Superposition - World of Color and Hardness

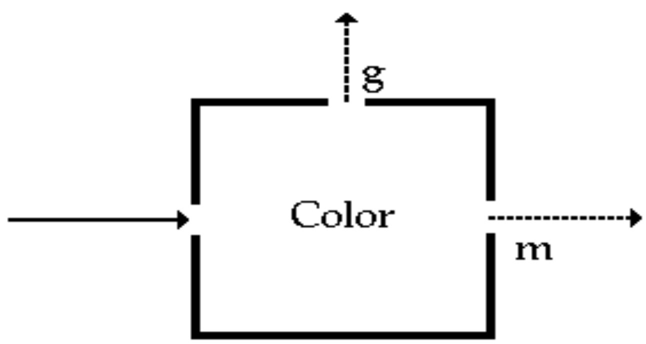
We start our formal discussion of quantum mechanics with a story about something that can happen to various particles in the microworld, which we generically call **electrons** . All the experiments that will be described in this story have actually been performed. We will discuss some of them later. The story is about two **physical properties** of electrons that we can measure with great accuracy. The precise physical definitions of these properties will not matter. They do however, correspond to real properties of electrons or photons as we shall see later.

We will call them **hardness** and **color**.

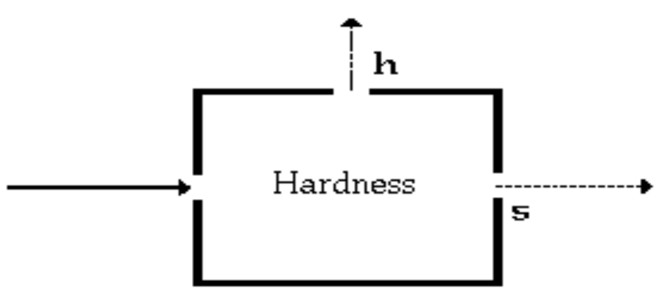
The Strange World of Color and Hardness

It is **experimental fact** that color property of electrons can assume only two values, namely, **green** or **magenta**. This means that **nothing else has ever been observed(measured)** for the color property of an electron. A similar situation exists for the hardness property. Electrons are either **hard** or **soft** (only possibilities). **Nothing else has ever been observed**.

It is possible to build a device we will call a **color box** , which measures the color of an electron. It is a box(complicated stuff inside) with three apertures as shown below:



We can also build hardness measuring boxes that work in a similar way.



For electrons, these hardness and color boxes are called a **Stern-Gerlach** apparatus, which is a region of non-uniform magnetic field.

For photons these hardness and color boxes are **Polaroids**. We will discuss these real world devices later.

The world of color and hardness we are discussing will exhibit all the same physics as the real world devices without introducing many of the real world complications, i.e., we do not need to discuss in detail how these boxes work.

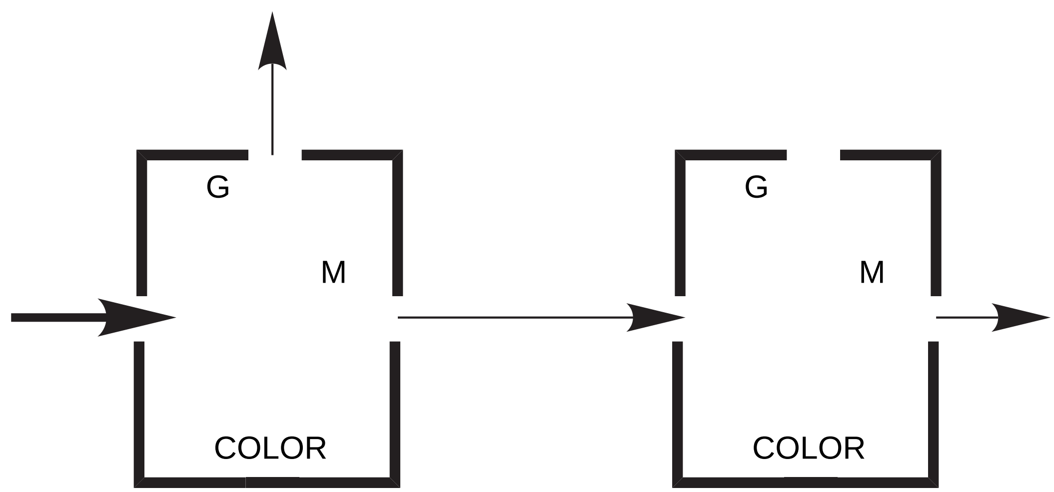
In both cases, electrons enter the boxes through the left aperture and the boxes separate the electrons **in physical space** by the value of the color or hardness as shown.

