

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”

My goal in this class is to teach you **enough** about the physics and mathematics of quantum mechanics so that you will be **able to understand** my discussion of the quantum measurement problem and my proposed solution and also be able to read most general articles about quantum mechanics

It will **not be necessary** for anyone to follow **all** the mathematics in detail and do **all** the mathematics algebra - the ideas presented in the class **can be fully understood** if you learn the terminology and understand how to use the results of all the mathematics.

Listen carefully, ask questions and now join me on this fun journey.

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

Determinism

Locality

Quantum Physics

Randomness

Non-locality

Foundation of physics 1650-1920

Foundation of all modern physics 1920 -2026

These two paths offer radically different views of “reality” as we will see.

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

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

They thought.....

Microscopic world = Quantum

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

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

Our everyday experience(classical world) 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 $\Rightarrow$ the fundamental building blocks of *everything*
 $\Rightarrow$ gives us an ability to develop a theory of microworld

Two important new properties arise.

They are adequately summed up by the words

Potentiality and Uncertainty

We will attempt to understand these terms!

Must use Experiments $\xrightarrow[\text{development of}]{\text{allows}}$ Postulates and Tools $\Rightarrow$ QM Theory

Physics is an experimental science!

The Goals of this Class

How QM works

Why we need it to work in this peculiar way

How to understand it

What it all means

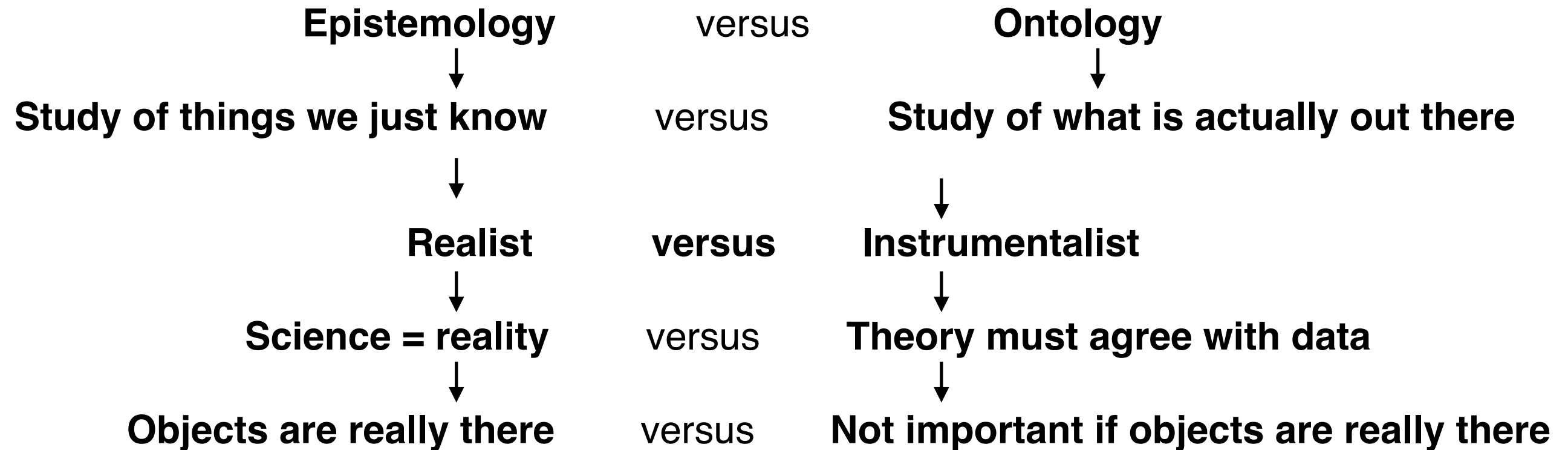
My assumptions about you

You remember HS math + you are *willing to learn some new mathematics*.

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

Basically, you will be **learning a new language!**

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



Here is an example to think about

Later, when we study the state of a QM System

it will **seem** to depend on what **we know(our knowledge)**.

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

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

Keep those two fundamentally different ideas in mind as we discuss QM.....

The Classical Point of View due to Newton and Maxwell

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

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

State = Values of set of observables or measurable quantities $\longrightarrow$ Trajectories = particle states

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

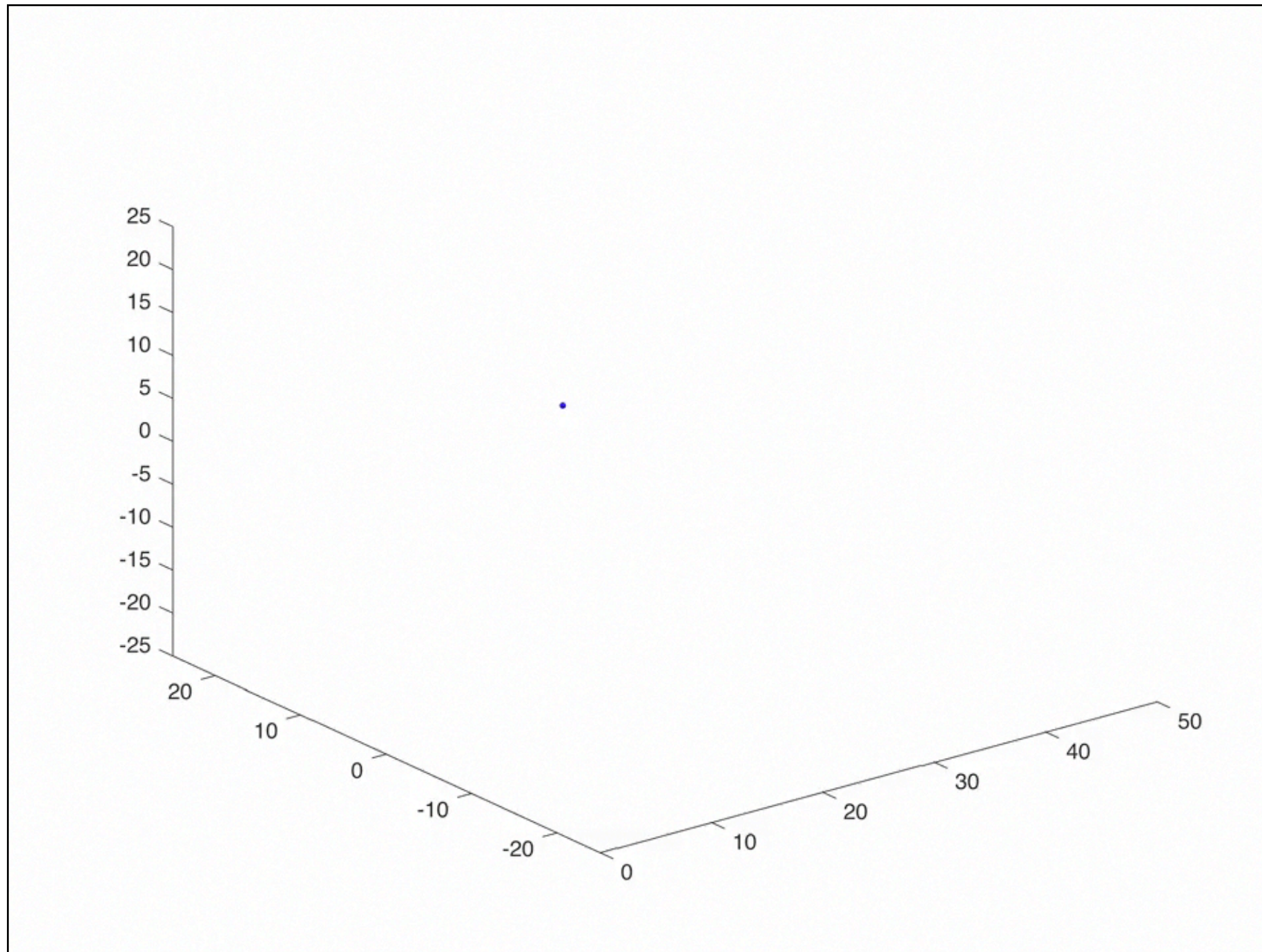
Newton's Laws of Motion $\longrightarrow$ $\left\{ \begin{array}{l} \text{Position+velocity+momentum+energy+force} \\ \text{Requires knowledge of position/velocity **at some time.**} \end{array} \right.$
 $\longrightarrow$ **initial conditions**

They believed that if we can determine initial conditions without disturbance.
then could **predict** trajectory $\longrightarrow$ 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** $\longrightarrow$ Sensitivity to initial conditions $\longrightarrow$ 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 **Deterministic** Universe

Everything we observe **had** an identifiable cause in the past!

