# Quantum Thoughts

How do we start our discussion of quantum physics?

Our goal is to delineate in a clear manner a theory of quantum phenomena and then determine if this theory is supported by real world experiments(**which is the only test for validity that we will accept**).

We will approach the problem without prejudice towards any ideas.

The goal of this discussion is for all of us to reach the point where we can understand what quantum physics is all about and how it proposes to explain the experiments that clearly defy classical physics.

We will first present a quick overview of the ideas that will occupy our attention for most of this seminar. Don't worry if there are things in the overview that do not make sense, we will come back to all of them in detail later and you will understand them eventually. Finally, we will return to the quantum world and investigate it in great detail.

**Quick Overview:**

I will note the appearance of many words when we use them during this overview so that we realize that we do not really understand their meaning at that point in our discussions....even though we may think we do!

Two major facts dominate the entire quantum physics story.......

**First, quantum theory works !!!!!!**

It is an extraordinarily accurate theory. It accurately describes(as we shall see) the microworld of atoms and beyond(smaller). It works better than any previous physical theory. Quantum theory works from aggregates of atoms like crystals (sizes of order $10^{-1}$cm) to fundamental particles(sizes of order $10^{-21}$cm). This is a truly amazing range of validity - a factor of $10^{20}$ - that is the same as the ratio between diameter of our galaxy ($10^{22}$cm) and a meter stick($10^{2}$cm)! Its predictive capabilities are shown clearly in an experiment that measures a property of the electron called a magnetic moment

$$\text{experiment} \to 1.0011596521 \pm 0.0000000093 \qquad \text{theory} \to 1.001159652 \ \pm 0.000000046$$

Quantum theory is able to clearly explain the stability of atoms, quantized energy levels in atom, emission of light at definite wavelengths, chemical forces determining all molecular properties, reliability of inheritance in DNA, lasers, superconductors and superfluids, semiconductor electronics, computers and so on ....

QM is at the heart of all areas of modern advanced technology.

**Second, no one understands quantum theory !!!!!!**

When we apply the theory to calculate various quantities associated with a physical system we will always get the correct (agreement with all experiments) answer. Although this is true even after 80 years of successful predictions, there is still significant argument about

(a) **the meaning of its assumptions**
(b) **how the assumptions relate to "reality"**
    (as we shall see after we are able define it)

We will find out that all these arguments are about "**interpretation**".

By this I mean that everyone, no matter how they might choose to interpret quantum theory(and they will do it very different and sometime exceedingly strange ways), calculates the **SAME** answers for **ALL** phenomena under consideration. They **ALL** get the same answers when they make predictions!

We will spend most of our time with two central issues:

(1) **the nature of measurement**
(2) **the nature of reality**

because these ideas are at the heart of quantum physics.

When people are doing physics or when non-physicists think about what physicists are doing, they sometimes think that physicists are

"**finding out the way things are**"

As we shall see, this is a sensible thing to say in "**classical**" or "p**re-quantum**" physics, where we are able to

"**relate the REAL world to our EVERYDAY experiences**"
(this is one way to define "reality")

Classical physics relies on the **assumption** that an "**observer**"

**can "know" BOTH "where" an electron(or a cow or a 747) is and "what" it is doing**

Making this statement more rigorously, we would state that a classical "observer" **can "know" the POSITION and VELOCITY of an object "simultaneously"**

This statement turns out to be very nearly true. In fact, we can do it with seemingly arbitrary accuracy for cows and 747s. But it will turn out **NOT** to be true for electrons or any other objects in the microworld! As we shall see in our upcoming discussions, quantum theory will completely destroy any analogy we might try to make between electrons and cows!

The theory will imply that **BOTH** position and velocity cannot be simultaneously known with arbitrary accuracy no matter what we do or how clever we are! Think about the implications of that statement for a second. Think about what that statement means for subsequent predictions of motion!

Based on the special theory of relativity, all physicists believe that no information can be propagated at speeds faster than that of light. Yet we will be faced with quantum experiments that seemingly have no other explanation than the requirement that one quantum system has **instantaneously** influenced all other quantum systems anywhere in the universe....in what Einstein called **"spooky action at a distance".**

What then is the "reality" that we will eventually associate with an electron? What will quantum theory have to say? The act of measurement(**we will have to be very, very careful about how we define measurement later on**) in quantum theory introduces inescapable "random(**need to be careful about meaning**)" elements into the measured system.....consider the following:

We have a large number of "**identical**" particles (systems)....

Classical measurements give **EXACTLY** the **SAME** value of all dynamical variables, the position, for example, for each identical particle - **that is what the classical physicist means by the word identical**

While quantum measurements give **DIFFERENT** and **UNPREDICTABLE** values for each particle **even though we said they were identical so I guess we are going to have to carefully define the word "identical"**

It will turn out, however, that in the quantum world I can, after making a very **large** number of measurements on these "**identical**" systems, state a "**probability**" that the position will have a particular value........that is, for the next measurement to be made of the position $x$, we have

$$probability(x) = \frac{\text{number of times value } x \text{ was measured}}{\text{total number of measurements}}$$

This type of statement is one that is based on the results of **all previous measurements.** The goal of quantum mechanics is to predict these probabilities before the measurements are done.

Let us see how this probability stuff works. Consider this example. Suppose we measure the heights of Swarthmore students and we find:

$N = 1300$ = total number of measured heights(in cm)

