Start of Part #1

By the end of this class you will understand these sentences:

Everything we call real is made of things that cannot be regarded as real.

Quantum mechanics asks: Is FALSE the SAME as NOT TRUE?

What is quantum mechanics trying to tell us?
“Correlations have physical reality, that which they correlate does not"

Beginning Ideas and Thoughts

Two Big questions. How does the universe work?

What are the fundamental principles involved?

Any discussions/answers must involve Physics, Mathematics AND possibly Philosophy

19th century versus 20th century

Physicists arrived at very different ways of thinking.

Classical Physics	Quantum Physics
Determinism	Randomness
Locality	Non-locality
Foundation of physics 1650-1920	Foundation of all modern physics 1920 -2024

These two paths offer radically different views of reality

For our present purposes: Let us ask: What is quantum mechanics?

Before 1920 physicists thought they understood everything, but world was not what it seemed!

Microscopic world = Quantum Macroscopic world = Classical (but not so sure now!)

Clear they needed a new theory to explain new experiments being done in the Microworld.

Our everyday experience(classical) is very misleading, i.e.,
it leads to ideas that do not work in the microworld as we will see.

We will find that QM => the fundamental building blocks of everything
=> the us with an ability to develop a theory of microworld

Two important new properties arise.

They are adequately summed up by the words

Potentiality and Uncertainty

Must use Experiments $\xrightarrow[\text{development}]{\text{allow}}$ Postulates and Tools ==> QM Theory

The Goals of this Class

How QM works
Why it must work this way
How to understand it
What it all means

My assumptions about you

You remember some HS math + you are willing to learn some new mathematics.
Basically, you will be learning a new language!

You are willing to **completely** change your view about how the universe works.

To discuss QM - we first need to agree on some terminology from Philosophy

Epistemology versus **Ontology**

↓ ↓

Study of things we just know versus **Study of what is actually out there**

↓ ↓

Realist **versus** **Instrumentalist**

↓ ↓

Science = reality versus **Theory must agree with data**

↓ ↓

Objects are really there versus **Does not care if objects are really there**

Example to think about ………..

When we study the **state** of a QM System

It will **seem** to depend on what **we know.**

Realist ⟶ will say state is not real because our knowledge can change

Instrumentalist ⟶ will say all OK, it is just our information that changes

The Classical Point of View due to Newton and Maxwell

Fundamental concept = particle trajectory in physical variable(position/time) spaces

System = collection of particles **isolated** from universe

State = Values of set of observables or measurable quantities → Trajectory = particle state

State = collection of particle states

Extrinsic versus Intrinsic observables

↓ ↓

position/velocity versus mass/charge

Information is known with infinite precision (in principle)

Limited only by instrument precision but **not** by Nature

Outcome of all measurements can be predicted using trajectories

Newton's Laws of Motion → {
Position+velocity+momentum+energy+force
Requires knowledge of position/velocity **at some time**.

—> initial conditions

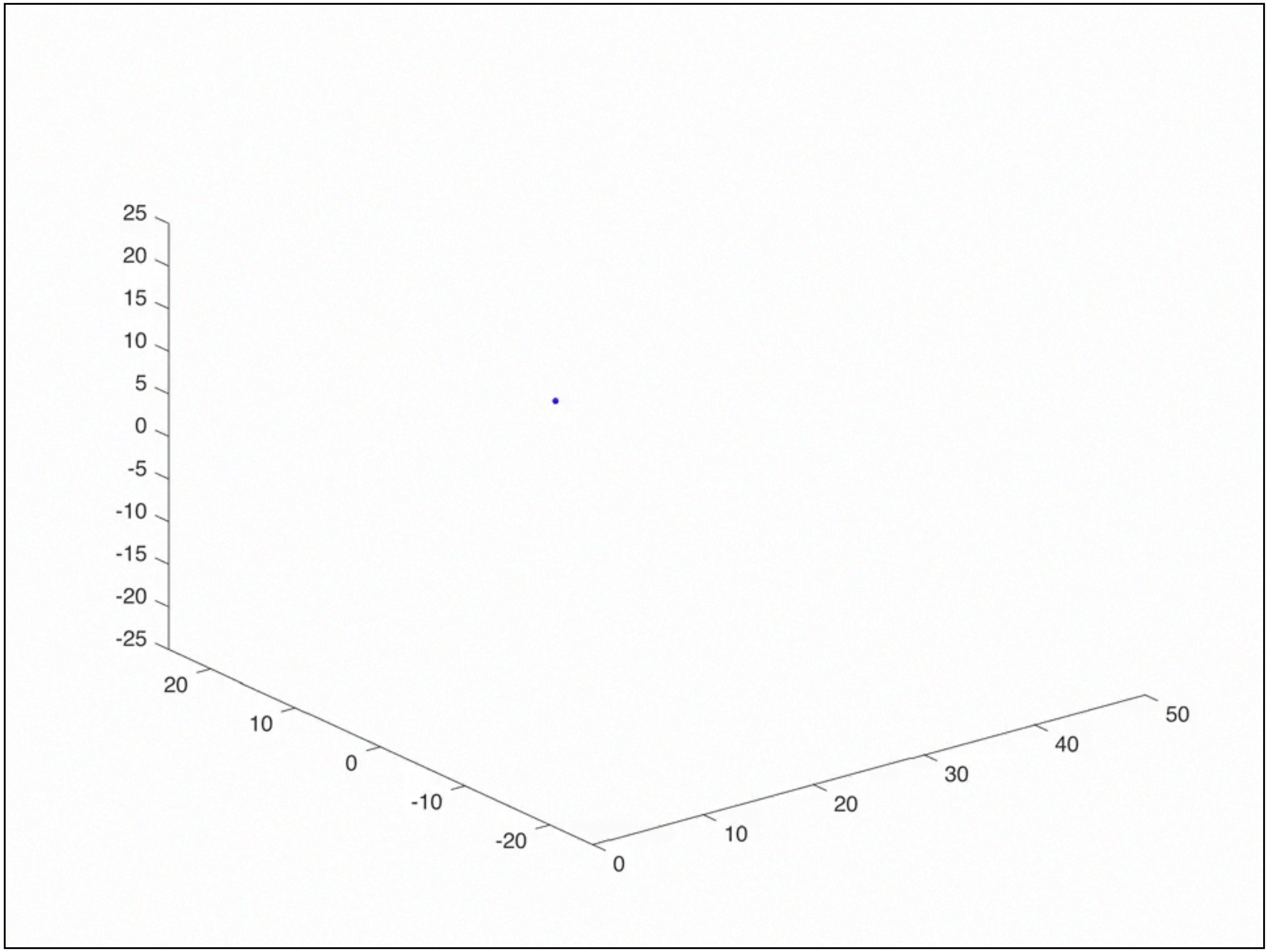
They believed that if we can determine initial conditions without disturbance.

then could **predict** trajectory ⟶ then know all **future** behavior

Belief: accurate predictions limited only by accuracy of initial conditions + knowledge of forces

These ideas work very well for macroworld for centuries - **We did land on the moon!!**

One fly in the ointment = **chaos** ⟶ Sensitivity to initial conditions ⟶ not predictable



There is no randomness involved in this chaotic motion; it just looks like it!

In QM, as it turns out, we will discover that **true** randomness actually exists

Concept of a Newtonian Clock ==> a **Determinate** Universe

Everything we observe **had** a cause in the past!
Causality is **fundamental** in this classical world
If same cause **,** then same effect! (**QM will say this is WRONG!!**)
It will seem like there is no **free will** (and **maybe** there is none!)

Now we go through the Looking Glass: The Quantum Point of View(#1)

Will observe that "classical particles" **do not exist** in the microword!

⟶ we will **need** a radical revision of the definition of a particle.

We will struggle with understanding **when/why** it seems that a "Particle **not** a Particle"?

We will see: objects seem to behave like a classical particle sometimes **and** seem to behave like a classical wave sometimes ——> the so-called **wave-particle duality** that you have all probably heard about!

We will find, however, that quantum particles are **neither** classical particles **nor** classical waves.

They only **seem** to be in particular circumstances!

WE MUST KEEP AN OPEN MIND

Object properties **may have nothing** to do with either classical idea(waves or particles)!
All such classical ideas may be **totally** wrong!!

If we do find classical physics is WRONG(it disagrees with experiment), **then we should not** try to make quantum things be like the classical things that do not work!

To set the stage for our later discussions - here are some of the strange quantum ideas that will appear in during those discussions:

(1) Quantum properties are not well-defined **until** measured

(2) QM rarely gives a **definite** answer to any question

(3) The quantum state will be a mixture of **all** possibilities

(4) QM will **only** predict possibilities and probabilities

(5) QM will **seem** statistical - i.e., seem to only apply to ensembles of systems.

(6) Random chance will **seem** to control everything

(7) Will find that when measurement gives value - then repeat - get same value
—> **HAS** that value at that moment

(8) Will find that before measurement there is **no** value! **Only** a **potentiality** exists!

(9) Will find that measurement **alters** system - it is unavoidable - effect cannot be zero!

(10) Will wonder if particles exist when their properties are **not** being measured?

(11) Will ask, is what we study in physics, reality or merely our **perceptions** of reality?