Causality is a **fundamental** aspect of the classical world

If have same cause , then always have 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(Pass #1)

We will observe that “classical particles” **do not exist** in the microword!

There are no trajectories.

————→ 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 these “things” 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 in the microworld!!

VERY IMPORTANT RULE

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 the notes during those discussions(no explanations at this point):

- (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 or so it seems!
- (8) Will find that before measurement there is **no** value! **Only** a **potentiality** exists!
- (9) Will find that measurement **alters** system - it is unavoidable - the 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!!

All I can say is WOW!

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

trajectory = set of (positions, momentums, times) for a particle

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

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

classical world $\rightarrow$ errors can be made small as we wish (no theoretical limit) - **ASSUMPTION**

quantum world $\rightarrow$ this is **NOT TRUE** $\leftarrow$ exists an uncertainty principle $\Rightarrow$ fundamental limit

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

Question often asked : Can Classical and Quantum Physics Get Together Somewhere?

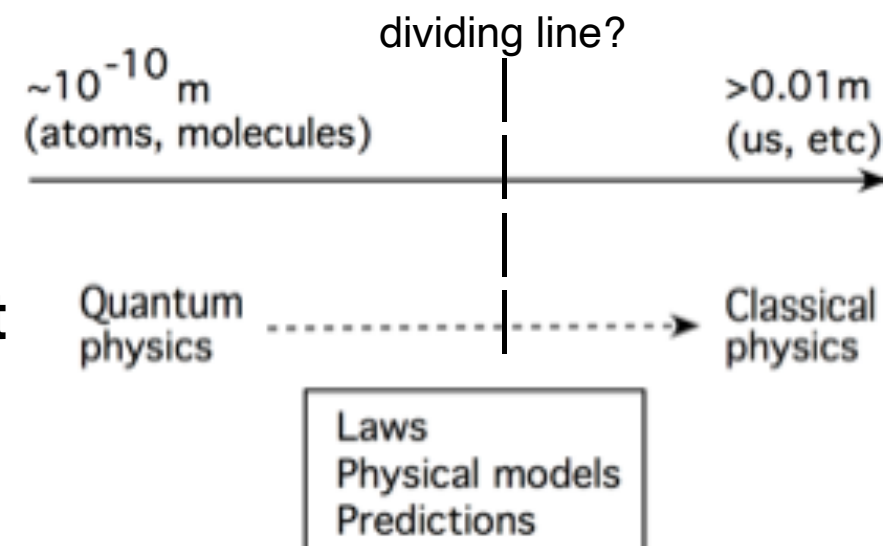
Since limit of large systems in microworld $\longrightarrow$ macro world (it will seem like this is true!)

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

$\rightarrow$ **Bohr proposal - Correspondence Principle**

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

No one knows - it may not exist!!



QM will 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 truly 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 other measurements, QM **cannot** talk about particle in **between** two points

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

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

The study of QM(theory of microworld) 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 be 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 (of the universe!).

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 will 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 and its meaning.

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

- we will get past it and the universe will open up.

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 that it requires approximations to make predictions.

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

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

—> **The Double-Slit Experiment**

First we must discuss — — Waves versus Particles Classically

Particle = trajectory => system is spatially localized + has a well-defined speed.

Carries energy (a localized quantity)

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.**

—> exhibits Diffraction, Interference and Polarization phenomena

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 such classical ideas have to be tossed away!

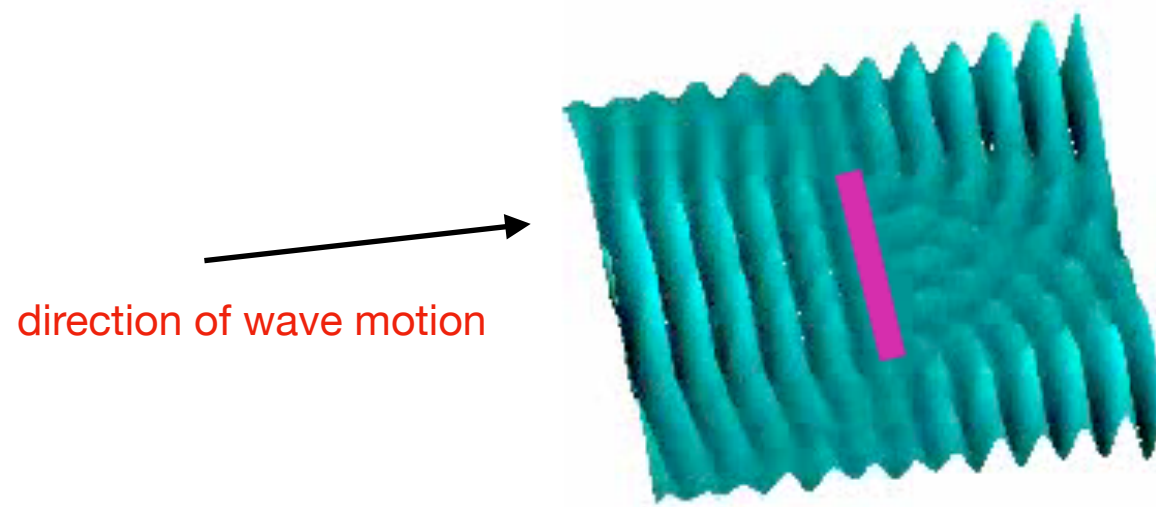
Light

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 —> would 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 in Young type experiment**.

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**.