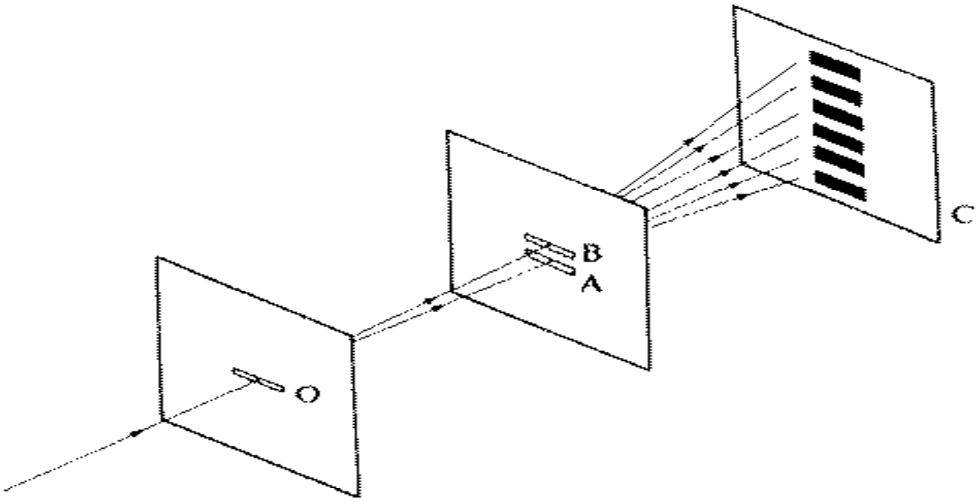
| $n_h$ | $h$ |
|---|---|
| 50 | 150 |
| 100 | 160 |
| 200 | 170 |
| 300 | 180 |
| 300 | 190 |
| 200 | 200 |
| 100 | 210 |
| 50 | 220 |

where $n_h$ = number of times height $h$ was measured. Then the probability that we will measure $h = 190$ cm if another student (if we missed one) walks in is

$$probability(x) = \frac{\text{number of times value 190 was measured}}{\text{total number of measurements}} = \frac{3}{13}(23\%)$$

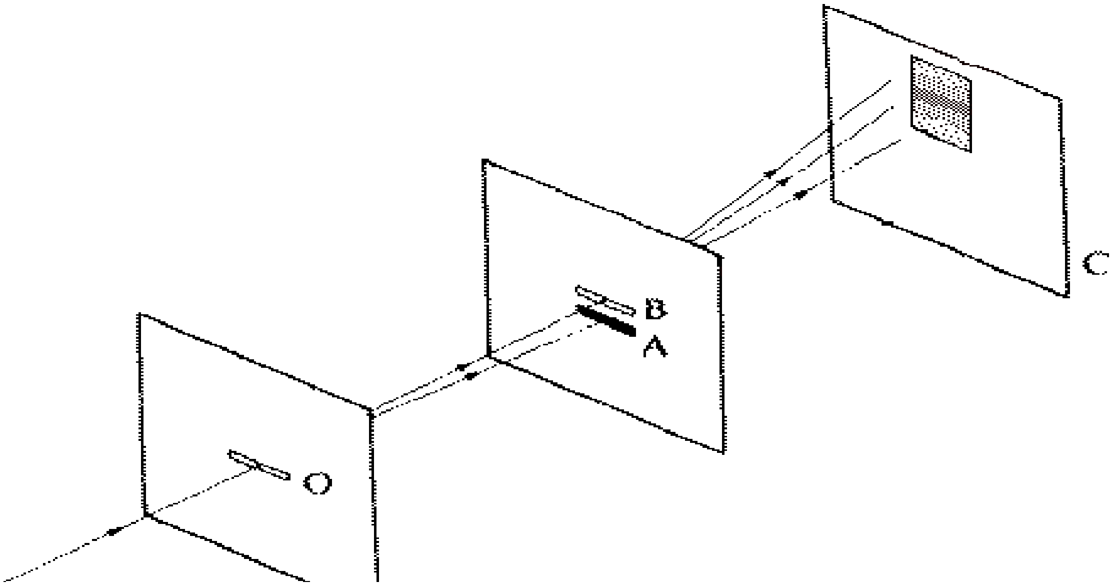
This is a very simple and intuitive definition and it seems to work very well (it is exact in the limit of $N$ = total number $\to \infty$ which we cannot really do). Being comfortable with it, however, does not mean that it is correct! We will also look at other ways of thinking about probability, for example Bayesian ideas.

Now, we consider an example of an experiment that exhibits quantum mechanical effects. We return to our earlier discussion of slits and interference patterns. We have a source of photons(single slit O = laser) + double slit(B and A) and screen(C), which detects photons **individually as discrete events**(flashes).

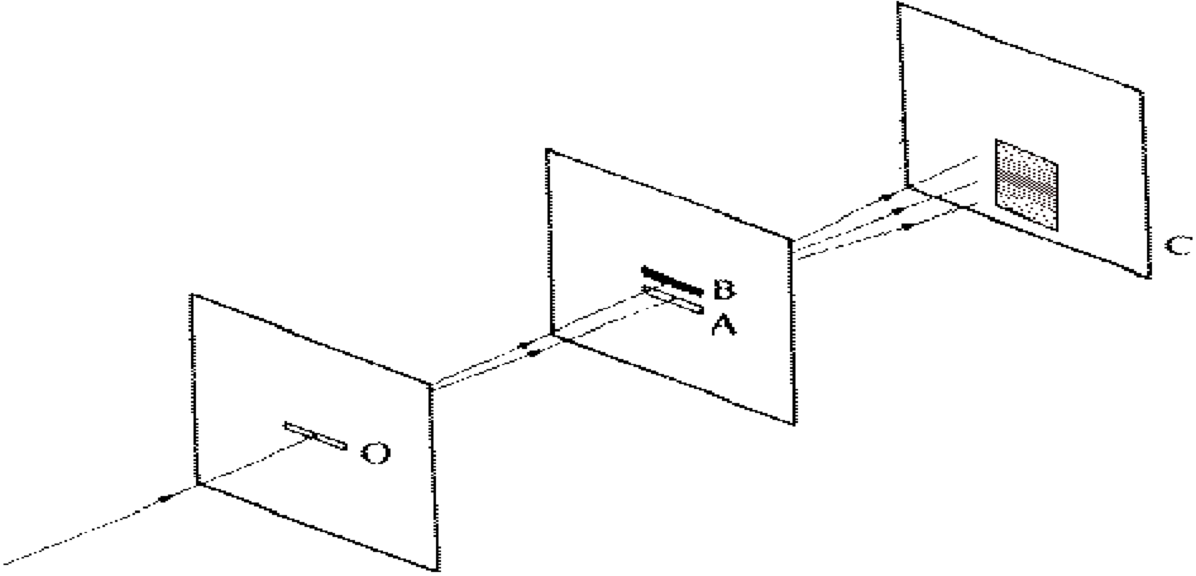


Some very curious quantum behavior occurs as follows.

