Proposed ZOOM class in Quantum Theory

I have taught a class for adults as part of the Agnes Scott College Lifelong Learning program, in ZOOM classes and as part of the regular curriculum at Swarthmore College.

In the upcoming ZOOM class, based only on things you learned in high school, I will teach you some mathematics - the following lecture example will be repeated in the class.

This class will enable you to learn/understand the appropriate language of quantum physics and then we will be able figure out what is going on.

It takes 8-10 weeks (16-20 1-1/2 hour ZOOM lectures) and it works.

I have taught the class 4 times at Agnes Scott (100 total students), 1 time on ZOOM(15 students) and 3 times at Swarthmore (65 total students).

I hope you will join us in Fall 2026. Email me at boccio@me.com

Now sit back and read a sample lecture - always remember I would be saying this stuff and adding comments, etc so all is understood!

A Simple Introduction to Quantum Ideas via Experiments

I am going to tell you a story about a world of electrons that have 2 properties

Color and Hardness

In this imagined Microworld:

Electrons have 2 properties ==> color and hardness

In the Real world:

Electrons also have 2 properties ==> z- and x-spin

and

Photons also have 2 properties => horizontal and vertical polarization

The Strange World of Color and Hardness

Known experimental facts:

Color has **two** possible values = green or magenta.

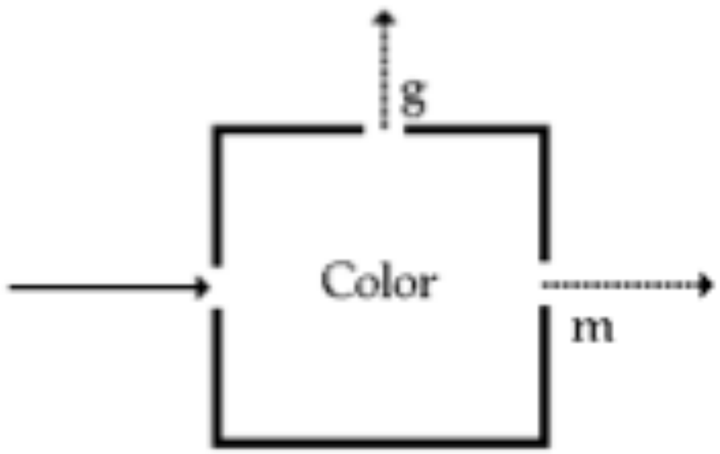
This means that **nothing else** has ever been **measured** for electron color.

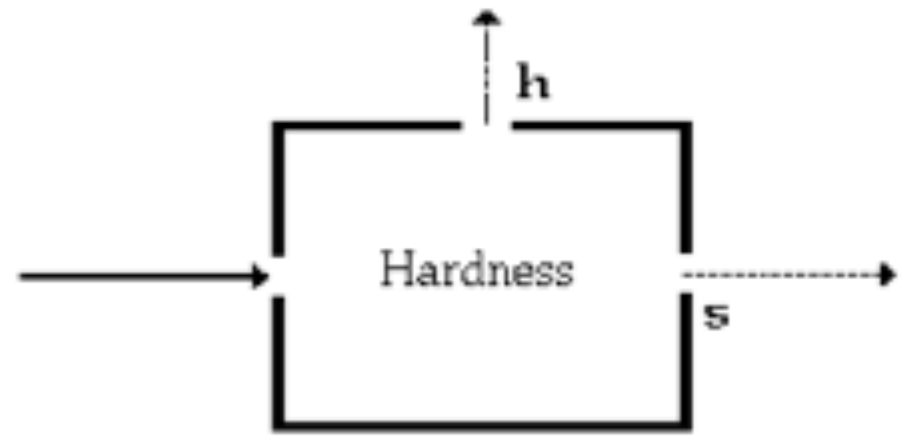
Similarly, for hardness property.

Electrons are either hard or soft (**only** possibilities).

Nothing else ever **measured**.

Color/Hardness Boxes (3 apertures)

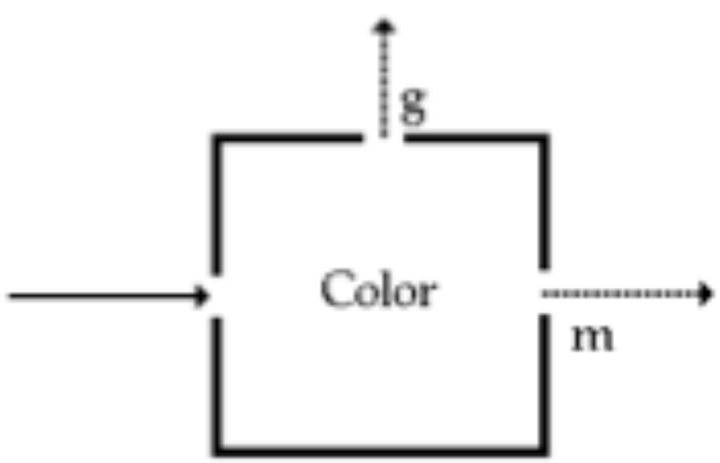


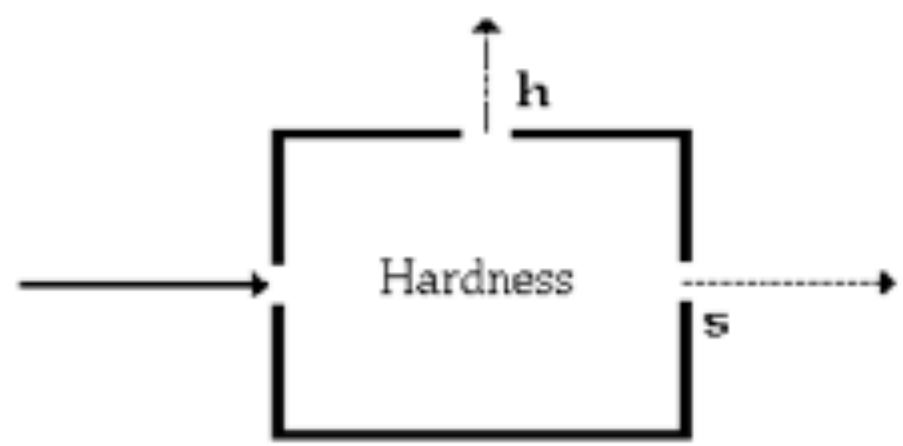


Electrons enter boxes through **left** aperture.

These boxes represent the same physics as real world devices without complications.