Needed a dramatic new **experiment** to change things: **Walking the Planck**

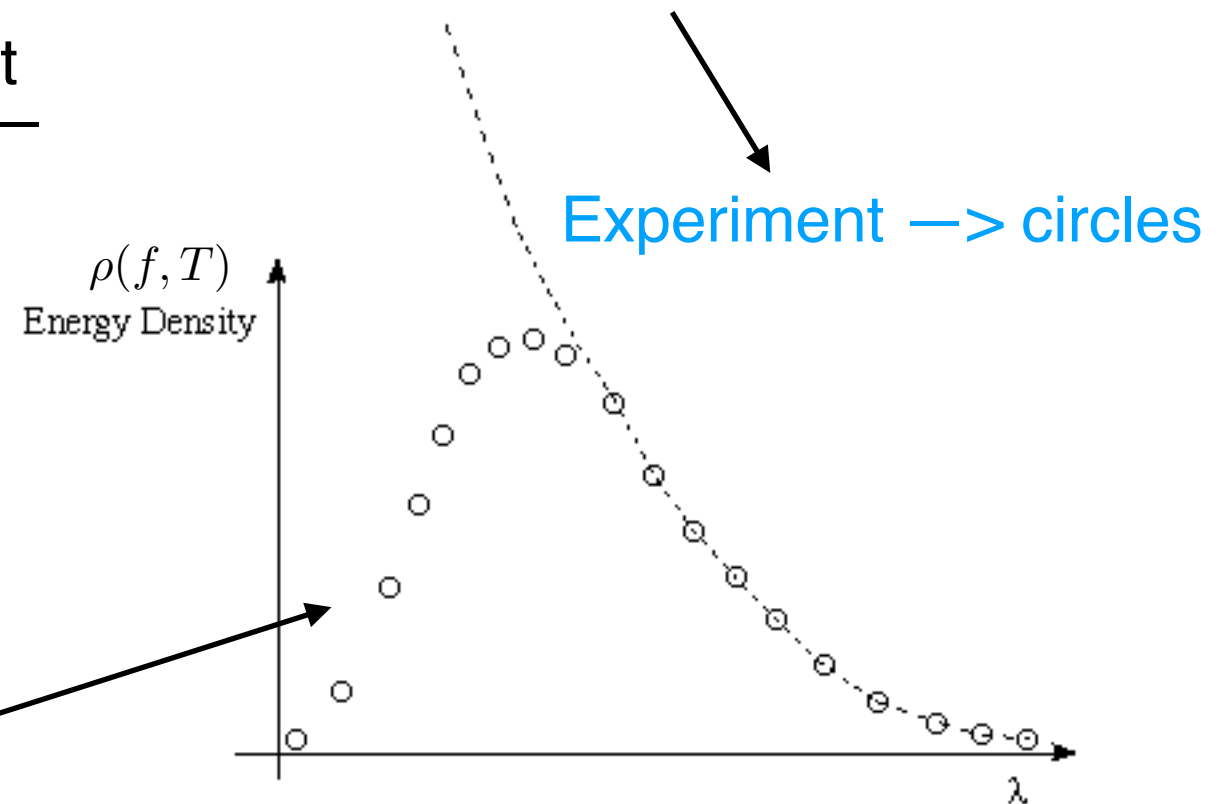
Blackbody radiation - What is it? —> Radiation observed when a body is heated!

$$\lambda = \frac{c}{f} \quad \text{wavelength} = \frac{\text{speed of light}}{\text{frequency}}$$

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

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

clear it totally fails at low wavelength!!



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(EM)

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

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 behavior limits were perfect.

But he could not justify law(values of A and B) rigorously.

Standard mathematical trick now leads to a new physical idea and a puzzle!

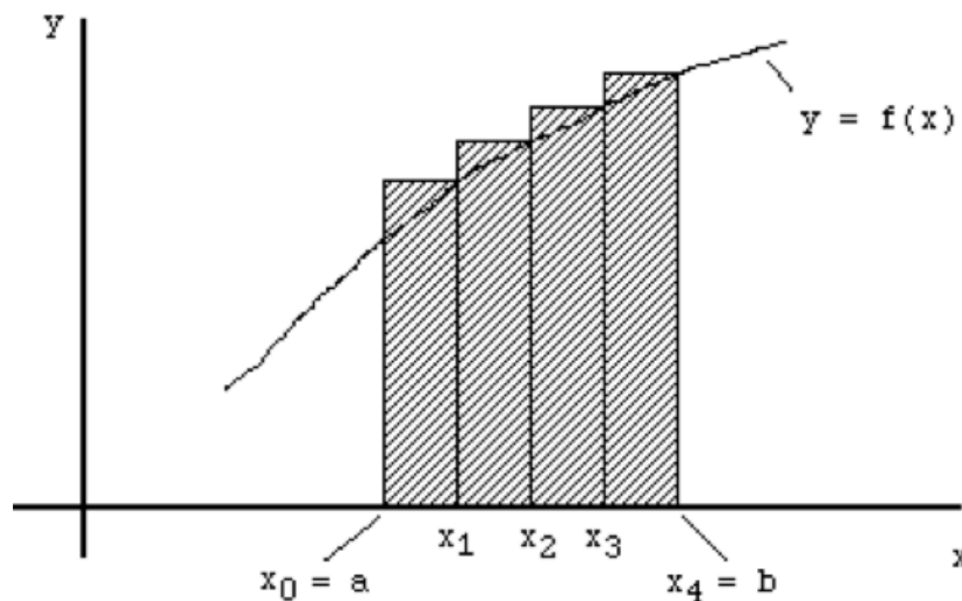
During a 2nd attempt at the derivation, Planck used a common math trick(a simplifying assumption) in order to do a calculation during an intermediate step in the derivation.

Usually after doing the algebra and taking appropriate limits, the simplifying assumption about the mathematics is removed.

It was a standard mathematical procedure that was used everywhere(**because it works!**).

It is changing continuous variables to discrete variables and then back to continuous.

It corresponds to making the standard calculus approximation (integral = area under curve)



area is **approximately** the shaded region

In limit that width of bars $\rightarrow 0$ and number of bars $\rightarrow \infty$, clearly we end up with the area.

Planck just approximated integrals(which gave *infinite* answers) by sums, did the sums, and reversed the limits to return to original formula - assuming SUM result is valid for INTEGRAL.

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

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

Planck's constant

Experimental agreement —> constant **h** **must** be exactly 6.63×10^{-34} J-sec

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

However his new result disappeared when he removed the trick!!!!

If makes $h = 0$, which the math trick always requires at the end, then the theory fails to work!

Puzzle for us: 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 in mathematics..... People were very puzzled!

Quantized light or “Particles” of light

Einstein grabbed hold of the “energy is not continuous” idea and did this.....

Einstein $\rightarrow$ energy in EM field not spread out on wavefronts $\rightarrow$ light is **not** a wave!!!!

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

Only **very intense** light appears to be a wave! This can actually be proved(Ex/Th)!

He said Planck’s “trick” worked in the derivation **because energy IS quantized**.

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

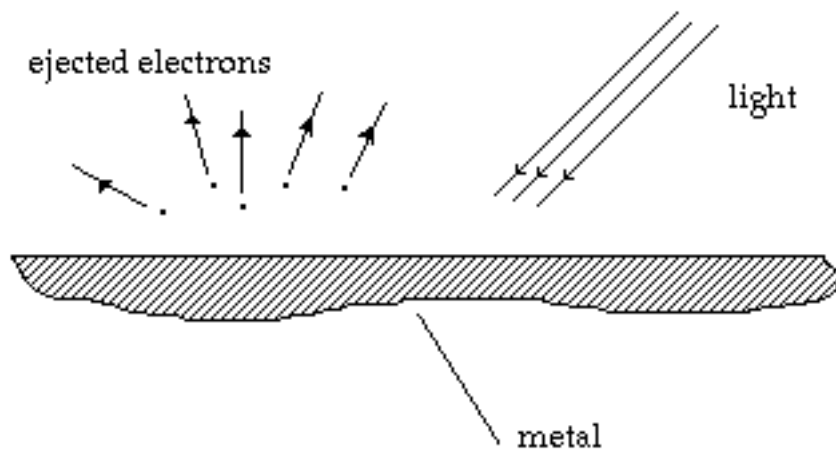
This quantum idea will be fundamental later to order to explain quantum measurement.

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 - 10^{-12} sec
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 are satisfied!!**

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

Explain **bathtub-rubber duck** analogy.

The photon (quantized light) model $\longleftrightarrow$ Explains every feature of the experiment!