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

EXPERIMENTAL PROPERTY: Measurements with hardness or color boxes are repeatable.

That is, if one color box determines that an electron is magenta and if that electron(without having been tampered with in between measurements) is subsequently(immediately) sent into the left aperture of another color box, then that electron will (**with probability = 1**) emerge from the second box through the magenta aperture.

This is illustrated in the figure below:



The **same property** of repeatability **holds** for green electrons and color boxes and for hard or soft electrons with hardness boxes.

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

Now, suppose that we **suspect** there is a possibility that the color and hardness properties of electrons are **related** in some way.

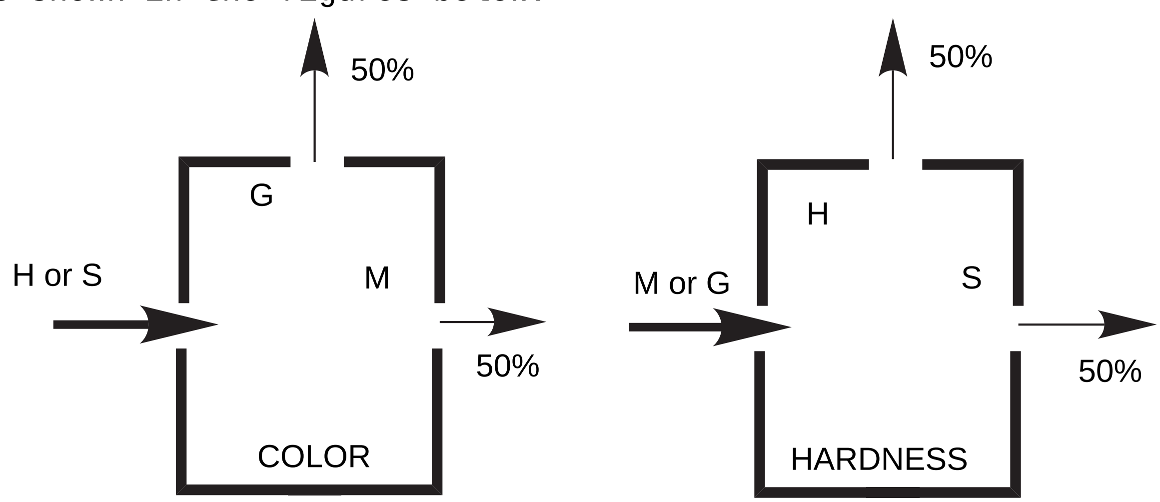
One way to look for such a relation is to check for **correlations** (or relationships) between the measured values of the hardness and color properties of electrons. Our boxes(**real world experiments**) make it very easy to check whether such correlations exist.

After much experimentation, it turns out that no such correlations exist,i.e.,

> of any large collection of, say, magenta electrons, all of which are fed into the left aperture of a hardness box, **precisely** half emerge through the hard aperture, and **precisely** half emerge through the soft aperture.

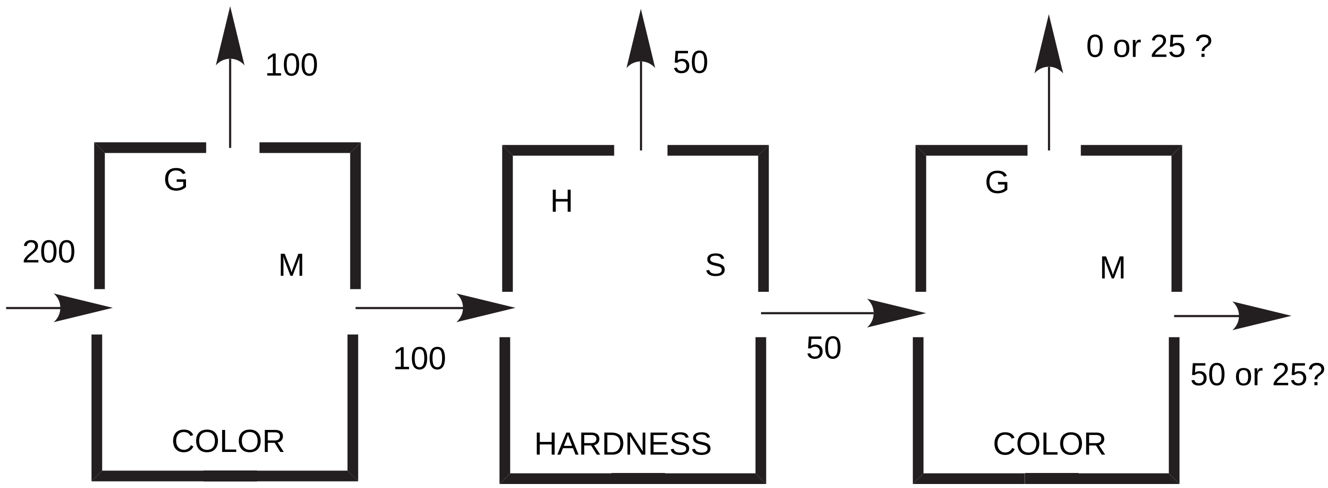
The same result occurs for green electrons and similar results hold if we switch the order of the color and hardness measurements.

