Title: The Entanglement Game and 21st-century applications of quantum theory including quantum computers

Date: Jul 12, 2006 09:00 AM

URL: http://pirsa.org/06070022

Abstract: This presentation will introduce the counter-intuitive quantum concept of entanglement and help to explain it via the Â‘entanglement gameÂ’, a hands-on interactive activity that has been successfully tested with a number of Grade 12 classes. It will also introduce the emerging field of quantum technology within which researchers are harnessing some of the strange features of quantum theory to build new powerful 21stÂ–century technologies such as quantum computers, quantum teleporters and quantum secret codes.

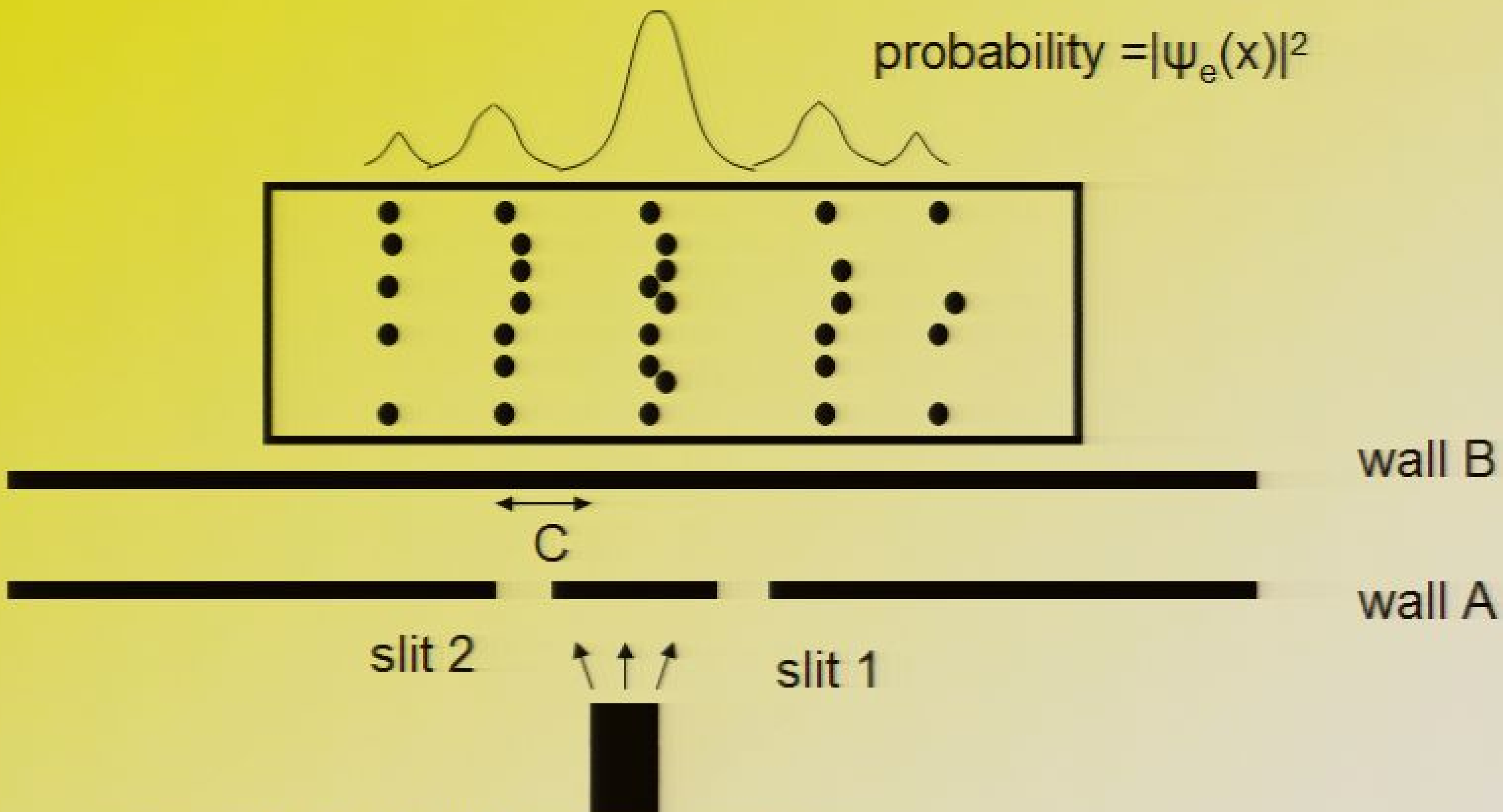
- Can open a second slit and *decrease* the number of electrons detected at C.

- Makes no sense within the particle model.

- Probability (slits 1 & 2 open) (x) < Probability (slit 1 open) (x) + Probability (slit 2 open) (x),

  where the probabilities relate to the likelihoods of finding particles at position x.

What do we actually see?



- wave-water double-slit interference pattern
  See http://www.hqrd.hitachi.co.jp/em/movie/doubleslite.mpeg for a video illustrating how the pattern builds up

- What happened?

- Particle model fails.

- Electrons are not like scaled-down, tiny tennis balls.

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- To calculate Probability (slits 1 & 2 open) (x), we do the same thing as for ordinary water waves:

  Add the two contributing amplitudes, find the magnitude of the resulting sum and then square this.