There are many more I could list!! **WOW!**

The Decline and Fall of the Trajectory (remember : Trajectory = Classical View)

trajectory = set of (positions, momentum, time) for a particle

where first elements of the set = **initial conditions**

ensemble of “identical” systems = set of “identical” trajectories
= set of “points + errors”

classical world —> errors can be made small as we wish(no theoretical limit) - **ASSUMPTION**

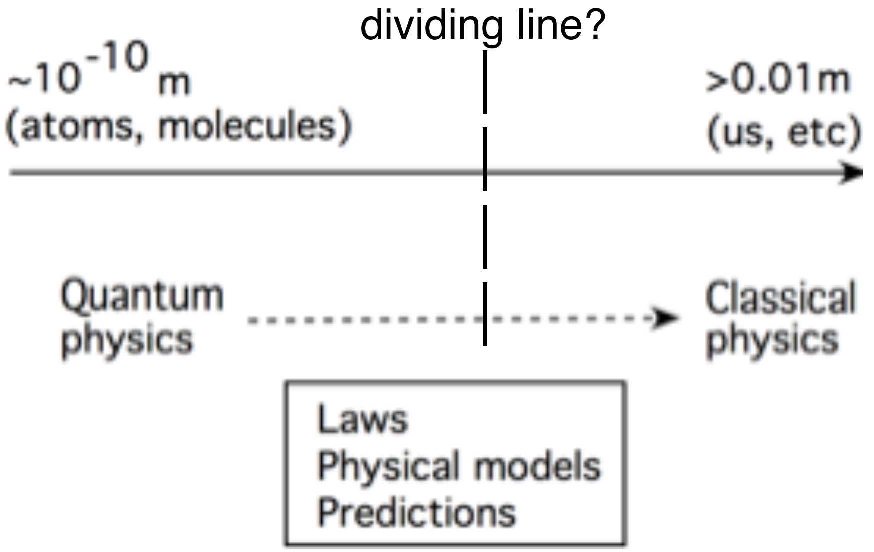
quantum world —> this is **NOT TRUE** <— exists an uncertainty principle = fundamental limit

True randomness in quantum world **will destroy** the old classical deterministic idea!

Question: Can Classical and Quantum Physics Get Together Somewhere?

Since limit of large systems in microworld $\longrightarrow$ macro world

does QM $\longrightarrow$ CM in this limit? Is there a “dividing line”?



Bohr proposal - Correspondence Principle

Where is dividing line? The so-called **Heisenberg Cut**

No one knows - it may not exist!!

QM will try to tell us - will have to see what it says!!

QM will tell us:

Do not make any statements that can not be verified.

or put another way……

We can only know properties that can be measured.

Physics(QM), as we will see, is an **experimental** science

We get ideas from experiments and theory predictions **must be verified by experiment**

If particle **is** measured to be at (x_1,t_1) and (x_2,t_2), **then** particle **was** at x_1 at t_1 **and** x_2 at t_2

Since there were no measurements, QM **cannot** talk about particle in **between** two points

i.e., we did not measure particle to be anywhere else, so we cannot say it was in QM!

Clearly, this strange manner of thinking will affect the QM view of Reality

The study of QM is **difficult for many reasons**:

(1) We are **macro objects — here is a quote —**

> **Things on a very small scale behave like nothing you have any direct experience about. They do not behave like waves, they do not behave like particles, they do not behave like clouds, or billiard balls, or weights on springs, or like anything that you have ever seen.**
>
> — Feynman

(2) The microworld can be understood, but it **cannot be seen(with our eyes!)**.
It can only measured with sensitive instruments which our eyes can then read.

(3) Quantum mechanics is inherently **mathematical. Why?**

Because **Mathematics** is the **language** of quantum physics.

It will only make sense when described with mathematics.

We must deal with that fact and we **will**!

Be prepared to **give up** many ideas that you did not possibly think could be wrong!!!!

Let us proceed! ⟶ **Into the Microworld we go.**

Like Alice though the Looking Glass!

Our **first pass** through the quantum ideas and experiments will now be done **without** knowing the theory that follows.

3 important ideas dominate: **Quantization, Uncertainty and Duality**

Quantization: Macroworld **seems** to be **continuous**.
Microworld is **discrete**. **This will be most important!**

Uncertainty: Fundamental **limitation** on measurement.
Some observables cannot be measured at **same** time.
——> Heisenberg Uncertainty Principle

Duality: Usually seen in so-called Wave-Particle Duality, but is a much wider effect than that.

It will be the first **challenge** to our classical intuition.

How Physics Works(or is supposed to work).

Physics **starts** with experimental data, which is then **followed** by a **hypothesis** that explains the data.

Usually we build a hypothesis slowly via **many** experiments.

Full theory can be so complex it requires approximations to make predictions.

Sometimes we use **thought** experiments; but real experiments are **required** before conclusions can be made.

Let us look at an experiment that has been both kinds of things!

—> **The Double-Slit Experiment**

First discuss —— Waves versus Particles Classically

Particle = trajectory => spatially localized + well-defined speed.

Carries energy (localized)

Obeys Newton's laws

Wave => not spatially localized => wavelengths and frequencies.

Carries energy/momentum spread over a wave front.

Exhibits non-particle-like properties;

Maxwell's equations —> **light = EM wave**.

—> Diffraction, Interference and Polarization

Waves versus Particles in the Microworld

The Microworld does not seem to have such a **clean** separation between the two ideas.

It will be very **hard** to classify objects as a particle or a wave or neither.

It will **seem** that all classical ideas have to be tossed away!

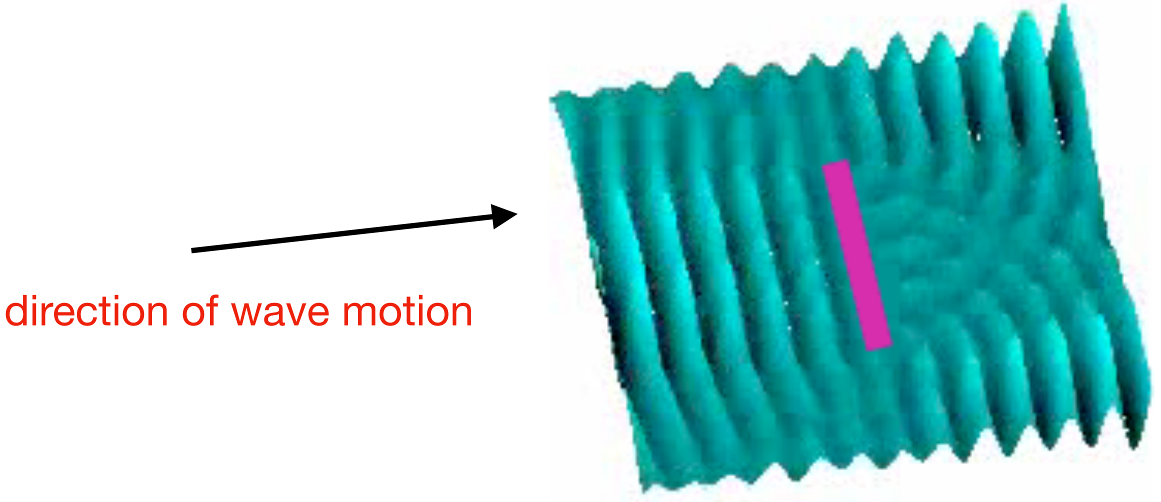
Light

Newton **thought** light = particles based on experiment + classical theory;

Young (then Maxwell) **thought** light = wave based on experiment + classical theory

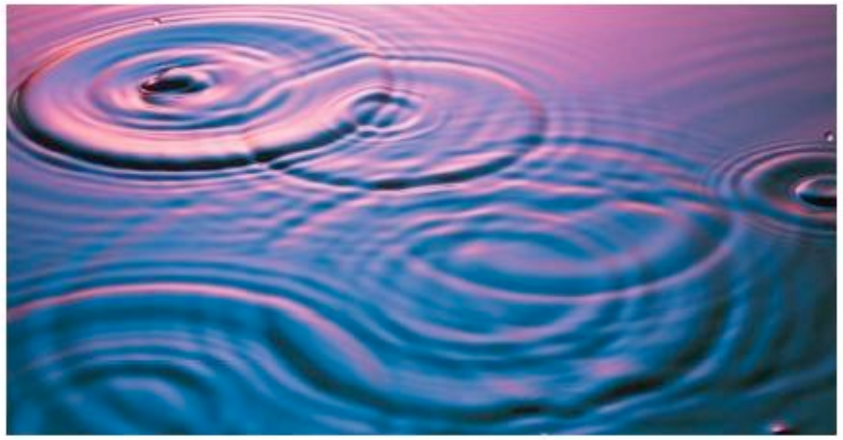
Einstein finally **showed** light = particle based on experiment/theory(photoelectric effect)

If it was a particle —> see sharp shadows, but waves can bend around objects.



wave get behind barrier!

particles would exhibit sharp edge



Young said it is a wave. Shadows would be fuzzy!

Used **wave interference** property to confirm this fact.

Ultimately devised a 2-slit experiment to confirm ideas.

—-> Light is a wave **because** it exhibits **interference**.

Maxwell says light = electromagnetic radiation(wave) from his famous equations.

