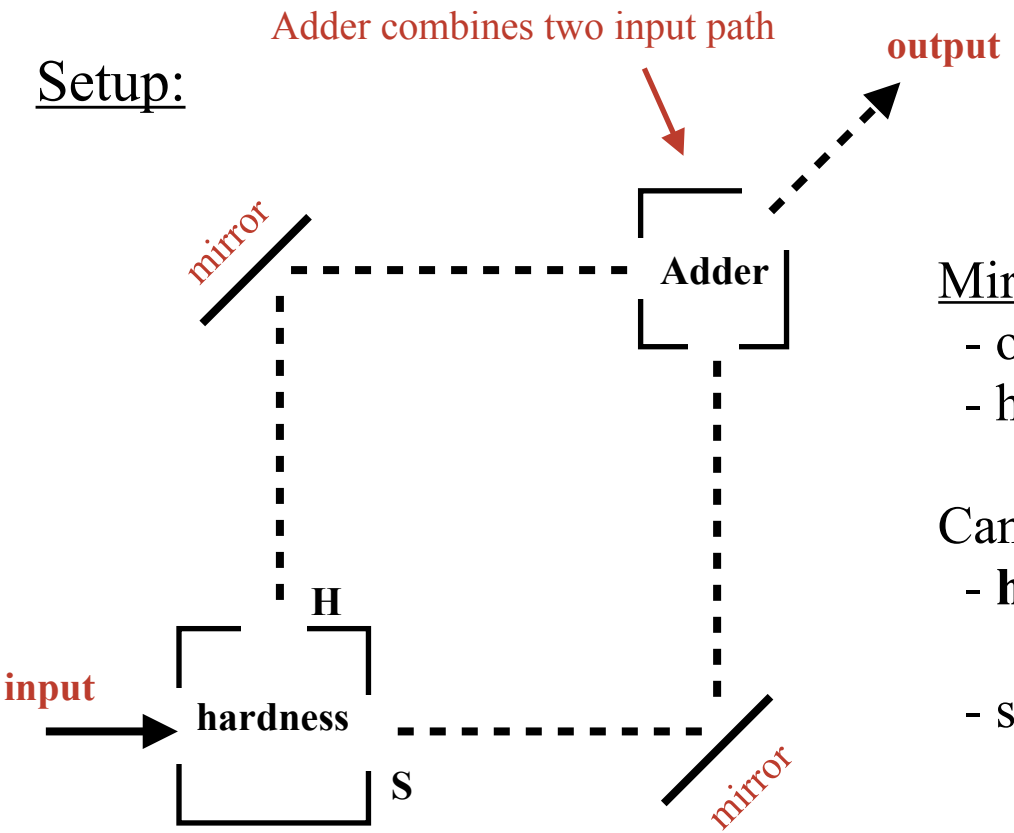
no answer.

uce the same statistics.

Always exactly 50/50, unable to change in anyway

Combining Outputs

Setup:



Mirrors and the adder box:

- only change electron direction of motion.
- hardness/color unaffected

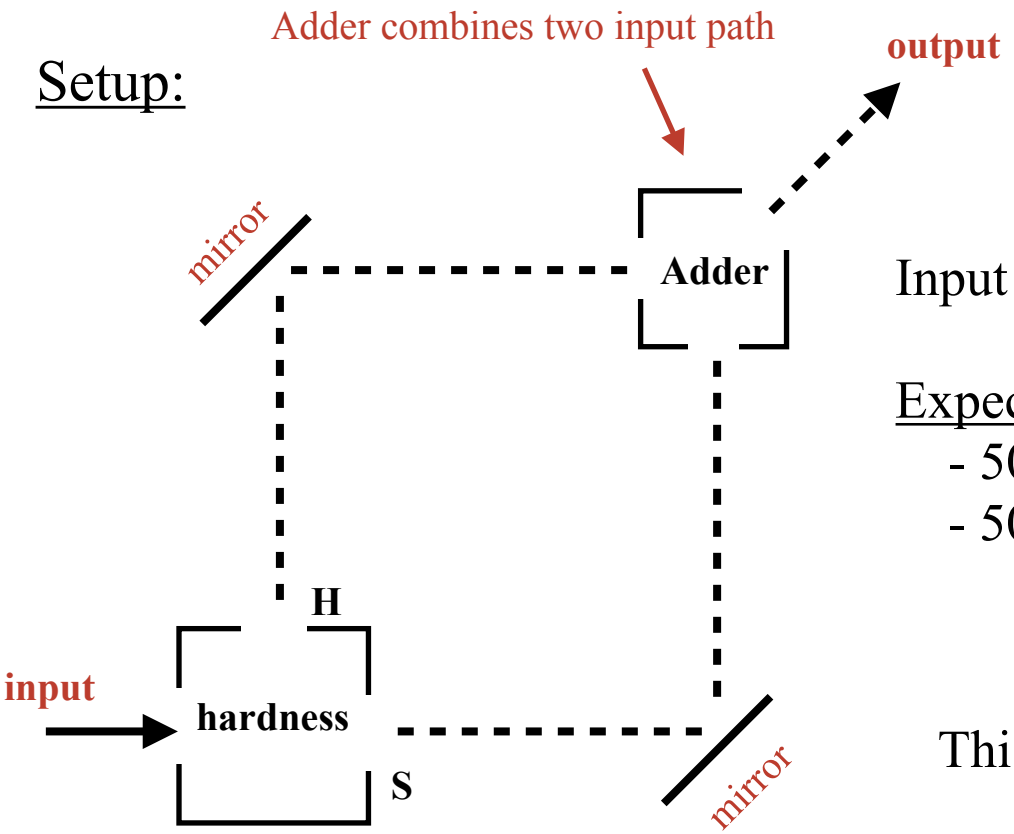
Can confirm this explicitly:

- **hard** input electrons take upper path and are always measured **hard** at output
- same with **soft** electrons on lower path

Lets do some experiments…

Combining Outputs

Setup:



Input a **white** electron, measure output hardness

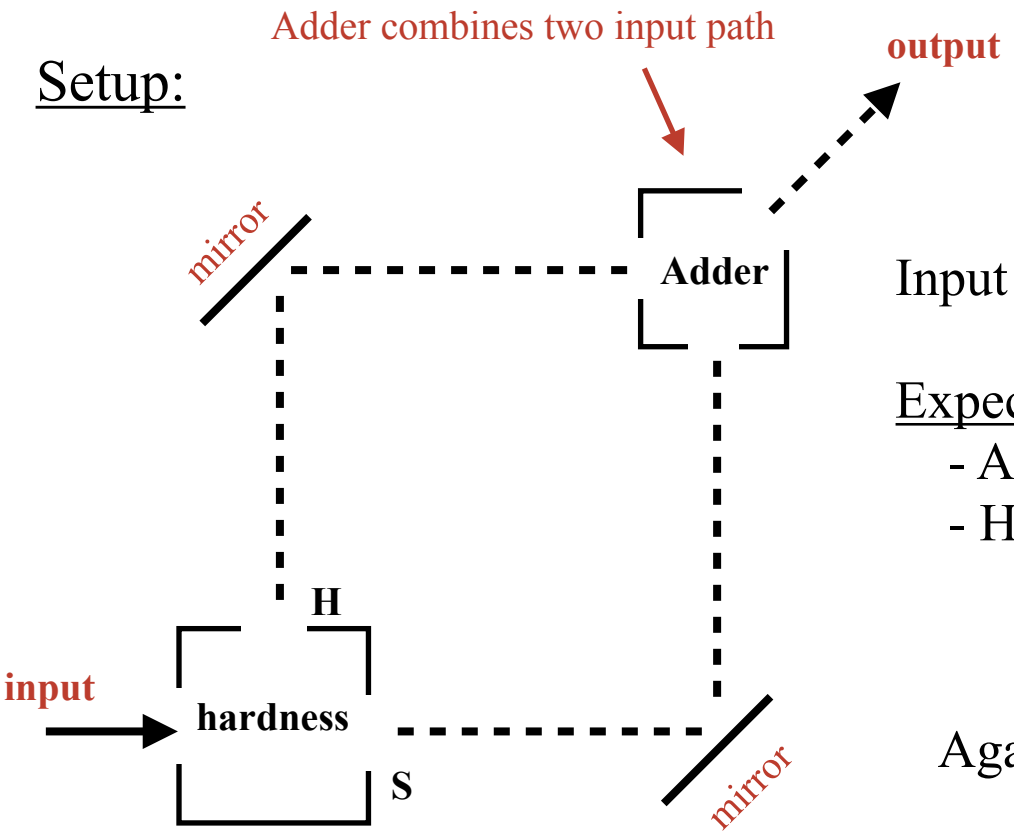
Expect: output to be 50% **hard** / 50% **soft**