Suppose only slit B is open. Many places on the screen are reached by photons(photons are detected there) as shown in figure.



If only slit A is open, we get similar results in different place with some overlap of the two regions as shown.

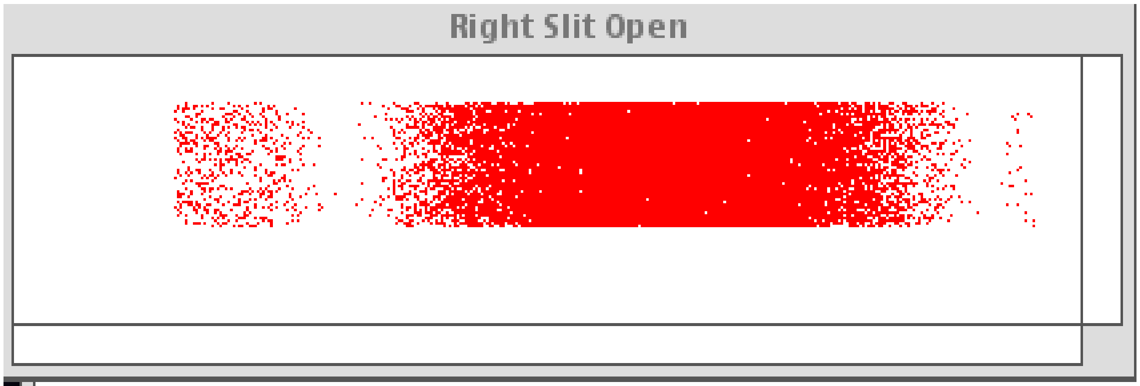


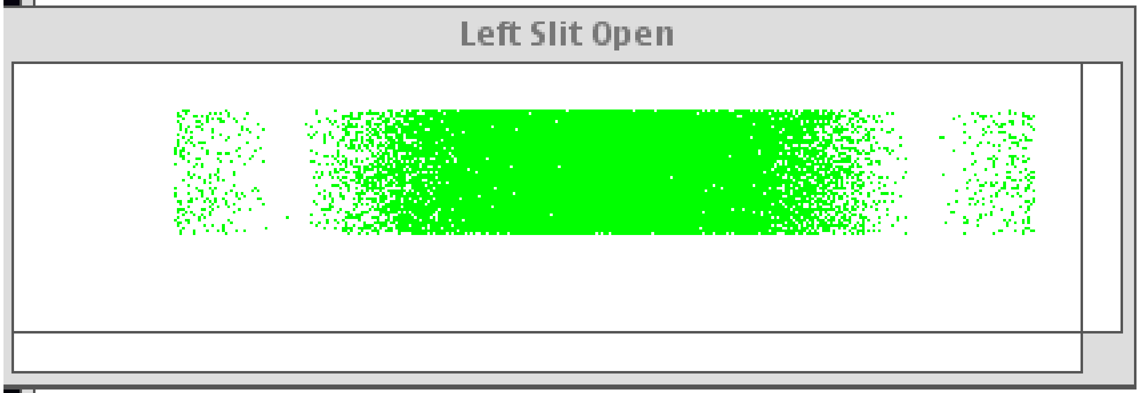
If we open both slits, then a strange thing occurs. Some spots where photons had been detected with only one slit open(A or B) now have **NO** photons being detected, that is, opening more slits causes less photons to reach a some spots on the screen! Let us see how this works via a simulation where we see the flashes:IDL PROGRAM

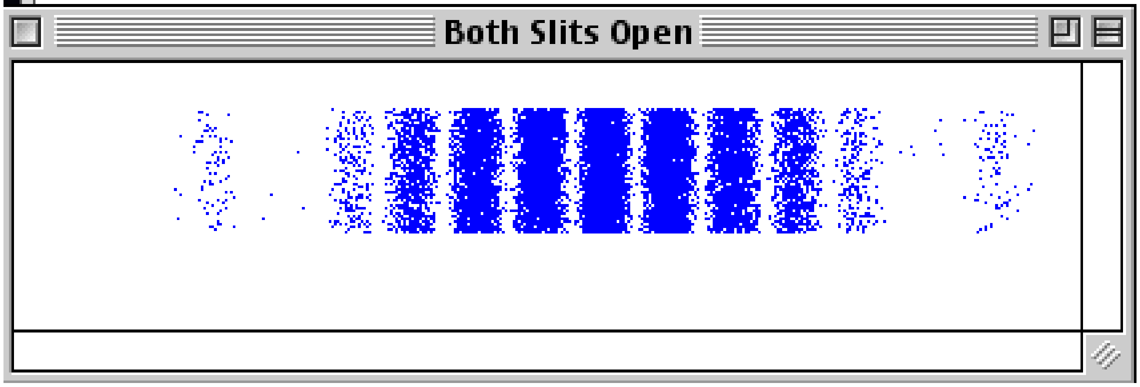
```
function prb2,xx,cent,nn
d=0.5 & b=0.0001 & lam=0.0000003
sep=5.0*b
xx=xx+cent*(sep+b)/2.0
```

```
sth=xx/sqrt(xx^2+d^2)
u=!pi*b*sth/lam
if (u EQ 0.0) then begin
  z = 1.0
endif else begin
  z=(sin(u)/u)^2
endelse
if (nn NE 1.0) then begin
  z=z*(cos(!pi*sep*sth/lam))^2
endif
return,z
end

pro elecint1
temp1=[0.0,0.0] & temp2=[0.0,0.0] & xr=0.0020
red=   [1,0,1,0,0,1,1,0] & green= [1,0,0,1,0,1,0,1] & blue=  [1,0,0,0,1,0,1,1]
window,0,title='Right Slit Open',xpos=10,ypos=10,xsize=400,ysize=100
tvlct, 255*red,255*green,255*blue
plot,temp1,temp2,xrange=xr*[-1.0,1.0],yrange=[0.0,1.0],/nodata, $
psym=3,color=1,xstyle=4,ystyle=4
xr0=!x & yr0=!y
window,1,title='Left Slit Open',xpos=10,ypos=160,xsize=400,ysize=100
tvlct, 255*red,255*green,255*blue
plot,temp1,temp2,xrange=xr*[-1.0,1.0],yrange=[0.0,1.0],/nodata, $
psym=3,color=1,xstyle=4,ystyle=4
xr1=!x & yr1=!y
window,2,title='Both Slits Open',xpos=10,ypos=310,xsize=400,ysize=100
tvlct, 255*red,255*green,255*blue
plot,temp1,temp2,xrange=xr*[-1.0,1.0],yrange=[0.0,1.0],/nodata, $
psym=3,color=1,xstyle=4,ystyle=4
xr2=!x & yr2=!y
count=1L
while (count LT 100000L) do begin
  x= xr*(-1.0+2.0*randomu(seed))
  y=x
  count=count+1
  wset,0
  !X=xr0 & !Y=yr0
  if (randomu(seed) LT prb2(y,-1.0,1.0)) then $
       plots,x,randomu(seed),psym=3,color=2,symsize=1
  wset,1
  !X=xr1 & !Y=yr1
  if (randomu(seed) LT prb2(y,1.0,1.0)) then $
        plots,x,randomu(seed),psym=3,color=3,symsize=1
  wset,2
  !X=xr2 & !Y=yr2
  if (randomu(seed) LT prb2(y,0.0,2.0)) then $
        plots,x,randomu(seed),psym=3,color=4,symsize=1
 endwhile
 end
```