Probability (slits 1 & 2 open) (x)

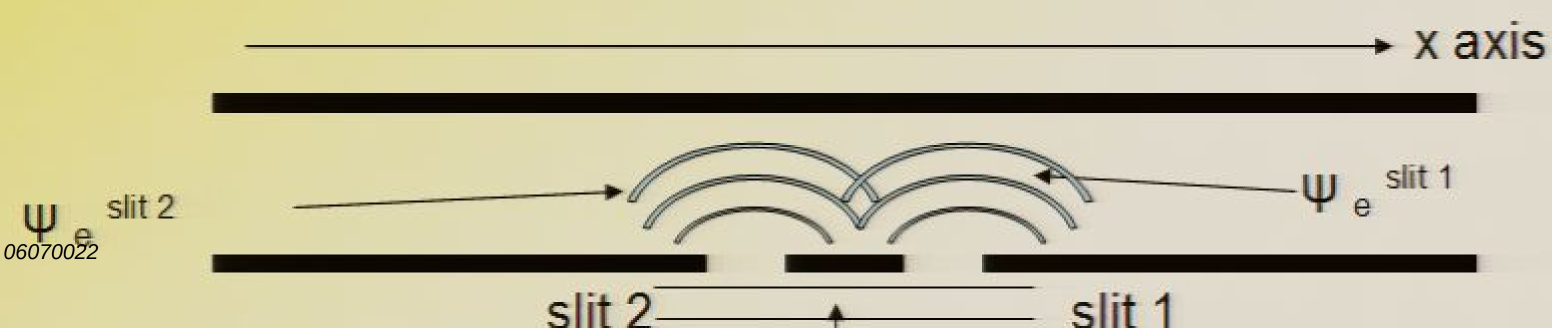
$= |\psi_e(x)|^2$

$= |\psi_e^{\text{slit 1}}(x) + \psi_e^{\text{slit 2}}(x)|^2$,

where $\psi_e^{\text{slit 1}}(x)$ and $\psi_e^{\text{slit 2}}(x)$ are wavefunctions* for electrons passing through slits 1 and 2

(Strictly speaking, we are dealing with probability densities rather than probabilities.)

•Assuming ψ_e is normalized, $\psi_e^{\text{slit 1}}(x)$ and $\psi_e^{\text{slit 2}}(x)$ will be unnormalized



Sometimes, $|\psi_e^{\text{slit 1}}(x) + \psi_e^{\text{slit 2}}(x)|^2 < |\psi_e^{\text{slit 1}}(x)|^2 + |\psi_e^{\text{slit 2}}(x)|^2$

sum of the two probabilities when just one slit is open

Eg. let $\psi_e^{\text{slit 1}}(x)=1/5$ and $\psi_e^{\text{slit 2}}(x)= -1/4$.

$|\psi_e^{\text{slit 1}}(x)+ \psi_e^{\text{slit 2}}(x)|^2=(1/5 - 1/4)^2 =1/400 < |1/4|^2 + |1/5|^2 = 41/400$

Destructive interference: explains why we can detect fewer electrons with both slits open

Can also get constructive interference, just as with water waves

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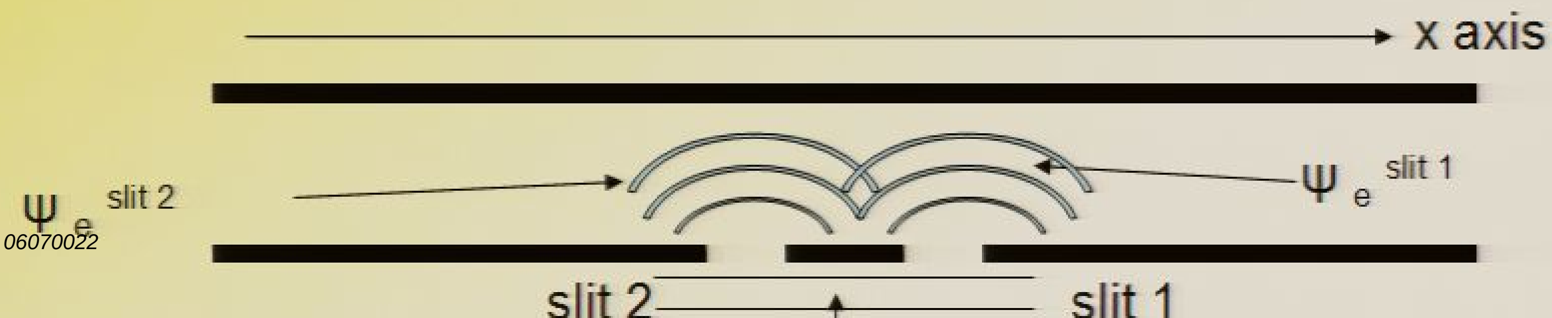