This is shown in the figures below.



The color (hardness) of an electron **apparently gives no information** about its hardness (color).

Now, suppose we set up a **sequence of three boxes**. First a color box, then a hardness box and finally another color box as shown below:



In this experiment, suppose an electron that emerges from the magenta aperture of the first color box then goes into the left aperture of the hardness box (remember it must not be tampered with in between or there must be no other measurements of any kind or any essentially no time interval).

Suppose it then emerges from the hardness box through the soft aperture (as half of the magenta electrons will do) and it is sent into the left aperture of the last color box (again no measurements or time intervals allowed).

Presumably, the electron that enters that last box is known to be both magenta and soft, which were the results of the two previous measurements just made on it.

If this were so, then we would expect the electron to emerge from the magenta aperture(**with probability = 1**), **confirming** the result of the first measurement.

Any reputable **classical** physicist would say at this point that electrons entering the last color box are

magenta AND soft

In the classical world particles have objective reality - they have "real" properties and we measure to find out the values of the properties.

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

Precisely **half** of the electrons entering the last box emerge from the magenta aperture and precisely **half** emerge from the green aperture!!

Therein lies the fundamental puzzle of the quantum world.

In fact, if the first two measurements give

```
     magenta AND soft
or   magenta AND hard
or   green   AND soft
or   green   AND hard
```

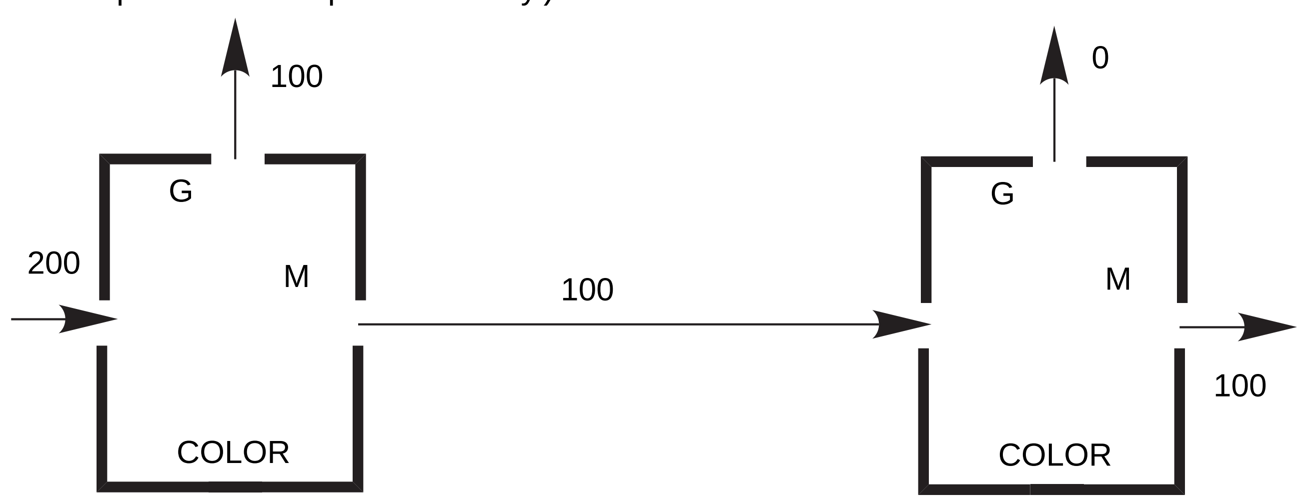
which represents **all** the possible cases, then when any of these beams is sent into the last box, precisely half emerge from each aperture!!