- 50% **white** e's are **hard**, take upper path
- 50% **white** e's are **soft**, take lower path

This is exactly what we find.

Combining Outputs

Setup:



Input a **hard** electron, measure output color

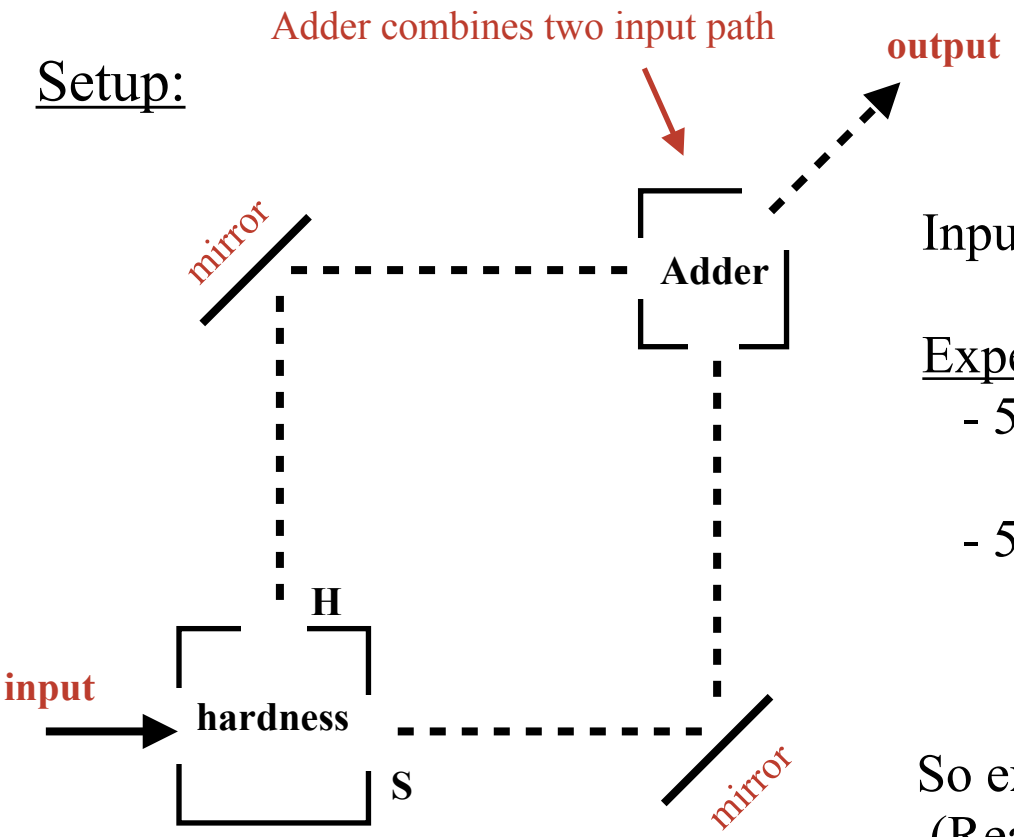
Expect: output to be 50% **white** / 50% **black**
- All **hard** e's take upper path
- Hard e's 50% **white** and 50% **black**

Again, exactly what we find.