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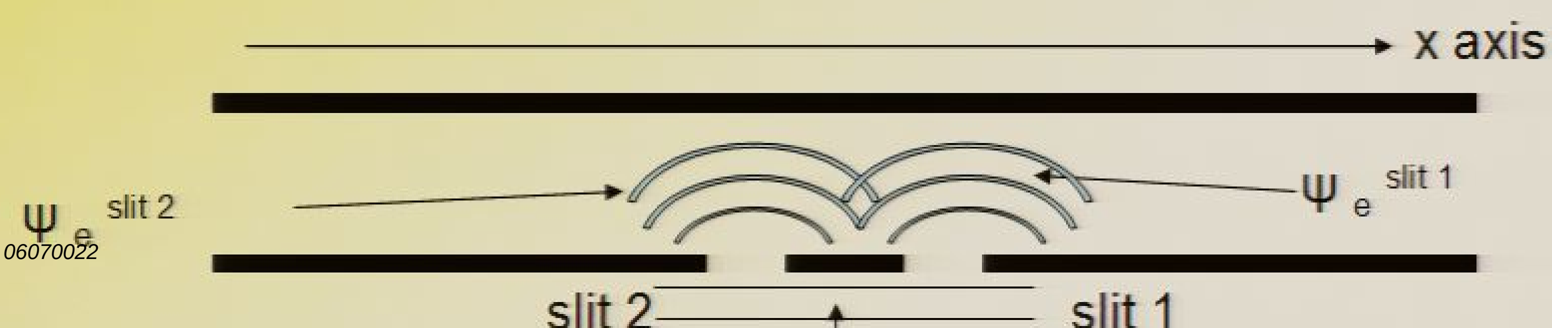

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Can also get constructive interference, just as with water waves

- General rule in quantum theory is that if there are two (or more) ways of detecting a particle at some particular point AND there is no way to distinguish between them, then we add up the probability amplitudes (i.e. ψ's) associated with these possibilities first & then find the square of the magnitude of the resulting sum to get the overall probability.

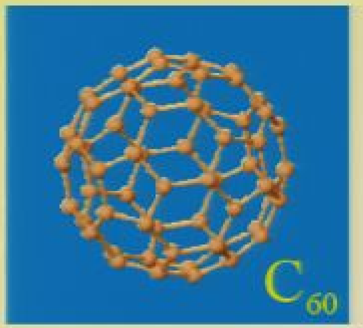
- $\text{Prob} = | \psi_1 + \psi_2 + \psi_3 + \dots |^2$

Activity

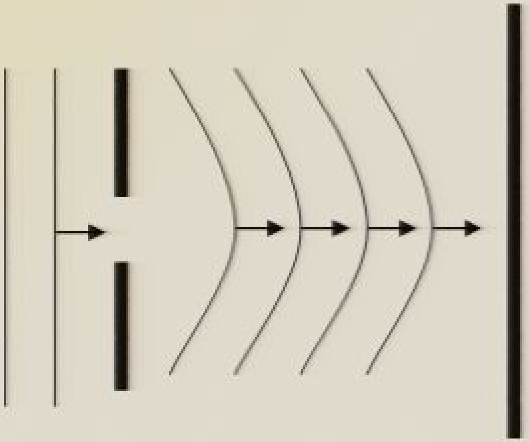
- Assume that at point Y, $\psi_e^{\text{slit 1}}(x=Y) = 1/10$ and $\psi_e^{\text{slit 2}}(x=Y) = 1/5$.
- What is the probability (density) $|\psi(x=Y)|^2$ of detecting the electron at Y when just slit 1 is open? i.e. $|\psi_e^{\text{slit 1}}(x=Y)|^2 = ?$
- When just slit 2 is open?
- When both slits are open?
- Is $|\psi_e^{\text{slit 1}}(x)+\psi_e^{\text{slit 2}}(x)|^2 < |\psi_e^{\text{slit 1}}(x)|^2 + |\psi_e^{\text{slit 2}}(x)|^2$ in this case?