The **same** kind of results hold if we switch the hardness and color boxes.

It seems as if the presence of the hardness box between the two color boxes itself constitutes some sort of color measurement or color tampering and vice versa.

The hardness box **seems** to be "changing" **half** of the magenta electrons into green electrons".

The hardness box **must be the blame** since if it not there, then the last box would only see magenta electrons(a different experiment that corresponds to repeatability) as shown below:



Now all this seems so wierd(non-classical) that we must question (challenge) all features of the experiment before we accept the story as truth.

Perhaps the hardness box is **poorly built** (we did not get enough **$$$$** from Congress).

Maybe it is measuring hardness correctly, but while doing that job it apparently **does disrupt color** because of bad design.

This raises **two fundamental questions**:

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

[2] In the case of a poorly built apparatus half of the electrons change color....what is it that determines which electrons have their color changed and which don't?

We address the second question first.

The way to discover the determining factor(s) (**if there are any to be discovered!**) is to carefully monitor the **correlations** between all the measurable properties of the electrons that are sent into the first color box and found to be magenta and which aperture of the final color box they come out of.

Any **correlation** will tell us which property is the determining one.

All known experiments say no such correlations exist.

Those electrons that have their color changed by passage through the hardness box and those electrons whose color is not changed by passage through the hardness box **do not differ** from one another in **any measurable way**.

So the second question has no answer that we can figure out from measurements.

If we believe that **we can only know properties that we can measure**, then this would mean that there is **NO** answer to this question, i.e.,

> **there is no property of the electrons that determines which electrons get their color changed**

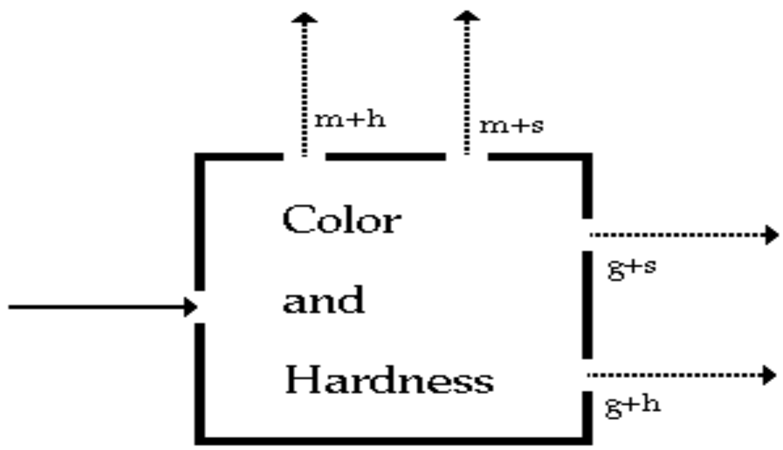
which is completely counter to our classical notion of cause and effect and objective reality!!!

What about the first question?

It turns out that no matter how we build hardness boxes..... r**emember that a device qualifies as a hardness box if it can separate electrons by their hardness value** ...... they **all** disrupt color measurements in the same way.... they all change **precisely** half ... **exactly** as far as any experiment can determine. Any hardness (color) measurement seems to **randomize** the next color (hardness) measurement, i.e., make it **50% green/50% magenta**.

Suppose we want to build a **color-AND-hardness box**.... a box that could determine both color and hardness for a single electron simultaneously (and we could convince some funding source to support us).

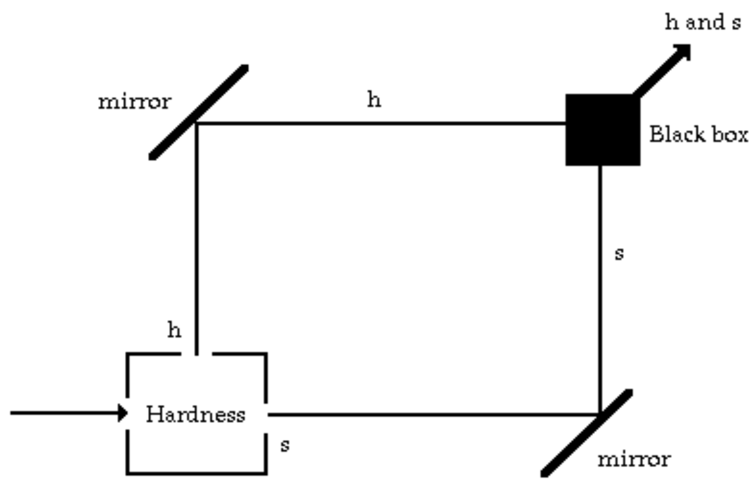
This box would need five apertures as shown:



Let us try to build this device.