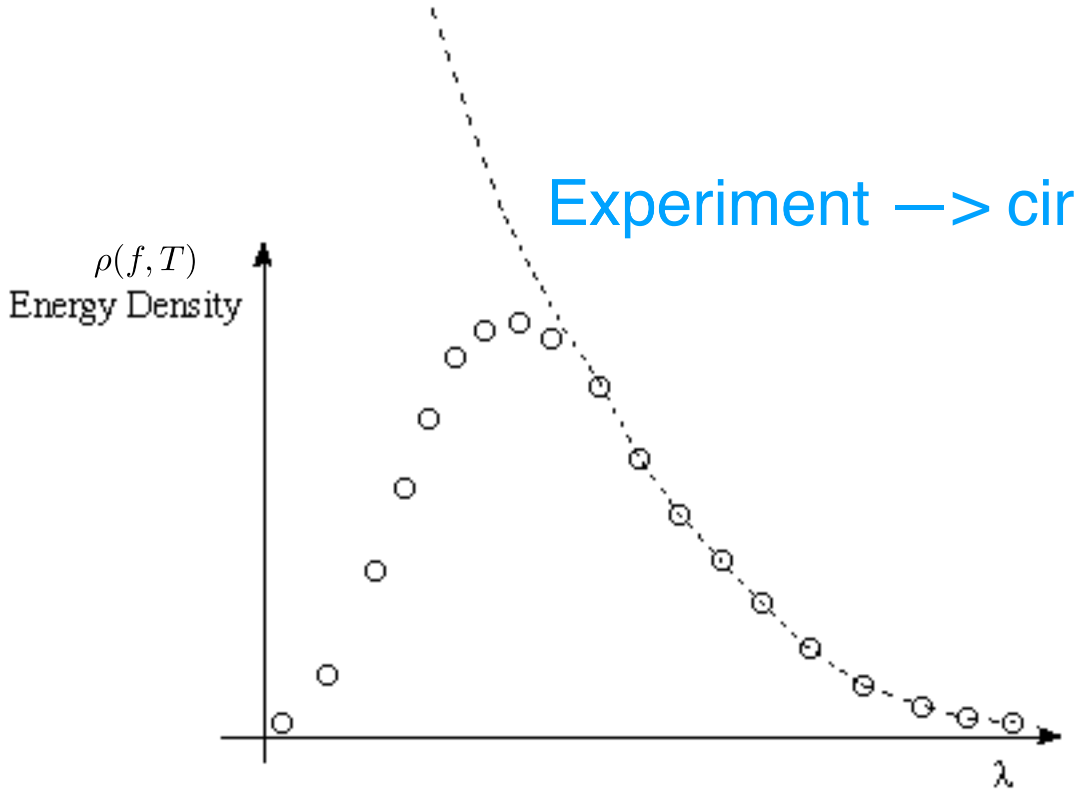
Wave ideas and explanations so **perfect** in classical realm that light as particle idea **fades**.

Walking the Planck

Blackbody radiation - What is it? —> Radiation observed when a body is heated!

$$\lambda = \frac{c}{f}$$

—> Blackbody Spectrum and first theory by Wien —> dashed line



Experiment —> circles

$$\longrightarrow \quad \rho(f,T) = \frac{8\pi k_B T}{c^3} f^2 = \frac{8\pi k_B T}{c} \lambda^{-2}$$

How did Planck explain it? Planck used thermodynamics + intuition(always dangerous!)

Model = radiation from atoms in solid due to charge(in walls of cavity) oscillations

$$\longrightarrow \quad \rho(f,T) = \frac{Af^3}{e^{Bf/T} - 1}$$

Agrees with experiment perfectly - but it is an **empirical** formula - he could not predict A and B

—> A and B must be determined by experiment —> **not** a real **predictive** theory

Low and high frequency limits were perfect. But he could not justify law rigorously.

Mathematical trick now leads to a new physical idea and a puzzle!

During a 2nd attempt at the derivation Planck used a common math trick(a simplifying assumption) during an intermediate step in the derivation.

Usually after doing algebra and taking appropriate limits the simplifying assumption is removed. It was a standard mathematical procedure that was used everywhere(**it works!**).

Now electromagnetic theory says a body emits/absorbs energy **continuously(waves)**;

During his derivation Planck assumed(the trick) the emission/absorption process was discrete(particle), i.e., the radiation did not come out continuously(wavelike) but in discrete chunks(particle-like) governed by a new constant **h**;

He then did the math and then took the appropriate limits at the end(the standard mathematical procedure) to go back to emission being a continuous property.

When energy value was discrete in units (constant(h) x frequency) he derived that

$$\rho(f,T) = \frac{8\pi f^2}{c^3}\frac{hf}{e^{hf/k_B T} - 1}$$

The mathematics trick enabled Planck to derive values for A and B as seen above.

He now had a full-fledged theory!

However his result disappears if he removes the trick!!!!!

Experimental agreement —> constant h **must** be 6.63.x10^{-34} J-sec

Planck's constant

Because it is not zero ===> energy not continuous (energy is quantized)!

If make h=0, which the math trick always requires in the end, then theory fails to work!

Puzzle: Is getting the correct answer an accident due to using the math trick or is this episode telling us something about world that we would not have guessed?

That is the danger of using intuition…….

Quantized light or "Particles" of light

Einstein grabbed hold of the "energy is not continuous" idea and did this………

Einstein —> energy in EM field not spread out on wavefronts —> light is **not** a wave!!!!

Energy is localized in clumps(**quanta**!) = photon where $E = hf$ f = frequency

Only **very intense** light appears to be a wave! This can be proved!

He said Planck's trick worked in the derivation **because energy IS quantized**.

IT WAS NOT THE TRICK - NATURE ACTUALLY WORKS THAT WAY!

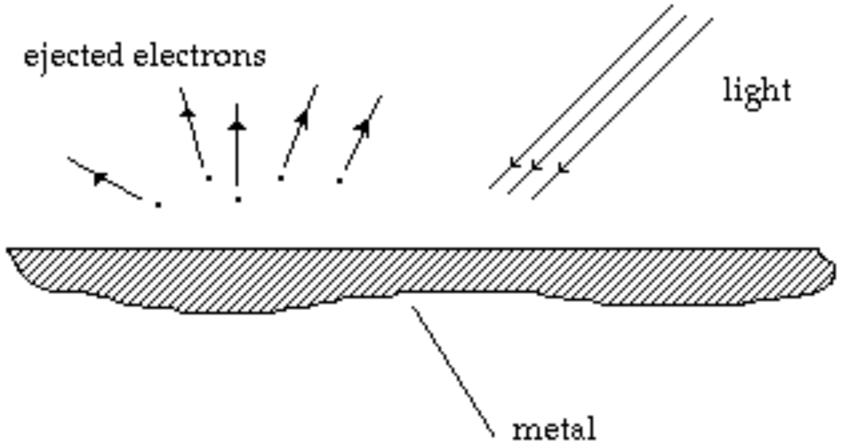
This quantum idea will be fundamental later to order to explain quantum measurement.

Quantized light energy or the photon idea had now explained blackbody radiation.

But any good theory should be able to explain **all** other phenomena also.

Photoelectric Effect - Einstein gets Nobel Prize

= Ejection of electrons from metal when light shines on it



Experimental results:

1. Exists a threshold frequency f_0
2. Ejection independent of light intensity unless $f < f_0$
3. If $f > f_0$ detection is instantaneous
4. Detected electron energy $= h(f - f_0)$

If light = wave, then energy proportional to **intensity** —> if bright enough should eject electrons independent of frequency, **but it does not unless above rules satisfied!!**

Also, waves cannot transmit energy so **quickly**.

Explain **bathtub-rubber duck** analogy.

The photon (quantized light) model **<—>** Explains every feature of the experiment!

1. $f < f_0$ —> single photon energy too small
   threshold => minimum energy to eject(called the material **work function**)
2. Energy of photon depends on frequency NOT intensity
3. Photon absorption is instantaneous (true for all quantum creation/annihilations)
4. Energy must be larger than work function of metal

Note that photon picture later also corroborated by Compton in x-ray scattering by electrons.

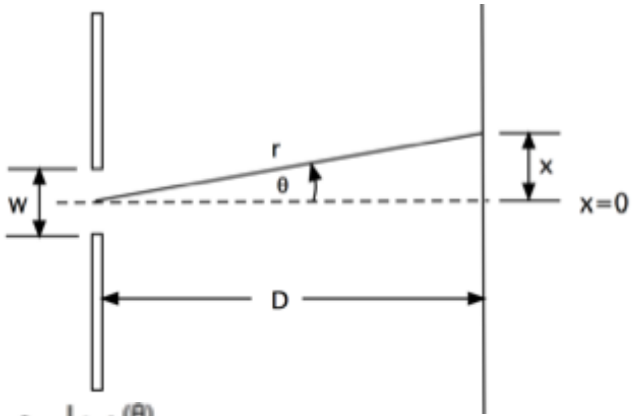
Problem: Light exhibits interference and particles do not interfere or so everyone thought!