1. $f < f_0 \rightarrow$ single photon energy too small
threshold $\Rightarrow$ 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.

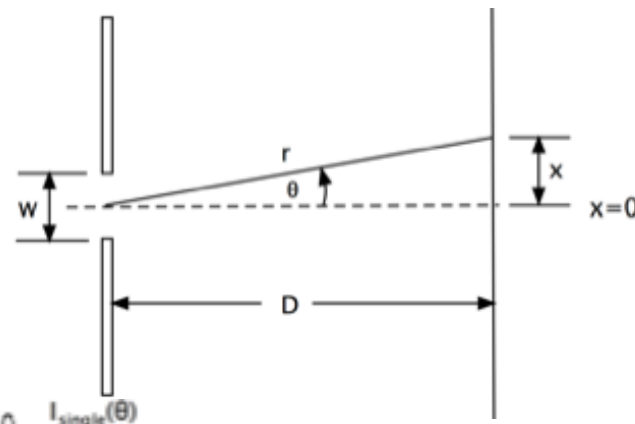
Problem: Light exhibits interference and *particles cannot interfere or so everyone thought!*

Interference and Diffraction

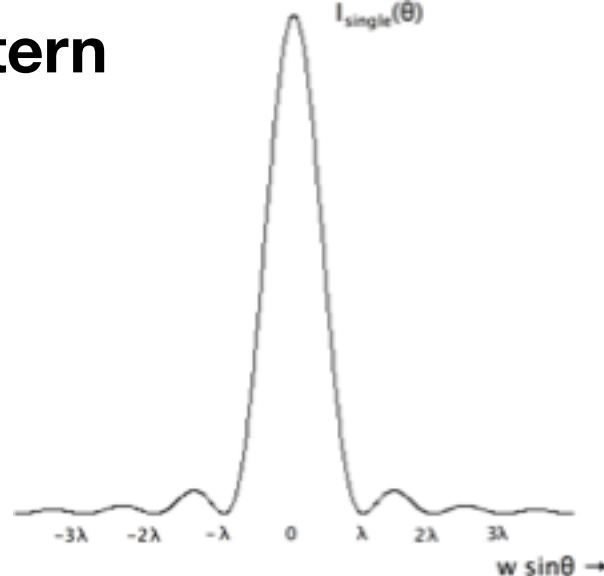
For lots of details read **Light and Interference** see supplementary notes.

or Ask questions after class

Single-slit



screen pattern



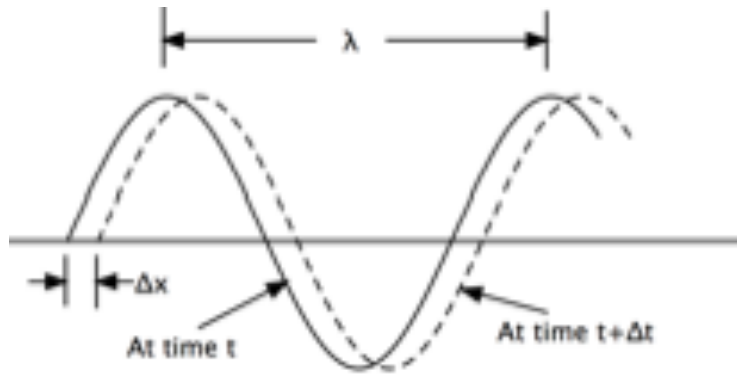
Interference Pattern



Note the nodes or zeroes $\rightarrow$ NO PHOTONS

Simple Theory - see supplementary readings for all details

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



→ wave transports energy and momentum

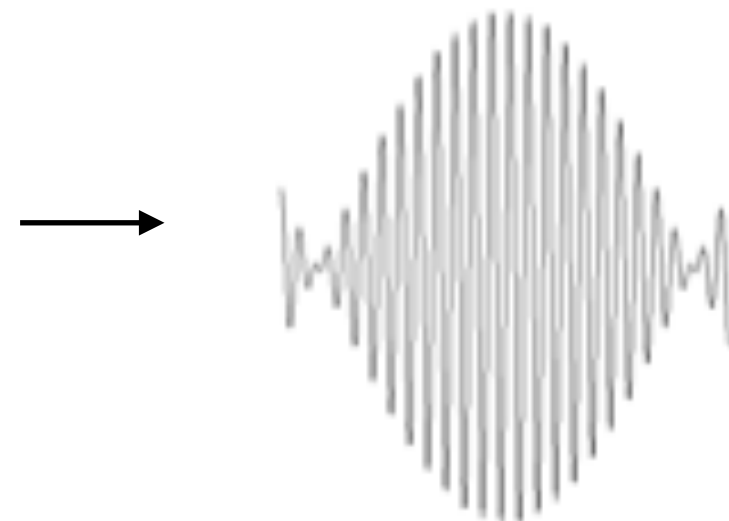
Waves can be added/subtracted = **superposition**

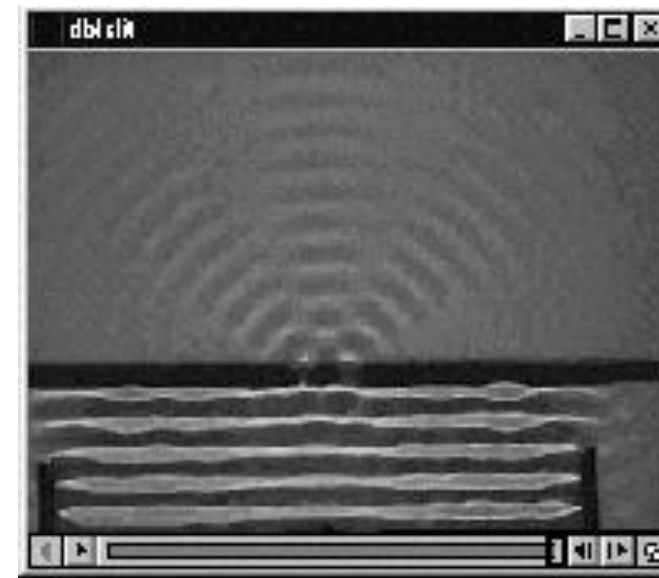
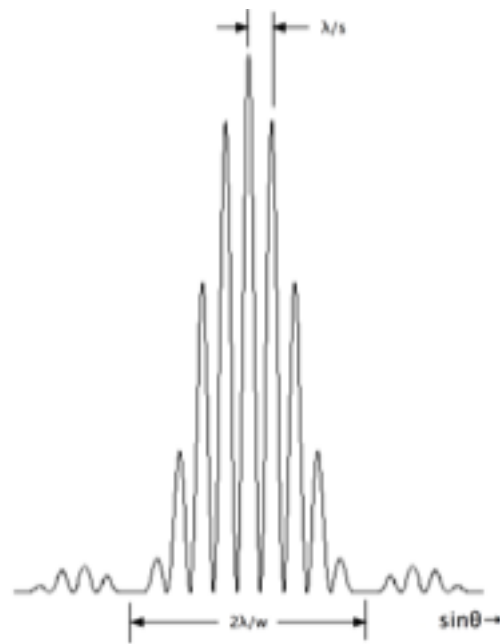
$$y_1(x, t) = A \sin \left(\frac{2\pi}{\lambda_1} (x - vt) \right) \quad y_2(x, t) = A \sin \left(\frac{2\pi}{\lambda_2} (x - vt) \right)$$

