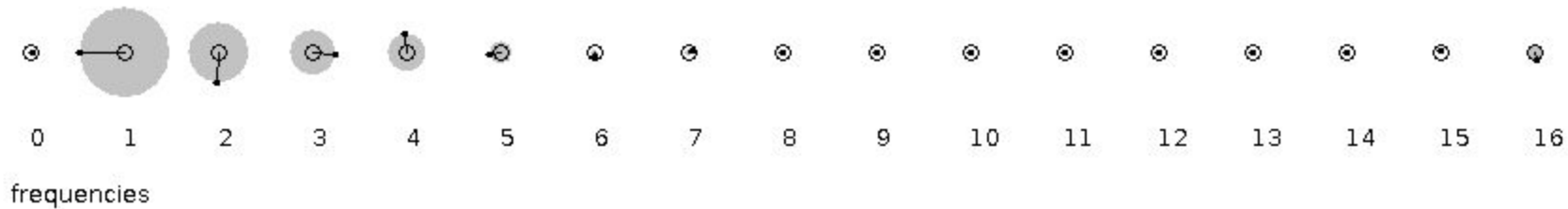


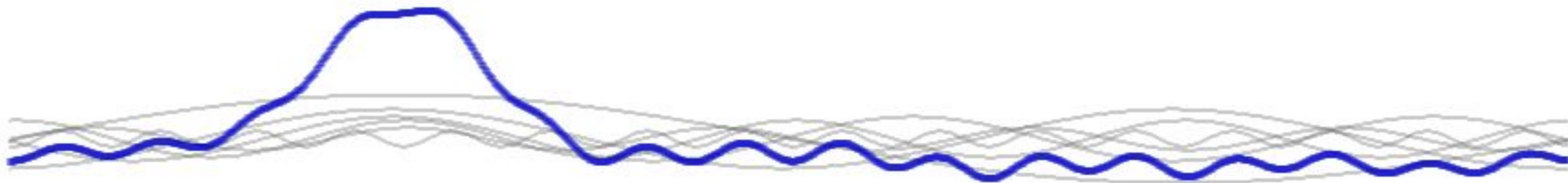
ENTANGLEMENT

in which we attempt to grasp the ungraspable

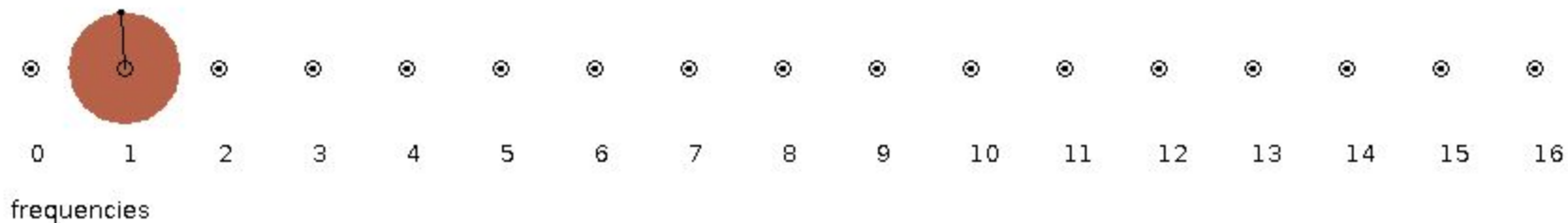
QUICK RECAP FROM LAST WEEK



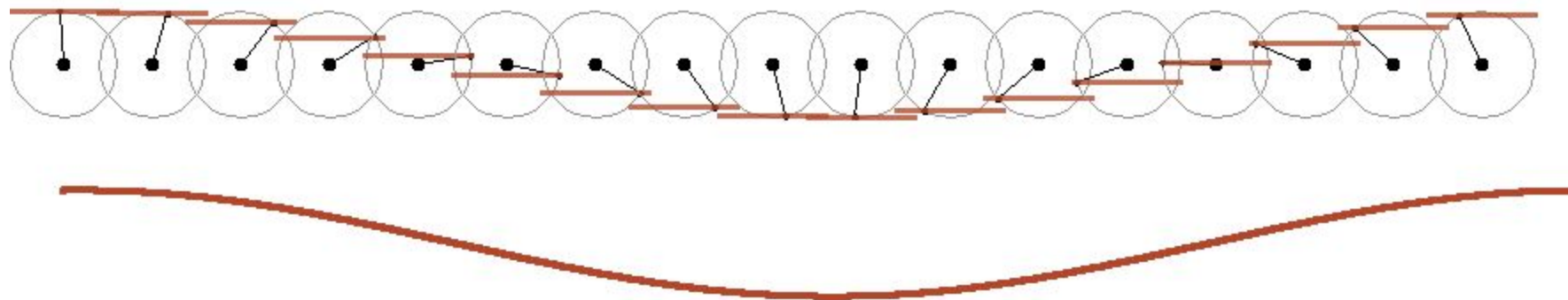
space (or time)