[Examples : Stern-Gerlach devices and Polarizers]



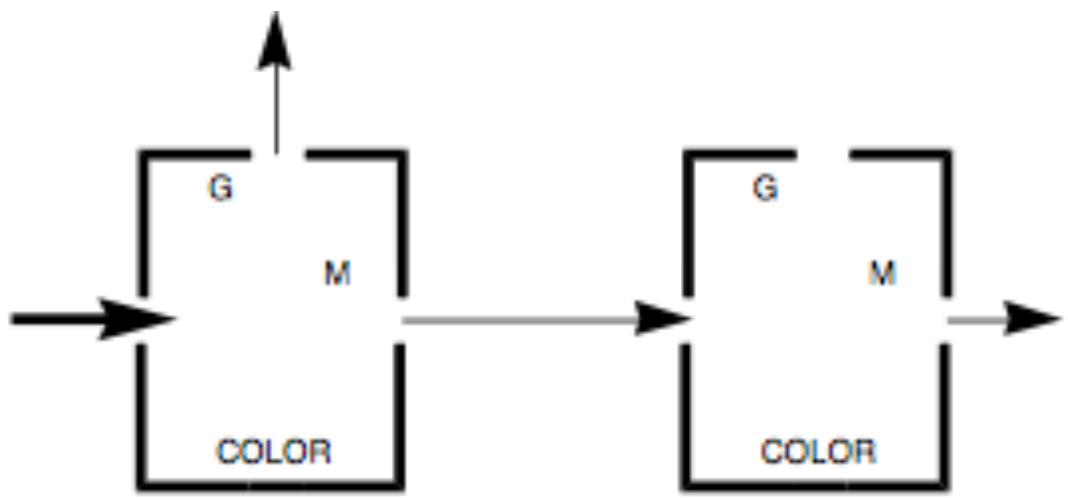


Boxes **separate** electrons in physical space (put them onto **different paths**) according to the value of color or hardness as shown.

Thus, in either case, one can distinguish the electrons **after** they pass through a box by their final position(path) in real physical space, i.e., we have **separate** beams at end.

AN EXPERIMENTAL PROPERTY

Measurements with hardness or color boxes are **repeatable**.



The 1st color box determines the electron color and we choose the magenta beam.

Then, without tampering(must define this concept) between measurements the magenta beam is subsequently (immediately=> $\Delta t=0$) sent into left aperture of another color box.

The electron will (with probability = 1) emerge from 2nd box through magenta aperture.

This **same** property of repeatability holds for green electrons and color boxes

and for hard or soft electrons with hardness boxes.

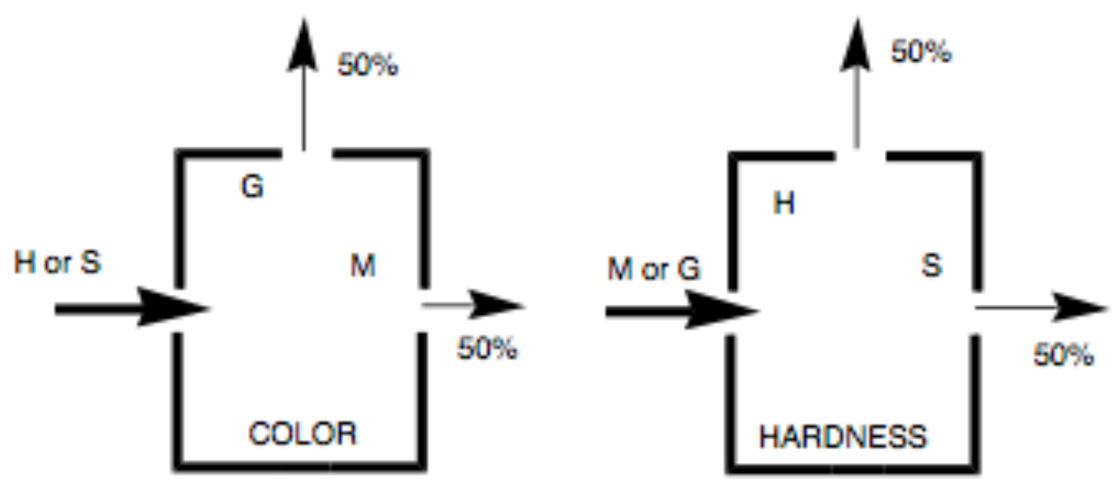
It is **simply** a statement of the way the real microworld and its measuring devices work in the laboratory.

So our representation of real world should behave that way also.

Suppose we suspect the possibility that color and hardness properties are related in some way.

We must investigate => check for correlations (or relationships) between the measured values of hardness and color properties.

The boxes allow for checking whether such correlations exist.



No such correlations exist,

i.e., of any large collection of, say, magenta electrons,

all fed into left aperture of hardness box, precisely 1/2 emerge through hard aperture,

and precisely 1/2 emerge through soft aperture - cannot predict which goes where!

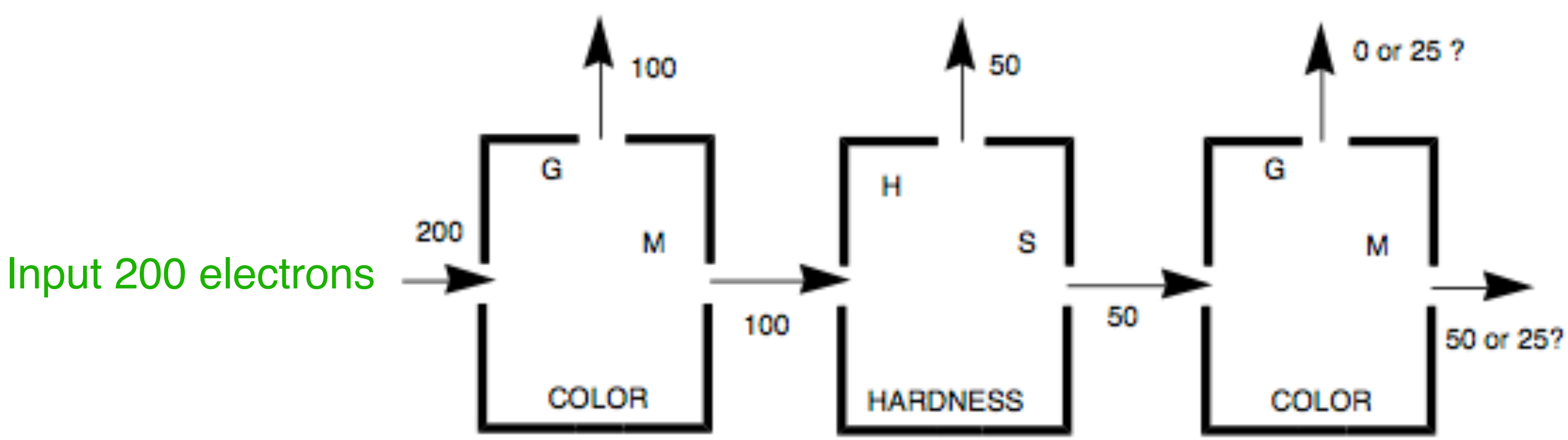
Same result occurs for green electrons and similar results hold if we send hard or soft electrons into color box - all results are exactly 50% —> **there are no correlations**.

Color (hardness) of electron apparently gives no information about hardness (color).

This usually means that no correlations seem to exist.

Now, suppose we set up a sequence of three boxes.