All quantum entities exhibit wave-like properties, not just electrons

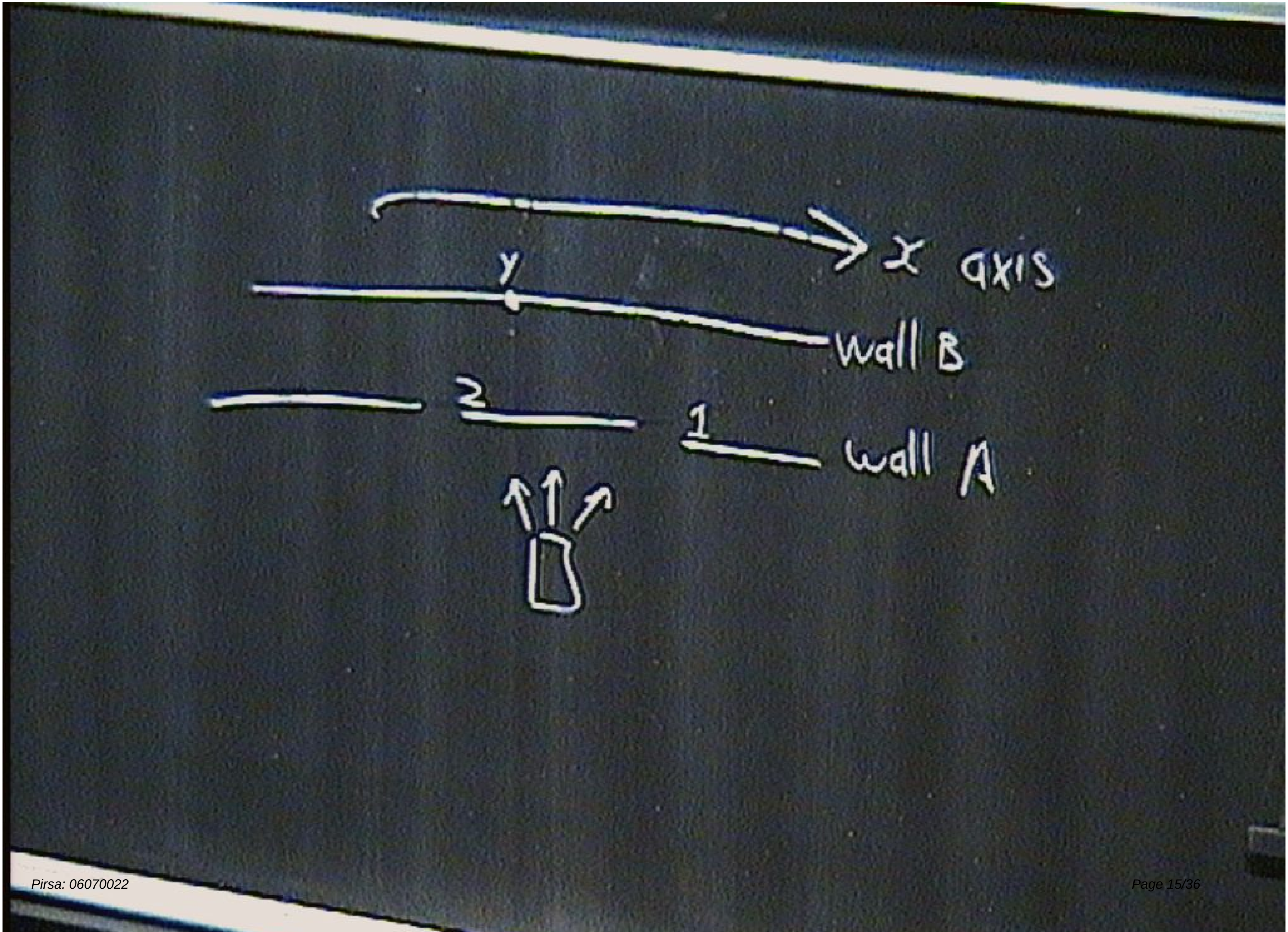
- 2001: Diffraction observed for fullerene molecules or Buckyballs.
- **C-60** : sixty Carbon atoms arranged in a soccer-ball configuration



- Essentially did the single slit experiment



- Slit width: 50 nm
- Wavelength $\lambda = 2.5 \times 10^{-12}$ m
- m ≈ 1,300,000 times mass of electron!
- v ≈ 210 ms^{-1}


x axis
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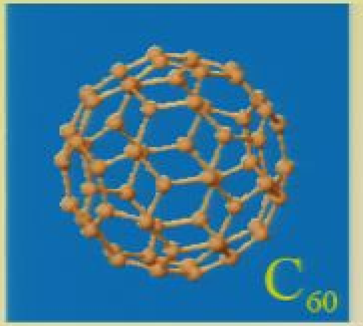

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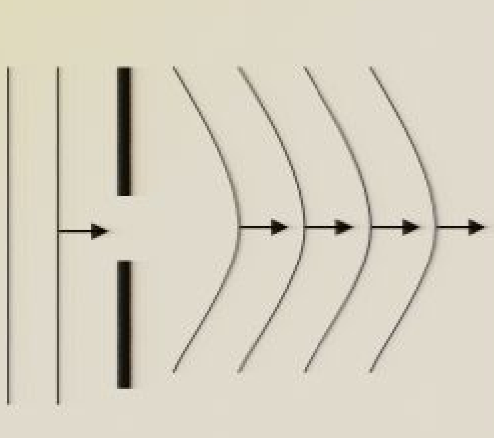

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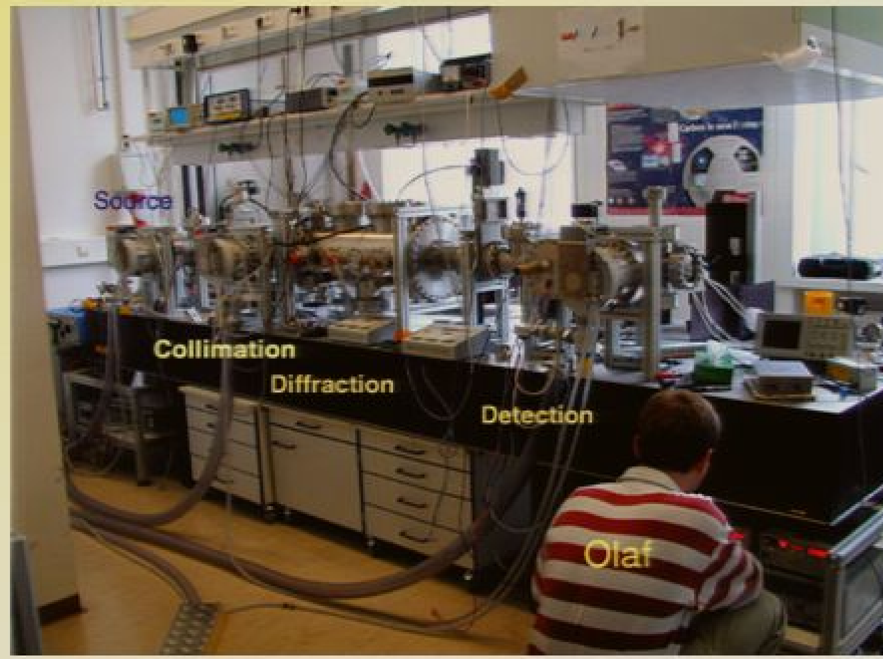
- Wavelength $\lambda = 2.5 \times 10^{-12}$ m
- $m \approx$ 1,300,000 times mass of electron!
- $v \approx 210\ ms^{-1}$