EFFECT OF EACH FREQUENCY: THEY'RE LIKE CLOCKS



space (or time)

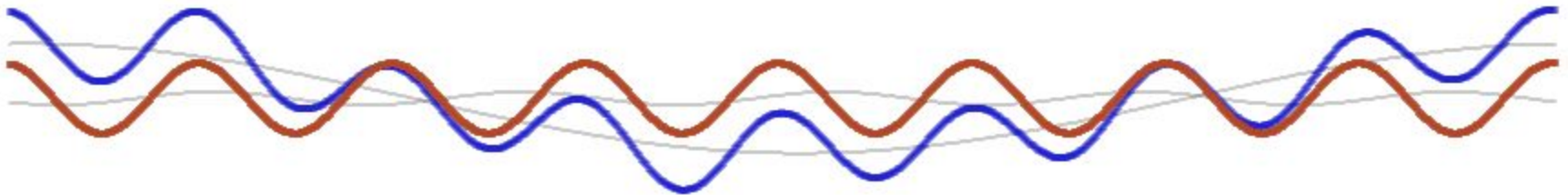


THE CLOCKS GO AT DIFFERENT SPEEDS, BUT WE ADD THEM ALL UP



frequencies

space (or time)

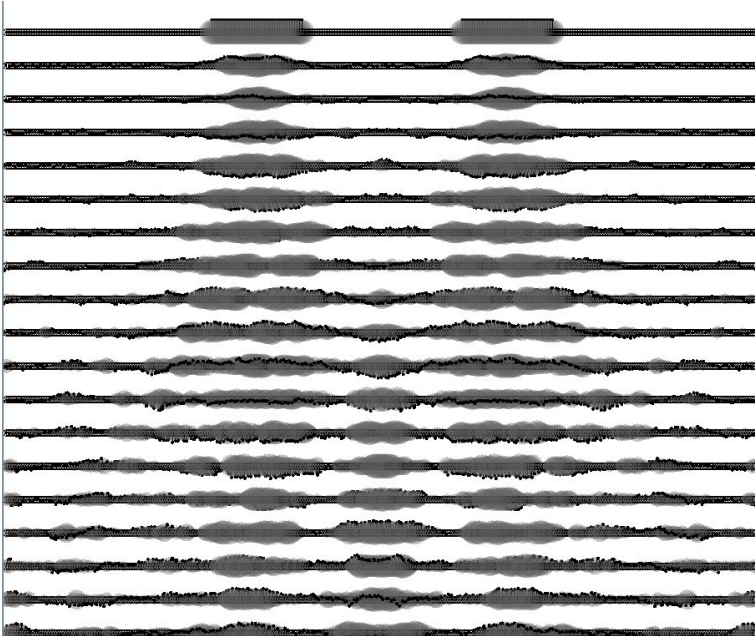


let's talk about

QUANTUM MECHANICS

for the first, and possibly last, time ever in a 100 level COMP course

NOT THIS



THIS

NEWTON'S WORLD

- objects exist at **definite places**,
and **move** over time to new places, **nearby, smoothly**

Also...

- light is a wave, just like water, except what waves is electric and magnetic “fields”
- everything's made of atoms, which are made of particles, which are objects (see above)



Basically all of that turned out to be wrong

100 YEARS AGO

Albert Einstein (aged 26 in 1905)

Louis de Broglie (was 31 in 1923)

Werner Heisenberg (24 in 1925)

Paul Dirac (was 23 in 1925)

Erwin Schrödinger (ok, 39 in 1926)

and later Richard Feynman (who was 24 in 1942)