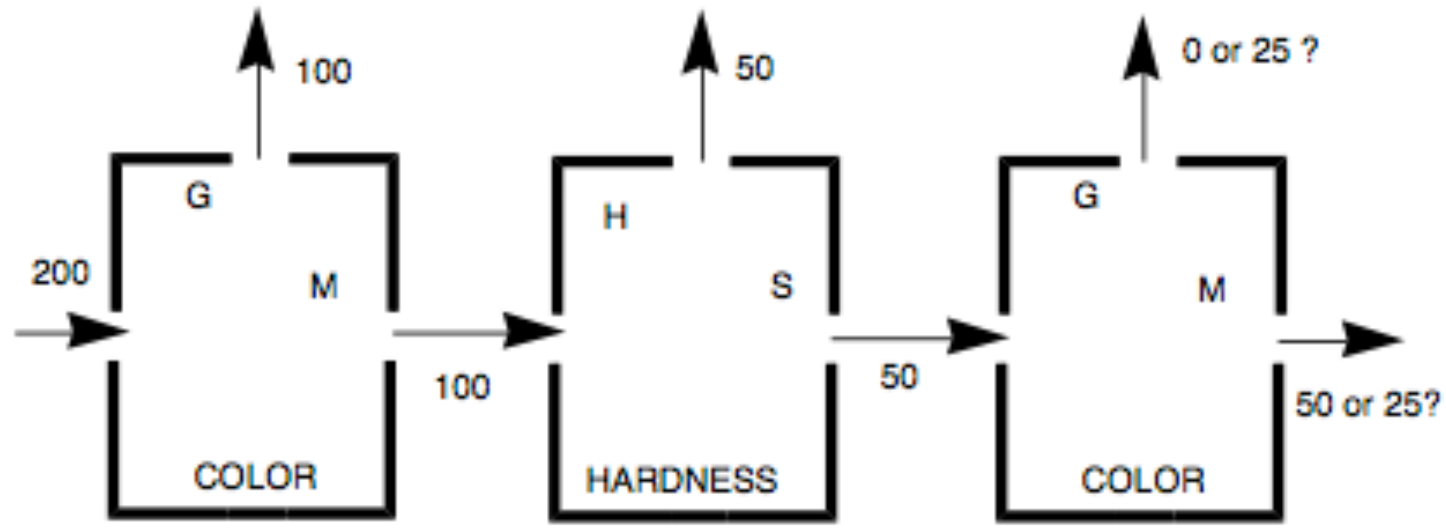
Color box, then hardness box and finally color box.



Suppose an electron(1 of 100) that emerges from magenta aperture of 1st color box

then goes into left aperture of hardness box

(no tampering = no other measurements or no time interval).



Then suppose an electron that emerges(50 out of 100 do) from hardness box through soft aperture (1/2 of input magenta electrons)

and are sent into left aperture of last color box

(again no measurements or time intervals allowed).

Presumably, electron(1 out of 50) that enters that last box

is known to be **BOTH** magenta **and** soft,

which were results of two previous measurements just made on it!

If so, then we expect the electrons(50) to emerge from magenta aperture(probability = 1),

confirming the result of 1st measurement.

Any **reputable** classical physicist would say at this point

that electrons entering last color box are known to be **magenta/soft**.

In classical world, particles have **objective reality** - have **real properties**

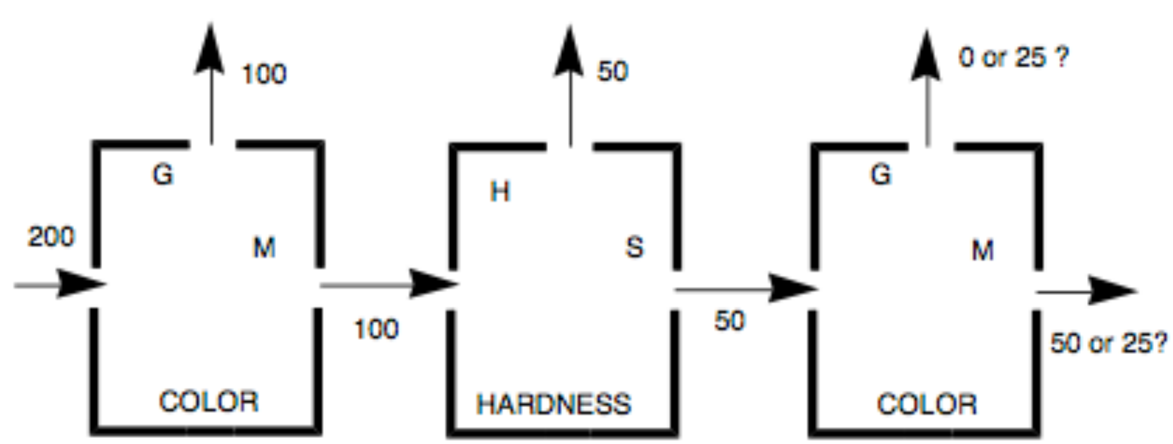
and we just **measure to find out** values of properties.

We just used 2 experiments to determine properties!

PROBLEM: this is not what happens in the real world in this experiment!

Precisely half of electrons entering last box emerge from magenta aperture

and precisely half emerge from green aperture!!



Therein lies the fundamental puzzle of the quantum world.

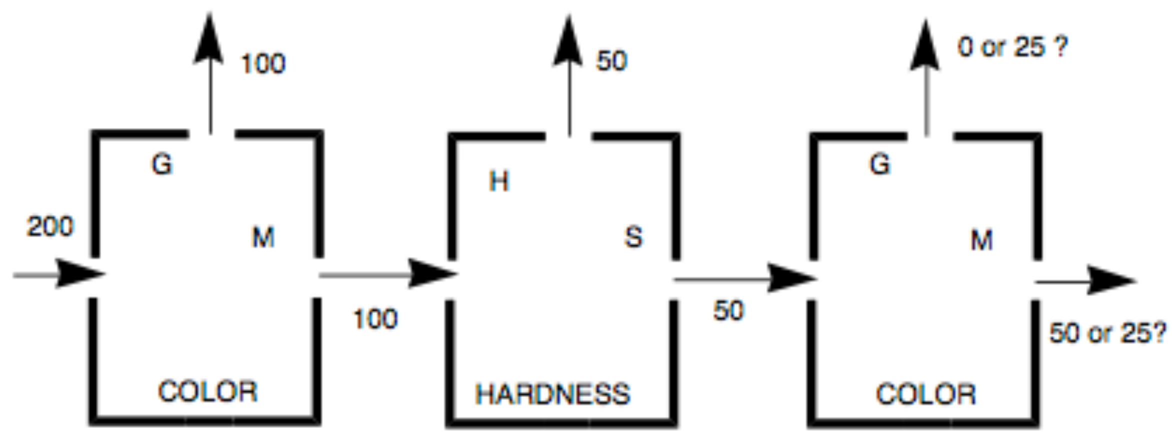
Any theory must account for this result.

In fact, if 1st two measurements give magenta/soft, magenta/hard, green/soft or green/hard

which represents all possible cases, then,

when any of these beams sent into last box,

precisely half emerge from each aperture!!



It seems as if presence of hardness box between two color boxes

constitutes some sort of color measurement or color tampering and vice versa.

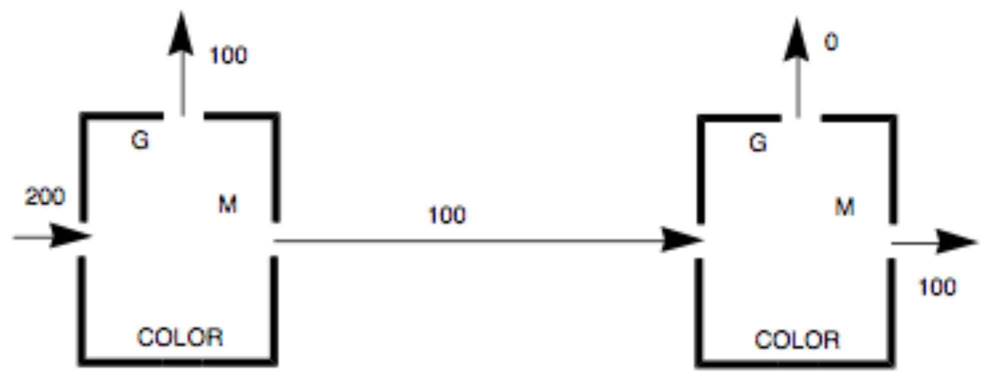
Hardness box seems to be changing half of magenta electrons into green electrons.