Interference and Diffraction

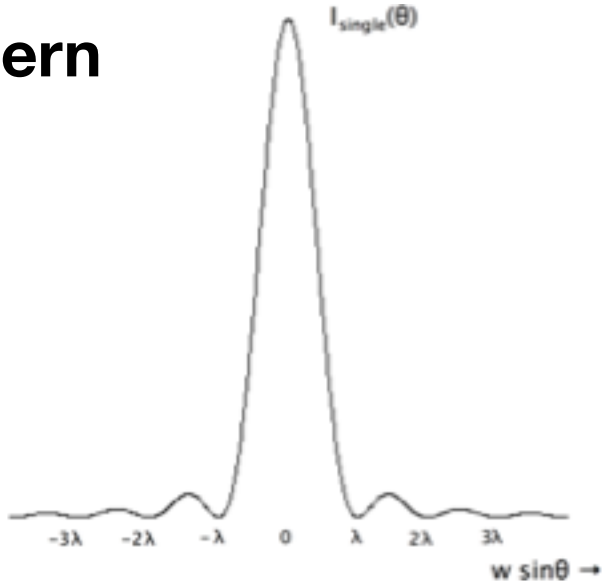
For lots of details read **Light and Interference** see supplementary notes.

or Ask questions after class

Single-slit



screen pattern

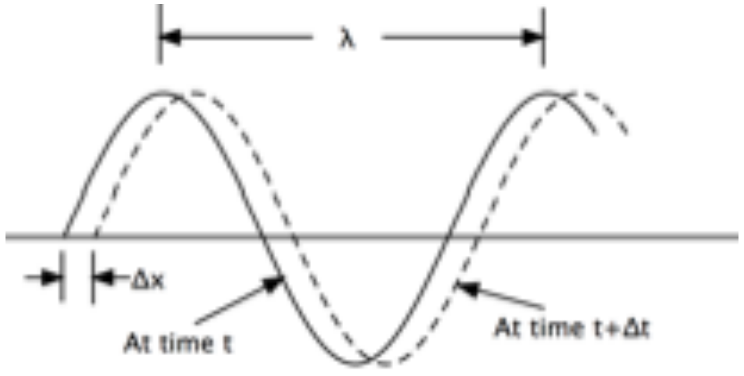


Interference Pattern

Note the nodes or zeroes -> NO PHOTONS

Simple Theory - see supplementary readings for more details

Wave form is $$y(x,t) = A\sin\left(\frac{2\pi}{\lambda}(x - vt)\right)$$



—> wave transports energy and momentum

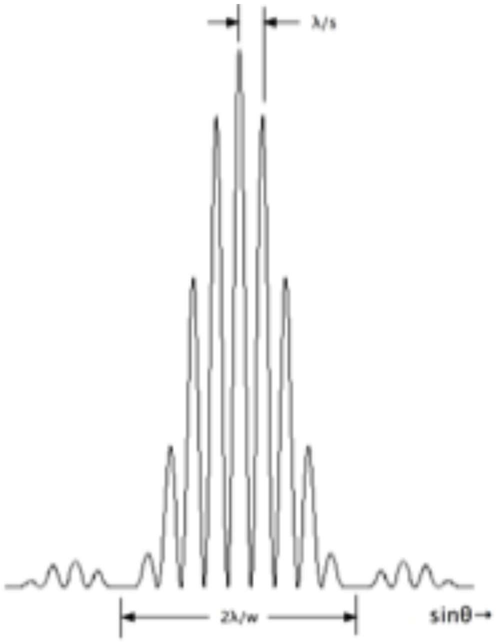
Waves can be added/subtracted = **superposition**

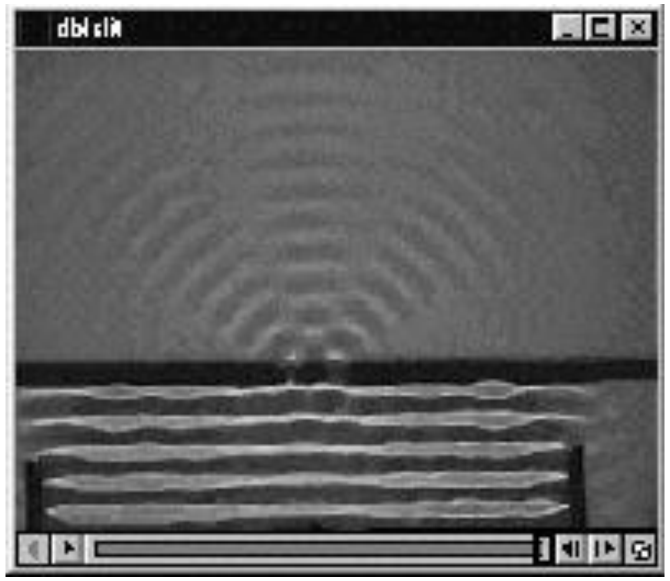
$$y_1(x,t) = A\sin\left(\frac{2\pi}{\lambda_1}(x - vt)\right) \qquad y_2(x,t) = A\sin\left(\frac{2\pi}{\lambda_2}(x - vt)\right)$$

$$y(x,t) = y_1(x,t) + y_2(x,t) = A\sin\left(\frac{2\pi}{\lambda_1}(x - vt)\right) + A\sin\left(\frac{2\pi}{\lambda_2}(x - vt)\right)$$

$$y(x,0) = 2A\underbrace{\cos\left[\pi(\bar{k}_1 - \bar{k}_2)x\right]}_{\text{low frequency}}\underbrace{\sin\left[\pi(\bar{k}_1 + \bar{k}_2)x\right]}_{\text{high frequency}} \longrightarrow$$

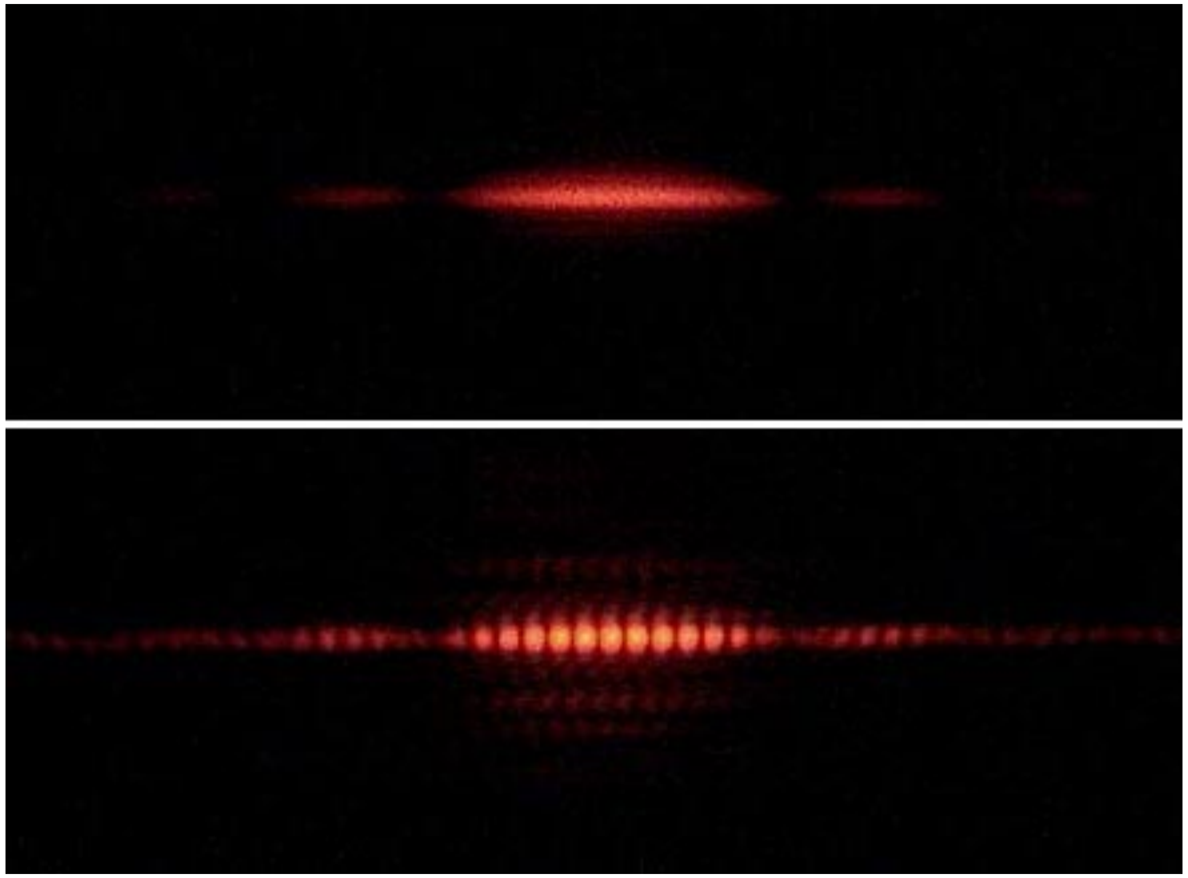
$$\bar{k} = 1/\lambda$$





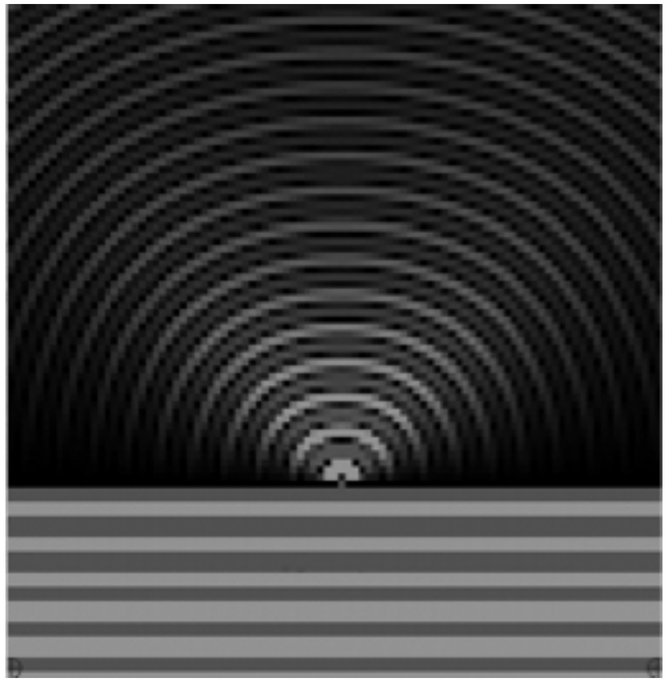
Example:
Water Waves

2-slit interference pattern(light)