In **some manner** it has to consist of a hardness box **and** a color box (or there equivalents) because we 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 a device which can simultaneously measure both color and hardness. It seems to **fundamentally** be beyond our means **no matter how clever we are.** The universe just seems to work in this peculiar manner!! This just the **Uncertainty Principle of Heisenberg** rearing its head again as we shall see later. **Measurable quantities** like hardness and color are said to be **incompatible** with one another since a measurement of one **ALWAYS NECESSARILY disrupts(randomizes)** the other.

Let us probe into this situation more deeply. Consider the more complicated experimental device shown below:



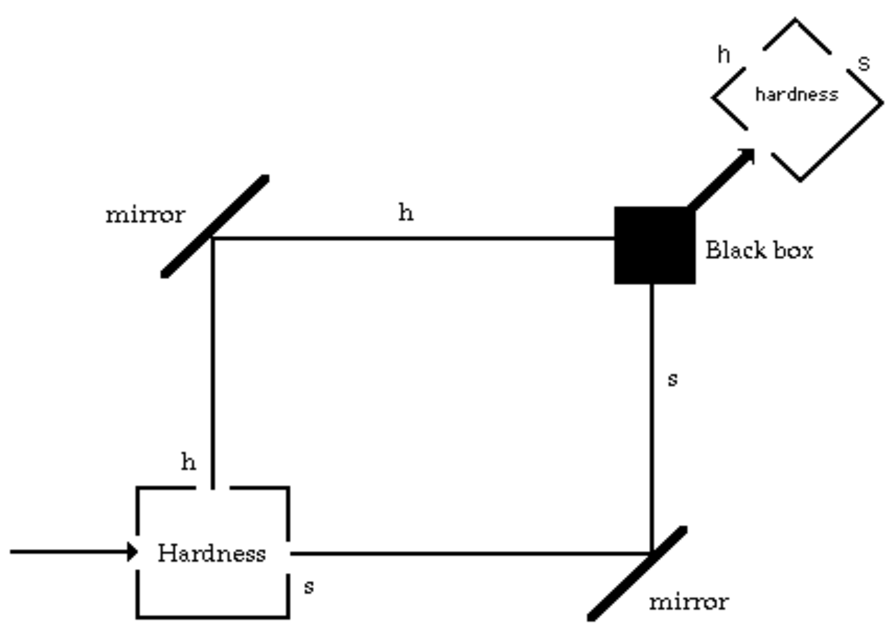
The "**mirrors"** in this device are just a reflecting device of some kind which only changes electron direction and does nothing else (in particular it **does not** change hardness or color during the direction changing process). We have drawn the device in this way so that you could easily see what it is doing. No real mirrors are necessarily involved.

In this device, hard and soft electrons **follow different paths** in physical space (like a **calcite** crystal does for polarizations or a Stern-Gerlach apparatus does for electrons - as we shall see) and eventually are recombined into a single beam again in the **black box** (some kind of **UN**-calcite device or **INVERSE**-Stern-Gerlach device) at the end, i.e., all the **black box** does is to recombine the two beams back into one beam by direction changes (again without changing hardness or color values). So if we start with a mixed hard + soft beam of electrons, then we end up with a mixed hard + soft beam.

The effectiveness of the device can be checked separately for both hard and soft electrons and it works. That is, if hard or soft electrons are sent in separately, they simply travel along different paths and end up in the same place with their hardness **unchanged.**

Here are some experiments we might **imagine** could be done with this apparatus. All of these experiments have actually been done with equivalent setups. **Listen carefully to see where your classical mind is misleading you.**