This will turn out to be an **incorrect way** of thinking about the results of the experiment!

Hardness box must be the blame since if it were not there,

then the last box would only see magenta electrons

(**different** experiment that corresponds to repeatability)



This all seems so weird (non-classical)

—> we must question (challenge) all features of experiment before we accept story as truth.

Perhaps hardness box poorly built (not enough $$$$ from Congress in our research grant).

Maybe measuring hardness correctly disrupts color - bad design.

Two fundamental questions arise:

1. Can hardness boxes be built that will measure hardness without disrupting color?

2. In case of poorly built apparatus, it seems as if half of electrons change color….

   what is it that determines which electrons have color changed and which do not change?

Question 2 answered by checking correlations - **none exist**.

Those electrons that have color changed by hardness box

and those electrons whose color is not changed by hardness box

do not differ from one another in any **measurable** way.

So 2nd question has no answer that we can figure out from measurements.

If we believe, as I do, that **I can only know properties that I can measure**,

then it means there is NO answer to this question,

i.e., there is no property of electrons that determines which electrons get color changed.

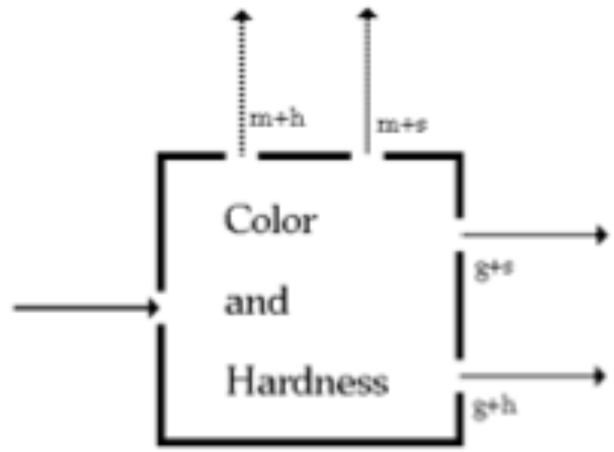
This is completely counter to classical notion of cause/effect and objective reality!!!

Question 1: no matter how we build hardness box (remember a device qualifies as a hardness box if it can separate electrons by hardness value) **all disrupt color measurements** - all change half of entering electrons.

Any hardness (color) measurement seems to **randomize** next color (hardness) measurement, i.e., make it 50% green/ 50% magenta.

What about building a color AND hardness box?

This need 5 apertures as shown.



Has to consist of hardness boxes and color boxes

because must be measuring hardness and color in some way.

But as we have already seen, whichever box the electrons pass through last

provides reliable information ONLY about that measured quantity

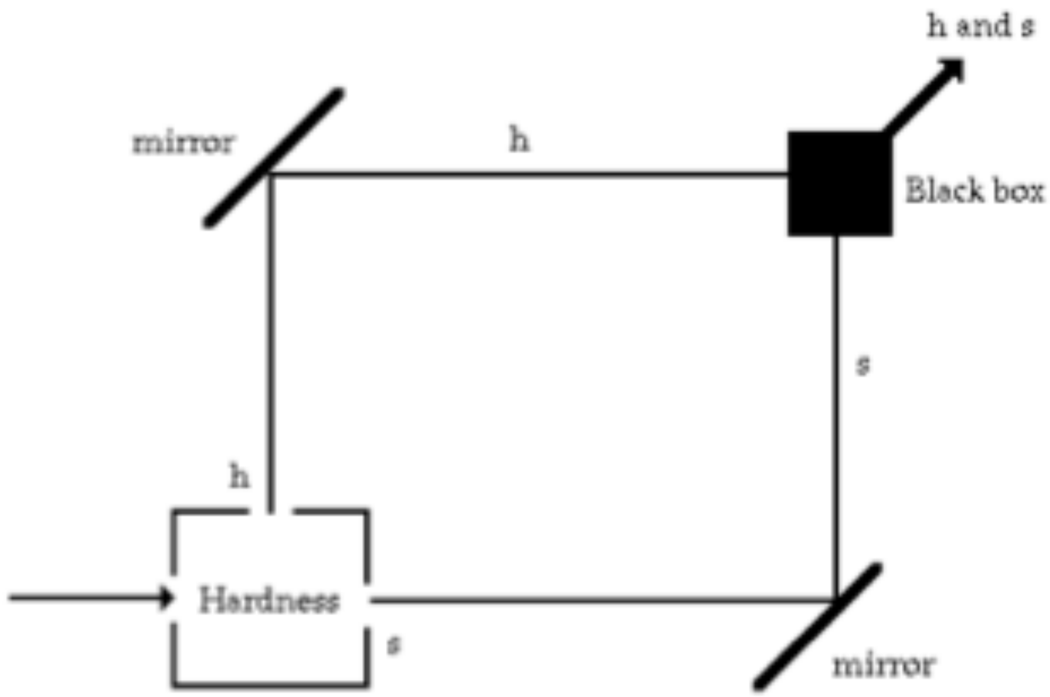
and the other quantity is **randomized** (i.e., half/half).

No one has succeeded in building device

which can simultaneously measure both color and hardness.

Seems fundamentally beyond our means no matter how clever we are.

Probing Deeper



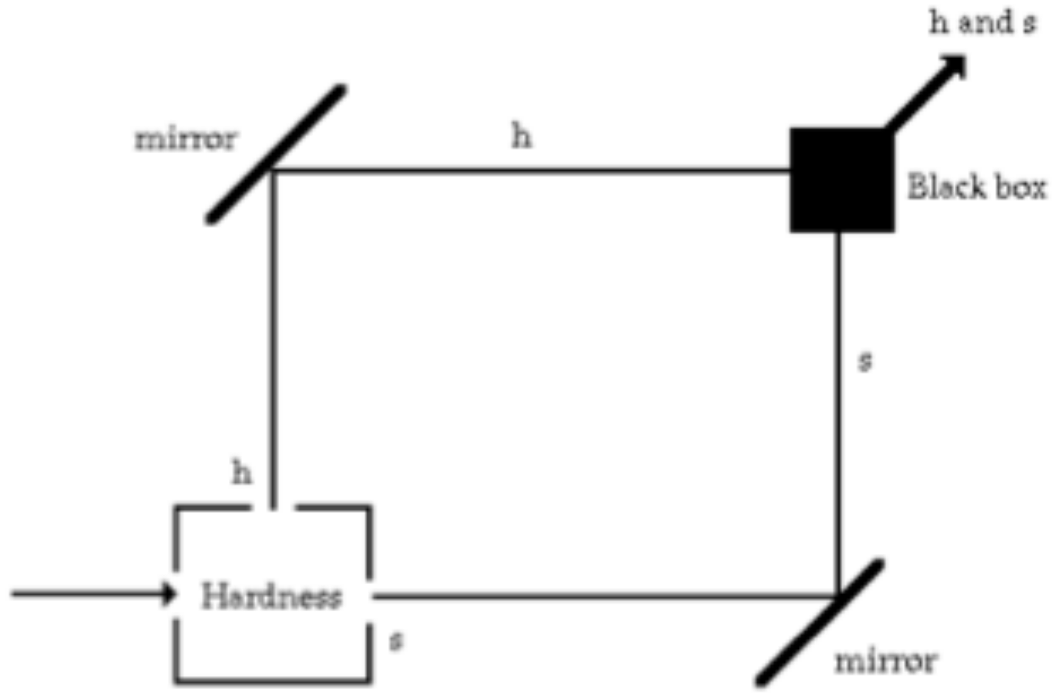
We build a more complicated experimental setup involving two paths as shown.