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

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

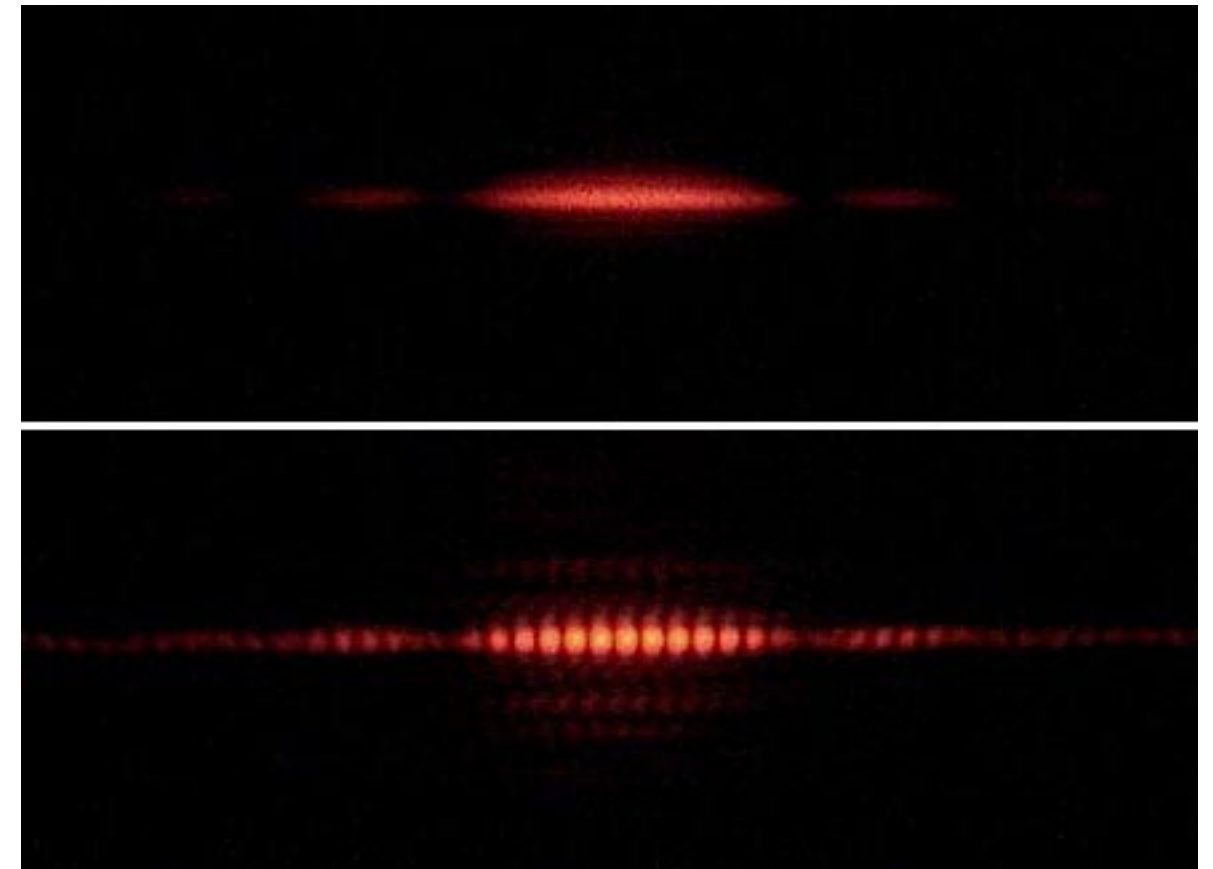
$$\bar{k} = 1/\lambda$$





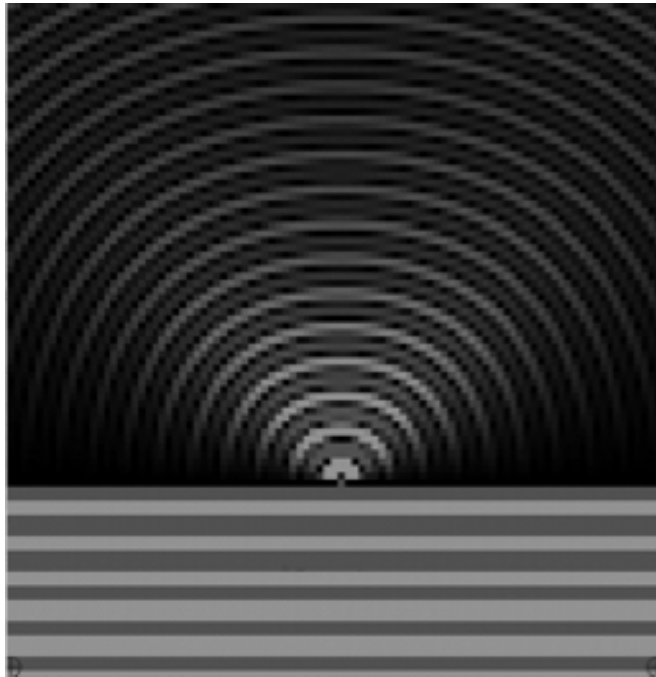
**Example:
Water Waves**

2-slit interference pattern(light)