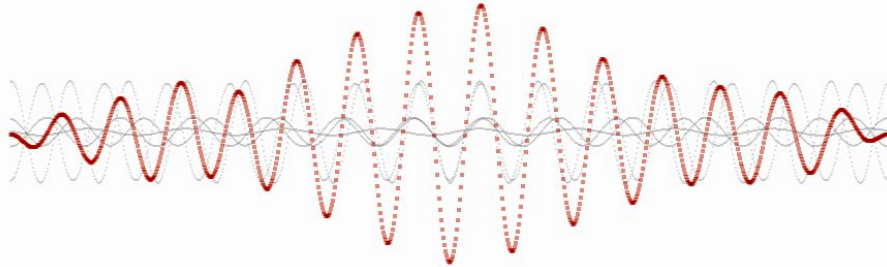
} the mid 1920's
were amazing

IN THE QUANTUM WORLD

- particles can “be” **both here and there**,
between observations



- a wave determines the “dynamics” of the world, but it only gives the **chance** of later finding the particle at a place - up until an observation - everything is uncertain



and not just
epistemic: the
other one...
aleotoric

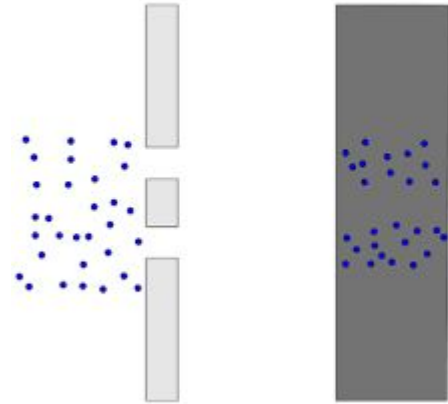
DOUBLE SLIT EXPERIMENT – WHAT SHOULD HAPPEN

We fire electrons in from the left

The “wall” has two slits in it

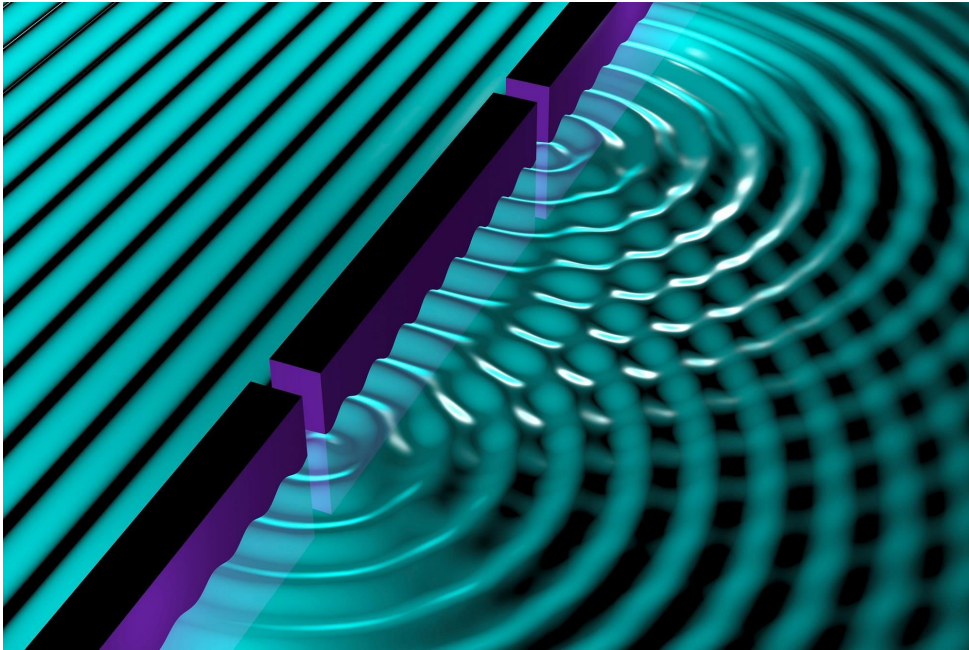
We can detect the electrons hitting the opposite wall, one by one

Electrons are definitely particles, so they ought to pile up in two bunches, behind the two slits