Now the surprise…

Combining Outputs

Setup:



Input a **white** electron, measure output color

Expect:

- 50% **white** e's are **hard**, take upper path
  of these, expect 50/50 **white** and **black**
- 50% **white** e's are **soft**, take lower path
  of these, expect 50/50 **white** and **black**

So expect output to be 50% **white** / 50% **black**
(Reasonable, really just hardness box with mirrors)

Combining Outputs

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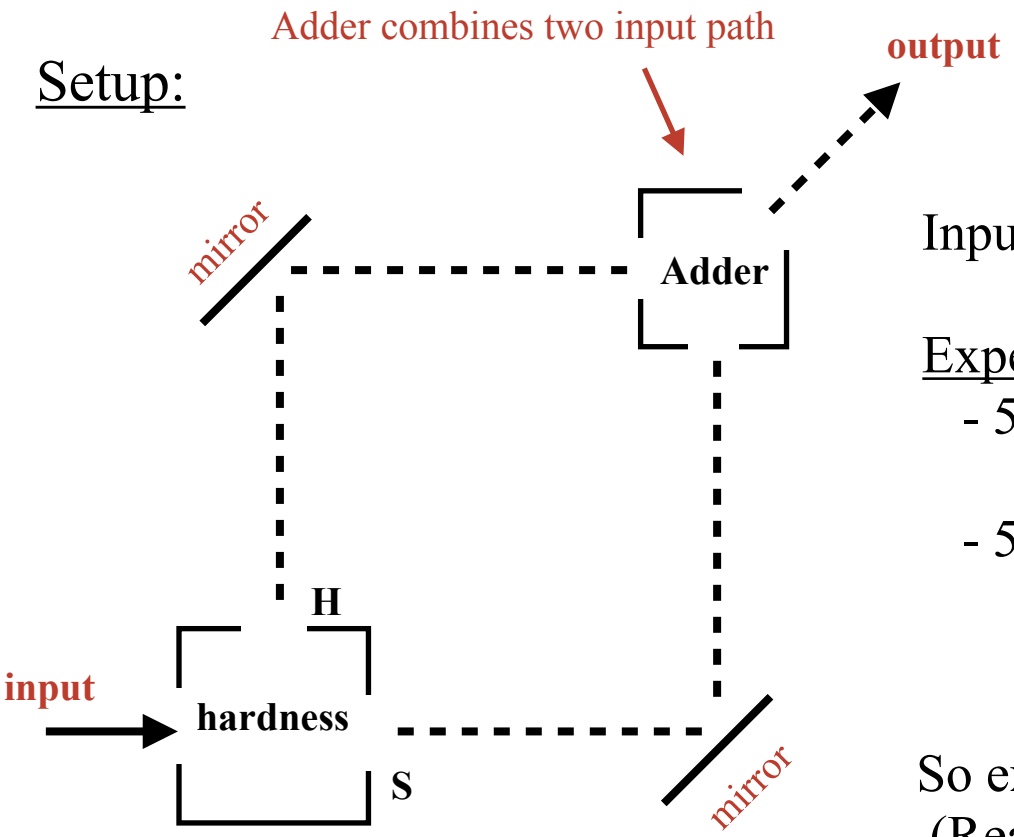

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Expect:

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- 50% **white** e's are **soft**, take lower path
  of these, expect 50/50 **white** and **black**

So expect output to be 50% **white** / 50% **black**
(Reasonable, really just hardness box with mirrors)

However, observe 100% of the output electrons are white !