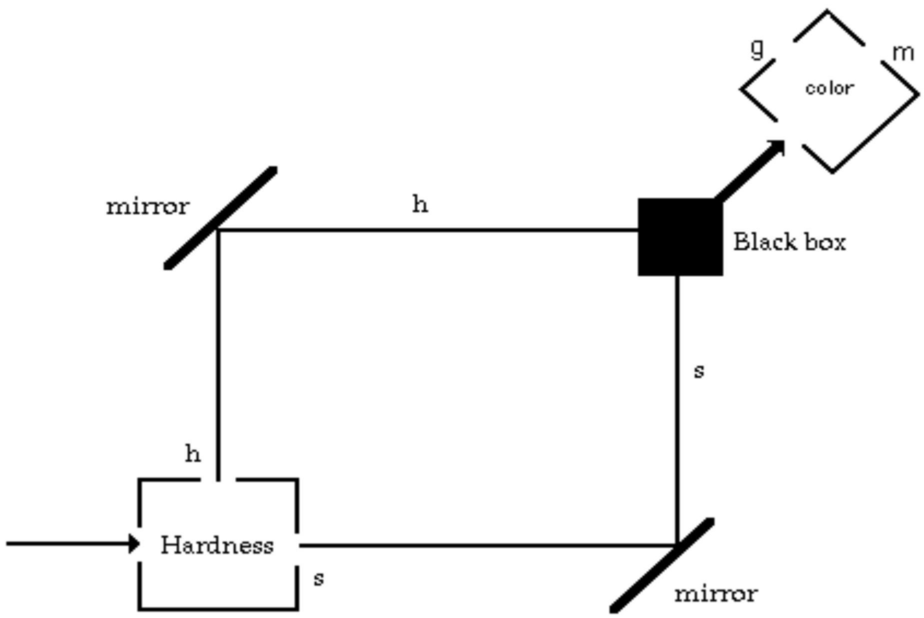
[1] Send **magenta electrons** into the first hardness box. At the end (after beams are recombined) we **add** a hardness box and thus we measure their hardness at that point.



Analysis: For magenta electrons, 50% will take the h route and 50% will take the s route so that at the end(recombined beam) 50% are hard electrons (**remember nothing bothers hardness along the routes**) and 50% are soft electrons.

[2] Send **hard electrons** into the hardness box. At the end we **add** a color box and we measure their color.

Analysis: All hard electrons follow the h route. When you measure the color of a hard electron it is 50-50 green-magenta. Similarly for a soft electrons. Therefore we end up with 50-50 green/magenta coming out of the color box.



These experimental outcomes are what we would expect from our earlier results and they **do happen exactly as described** in the real world.

So no problems yet!!!

[3] Now send **magenta** electrons into the hardness box. At the end we **add** a color box and we measure its **COLOR**.

What do you expect?

The true classical physicist would give this **argument**:

Since 50% are hard and 50% are soft (**that is what happens to magenta electrons when they are sent into a hardness box**)and each kind of electrons take the appropriate h and s routes, at the end, 50% of h (**those on h route**) electrons or 25% of the total are magenta and 50% of s (**those on s route**) electrons or 25% of total are magenta.

Thus, for 100% magenta sent in, our **classical reasoning** says that only 50% are magenta at the end.

This seems to be an valid conclusion since hardness boxes(**first box**) supposedly randomize color.

The problem is that this last part of the story, which your classical mind so desperately wants to accept as correct, **is false**.

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

This is very odd.

It is hard to imagine 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 retooled!!!

[4] Let us try another experiment in the hopes of understanding what is going on.

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

When the wall is **out**, we have precisely our earlier apparatus. When the wall is **in**, only those electrons moving along the h route get through to the beam recombination device.

What should we expect to happen when we slide the wall in?

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

When wall is out all(100%) of the electrons that get to the beam recombination device are magenta(**earlier experimental result**) at the end.

That means that all the electrons that take the s route end up magenta and all that take the h route end up magenta at the beam recombination device when no wall is inserted.

This means that with the wall inserted, we should end up with 50% (**1/2 lost at wall**) magenta at the beam recombination device. They should all be magenta however based on the earlier experiment since the inserted wall **cannot affect** the electrons on the h path!

What is the actual result?

Again we are wrong in the classical way we are analyzing things.

The result is only 25%.

The h route beam seems to end up **randomized**(50-50 green-magenta) and 50% of 50% is 25%.

If we insert the wall in the h route, the same thing happens. We still end up only with 25% magenta!

Clearly, we have real trouble!

If we forget the wall, then 100% magenta into the device, ends up as 100% magenta out of the device.

If we put a wall on one path, then 100% magenta into the device, ends up as 25% magenta out of the device. Same result if we put the wall in the other path.