The mirrors are just reflectors which do not affect color/hardness values.

That means it has been experimentally checked

In this device, the hard and soft electrons follow **different paths in physical space** and eventually electrons are recombined into single beam again in black box at end.

All black box does is recombine two beams into one beam by direction changes (again without changing hardness or color values - checked experimentally).



So if we start

with a mixed (hard + soft) beam of electrons,

entering the first hardness box

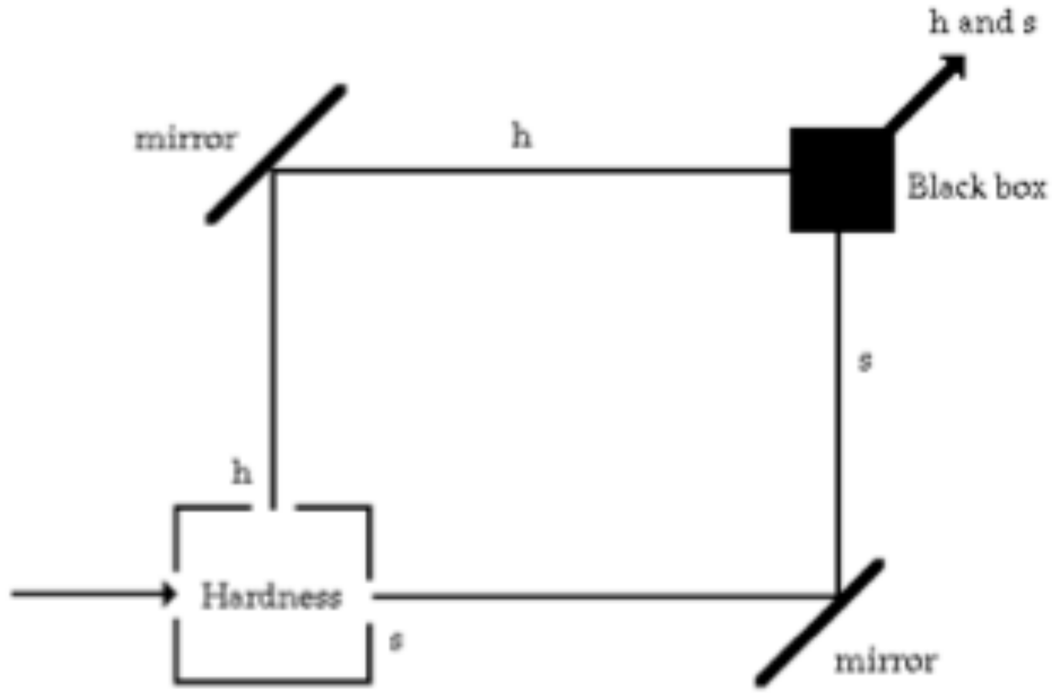
then we end up

with a mixed (hard + soft) beam at the end.

The effectiveness of device has been checked separately for both hard and soft electrons and it works.

Start with hard —> hard at end - they went on hard path!

Start with soft —> soft at end - they went on the soft path!



This is very important so I repeat:

If hard or soft electrons sent in separately,

simply travel along different paths and end up in same place

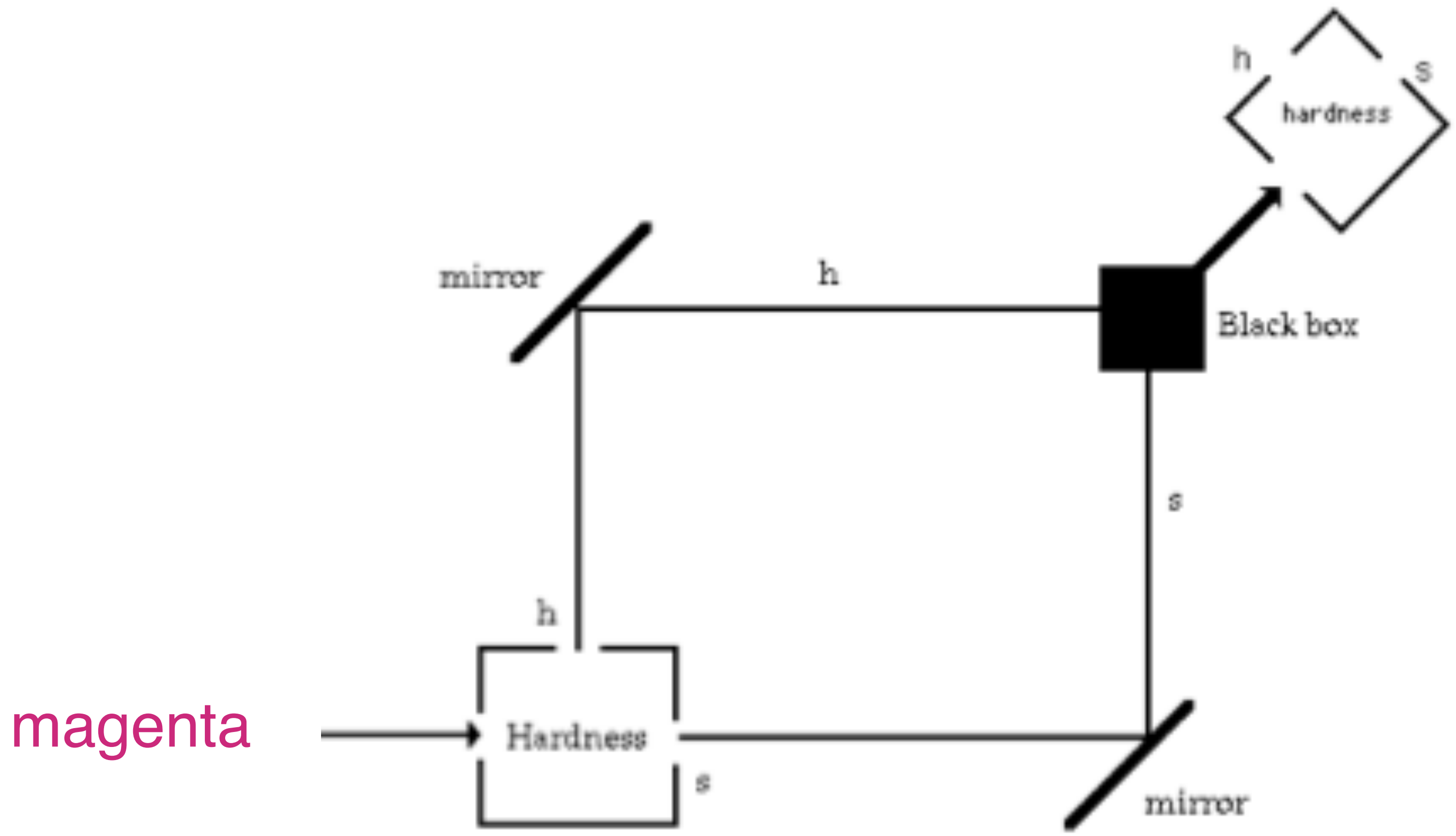
with their hardness property **unchanged**.