For more information visit:

http://www.quantum.univie.ac.at/research/matterwave/c60/index.html



picture from http://www.quantum.univie.ac.at/

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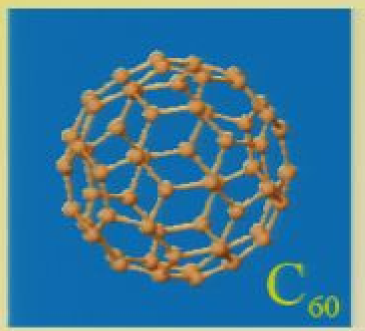

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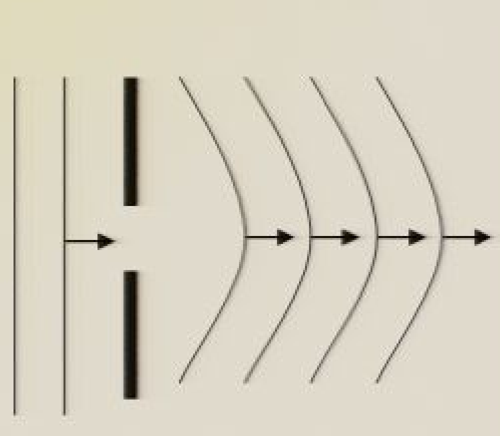

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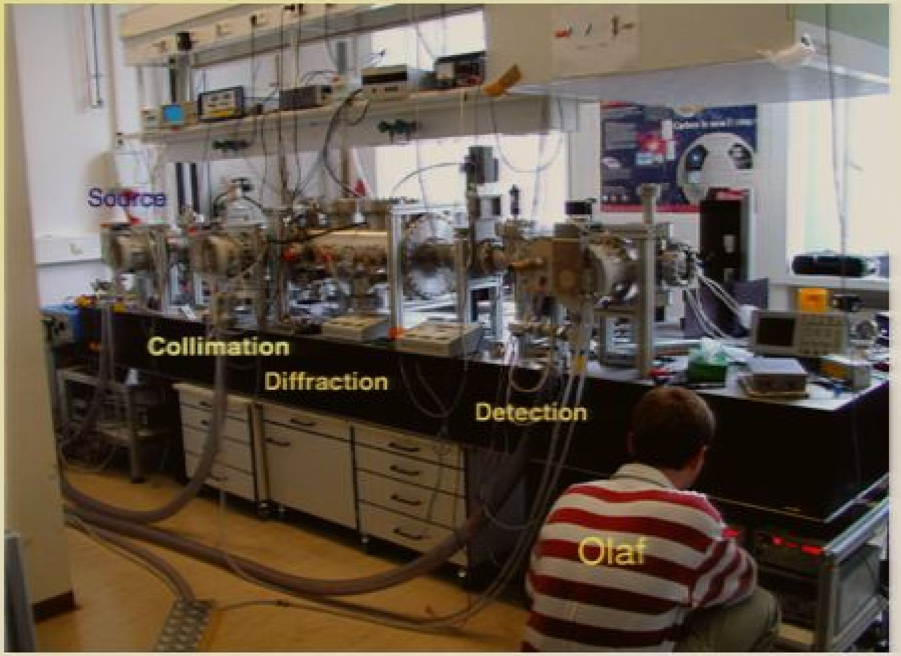

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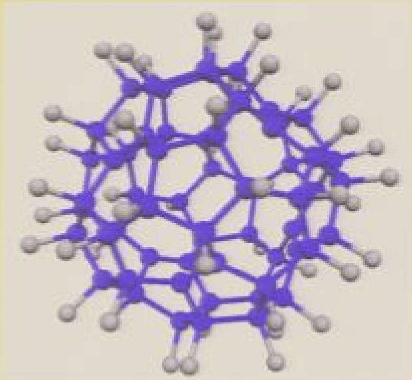


- WORLD RECORD FOR WAVE BEHAVIOUR OF MASSIVE PARTICLES
- Vienna, 2003: $C_{60}F_{48}$: fluorinated fullerene
- More than 1.5 millions times more massive than an electron
- Same scientists trying to observe the wave nature of viruses
- Any fundamental limits?
- Could we see the wave nature of a mouse? a cat? A grade 12 physics student?
- More information at: http://www.quantum.univie.ac.at/research/matterwave/TPPC60F48/index.html

Core Feature No. 1: Wave-particle duality

- A particle always behaves like a particle and a wave always behaves like a wave. Electrons sometimes behave like particles and sometimes like waves and so are neither.

- "Historically, the electron, for example, was thought to behave like a particle, and then it was found that in many respects it behaved like a wave. So it really behaves like neither. Now we have given up. We say: 'It is like *neither*.'"
  - Richard Feynman

- Electrons are simply electrons.