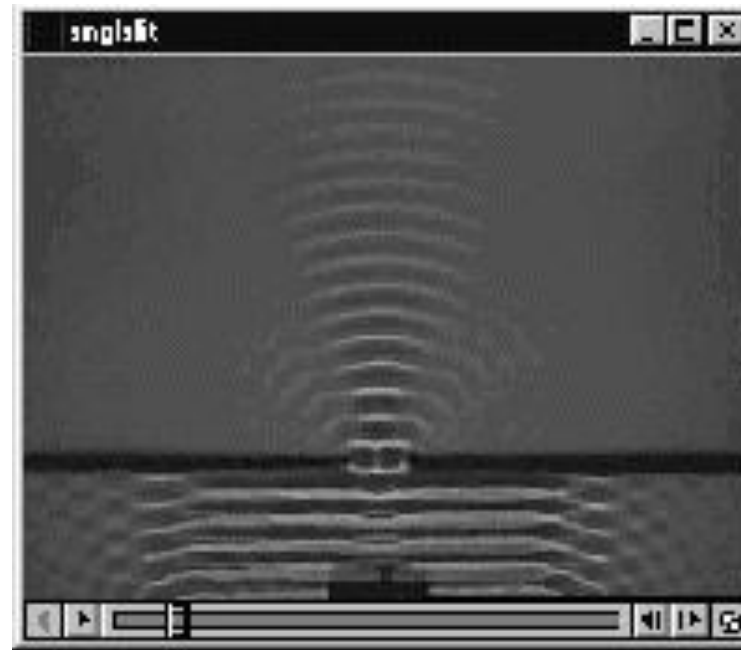


The Huygens-Fresnel Principle

Each point on waveform is source of new spherical waves



Theory



Experiment

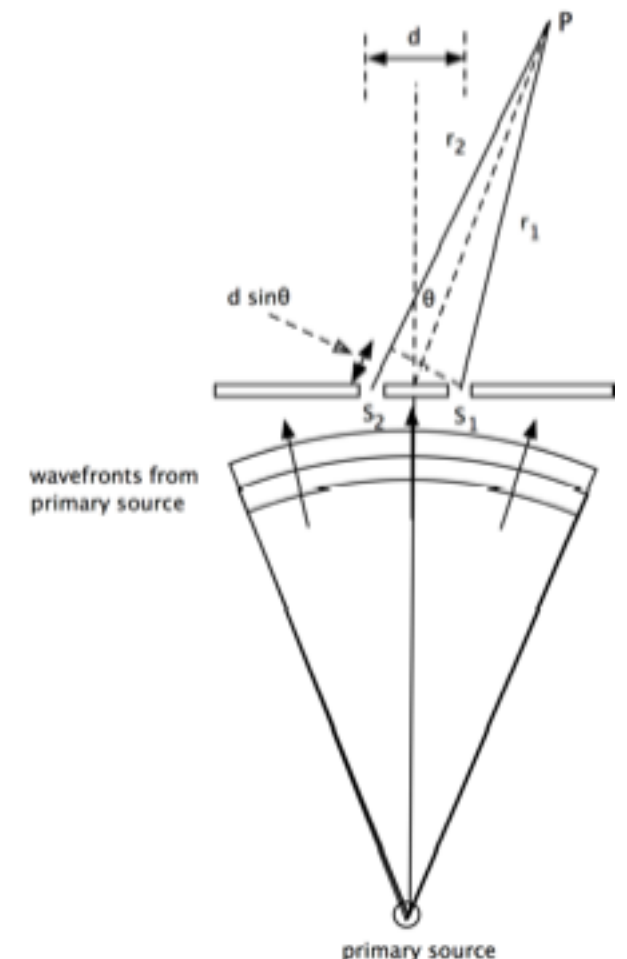
using water waves

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 seems to be a **wave property!!**

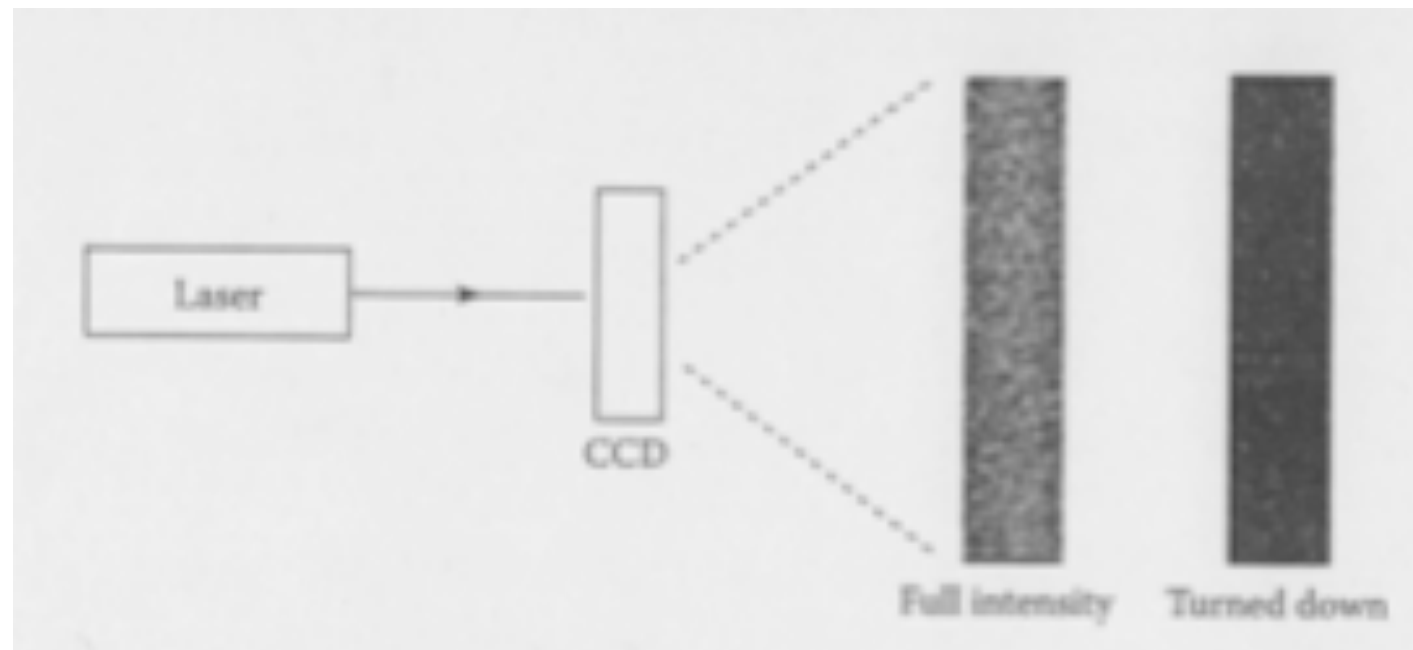
But Einstein had **proved** that light is photons = particles

AND

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

The amazing experimentalists come to the rescue!!

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



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

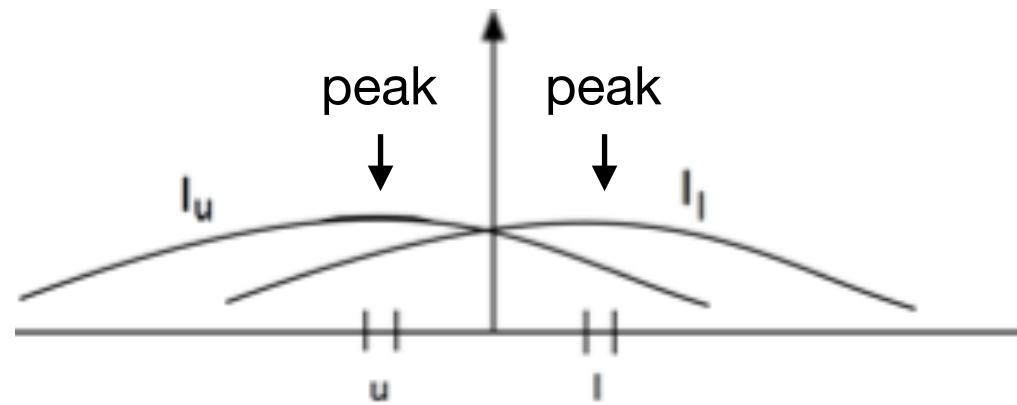
Light seems to be a particle when it needs to be and a wave when it needs to be - what it **looks like** seems to depend on the **CONTEXT** of the experiment (the question the experiment asked) - **a very important (a crucial) point as we will see!**

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:

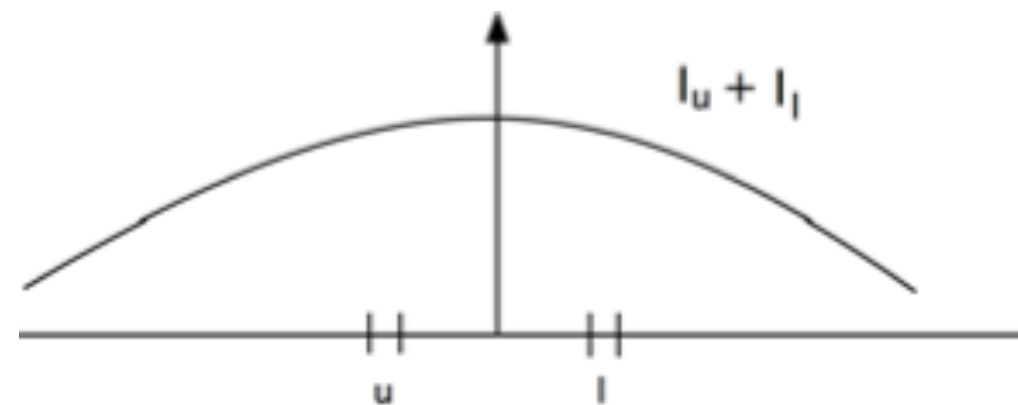


Particles through doors(slits)(only 1 open) see either pattern I_u or I_l

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.