They go their separate paths and emerged unchanged at end

Some experiments can be done with apparatus.

All of these experiments have **actually** been done in real laboratories with equivalent setups.

Listen carefully now to see where your classical mind is misleading you.



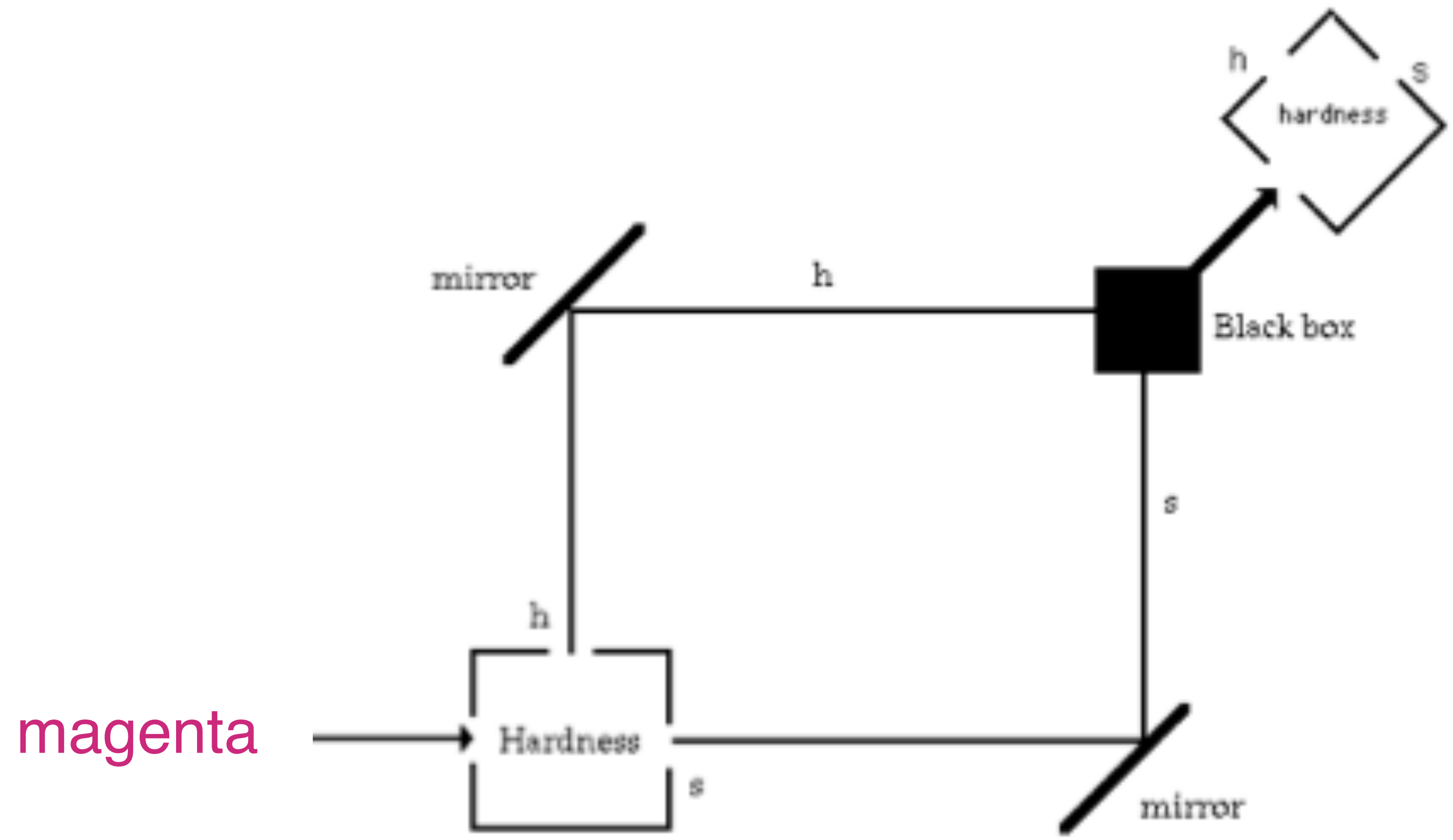
Send magenta electrons into 1st hardness box.

At end (after recombination of beams)

add final hardness box

and thus we are measuring hardness at that point

i.e., after the electrons have **"passed"** through the apparatus.



Analysis:

For entering magenta electrons,

50% take h route and 50% take s route

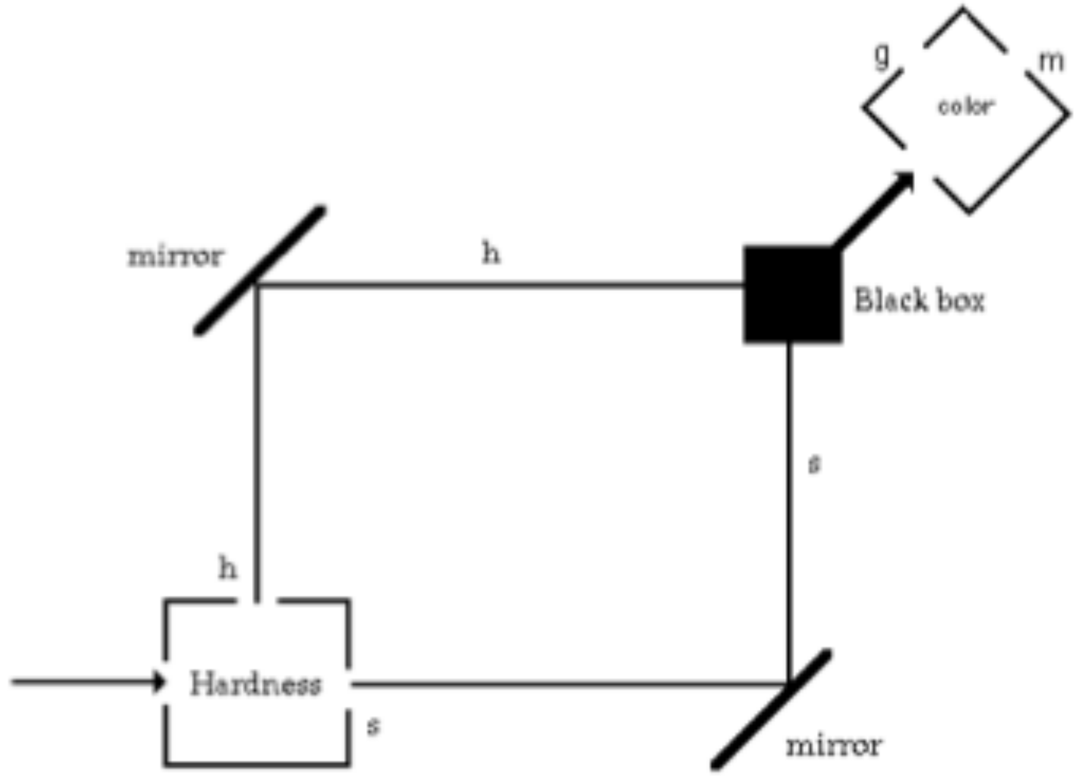
at the end(recombined beam) 50% are hard electrons

(remember nothing bothers hardness along routes)

and 50% are soft electrons. —-> Experimentally verified!