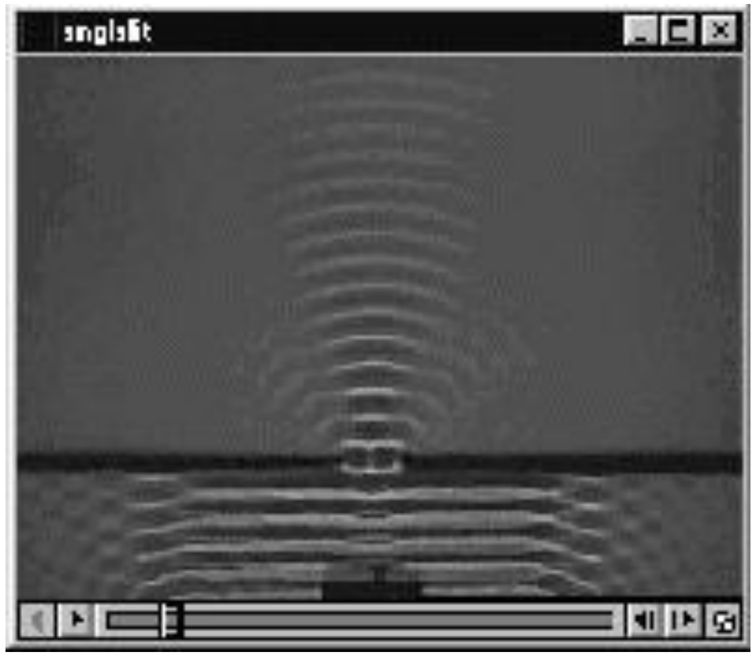


The Huygens-Fresnel Principle

Each point on waveform is source of new spherical waves



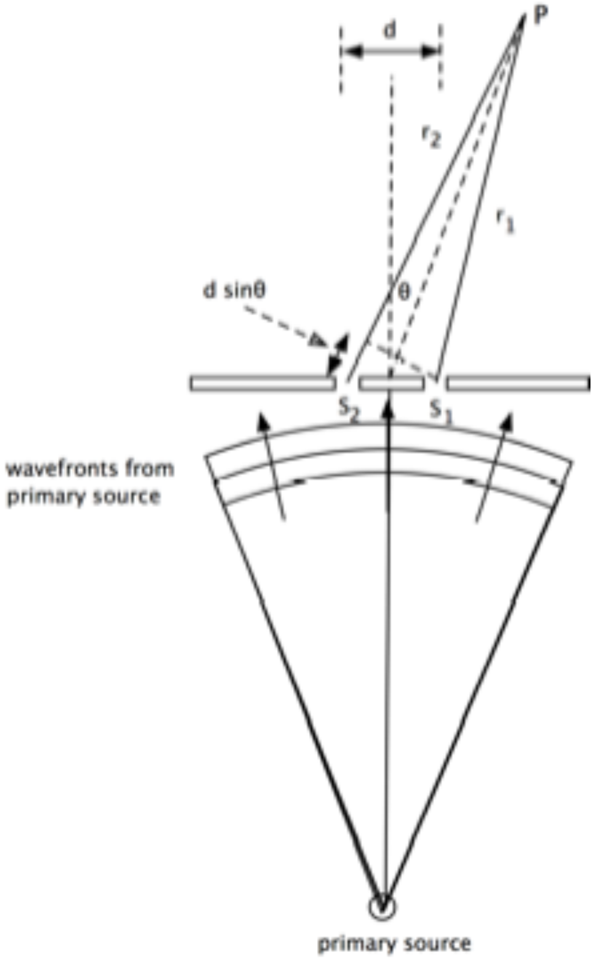
Theory



Experiment

using water waves

Double slit using this principle.



Slits = new sources —— new waves superpose and interfere

Amount of interference depends on wavelength and distance from source to screen —>

$$A(\theta) = 2A_0 \cos\left(\frac{\pi d \sin\theta}{\lambda}\right)$$

Features
peaks = constructive interference
nodes = destructive interference

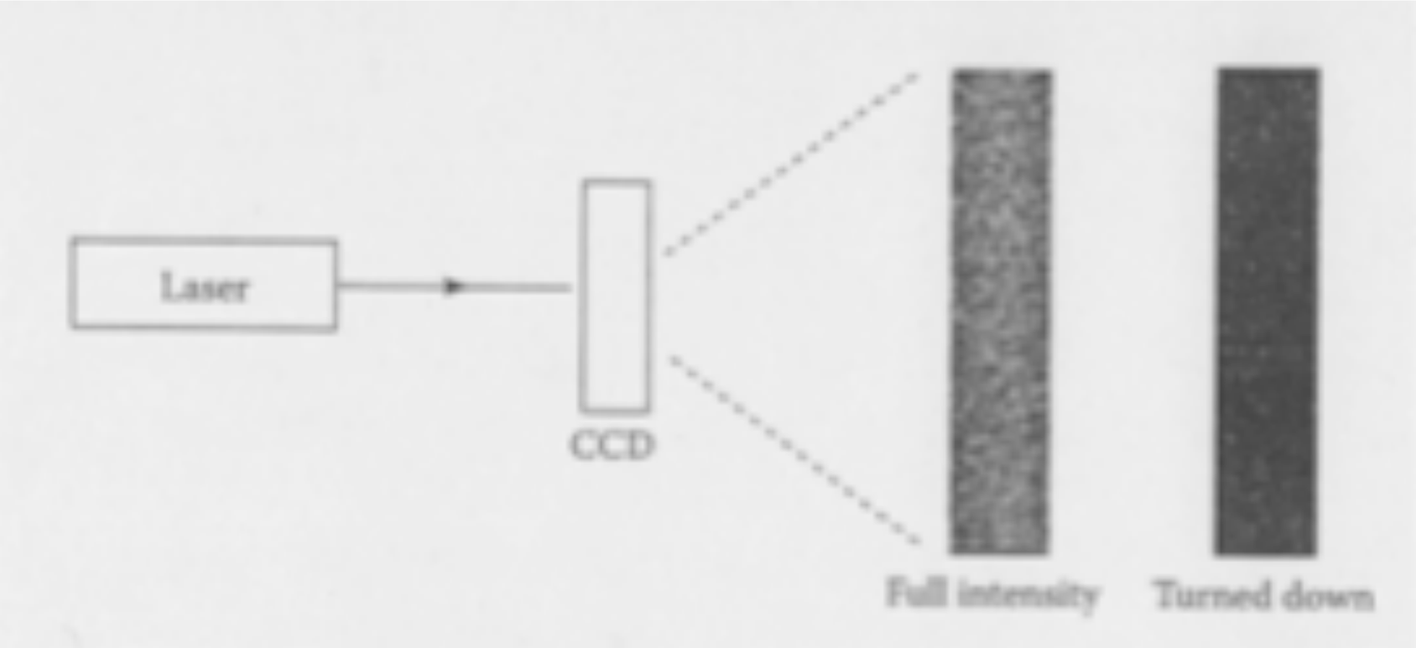
This is a **wave property**!!

But Einstein **proved** that light is photons = particles

Wave properties **cannot** explain photoelectric and Compton effects

The amazing experimentalists to the rescue!!

New Technology Lasers(controlled light beams) + CCD cameras(single photon detectors)



Light registers in detectors as single impacts = particle-like property

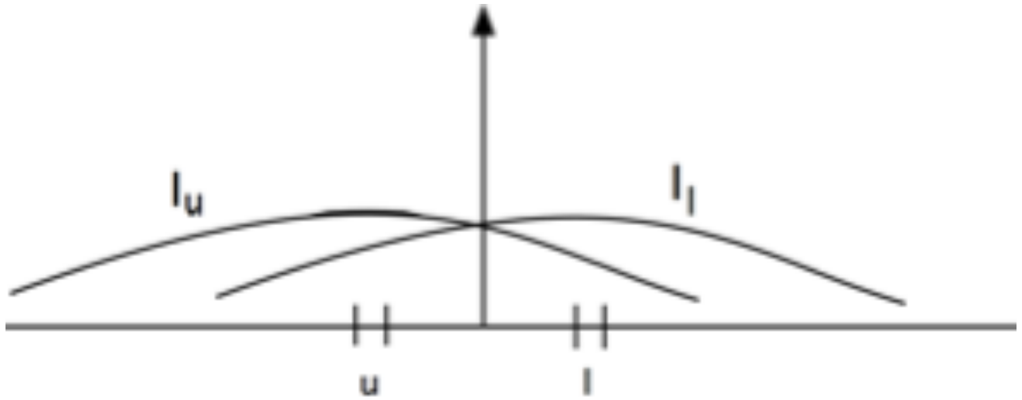
Light seems to be a particle when it needs to be and a wave when it needs to be - what it **looks like** seems to depend on the **CONTEXT** of the experiment (the question the experiment asked) - **a very important (a crucial) point as we will see**!

Much more about this later.

Now electrons are particles classically and in microworld they exhibit particle-like properties in many experiments.

Do electrons exhibit wave-like properties (in the macroworld) - do they interfere?