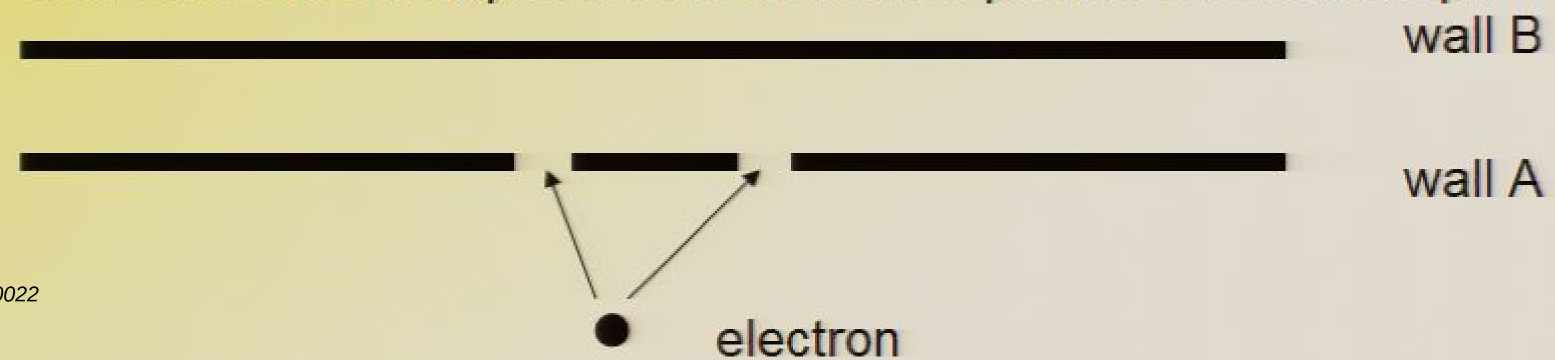
- Wavicles? 

- Particle-like <u>and</u> wave-like aspects: *Dual nature*

- In general, neither the traditional pictures of waves or particles are, by themselves, sufficient at the quantum level (for all quantum entities; electrons, protons, neutrons etc.).
- Can only use each of them with certain experimental set-ups or arrangements
- But, together, they can be used to describe all quantum phenomena.
- piecemeal solution

Core feature No. 2: Superposition

- Double-slit experiment has been done with only one electron passing through wall A at a time.
- Scientists still saw, after 1000's of electrons had been detected, an interference pattern.
- Suggests (perhaps) that each individual electron goes through *both* slits at the same time and interferes *with itself*. (Although some debate about this.)
- How else can we explain the interference pattern that builds up?

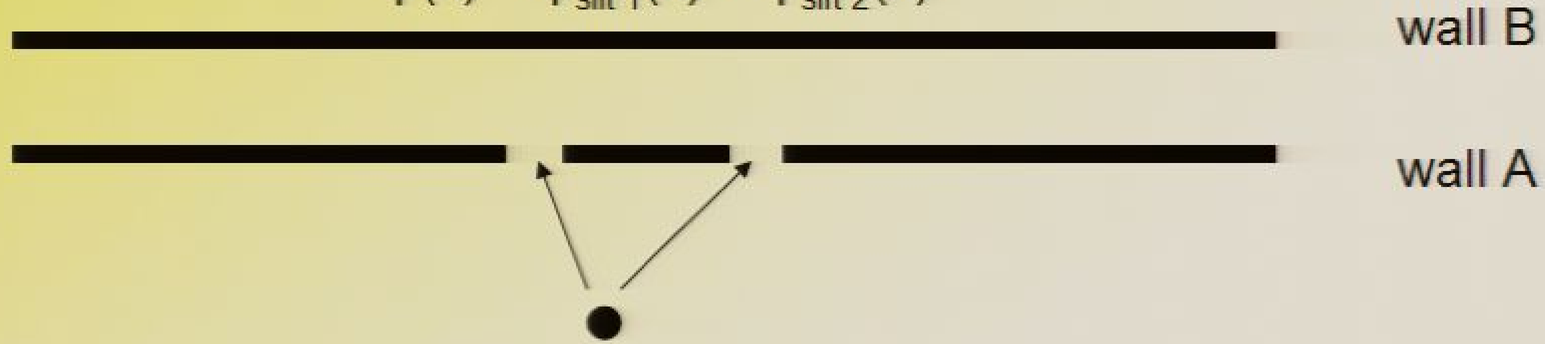


- Everyday objects such as baseballs, cars and trees are constrained to only exist in one place at any given time.

- Individual quantum entities such as electrons, atoms and photons, however, can exist in ‘fuzzy’ states of affairs called *superposition states* in which it seems that multiple possibilities are simultaneously realized