Odd, hard to imagine what can be going on…

Combining Outputs

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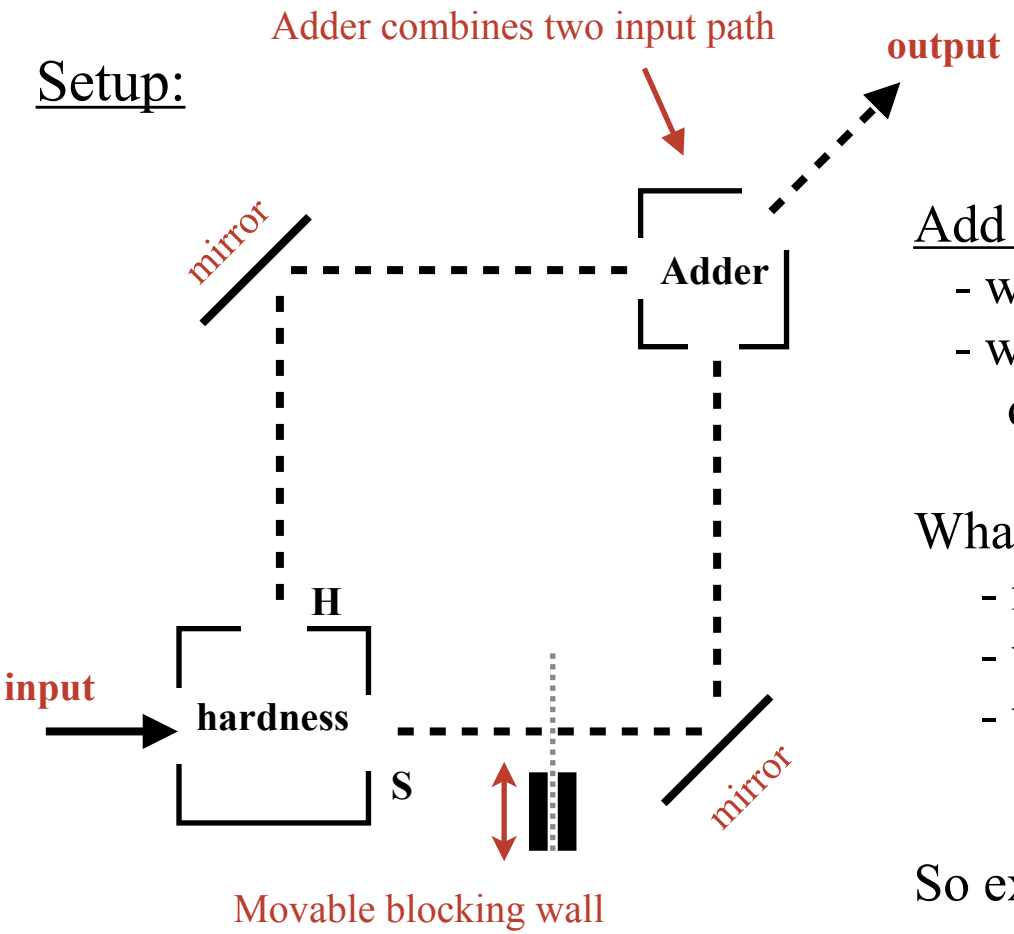

Add sliding wall to stop electrons on lower path.

- when wall is out, same as previous experiment
- when wall in, electrons along **S** get stopped, only those moving along **H** output

What do we expect when wall is in?

- number of output electrons drop by 50%
- when wall is out 100% **white**
- wall on S has no effect on electrons on H

So expect less out output, but 100% **white**

Observe: Total output reduced by 50 %, but not all white !
1/2 black and 1/2 white.

(same thing if wall along **H**)

Which path could the electron take?

Think about case when wall is out.

Which path could the electron take?

- upper path: no, electrons on H 50/50 white/black
- lower path: no, for the same reason
- both paths: if put detectors along both paths, always find it on either one or the other
  Never on both.
- neither path: When we block both paths, nothing gets through.

As far as we can make out, electrons passing the apparatus do not take the upper path, the lower path, both paths, or neither path.

Trouble is these are all the logical possibilities !

Seems that the electrons have modes of moving available to them that is unlike anything we know how to think about: ***"Superposition"***

Upsetting. Big part of this course is understanding what is going on here and what are the (as we will see) major implications for how the world around us works