So it seems if check (**do a measurement**) to see which path the electron are passing through the device on (**i.e., if we check to see whether a magenta electron is passing through the apparatus as a hard or soft electron**) we get 25% magenta (50% change to green) at the end and if we **DO NOT** check we get 100% magenta (0% change to green) at the end.

Our classical minds are spinning at this point!!

To begin to try to resolve this dilemma, we turn to a quantum system containing only one particle instead of beams of many particles.

So now consider a **single** magenta electron which passes through our apparatus when the wall is out.

Can it have taken the h route? **No**, since those electrons are 50-50 green-magenta(and we need 100% magenta).

Can it have taken the s route? **No**, for the same reasons.

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

If we look (**measure**), then half the time we find an electron on the h route and half the time we find an electron on the s route, but we **never find** two electrons in the apparatus, or **two halves** of a single, split electron, one-half on each route, or anything like that.

There just is **not any experimental way** in which the electron seems to be taking both routes simultaneously. Therefore, as physicists we must rule out this possibility.

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

Certainly not.

If I put **walls in both routes**, then **NOTHING** gets through at all. Thus, it had to have **something** to do with the box.

Let us **summarize** these results to see the dilemma we (as classical physicists) are faced with in this experiment.

Electrons passing through this apparatus, in so far as we are able to figure out so far, **do not take route h** and **do not take route s** and **do not take both routes at the same time** and **do not take neither of the routes**, i.e., they have zero probability for doing these things (from experiment).

Our problem is that those **four possibilities** are simply **all of the logical possibilities** we have any notion of how to entertain using the **everyday language of classical physics**!

What can these electrons be doing?

They must be doing something which has simply never been thought of before (assuming the experiments are correct and they are!) by classical physics.

Electrons seem to have **modes of being**, or **modes of moving**, available to them which are **quite unlike** anything we **know** how to think about using words derived from **everyday ideas and classical physics**. The name of the new mode (**a name for something we do not understand at the moment**) is **SUPERPOSITION**. The same phenomena we mentioned earlier with light resurrecting itself in altogether different and very dramatic new way. In fact, this experiment is just the double-slit experiment and we are seeing wave-like versus particle-like behaviors.

What we now say about our initially magenta electron, which is now passing through our apparatus with the wall out, is that it is **NOT** on the h path and **NOT** on the s path and **NOT** on both paths and **NOT** on neither, but rather **it is in a SUPERPOSITION of being on h and being on s**. What this last statement **means**, other than **none of the above**, we don't know at this time.

That is what we shall be trying to find out as we develop quantum theory.

It will force us, however, to think in terms of **probabilities**, i.e., the magenta electron will have a probability of being hard or soft but is only observed to be magenta at the end if we do not check to see whether it is hard or soft during any intermediate stage of the experiment.

If we check to see if it is hard, then the probability that it is hard is **irreversibly realized** and we have hard electrons in the apparatus(**because we looked??**).

Because this is a very important point in our discussions, we will now look at it in another way. The hope is that we will learn more about it and be able to decide how to build a theory that describes what is happening.

[5] Let us construct a new experimental box which we will call a "**total-of-nothing**" box. It has only two apertures. An electron goes into one aperture and emerges from the other aperture with **ALL** of its measurable properties (color, hardness, energy, momentum, whatever) **UNCHANGED.**

Also the time it takes for the electron to get through the box is **identica**l to the time is would have taken if the box were not there. So **nothing mysterious** seems to be delaying it and messing around with it while it is in the box.

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

Now recall our two-path apparatus from our earlier discussions and hold on to your seats. It is possible to build such a **total-of-nothing** box, which, when inserted into **either** one of the two paths of our apparatus, will **change** all of the electrons that were magenta at the end into green electrons at the end.

When the box is removed they go back to all being magenta.So inserting such a box into **one of those paths** will change the resultant color of an electron passing through the apparatus.

What is going on here?

Total-of nothing boxes **do not change** any measurable property of electrons that pass through them(**by definition**) **AND of course**, total-of nothing boxes **do not change** any measurable property of electrons that **DO NOT** pass through them. That would not make any sense at all.

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

It is not possible for the electron to have passed through the total-of 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 inside and outside of the box or neither as before.

The only answer is that the electron passes through our apparatus in a superposition of passing through the total-of nothing box and not passing through the total-of nothing box and this must cause the color change somehow.

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