This same experiment can be done with electrons with the same results!

We get this interference pattern buildup even when the intensity goes to zero or we reduce the number of photons per second to a very small number.

In particular, let us reduce the intensity so that the number of photons in the apparatus at any given time is just 1 ! These experiments have only become possible in the last decade.

How do we know only 1 photon or electron is in the vicinity of the apparatus?

Say apparatus has a length $L = 3m$. Since the speed of light is $c = 3x10^8$ m/sec, the time it takes a photon to pass through the apparatus is $T = L/c = 10^{-8}$sec.

Therefore, if we want only 1 photon in apparatus at any time, then the time between photons coming out of the source and entering the apparatus must be greater than $10^{-8}$sec or equivalently, the number of photons per second is less than $10^8$/sec (the intensity of the beam entering the apparatus).

typical light = $10^{-19}$ Joule per photon ($E = h\nu$)

$10^8$ photons/sec = $10^{-11}$ joules/sec = $10^{-11}$ watts
(typical light bulb = 60-100 watts).

If we surround the source with a sphere that has a small pinhole in it, then the ratio of the area of the pinhole(diameter = $10^{-6}m$) to the area of the sphere (radius = 10m) is approximately $10^{-13}$.

Therefore, a source delivering a total of $10^{-2}$ watts (in all directions) will deliver $10^{-11}$ watts to the apparatus through the pinhole.

**So it is easily possible create an experiment where only one photon is in the apparatus at a given time.**

In this case, one can actually observe the screen flashes from individual particle impacts as the pattern builds up!!!

So let us say again what happens.

In this experiment a stream of particles is directed toward a screen. A second screen containing parallel slits is put in between the source and the screen. In this way, each particle must pass through one slit or the other in order to reach the final screen(**or so we think**). Each time a particle reaches the screen it causes a flash or a detector to click.

Yet the most amazing thing(according to classical physicists) is that if you close down one of the slits more particles make their way to certain places on the final screen than if we leave both slits open.

There is no way to understand this paradox if you insist on regarding the beam as simply made up of little particles(bullets). Especially as we reduce the intensity towards zero.

Let me ask what will turn out to be a poorly worded question. How does a single particle "KNOW" if you have one or two slits open?

If this is an interference effect(wave theory of light) ... what is the single photon interfering with?

Photons cannot split, so it cannot be one piece interfering with another.

The photon goes through one slit or the other (**maybe?**) and if we wait long enough(even days) the proper interference pattern appears anyway.

If we try to detect(no matter how clever we are) which slit it went through we destroy the interference pattern and end up with the sum of two single slit patterns.

Some **totally new way of thinking** will be necessary in order to understand this!!!

Let us step back a second and consider a **comparable "classical" experiment.**

Imagine pouring a container of sand onto a flat plate with a small centrally located hole. A few centimeters below the plate is a tiny movable detector that counts the number of sand grains hitting it per unit of time. It would show, as we expect, that the greatest number of sand grains is registered directly under the hole and the number decreases as the detector is moved transversely(parallel to the plate) away from the hole.

If we puncture another hole in the plate near the first one, cover the first hole and repeat the experiment we get the same results just shifted so that the maximum number is now under the second hole.

If we open both holes then the total number of grains reaching the detector at any location is the sum of the number of grains reaching the detector at the location from each hole independently.

In other words, opening up more holes can only increase, and never decrease, the total amount of sand reaching the detector per unit time at any location.

In the experiment with photons or electrons, no photons or electrons can be created or destroyed by the apparatus(same as for sand grains).

Yet somehow less photons can reach a spot on the screen when both slits are open then the sum of the numbers from when each slit was open separately.

Somehow, scaling the properties of the particles down from macroscopic to microscopic radically alters the way in which the particles get distributed (they must still be somewhere).

We never see two things that can happen independently somehow conspiring to cancel each other out in the macroscopic world! But such occurrences seem to happen constantly in the microworld.

How will quantum theory want us to think about all of this so that we have some hope of understanding what is happening?

As we shall see, quantum theory will produce the following explanation (if I have to use "words"):

When the photon is "**going between the source and screen**" (**whatever that means**) the state of the photon cannot be described as

having gone through slit B
having gone through slit A
having gone through both slits simultaneously
having gone through neither slit

which exhausts all the **logical possibilities** we can imagine in the macroscopic world.

As we shall see, the photon is a mysterious combination (**superposition**) of **all** the possibilities or maybe **none of the above** in any fashion.

A "superposition" will **only be understandable** via the mathematical language we will develop. We will not be able to make a model of what is happening because, as we shall see, there are no models (in the classical sense) available to us in the quantum world. We will not be able to find words from everyday language that will allow us to give an accurate description of what is happening. It will not be possible!!! Words are an incorrect language for describing the microworld.

Since that has never happened to you before, it has to seem mighty strange. Not really, however, since you have never tried to described what electrons and such are doing.