If I had a room with two doors in one wall and a bunch of basketballs and I threw the basketballs at the wall then with only one door open I see the pattern (distribution of the basketballs in the next room - other side of wall) as shown below:

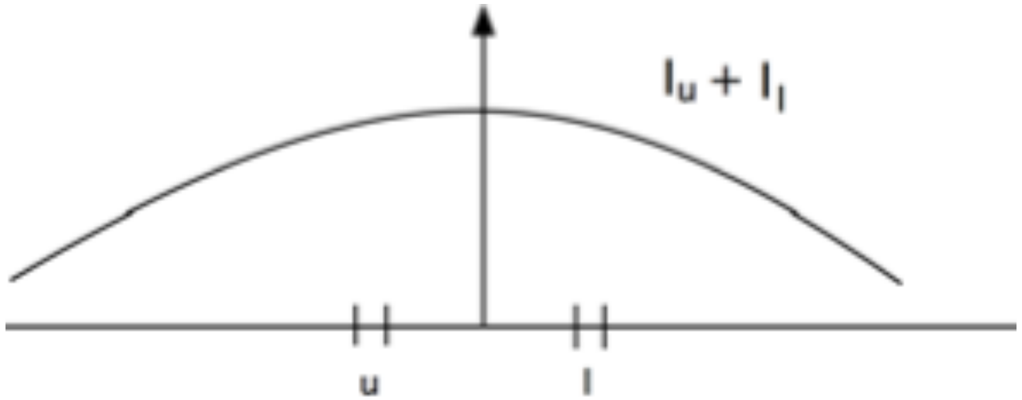


Particles through doors(slits)(only 1 open) see either pattern I_u or I_l

Peaks are directly behind doors(slits).

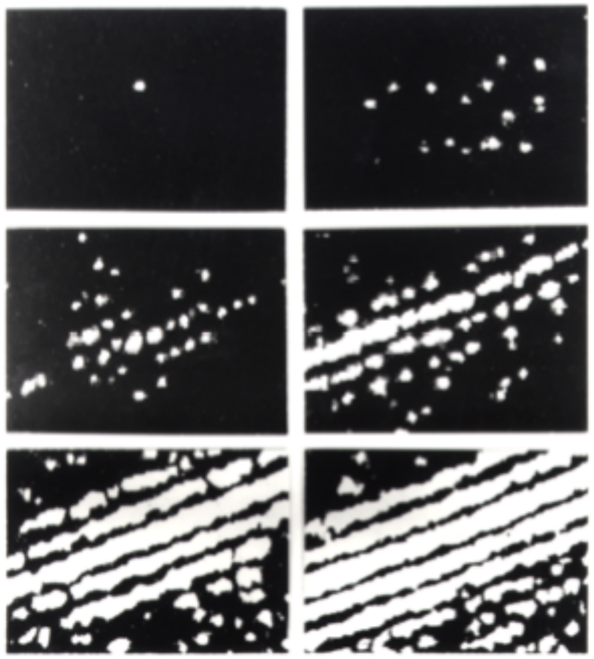
This is what is observed! With enough basketballs, the distribution is **non-zero** everywhere.

If we keep both doors (slits) open at the same time, then we see the pattern left.



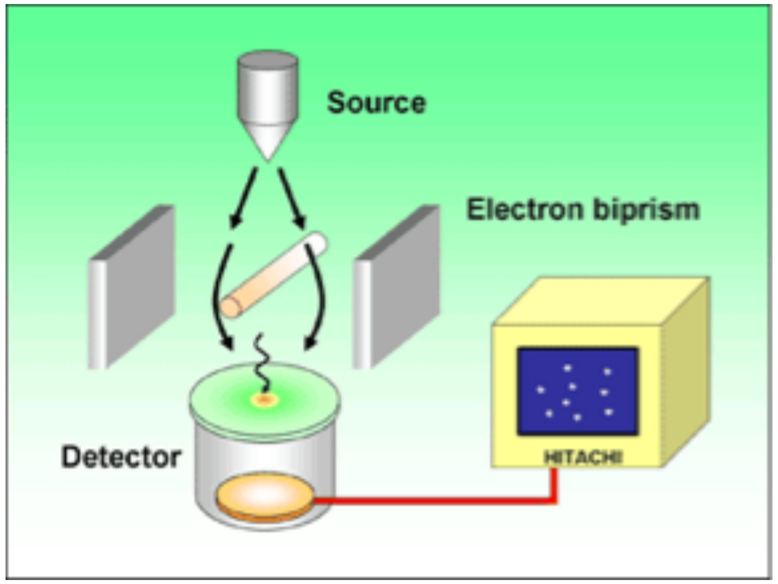
This is just the **sum** of the two previous distribution as we would **expect** classically since no basketballs are lost and standard classical particles **do not exhibit** any kind of interference effects.

What happens if we do the same experiment with electrons.

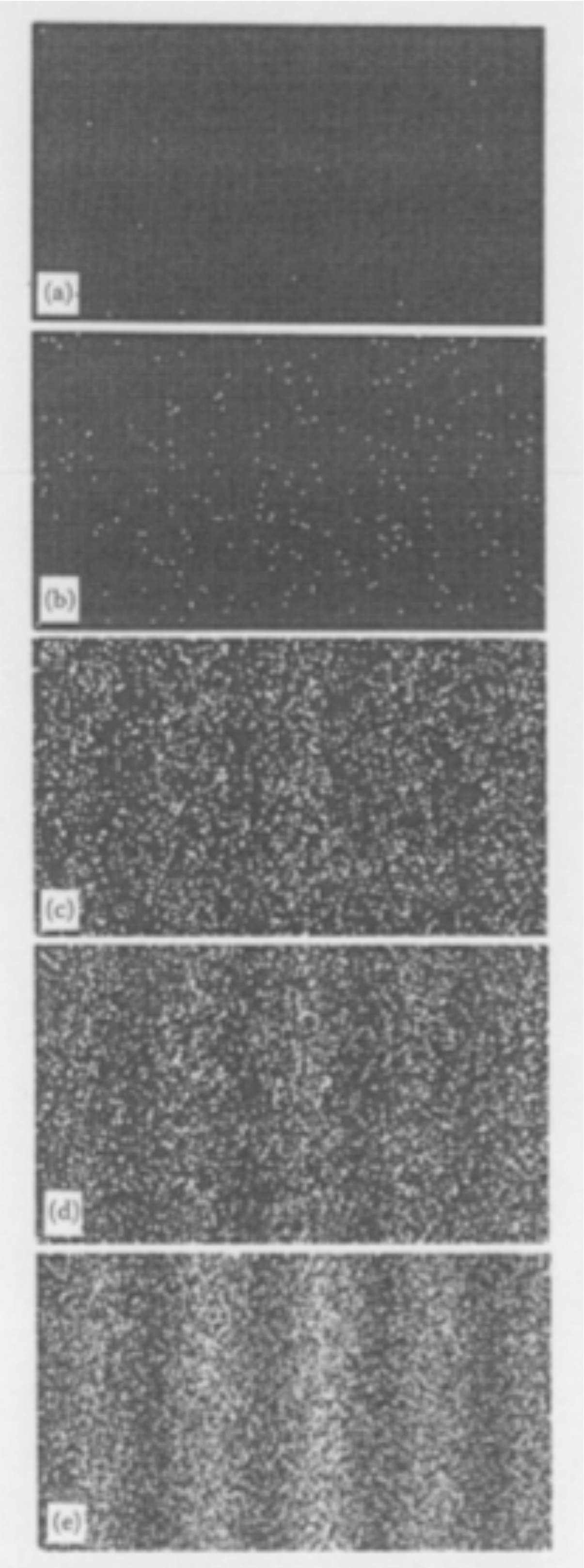


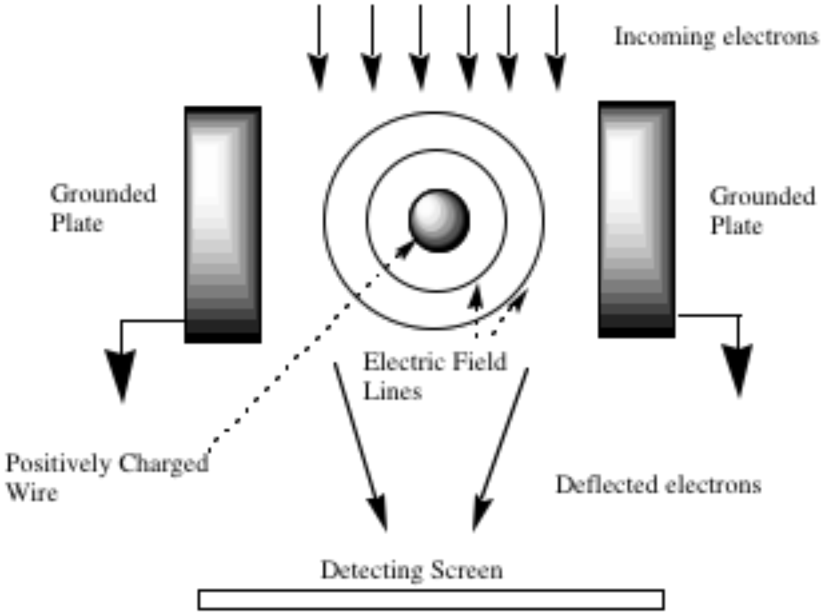
Davisson/Germer 1920

electron beams sent through crystal lattice,
i.e., parallel planes of atoms
replace slits!