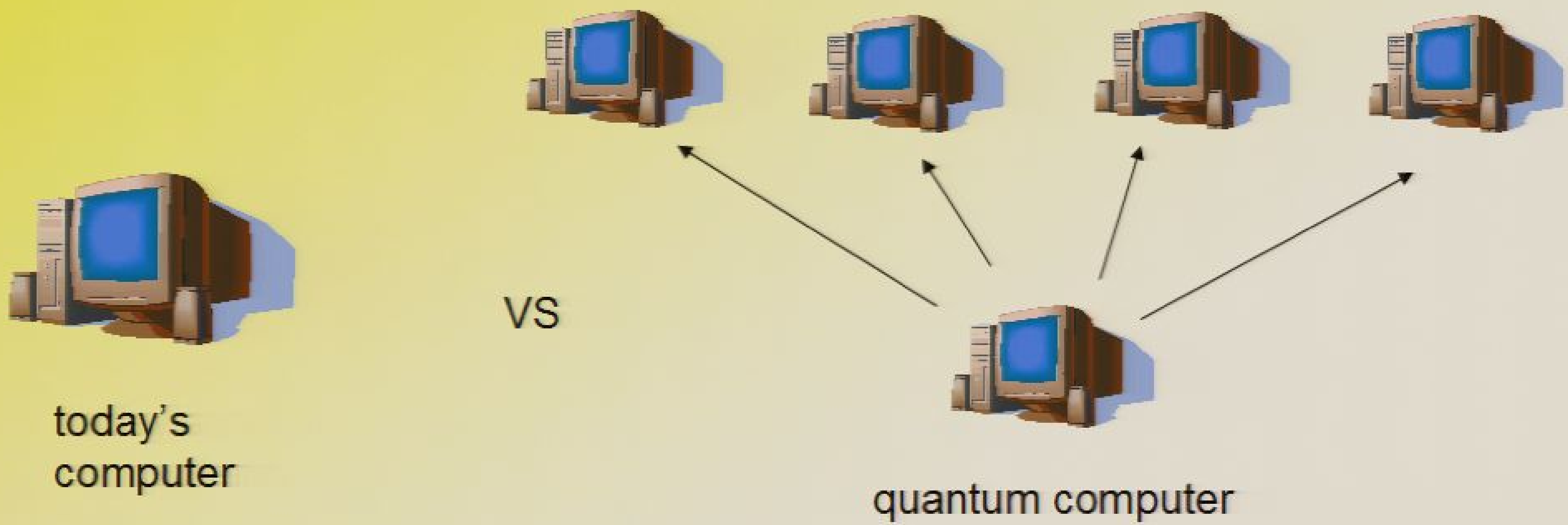
- Eg. the quantum state ψ in the double-slit experiment

$$\psi(x) = \psi_{\text{slit 1}}(x) + \psi_{\text{slit 2}}(x)$$



- (Although see Hans Westman’s keynote presentation *Cats, Collapses and the nature of reality: What does quantum theory really mean?* for alternate views)

- *This is related to quantum computing*: superposition allows quantum computers to perform thousands of computations simultaneously instead of just one at a time



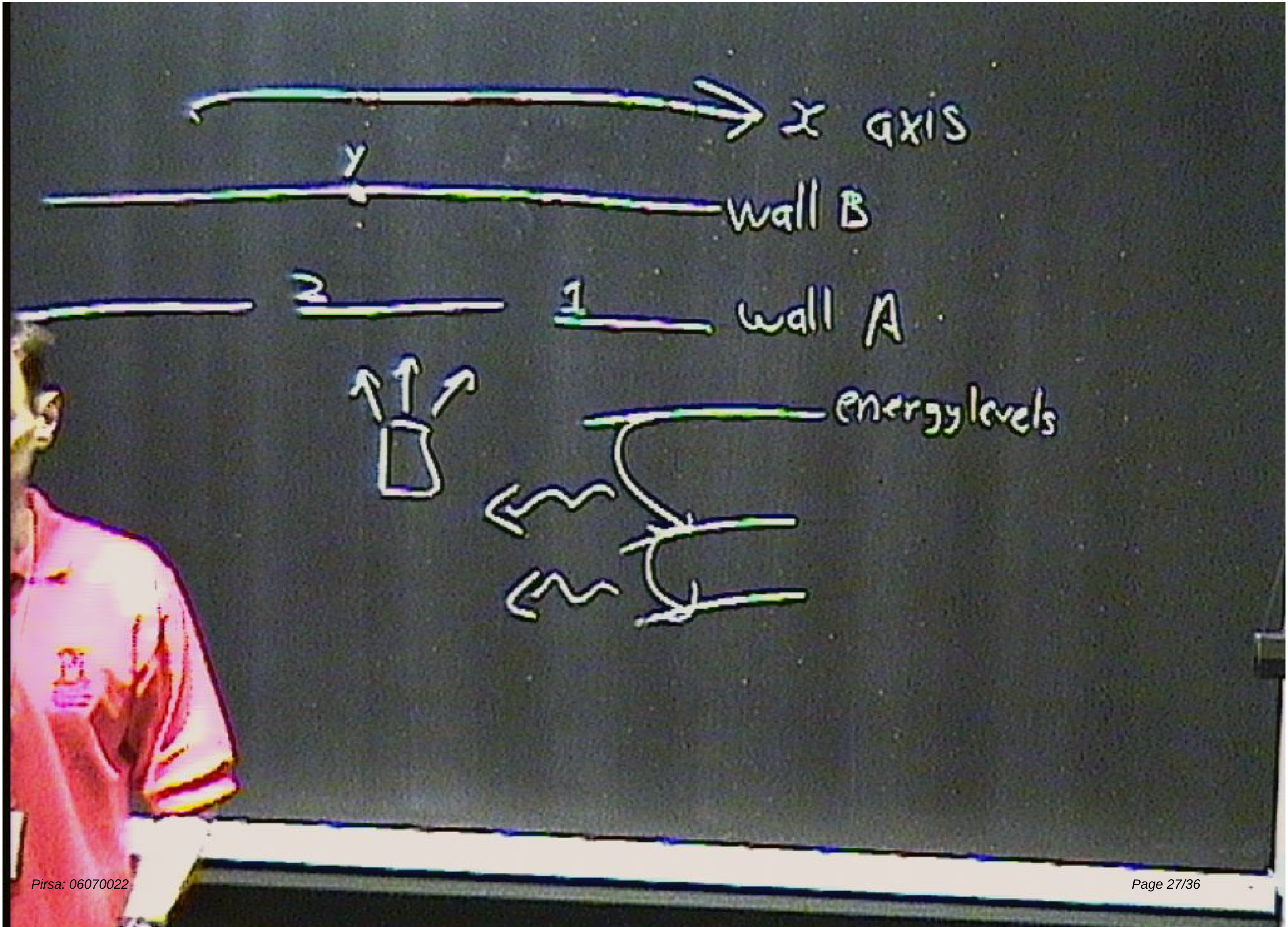
- Superposition is a core defining feature of quantum theory (*The* defining feature?)