The fact that this result holds even if we reduce the intensity of the photon beam so that only one photon is entering the apparatus per year will force us to think in terms of "probabilities" instead of "classical paths", which might allow us to say which slit the photon passed through. Each photon, which does something different than the other "identical" photons, will be forced to behave probabilistically.

We will consider many different experiments in our discussions. They will exhibit the very strange quantum behavior of systems in the microworld.

Our attitude will have to be.......

Well, if the microscopic world works in these strange ways no matter what quantities we are measuring, then so be it.

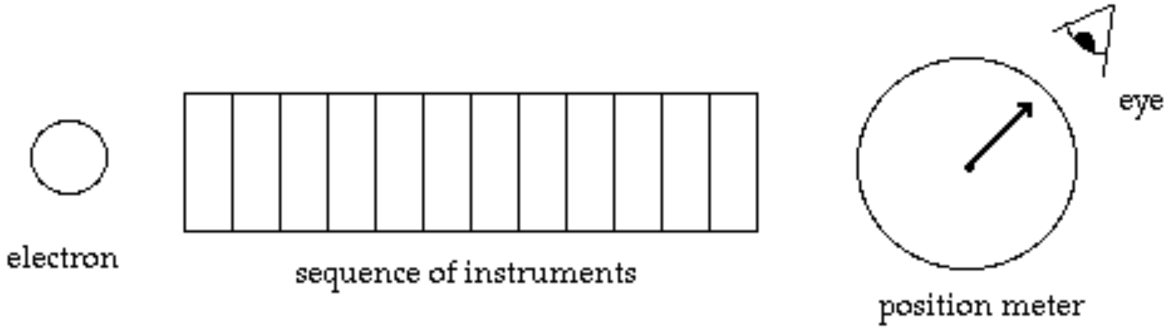
We must let our theories accommodate themselves to this new kind of "**reality**"

So, later in our discussions of the quantum world, we will accept the experimentally observed properties that we find and try to work out a theory that incorporates them fully. We feel that if we can it will be a theory that can be used to make predictions about other phenomena in the microworld.

Alas, if it only was going to be so easy. It turns out that the microworld is much worse than we can imagine even if you were having a nightmare from too much beer and pizza.

To see this.......consider the following:

Let us try to measure the position of an electron. Suppose we know that an electron is in some box. Then, schematically our measuring process must look something like



The point here is that you will NOT have observed the electron DIRECTLY!!!!

Some as yet undefined sequence of "expensive instruments" is between the observed electron and your eye looking at some pointer.

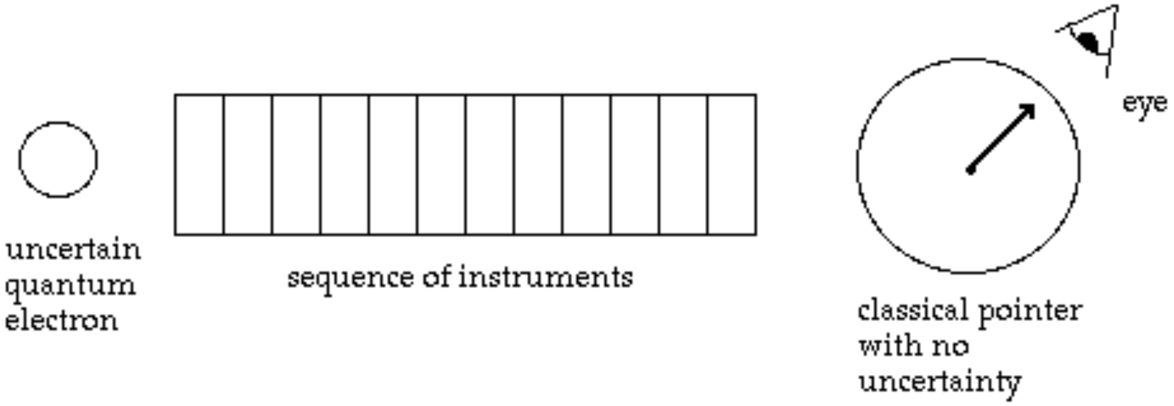
This means that we do not "see" things in the quantum world the way we think we "see" them in the classical world (where we seem to see objects directly or so we think).

Actually, as we shall see in our discussions, the two worlds are really exactly the same, but it will turn out that they will behave very differently in the way the act of "seeing" **interacts** with the system being "seen".

One of our crucial questions will be....

Where in the sequence of instruments (measurements) is the information or action or cause which makes the position dial point to a definite value replacing the quantum uncertainties of the electron with the definiteness of the pointer?

It will turn out that what we really should say is happening is



The crucial question will be ......... what happens in between?

Some kind of "discontinuity" will have to occur to abruptly remove the uncertainties of the quantum measurements.

But where does it occur?

This will be among the most puzzling parts of our discussions. Many great minds have fallen by the road side in trying to tackle this question.

So, these ideas are where the much of our course discussion will have to dwell.

This question is what all the interpretation debate in quantum theory is really all about !!!

**Among other thing**s that we shall find out, perhaps the strangest will be that an electron can pass through that wall (so could you by the way...just more difficult(less probable) and certainly more painful) in a very strange way.

It simply **vanishes** on one side and **reappears** on the other side and I mean that statement very **literally**.

Why should that be disturbing?

It is that we will not be able to say(measure) that it was ever at any place(position) in between.

Here and there and NEVER in between.

In fact, if we try to "see" if it is in between, then it will not be able to get through!!!! It will behave classically and no matter how much I try to throw this eraser that we are "watching" through the wall it will never make it.

Nothing in our **everyday experience** prepares us for this kind of phenomena.

By the way, suppose we put the eraser on the table and do not observe in any manner. Can it suddenly appear on the other side of the wall? The answer will be YES!!! The probability will be very small however...so small that we probably will not see it occur in the lifetime of the universe.

Now, interference works for intense beams (intense = wave behavior).

When we do not have an  intense beam (lots of photons), then the wave model fails. However, for a very weak beam of photons, i.e.,  one photon per century , as we said earlier, we eventually get the same pattern.

What then is interfering with what? Or is interference not the right idea?

Remember a single photon can only produce one bright dot on screen and not a pattern. Any one photon simply ends up at a particular spot on the screen.