and Hitachi 1989



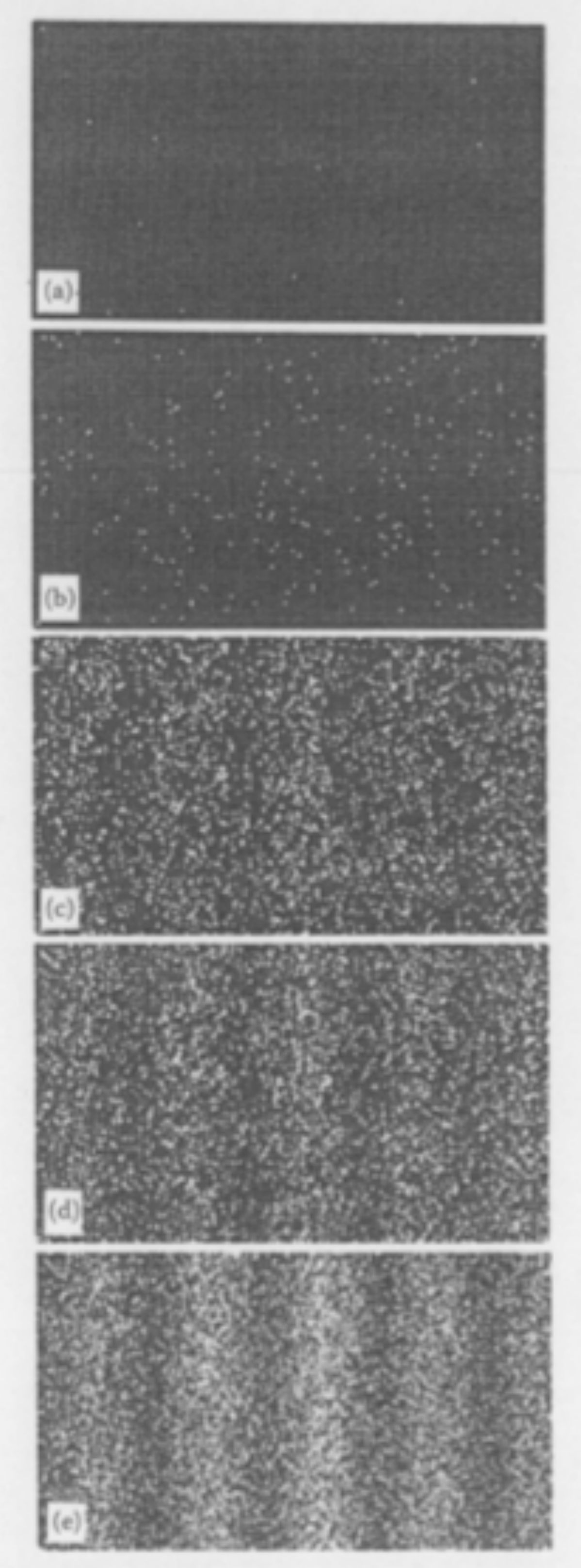


Electrons do not behave as classical waves; they behave like waves with a wavelength given by

$$\lambda = \frac{h}{\sqrt{2mE}} = \frac{h}{p}$$ **deBroglie**

SAME constant h as Planck used in Blackbody radiation

Note that there are regions in the data sets where **no** electrons arrive on the screen!
whereas stones(basketballs) would impact everywhere —— **Think about that for a second!**



Now reduce intensity so that we have only 1 electron in system at a time

If waves, then after few seconds should see only a weak interference pattern, but should **always** see entire pattern

Does not happen! Look at pictures. Initially pattern looks random
But clearly it is not after long time.

Arrive as particles (individual impacts/flashes - quantized!) randomly but generate interference pattern after long time.

Summary

impacts = particle behavior, but pattern = wave behavior

block 1 slit = pattern like particles through 1 slit

1 electron at a time - still get final pattern -> ask question: How does each separate electron “know” what to do? **A Bad question!**

Is electron behaving as a particle/wave in same experiment or **are we misinterpreting the whole thing by trying to describe what is happening with classical ideas and macro world words!**

Maybe it has nothing to do with particles and waves which are classical ideas and is the result of something totally NEW happening.

The statement:

“Experiment seems to say that objects can be both at same time”

may simply be **last desperate attempt** to maintain classical descriptions
as we proceed to find classical physics fails.

To explain double-slit results we need a completely new theory.
We need to rethink all of our ideas about the physical world.
We need to learn a new language to understand a new world!

Part of our problem is our use of ordinary words - that is the wrong language!

Quantum Mechanics, Ordinary Language and Mathematical Language

It is **not possible** to reduce the quantum universe to everyday ways of thinking (usually called **common sense**).

In fact, in order to understand the ideas and implications of the theory we will have to **adjust** all of our ways of thinking at the most fundamental level.

Imagine, for a moment, that you are attempting to **understand** a new culture.

If you are serious about it, the **first thing** you would do is to learn the language appropriate to that culture so that you can put your new experiences in the proper context.

Understanding the universe of quantum phenomena is **much like** understanding a new culture

where the **appropriate** language is **mathematics**

and the experiences we are attempting to put into context

are **microscopic experiments**.

We have to use a **mathematical language** to describe the quantum world

since ordinary language,

which was developed to explain everyday occurrences (experiments on macroscopic objects),

will turn out to be totally **inadequate**.

There are **no macroworld models or classical analogs** that will ever give us any insight into the workings of the quantum world - so we will not make any!

Since it **makes no sense** to attempt any understanding of the nature of quantum phenomena

without first learning to speak and use the language of the quantum world,

one should **spend some time very early** on in learning the appropriate mathematics,

in particular, the subject of linear vector spaces (we will in this class).

The **adjustment** of our ways of thinking at the fundamental level

that will be needed is not simply a mathematical matter, however.

The **development** of the necessary mathematical language will not come into **conflict**
with our everyday modes of thinking in any major way.

Although, the mathematics of linear vector spaces is very elegant,
you will be able to understand the simple features we need **without much difficulty**
and **without having** your basic view of the world changed at any fundamental level.

You will be **troubled**, however, when
we apply the mathematics to physical systems that develop according to quantum rules.

You will need to **attach physical meaning to the mathematical formalism**
in ways that will **conflict** with your well-developed views
(I will call these classical views) about how the world works.

Dirac was able to join the conceptual structure with the mathematical structure.

He **invented** a mathematical language (I purposely do not use the word notation like others)
that directly embeds the philosophy of quantum mechanics
into the mathematical structure used to do calculations.

The new language **directly exhibits** what is being said about nature in quantum mechanics.

Dirac language **exposes** the internal logic of quantum mechanics
in a way that mere words cannot possibly accomplish.

It **displays** the sense, the physical meaning of the theory

in every equation one writes

without the need for further explanation or any need for always inadequate models.

It is **very important** to understand that the Dirac language

is not simply a new notation for quantum mechanics (as many physicists seem to think).

It is not merely a way of writing ———— A way of writing **expresses** a way of thinking.

Dirac language, as we will see, is a way of thinking.

Dirac language will **allow us** to use the physical ideas of quantum mechanics

to develop the appropriate mathematical language

rather than the other way around.

This **allows** the very mathematical quantum theory

to be more closely connected to experiment than any other physical theory.

Dirac language **expresses** the quantum mechanical way of thinking.

With it one **can proceed** from the philosophy of the subject to its mathematical expression

rather than the other way around.

That is the way one should study quantum mechanics.

One should **proceed from meaning** and Dirac language is perfectly suited to this task.

Meaning for us **does not reside** in mathematical symbols, however.
It **resides** somehow in the thoughts surrounding these symbols.
It is **conveyed** in words, which we will use to **assign** meaning to the symbols.

Dirac language is able to take notions expressed in words
and **replace them** with simple mathematical statements
that we are eventually able to place within a complete and logical structure
that **allows** for a fundamental understanding
of what quantum mechanics means and is saying about nature.

This task is **impossible without mathematics**.
Mathematics is the **true language** of all of physics.
Words alone only suffice for thinking about the physics of everyday objects.
These statements about the importance of understanding the mathematical language
appropriate to the physics under consideration
do not only apply to the quantum world.
It is **true**, I believe, for all areas of physics and other sciences.

One **should always learn** the appropriate language
before studying any field that relies on that language for its understanding.
So be careful.

Beginning now we shall buckle down
and take a serious look at the mathematical and physical structure of quantum mechanics.
But **tread warily**,
lest you slip back into the black abyss of classical thinking and consequent confusion.
With this warning out of the way, we **can now proceed**.

Quantum Thoughts - A Quick Overview

Quantum theory works.	10000's of experiments - extraordinary accuracy
QM is thought to be not fully understood.	What is meaning of assumptions? What happens during a measurement? What is relation of QM to Reality? (Will need to define Reality first!) and lots more……

All physicists no matter their **interpretation** (answers to above questions) of QM make the same predictions —> all interpretations must be **equivalent**.

This class <—> Postulates + Time Evolution + Measurement + Interpretations + Reality

Some Contrasts.......

Classical View reality = everyday experiences
everyday experiences = language = reality

Classical View simultaneous measurement always OK (arbitrary accuracy)

Quantum View simultaneous measurement NOT always OK(fundamental limitations)

Einstein relativity(Classical) speed of light = maximum speed for information flow

Quantum Mechanics seemingly instantaneous influences ‘’**spooky action at a distance**”

(we will clear this up this kind of nonsense!)