Change experiment

hard



Send hard electrons into hardness box.

At end add color box (**replace** final hardness box with a color box) and **measure color**.

Analysis:

All hard electrons follow h route.

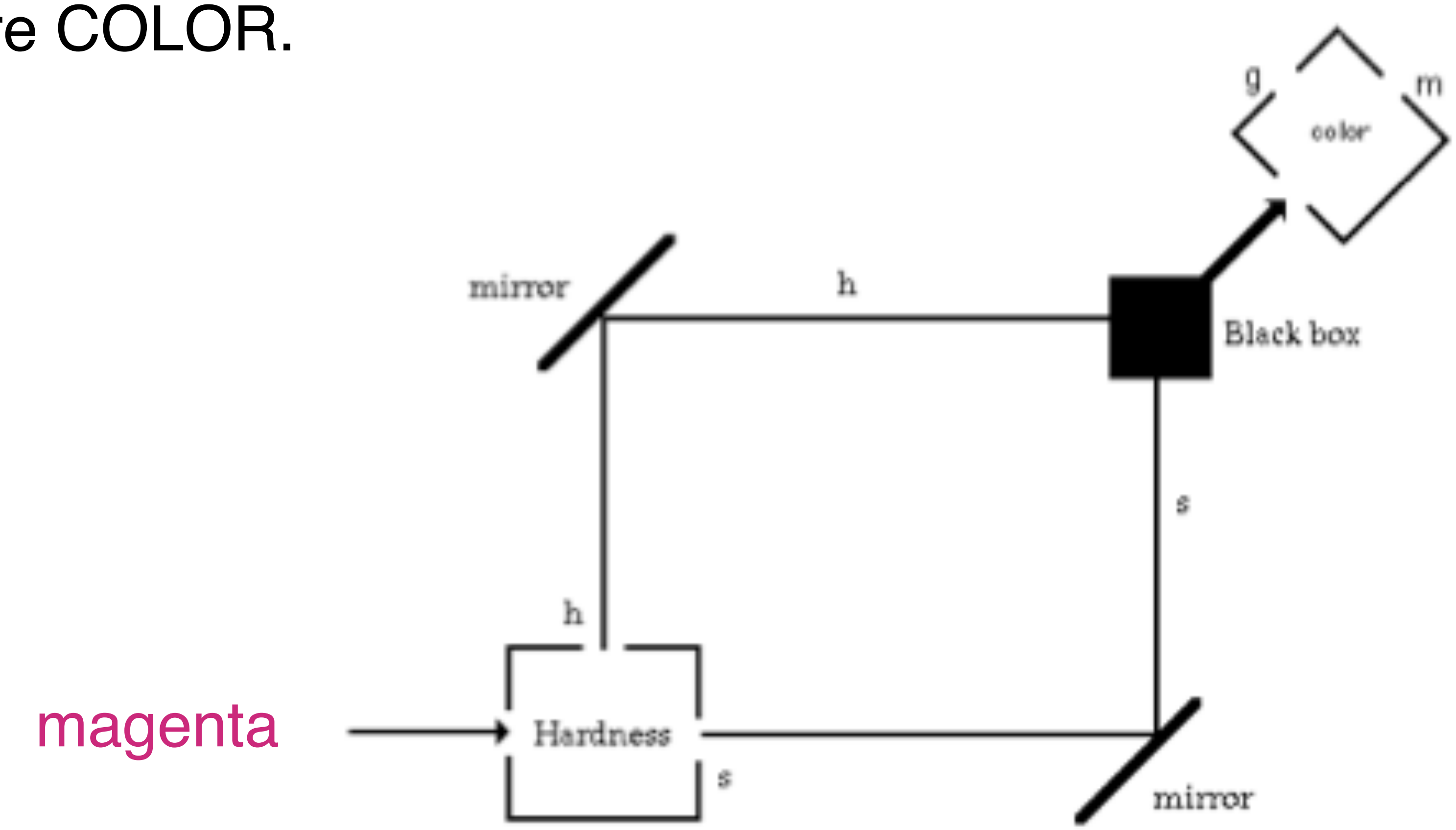
When we measure color of hard electron it is 50-50 green-magenta.

Similarly for soft electrons.

Therefore end up with 50-50 green/magenta coming out of color box.

These experimental outcomes are what would **expect** from earlier results and **do happen** exactly as described above in real world experiments. So **no** problems yet!!!

Now again send magenta electrons into hardness box, but at the end add a color box and measure COLOR.



What do you expect? True classical physicist would give this argument.

Since, for magenta electrons,

50% are hard and 50% are soft

(what happens to magenta electrons when sent into hardness box —> are randomized)

and each kind of electron takes the appropriate h and s routes,

at end, 50% of h (those on h route) electrons or 25% of total are magenta

and 50% of s (those on s route) electrons or 25% of total are magenta.

Thus, for 100% magenta sent in,

classical reasoning says that only 50% are magenta at end. A prediction!

Seems like a valid conclusion(prediction) since hardness boxes(1st box) **supposedly** randomize color.

Problem:

This last part of story, which a classical mind desperately wants to accept as correct, is **false**.

When we actually do experiment, **all(100%)** of electrons at end are magenta!!!

Very odd!

Hard to imagine (**classically**) what can possibly be going on in this system.

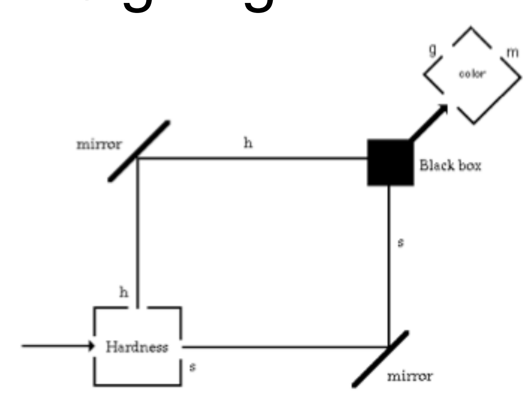
Of course, maybe our **classically oriented minds**

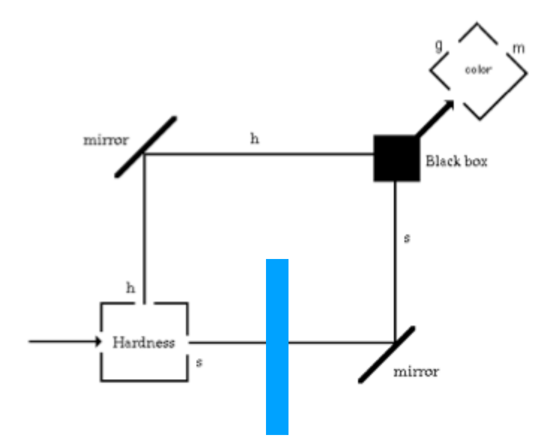
cannot imagine what is happening and need to be retrained!!!