Each photon is identically prepared.

We cannot predict where a particular photon will end up.

The end result after centuries is the same pattern as if interference had taken place.

**How do they each know what to do?** (this will turn out to be a poor question)

The only satisfying explanation will use probability.

Each photon has a probability $P(x)$ (where $P(x)$ implies the arrival pattern at the detector discussed earlier)of ending up at position $x$ on the screen.

We might say that each photon independently uses $P(x)$ to choose an impact point. We might say that each photon independently generates a part of interference pattern.

**Another useful way** to think about single-photon interference is as follows:

Suppose that a photon is a superposition of all things it can possibly do. Then it passes through the slits in a state that is a superposition of passing through slit b and passing through slit a.

Photons will not produce the interference pattern if we know (must measure)they are going through a particular slit.

Somehow they will "know" if other slit is open/closed and change the probabilities of doing things.

If we try to check which it goes through then quantum behavior disappears and they are like sand grains.

**In quantum physics you cannot know which slit it passes through - this question will make no sense - it will, in fact, be meaningless.**

If you check to see if it goes through a particular slit, then it either hits your detector(went through that slit) and no photon gets to screen --> no pattern or it does not hit your detector and hence it went through other slit.

But a single photon going through a single slit produces a different pattern, which, of course, it then does.

Your extra experiment forces the photon to go through one slit or the other and the interference pattern changes.

What was initially a photon with many possibilities (many probabilities to do different things) is now a photon doing a definite(single thing) because **you measured it doing that particular thing**.

We have **collapsed** possibilities into definiteness by trying to know what it is doing and in the process the experimental result is always destroyed.

If we wish to retain quantum effects, then we cannot know what is happening in between-- we can only have probabilities of final outcomes.

So if we do not look at photons they interfere, but if we look, then they behave like sand grains and do not interfere.

That is the way we shall find that the quantum world works.

Clearly, this behavior will have devastating effects on our notions of reality.

Before we jump into developing the theory, let me present some more food for thought so that our minds are in the right frame to proceed.

What will we find in the quantum theory?

Things will seem to move without following any mechanical law.

Things will seem to move in a disjointed or discontinuous manner. They will "jump" from one place to another, seemingly without effort and without bothering to go between the two places.

Quantum theory will suggest that what one uses to observe nature on an atomic scale "**created**" and determined what one saw. That nothing has properties independent of the observer. The values one observes will appear to depend upon what one chooses to observe.

Despite the natural disorder apparent in these experiments, quantum theory will indicates that there is an **order** to the universe.

**It simply is not the order we might expect.**

In the microworld, we will find that any path from causes to effects is constantly blurred by uncertainty and jogged from side to side by randomness and chance.

How can this be the ultimate theory that underlies the ordered and inevitable universe revealed by classical physics?

Let us say a little more about the early quantum theory according to Schrodinger,Heisenberg and Bohr.

**The Wave Equation......**

The first development of a formal quantum theory was due to Schrodinger. He used analogies with standard classical wave theory to come up with a new "wave" equation analogous to the classical wave equations for sound, light, strings, etc.

Schrodinger's "wave" equation provided a continuous mathematical description(via differential equations) of how quantum probabilities develop in time.

The problem was that no one could imagine what these "**waves**" looked like. They had no recognizable form in **physical space**. They did not behave like water or sound waves. They seemed to be only mathematical things ....only functions of space and time.

This is why Schrodinger disliked the theory he devised! He was looking for a real physical wave..... a de Broglie "matter" wave of some kind in physical 3-dimensional space.

By adding these waves together(like mathematical vector addition) physicists found out that they could represent particles (objects of limited extent) that behaved correctly.

Heisenberg and Dirac(almost simultaneously) came up with alternative formulations of quantum theory using matrices and vectors). Dirac developed most of the general principles we shall use shortly.

Born and Bohr developed the so called "standard" or "Copenhagen" interpretation of these theories in terms of probabilities and measurements. The principles espoused in this standard interpretation are the cause of all the vigorous debates about interpretation.

Central to the problems of interpretation will be the idea of a measurement.

We now look at some **examples** in order to clarify some of these thoughts:

When you look at something, you are detecting reflected light that has come from some source, "bounced" off the object and then entered your eye.

The reason we don’t normally think about seeing in this way is that in our everyday world we can safely assume that light bouncing off something macroscopic doesn’t change that object in any measurable way.....the photon energy is insignificant compared the macroscopic object energy.

When we get to the quantum world, however, this comfortable assumption **no longer** works. If we want to "**see**" the bundle of matter (bunch of E and p) that we "**call**" an electron, then we have to "**bounce**" another bundle off it. In the process the electron is significantly changed, since the bundle energy is comparable to the electron energy.

To understand this better, consider the following:

Suppose that you wanted to find out if there was a car in a long single-lane tunnel.  Also suppose that the ONLY(this is the equivalent situation for electrons) way that you could do this was to send another car into the tunnel and listen for the crash.

crash → a car was in the tunnel
no crash → no car was in the tunnel

Obviously our detection scheme will work and just as obviously, our detection scheme has a rather "**drastic**" effect on the object being detected (in this case it changes the object velocity to zero).

In the QUANTUM WORLD, this is the **ONLY** measurement we can do !

They are called "**destructive**" measurements. (the classical world is full of "**non-destructive**" measurements).

**This will be our first rule of QM:**

You cannot observe something without changing it in some way during the measurement process (this is related to the famous Uncertainty Principle of Heisenberg in action as we shall see later).

Think again about the car in the tunnel. When we chose to observe one thing......the location of a car in the tunnel........our measurement procedure was such that we had to forever be uncertain about something else (some other property of the car). In this case, we lose all information about how fast the car was moving before the collision.

When we walk into the tunnel, we can accurately locate the crash and thus we know what the position of the car at the instant of the crash and we have time to measure it exactly or $\Delta(\text{position}) = 0$.

However, we know nothing about the velocity before the measurement (collision in this case).

The inability to observe things in the microscopic world without at the same time disturbing them has some surprising consequences when you start to think about the way particles move from one point to another.

Again let us use cars as an **example**.

Suppose I ask where a particular car will be TOMORROW.