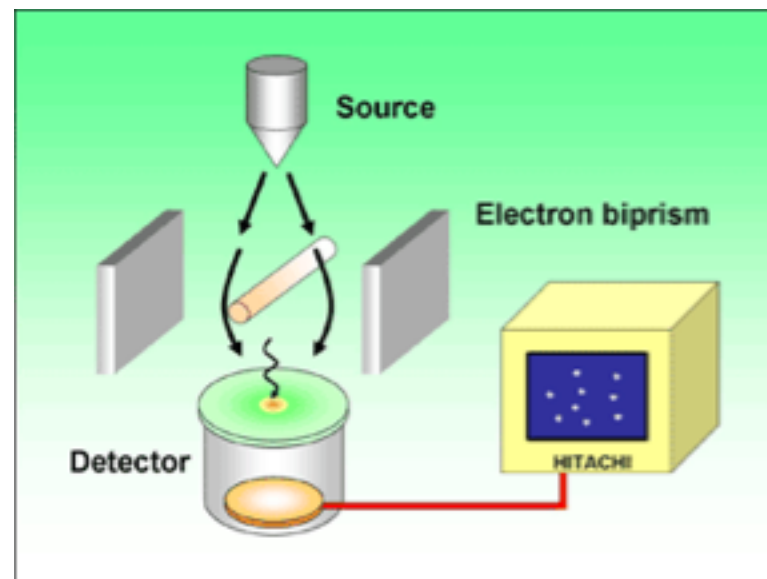
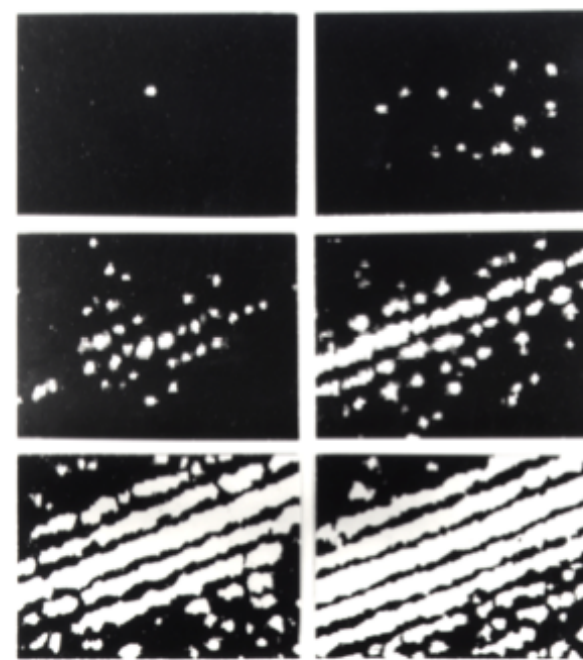


This is just the **sum** of the two previous distribution as we would **expect** classically since no basketballs are lost and standard classical particles **do not exhibit** any kind of interference effects.

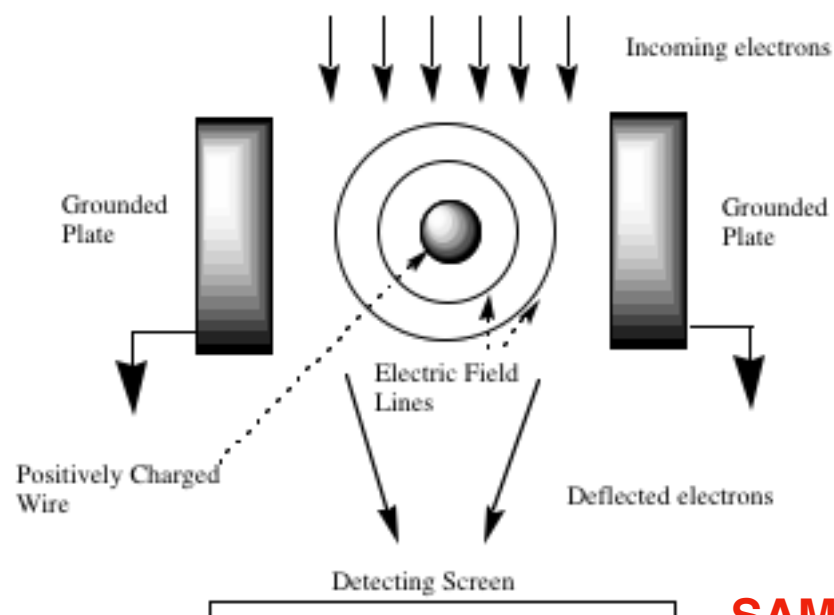
What happens if we do the same experiment with electrons.

Davisson/Germer 1920

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



and Hitachi 1989

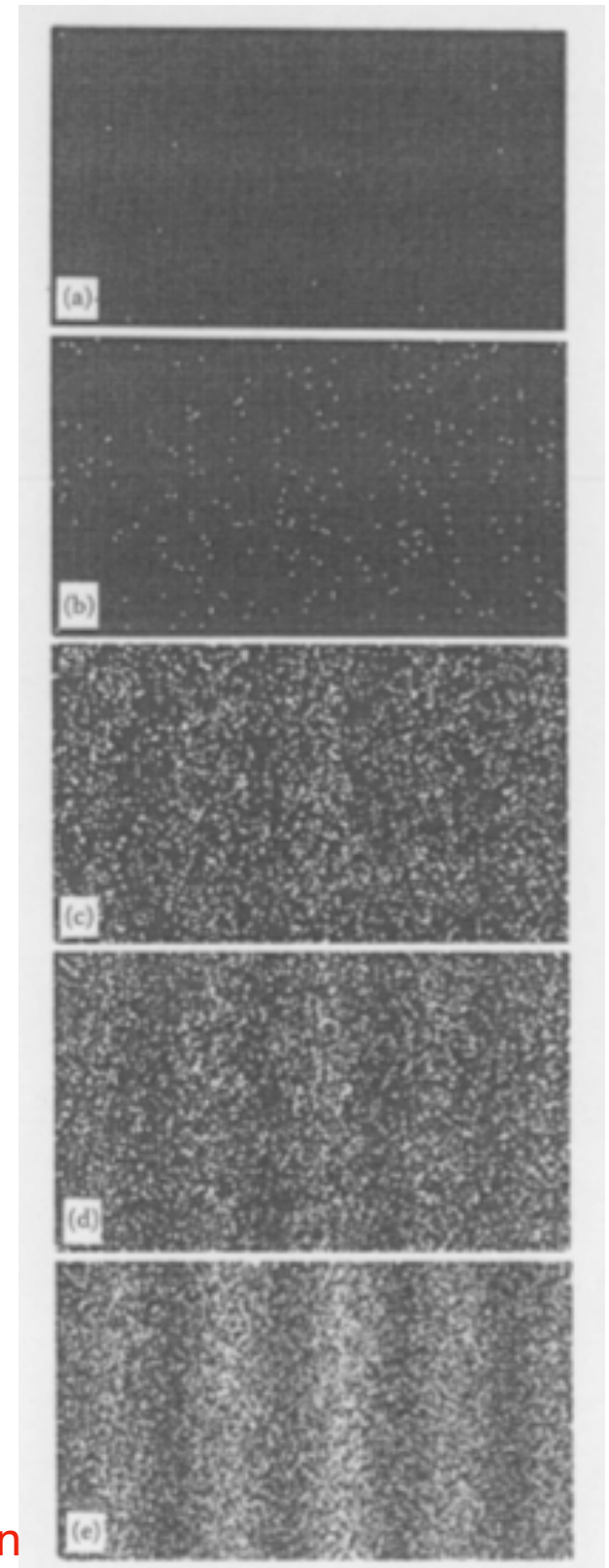


But electrons do not behave
as classical waves; they
behave like waves with a
wavelength given by