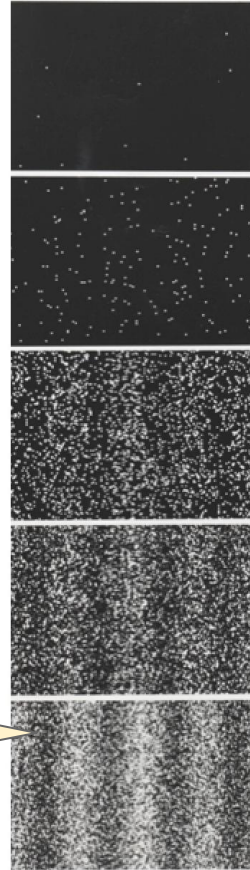
DOUBLE SLIT EXPERIMENT

– WHAT HAPPENS



see Ripple Tank Simulation at
<http://www.falstad.com/ripple/>
(suggest you set to slowest)

constructive and
destructive
interference



Particles
build up into
bands

Most dense *in
the middle*,
not right
behind slits

Wave-like
particles?!?

OH COME ON...

note: similar effects have since been shown for photons, neutrons, protons, atoms and even large molecules

- electrons arrive one by one - seems like they *must* go through one slit or the other?
- but the pattern is exactly what you'd get with a wave that goes through both slits → “interference”

Schrödinger → a wave equation, but **what's “waving”**? And how come the electrons **arrive as particles**, one by one?

Quantum Mechanics answer is:

- the wave is potentially spread out **everywhere**
- nothing is waving, and the size of the wave only gives the **chance** of finding the particle at a location, should you look there, and that's all we can say

THIS DOESN'T MAKE SENSE

“Subatomic particles do not behave like clouds, or billiard balls, or weights on springs, or like anything that you have ever seen”

Richard Feynman



Don't try to interpret this “electron wave” as a normal material disturbance, but as something that simply informs us *where the electron is likely to be found.*

ie. the sole job of the electron wave is to allow us to compute the odds about where the electron will hit the screen

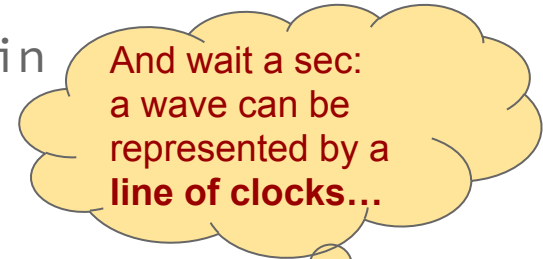
& we will shortly see how to do this!

ALL POSSIBLE PATHS AT ONCE

Let's check the logic:

- we need to allow the electron to go through both slits ✓
- if the electron were “really” somewhere in the wave, it wouldn't explain the interference ✓
- instead of “the electron is somewhere in the wave” we mean “the electron is everywhere in the wave”

the electron sweeps from source to screen following all possible paths at once



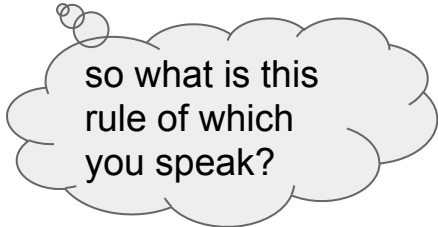
THE ONE WINDING RULE TO RULE THEM ALL

The “Schrödinger” wave equation can be turned into **a rule for winding the clocks**

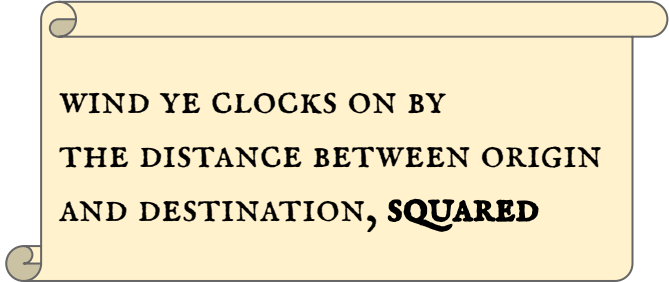
Otherwise everything is exactly as it was when we did the Fourier Transform. Each row is one time-step.

- each time step, all the clocks in a row get
 - cloned / copied and moved to all possible locations (the next row)
 - wound on appropriately
 - added up

and that's it!



so what is this
rule of which
you speak?



WIND YE CLOCKS ON BY
THE DISTANCE BETWEEN ORIGIN
AND DESTINATION, **SQUARED**

TOMORROW

We will code this up, and see it working on two test scenarios:

1. can we reproduce the “bands” in the double slit experiment?
2. can we make a “propagator” – a wave that travels along, like an electron does?!

note: did anybody ask about Quantum Computers and “qubits”?