In the ordinary everyday world we would just look to see where it is now and THEN look to see how fast it is moving and in what direction. The we use our calculator and figure out the answer - we get a DEFINITE ANSWER.

If the car is replaced by an electron, you can’t look at it more than once----the first look changes everything.

You cannot know with precision both where it is AND how fast it is going at any instant of time. The best you can do is to play one uncertainty against the other so you know both quantities "**reasonably well**" in some sense.

You might say(after a measurement) that the car is in the Chicago area and heading in a generally easterly direction at about 40-60 mph. More measurements imply more disturbances thereby increasing uncertainties and not helping us at all.

In order to talk about where the car will be tomorrow, we are forced to speak in terms of PROBABILITIES.

The car might be in Detroit or Cleveland or even NYC, but it is not likely to be in Miami or London. We can make similar statements about when it might be at these places.

The collection of all probability information will be everything we can know about the electron(car).

We will call this maximal set of information the **STATE** of the electron.

**IT WILL BE ALL THAT WE CAN KNOW !**

Up to this point, you have probably been following along pretty easily, perhaps thinking that you might as well humor this guy since he is the professor.

Well hold on, things are about to become really strange.

The reason you are **not bothered** by having to describe the car(electron) in terms of probabilities is that **DEEP DOWN** you **KNOW** that the car is "**really**" somewhere **ALL** the time and if you could just peek, you would see it merrily tootling along any time that you wanted to.

Of course, if you did, then you would change it and mess up the experiment, but you still have that confident feeling that some how the car is **REALLY** there, even if you don’t **SEE** it (this is called **objective reality**).

You might even imagine the entire country as an underground parking lot in which you can see the car **ONLY** at the exits. You may not be able to see it **BETWEEN** the exits, but, if you saw it enter the garage, then you **KNOW** it is always somewhere inside the garage.

**This is not the way, however, that a physicist envisions electrons.**

Their view,as we shall see, is that **UNTIL** you look(perform a measurement) at a particle you have to treat it as **ONLY** a set of probabilities(maximal possible information).

The car **IS NOT** really at **ANY** particular place **UNLESS** it is being measured.

In between, it is just a set of probabilities that describe what could happen if a new measurement were to take place -- in between, it is **ONLY** a **state.**

This assumption will, as we shall see, have directly measurable consequences. It is not just idle talk! If we assume anything different, then our predictions will not agree with experiment, as we shall see.

The idea that there **HAD** to be some sort of underlying reality beneath the states and their associated probabilities was what led Einstein to make his famous comment that:

"**God does not play dice with the universe**"

Less famous is Bohr’s reply:

"**Albert, stop telling God what to do**"

Finally, let us consider the saga of two gloves......this tale illustrates a central feature of quantum theory.

**The Tale of 2 Gloves (read carefully)**

You and a friend are at Mitchell airport in Milwaukee. You each have a locked box containing a glove. One box contains a right-handed glove of the pair, the other the left-handed glove, but you do not know which. Both of you also have keys, but they are not the keys to the boxes you are carrying.

Carrying your box, you each board a MidWest Express plane. You fly to San Francisco and your friend flies, at the same time, to Philadelphia.

When you get to San Francisco you use your key to open a locker at the airport, and inside you find another key. This is the key to your box, which you now open to discover that the glove you have brought to San Francisco is the right-handed one.

As soon as you know this, of course, you know also that your friend's box, by now in Philadelphia, contains the left-handed glove. With that instantaneous realization, you have acquired a piece of knowledge about a state of affairs on the other side of the continent.

Perfectly straightforward, you may say, and so it is. You may have heard of Einstein's rule that nothing, not even information, can travel faster than the speed of light, but no part of this story contradicts this rule in any way.

You have made a deduction, using information available to you at the San Francisco airport, about a fact that pertains to your friend in Philadelphia. We make this kind of **long-distance inference**, in big ways and small, all the time.

An astronomer observing the weak light that reaches a telescope here on earth uses it to deduce the surface temperature of stars many light years away. You get out of the shower one morning, look at your watch, and realize that a class meeting that you had to attend has already started.

**Figuring out** what is happening in some distant place is a **different** thing from **transferring** that knowledge from one place to another.

If, having discovered that your glove is right-handed, you wanted to tell your friend that she has a left-handed one, you would have to pick up the telephone, or send a telegram, or send her email or mail her a postcard. Some of these might even travel at close to the speed of light(under ideal conditions).

You have no way, however, of knowing whether she has already opened her box or not - unless you get a message from her telling you that you must have a right-handed glove.

The fact that you have found out which glove she has does not allow you to beat the laws of physics and get that information to her faster than Einstein allows.

But still, you think that there might be some way of exploiting your knowledge to influence your friend's behavior.  Suppose, before you both set off on your plane trips, you had agreed with your friend that if she found the left-handed glove in her box she would proceed onto London, but if she found the right-handed one she would fly to Paris.

Does your opening the box in San Francisco determine where she ends up?

**Not a chance!**

**Whichever glove was in her box was there from the outset(objective reality)**, so whether she has to fly to London or Paris is **predetermined**.

When you open your box in San Francisco you instantly know where she must be going next, but her destination is as much a surprise to her as it is to you.

As before, you have found out what happens next, but you have no influence over it.

**Now let us change this story.**

The gloves in the two boxes are, you are informed, of a strange and quantum-mechanical kind, **unlike** any gloves you have ever come across before.

They still make up a pair, but for as long as they are sealed up in the boxes, they are neither right-handed nor left-handed, but in an unfixed, indeterminate state.

Only when a box is **opened**, letting in the light, does the glove inside **instantaneously become** either right-handed or left-handed and there is a 50-50 chance of either eventuality.

During the several hours you are in the plane flying to San Francisco, you may well be puzzling over what the glove in your box - this strange glove, neither right-handed nor left handed but potentially either - actually looks like. But you do not have the key that would let you open the box and peek inside, and, in any case, as soon as you **peeked** the glove **would have** to take on a definite shape, right-handed or left handed.

The quantum-mechanical nature of the glove is such that you **can never see** it in its unformed state, because as soon as you look, it turns(**collapses**) into something familiar and recognizable.