Quantum Mechanics measurement introduces randomness

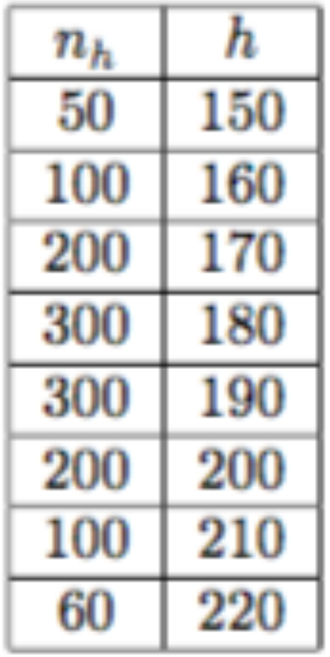
Identical Systems

Classical - all measure **exactly** the same within experimental error.

Quantum - random results within a fixed set —— only have a **Probability**

Simple Probability Idea we will use…..

Given a set of data



n_h	h
50	150
100	160
200	170
300	180
300	190
200	200
100	210
60	220

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

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

Important to remember: Rules of classical probability only predictive when the number of measurements gets very large.

—> This is an intuitive and comfortable definition.
But, not necessarily correct!

Back to 2-slit experiment

Only one slit(B) open => photons on screen centered directly behind B

Only one slit(A) open => photons on screen centered directly behind A

Both slits open = **no** photons in some spots where photons appeared when only one slit open

Think about that!
More Ways
=
Less Photons!

Experiment also work with electrons.

Experiment works no matter intensity of beam (even 1 particle at a time)

Reverse the thinking. 2 slits open = screen pattern with nodes(zero photons)

Close one slit = more particles make it to node region! Same for electrons!

Makes no classical sense - i..e., it does not happen if we were using marbles!!

A poorly worded question — How does a single particle ‘’know” 1 or 2 slits open?

Quantum particles(are quantized) cannot be split
—> so it cannot be one piece interfering with other piece

If we try to detect which slit —> experiment changed —> pattern is destroyed

Can use wave picture and interference to explain things, but Einstein already showed that photons were particles (actually showed they were quanta) and only look like waves when the beams are very intense - wave idea fails entirely when we have weak beams as we will see.

Clearly we need new way of thinking in Microworld.

Scaling down from macroscopic to microscopic radically alters particle distributions (they must be somewhere) and no interference effects becomes interference effects

Never see two independent things conspiring to cancel each in macroscopic world!

But happens often in microworld, i.e., the nodes in the interference pattern.

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 will see…….

For a photon ‘’going between source and screen’’ (whatever those ordinary words mean)
—> photon state CANNOT be described as

(1) having gone through slit B or
(2) having gone through slit A or

(3) having gone through both slits simultaneously or

(4)having gone through neither slit

This exhausts **all logical possibilities** in the macroscopic world (using **ordinary language**).

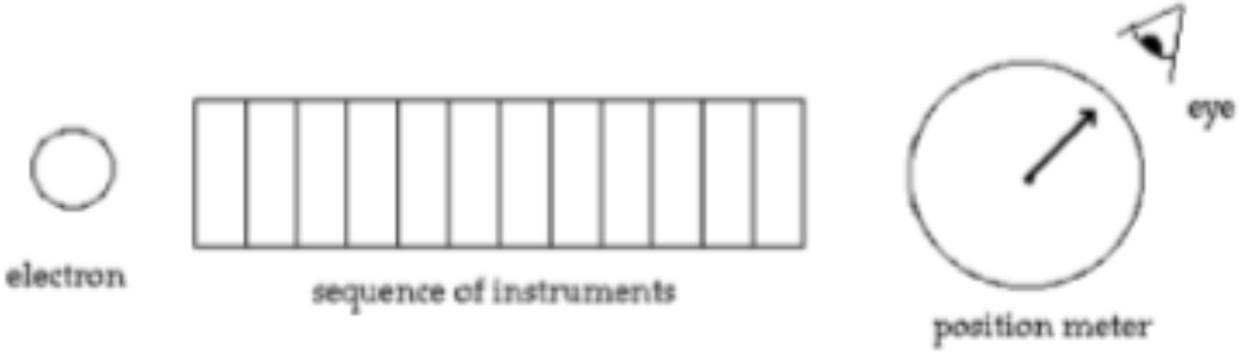
So **Ordinary Language Fails**.

In order to give an explanation classically we will only be adding new words/new definitions to old language and not explaining anything!

As we will see **probabilities** will win out over **exact trajectories**.

Let us try to measure the position of an electron.

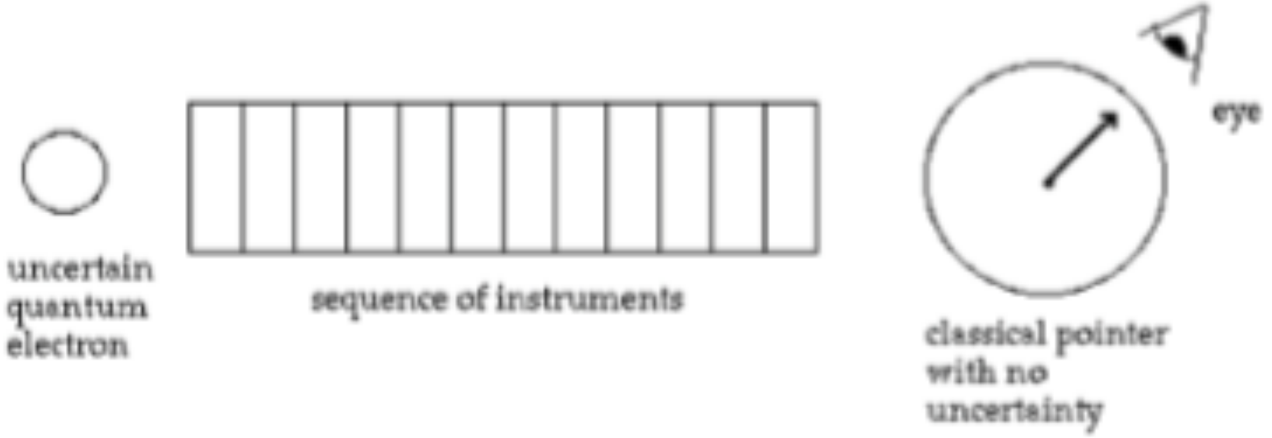
Measurement Process



——> Note that we do not observe the microword DIRECTLY!

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

i.e.,



Where is discontinuity?

Is there a discontinuity?

The saga of an electron passing through a wall.

Suppose we shoot a beam of electrons at a thick metal wall.

If we were shooting bullets instead, they would bounce off(that is what classical particles do!)

But, with electrons, **some** will appear on the other side of the wall.

How did they get there?

Obvious answer (to a classical mind) is they must have passed through the wall.

Therefore, I should be able to set up a detector inside the wall and detect them as they pass through - I mean, they had to pass through to get to the other side - CORRECT?

Experimental result: With the detector in place checking, no electrons appear on the other side!

No detector - electrons appear; detector in place - no electrons appear!

Seems like electrons just disappear on one side and appear on the other side without passing through the wall (since no measurement shows that if they are detected inside the wall that they get to other side!!)

Here and there and NEVER in between. **That is the way QM works!**

How do photons each **know** what to do? (this will turn out to be a **poor/incorrect question**).

Only satisfying explanation will be **probability**.

Each photon has probability P(x) to arrive at position x on the screen(detector).

Each photon **independently** uses P(x) to choose impact point.

Each photon **independently** generates **part** of interference pattern.

2 slits = interference pattern

If observe to see which slit = information about which slit particle then

photon either went through that slit or it did not and

we “mess up” or ‘’change’’ particle to a known slit state => pattern changes to 1 slit pattern

Some Last Thoughts Before Developing a Theory

We will find that:

We must resort to probabilities! Probabilistic information = maximum information!

Measurement disturbs our information(probability)!

In microworld we will find that probability is everything.

Until a measurement changes information we will have to say that there is no definite value for a state —> everything is simply set of probabilities before measurement!

Particle is not somewhere unless measured to be there!

In between measurements it is only probabilities!

This statement will have measurable (it can be proven) effects.

Read supplementary lecture notes ——- EinsteinBohrGod
Ask questions after class

Read supplementary lecture notes ——- Tale of Two Gloves
It illustrates QM phenomena via a story

Ask questions after class

Equivalent phenomena in the microword really behave this way

No explanations are given yet - that comes later in the class

As we will see, quantum theory **arrives** at what it deems to be an acceptable interpretation of these puzzles by **insisting** that we stick to practicalities.

It is no good, and indeed very dangerous, **to speculate** about what **seems** to happen in such any situation.

Stick to what actually occurs, and can be recorded and verified, and you will be **correct**.

For example, 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 in the story.

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!

Probabilities will be sufficient!

As will **see later** - Einstein took **one side** in this dispute - he was **WRONG**

Classical measurement => gain knowledge pre-existing state

Quantum measurement => impart specific value to state

We will approach QM from real theorist's viewpoint.

You have **never seen** theoretical physicist(me) in action.

I might do things that seem off the wall(no reason).

It is **important** to remember that theorist has **one goal** —> to understand universe.

No assumption is considered too crazy to be included.

Invention of new ways of thinking will be commonplace.

Strange interpretations will be all over the place.

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

We proceed **along lines** set out by Paul Dirac in 1920s

modified by much hindsight from intervening 100 years of discovery.

Now on to Lecture 2