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

E = energy. p = momentum

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 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

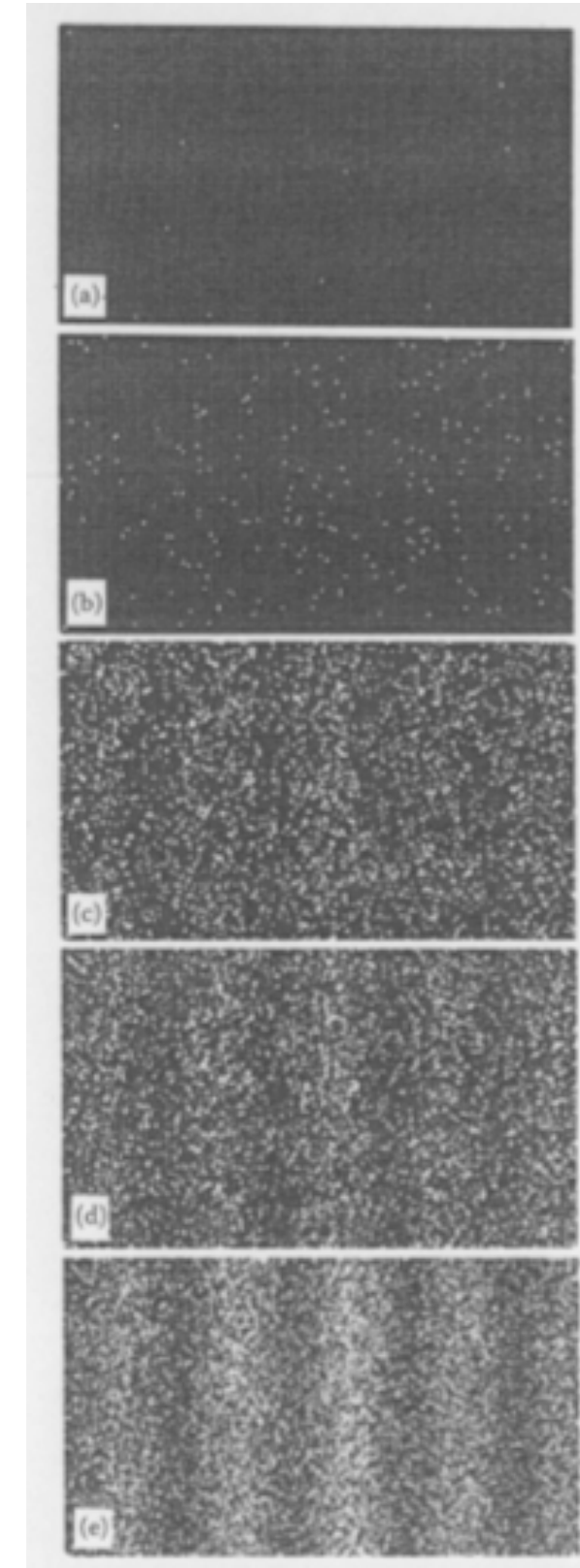
impacts = particle behavior, but pattern = wave behavior

block 1 slit = pattern looks like particles through 1 slit

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

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 valid words!**

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 (as 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.

As we will see 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 or words.

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 NEW 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 human 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 what it 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 and they will never be complete until they
are expressed in a mathematical language.

One **should always learn** the appropriate language

before studying any field that relies on that language for its understanding.

So be careful.

Beginning soon 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 $\longleftrightarrow$ 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 $\longrightarrow$ will 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

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

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

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

—> This is an intuitive and comfortable definition to use.
But, it is 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

Experiment also work with electrons.

Think about that!

More Ways to get there = Less Photons get there!

Experiment works no matter what the intensity of beam (even 1 particle at a time) is.....

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?

It is easy to come up with bad classical questions(wrong language) like this in the quantum world.

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?

Einstein already showed that photons were particles (actually showed they were **quanta**) and, in real experiments, only look like waves when the beams are very intense - wave idea fails entirely when we have weak beams as we will see, especially beams with only 1 particle at any time.

Clearly we need new way of thinking in Microworld.

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

Never see two independent objects 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**).

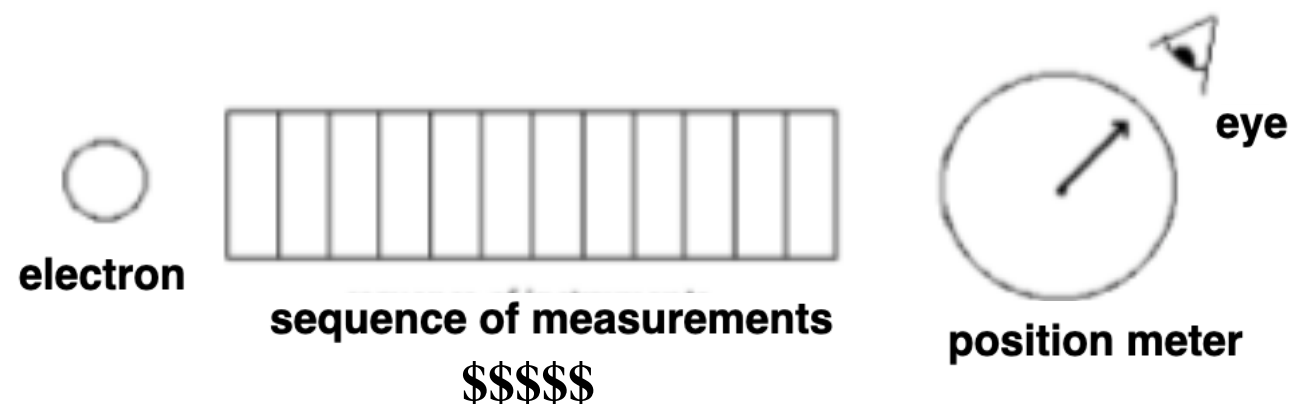
So **Ordinary Language Clearly Fails**.

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

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

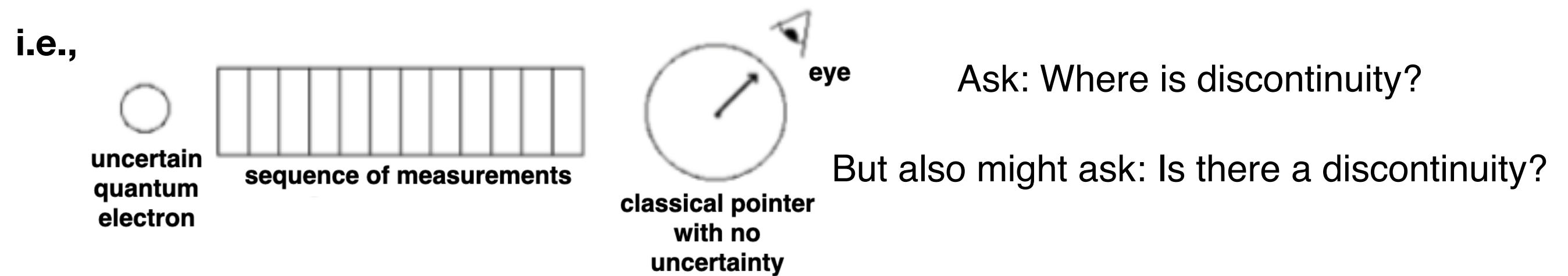
Let us try to measure the position of an electron.

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?



Another story: 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(experiment done) 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 if we use ordinary words!

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 an 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 microworld 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 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 at times that seem off the wall(no reason).

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