Try another experiment in hopes of understanding what is going on.

Rig up small, movable, electron-stopping wall that can be inserted in and out of route s.

When the wall **out**, we just have the earlier apparatus.





wall inserted

When wall is **in**, **only** those electrons moving along h route

get through apparatus to the beam recombination device.

The electrons on the s route are blocked.

Analysis: First, there are 50% less electrons reaching beam recombination device.

When wall out all(100%) of electrons that get to beam recombination device

are magenta at end (earlier experimental result).

That means (**or seems to mean**) that all electrons that take s route

(**or we think are taking s route**) end up magenta

and all that take h route (**or we think are taking h route**) end up magenta

at beam recombination device when **no wall is inserted**.

This means that with wall inserted, we should end up with 50%

(1/2 lost impacting inserted wall) electrons at beam recombination device.

Based on the earlier experiment results, they should **all** be magenta

since an inserted wall on soft path **cannot affect** electrons on h path

and they **all** came out magenta in the previous experiment!

This is an assumption called **locality**, which means the following:

We can separate the hard and soft paths by a very large distance

and therefore make sure that nothing we do on soft path(like inserting wall)

can affect electrons on hard path during time they are on hard path.

This is possible because the maximum speed of information transfer is

speed of light from the study of relativity.

What is actual result?

Again we are wrong in classical way we are analyzing things. Result is **50/50 again**.

h route beam(**if there really is one**) seems to end up randomized(50-50 green-magenta)
and 50% of 50% is 25% 25 magenta and 25 green at end!

If insert wall in h route, **same thing happens**. Still end up only with 25% magenta!

Clearly, have **real** trouble with classical way of reasoning!

Seems if check (**do measurement**)
to **see which path** electrons are passing through device

(i.e., if check to see whether magenta electron
is passing through apparatus as hard or soft electron)

get 25% magenta (50% change to green) at end
and if DO NOT check get 100% magenta (0% change to green).

Our classical minds are **spinning** at this point!!

We now turn to a quantum system **containing only one particle at any instant of time** instead of using beams with many particles at any instant of time.

This was not possible during the early formative day of quantum mechanics.

It only became possible in the 1980s.

Now consider a **single magenta electron** passing through apparatus when wall is out.

Can it have taken h route?

No, since all such electrons are hard and hard electrons are 50-50 green-magenta (and need 100% magenta).

If on hard path, then they are hard - that is a measurement.

Can it have taken s route?

No, since all such electrons are soft and soft electrons are 50-50 green-magenta (and need 100% magenta).

If on soft path, then are soft - it is measurement.

Can it somehow have taken **BOTH** routes at same time?

If **look** (**measure**), then half the time find electron on h route

and half the time find electron on s route,

but never find two electrons in apparatus,

or two halves of single, split electron,

one-half on each route, or anything like that.

No experimental way in which electron seems to be taking **both** routes simultaneously.

Therefore, as physicists, must **rule out** this possibility.

This eventually leads to the hypothesis for the meaning of the the word "quantum".

Can it have taken **neither** route (got there some other way)?

Certainly not.

If put walls in **both** routes, then NOTHING gets through at all.

Thus, results **had** to have something to do with box and paths.

Summarize dilemma for classical view.

Electrons passing through apparatus, based on measurements

do not take route h

and do not take route s

and do not take both routes at same time

and do not take neither of routes,

i.e., electrons have **zero probability** for doing any of these things (**from experiment**).

Problem is that those 4 possibilities are simply **all** of the logical possibilities

we have any notion of how to entertain using **everyday language** of classical physics!

What can these electrons be doing?

Must be doing something which has simply never been thought of before in classical physics.

Electrons seem to have modes of being, or modes of moving,

available to them which are unlike anything

we can think about using words derived from everyday ideas and classical physics.

Name of new mode (name for something do not understand at moment) is

SUPERPOSITION.

In the end all we can say about initially magenta electron, which is passing through our apparatus with the wall out,

Prepare yourself for this!

it is **NOT** on h path and **NOT** on s path and **NOT** on both paths and **NOT** on neither,

it is in a **SUPERPOSITION** of being on h and being on s.

What this last statement means, other than none of above, we do not know at this time;

it requires a theory to fill in the gaps.

That is what one does in a quantum theory class.

Final and most confusing experiment.

New experimental box = **do-nothing box** - It has 2 apertures.

An electron goes into one aperture and emerges from other aperture

with **ALL measurable properties** (color, hardness, energy, momentum, whatever)

UNCHANGED. Experimentally verified!

Box does not measure anything.

If we measure the properties of electrons before entering box and then after passing through box,

no measured properties are changed.

Also the time it takes for electron to get through box

is **identical** to time it would have taken if box were not there.

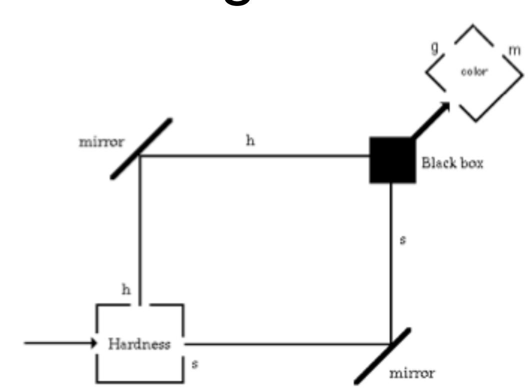
So nothing mysterious **seems** to be delaying it/messing around with it while in box.

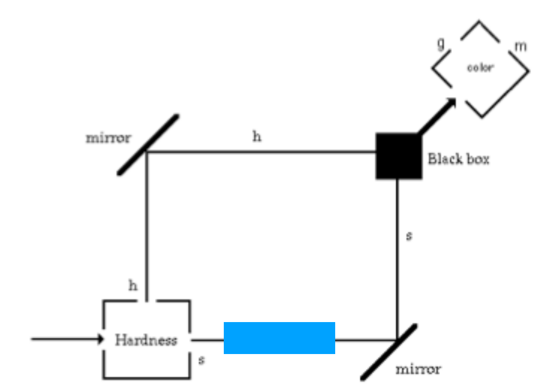
Such a **do-nothing box** can actually be constructed in the laboratory.

However, experimentally it is possible to build such a do-nothing box, which,

when inserted into **either** one of two paths (h or s),

will **change all** electrons that were **magenta** at end into **green** electrons at **end**.





box inserted

When the box is removed, they all go **back** to all being magenta.

So inserting box into **one** path changes the color of electrons passing through apparatus.

What is going on here?

Do-nothing boxes do not change any measurable property of electrons

that pass through it

AND of course,

do-nothing boxes do not change any measurable property of electrons

that DO NOT pass through.

That would not make any **sense** at all.

So once again our only explanation will go like......

It is not possible for the electron to have passed through the do-nothing box

since we already said that cannot change anything.

It is not possible for the electron to have passed outside the box

since the box certainly does not have a chance to bother anything

that does not even pass through it

(even though it would not do anything anyway).

It is not possible that the electron passes

both simultaneously inside and outside of the box or neither as before.

Only answer is that the electron passes through our apparatus

in a **superposition** of passing through do-nothing box

and not passing through do-nothing box

and this must **cause** the color change somehow.

This theory has got to be really neat when one finally figures out what it is we are saying about the world.

What is required to understand the theory?