**A frustrating catch-22.**

On the other hand, as soon as you arrive in San Francisco and open your box to find, let us suppose, a right-handed glove, you begin to think that things are not as straightforward as before. You immediately know that when your friend opens her box, she must discover a left-handed glove.

But now, apparently, some sort of signal or information must have traveled from your glove to hers, must it not?

If both gloves were truly indeterminate before you opened your box and looked inside, then presumably as soon as your glove decided to be(remember it is 50-50) a right-handed one, hers must have become left-handed, so that the two would be guaranteed to remain a pair. **That is the rule for these quantum-mechanical gloves.**

**Does this mean** that your act of observing the glove in San Francisco **instantaneously** reduced the indefiniteness of its partner in Philadelphia to a definite state of left-handedness?

**It now occurs to you that there is another possibility.**

How do you know that your friend did not get to Philadelphia first and open her box before you had a chance to open yours?

In that case, she evidently found a left-handed glove, which caused yours to be right-handed even before you looked inside your box. So, if there was an instantaneous transmission of information, it might have gone the other way. Your friend's act of opening her box determined what sort of glove you would find and not the other way around.

Now you realize that the only way to find out which way the instantaneous transmission of information went, from your glove to hers or from hers to yours, is to pick up the telephone and call Philadelphia and find out at what time she opened her box. That telephone call, however, travels slower than light. Now you are really getting confused.

There seems to have been some kind of instantaneous communication between the two gloves, but you cannot tell which way it went, and to find out you have to resort to old-fashioned, slower-than-light means of communication, which seems to spoil any interesting tricks you might be able to figure out if there **really** had been an instantaneous glove to-glove signal.

If you think again of the strategy whereby your friend had to get on a plane to either London or Paris, depending on which glove she found in her box, then you realize you are no more able than before to influence her choice by your action in San Francisco.

The rules of the game are such that you have a 50-50 chance of finding either a right-handed or a left-handed glove in your box, so even if you are sure that you have opened your box before she opened hers , and even if you think that opening your box sends an instantaneous signal to hers, causing her glove to be the partner of yours, you will still have no control over which glove you find.

It remains a 50-50 chance whether she will end up in London or Paris.

**You have no say in the matter!**

So now you are even more confused.

You think there has been some sort of instantaneous transmission of information, but you cannot tell which way it went, and you cannot seem to find a way to communicate anything to your friend by means of this secret link between the gloves.

Perhaps you might even conclude at this point that it is a good thing that real gloves are not like this.

In that case you would be in agreement with Einstein.

It is true that gloves do not behave this way, but according to quantum theory, as we shall see, electrons, photons and other elementary particles do!

These particles have properties which, apparently, lie in some unresolved indeterminate (**entangled**) state until an observer comes along and does an experiment that causes them to be one thing or the other(**collapses their state in some way**). The observer cannot know in advance what the result of any particular measurement is going to yield; quantum theory predicts only the probabilities of possible results.

This greatly offended Einstein's view of what physics should be like.

Before quantum theory, it was taken for granted that when we measure something, we were **gaining knowledge of a pre-existing state**. That is, gloves are always either right handed or left-handed, whether we are observing them or not, and when you discover what sort of glove you have, you are simply taking note of an independent fact about the world (objective reality).

Quantum theory says otherwise. Some things are not determined except when they are measured, and it is **only by being measured** that they take on their specific values. The gloves are neither right-handed nor left-handed until we check.

Einstein and his colleagues actually devised an experiment of this sort(not with gloves) as a way to show how absurd and unreasonable quantum theory really is. They hoped to convince their physicist colleagues that something must be wrong with a theory that seemed to demand signals traveling faster than light.

Not withstanding the genius of Einstein, in this case he was sadly wrong. Nothing genuinely unacceptable is actually happening with the gloves. The whole thing may seem very odd, and it may seem quite inescapable that some sort of instantaneous communication between gloves is essential for everything to work, but in the end it seems impossible to do anything with this communication. We will discuss this real experiment in detail later.

Quantum theory arrives at what it deemed an acceptable interpretation of this sort of puzzle by insisting that we stick to practicalities.

It is no good, and indeed very dangerous, to speculate about what **seems** to happen in such a case. Stick to what actually occurs, and can be recorded and verified, and you will be all right. If you cannot actually send an instantaneous message of your own devising, then it is meaningless to guess at what might or might not have been secretly going on between the two gloves.

You might think that if we do not "**understand**" all aspects of what is going on then we will not be able to do anything useful with this quantum theory stuff.  It turns out just the **opposite**!

Well, so much for our overview.

Now for the details of how quantum theory works........

Quantum Mechanics is a branch of physics that has a **well-defined set of rules** which tell physicists how to set up a certain class of problems and how to do the calculations needed to solve the problems. In **all cases**, if the rules are followed, then the calculated results always agree with experiment.

Physicists generally do not need to engage in a debate about the meaning of the assumptions of QM and most do not since it makes them very uncomfortable to realize that they really do not understand what it is they are using everyday.

As we shall see, the interpretations of the principles of Quantum Mechanics easily inspire a very vigorous debate about their meaning. The outcome of the debate, as we shall see, will have no effect on the values obtained from our calculations, i.e., the calculation rules are independent of their interpretations!

This is very convenient for the practicing physicist. They can discover fundamental effects, use them to create neat new devices, make lots of money and gain lots of fame while never understanding the meaning of their assumptions at all.

In this seminar, however, we are interested in the meanings and interpretation of the principles. In order to do this we must understand how to do Quantum Mechanics first.

We will now develop an understanding of the tools used by the physicist to do Quantum Mechanics. Only after we understand how to do Quantum Mechanics and see some of its dazzling and astounding effects will we discuss the interpretations.

We approach this discussion from a real **theorist’s** viewpoint.

Not many of you have ever seen a theoretical physicist in action, so some of this will seem very much off the wall. It is important to remember that the theorist has only one goal.....to understand the universe in some manner.

No assumption is considered too crazy to be included.

Invention of new ways of thinking will be commonplace.

Strange interpretations will be given all over the place.

What is correct? ....Only that which agrees with measurements!

We proceed along the lines set out by Paul Dirac in the 1920s modified by much hindsight from the intervening 75 years of discovery.