- Underlies the counterintuitive phenomena of electrons appearing to go through both slits at the same time and the electron interference pattern.

- A core aspect of quantum phenomena such as entanglement, quantum tunnelling and quantum interference in general

- N.B. Also found in water, sound, EM etc. waves and so not limited to quantum theory.

- Everyday wave analogies exist for many *quantum superposition* phenomena (But not all — eg. entanglement and Bell violations).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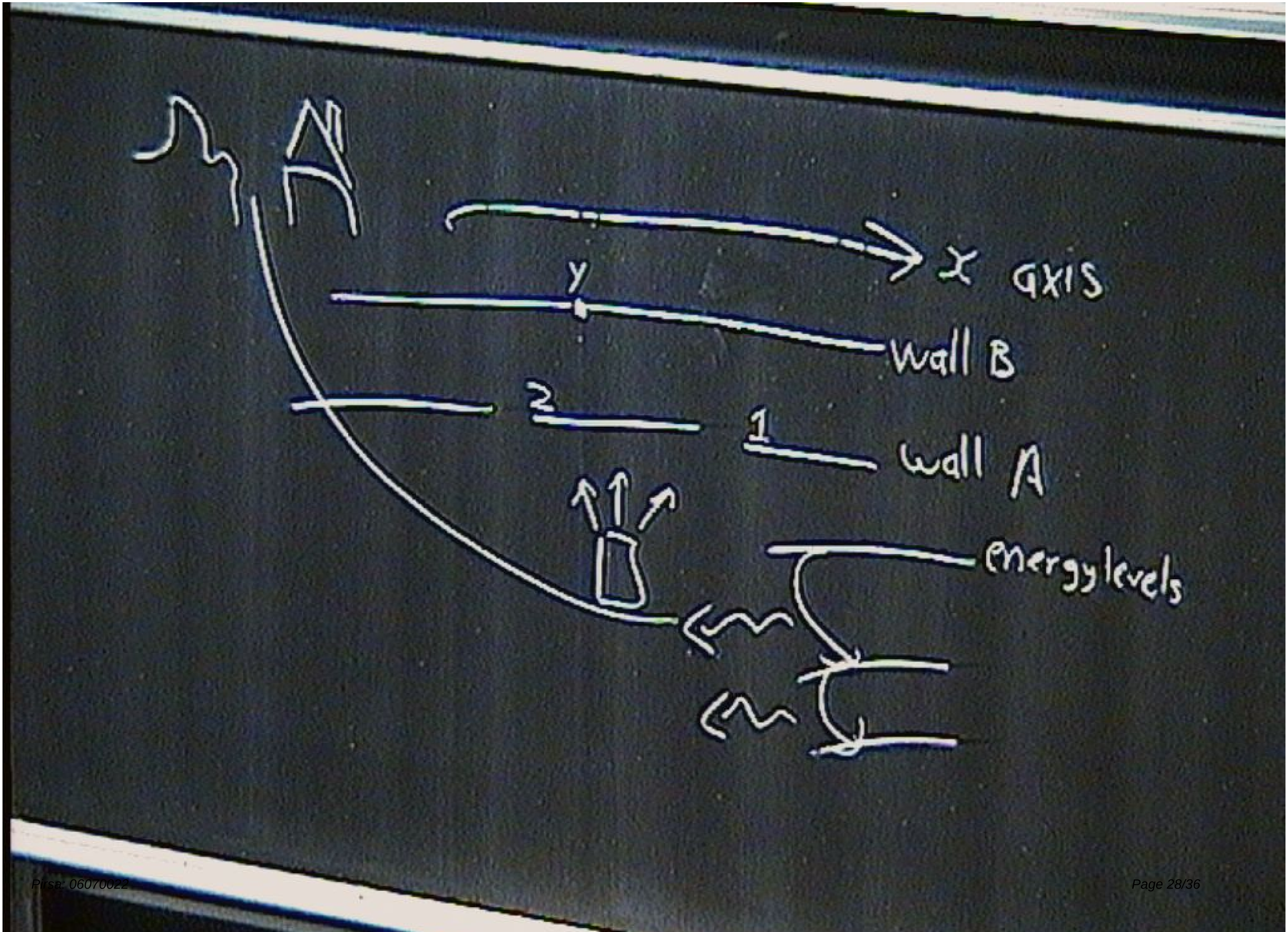
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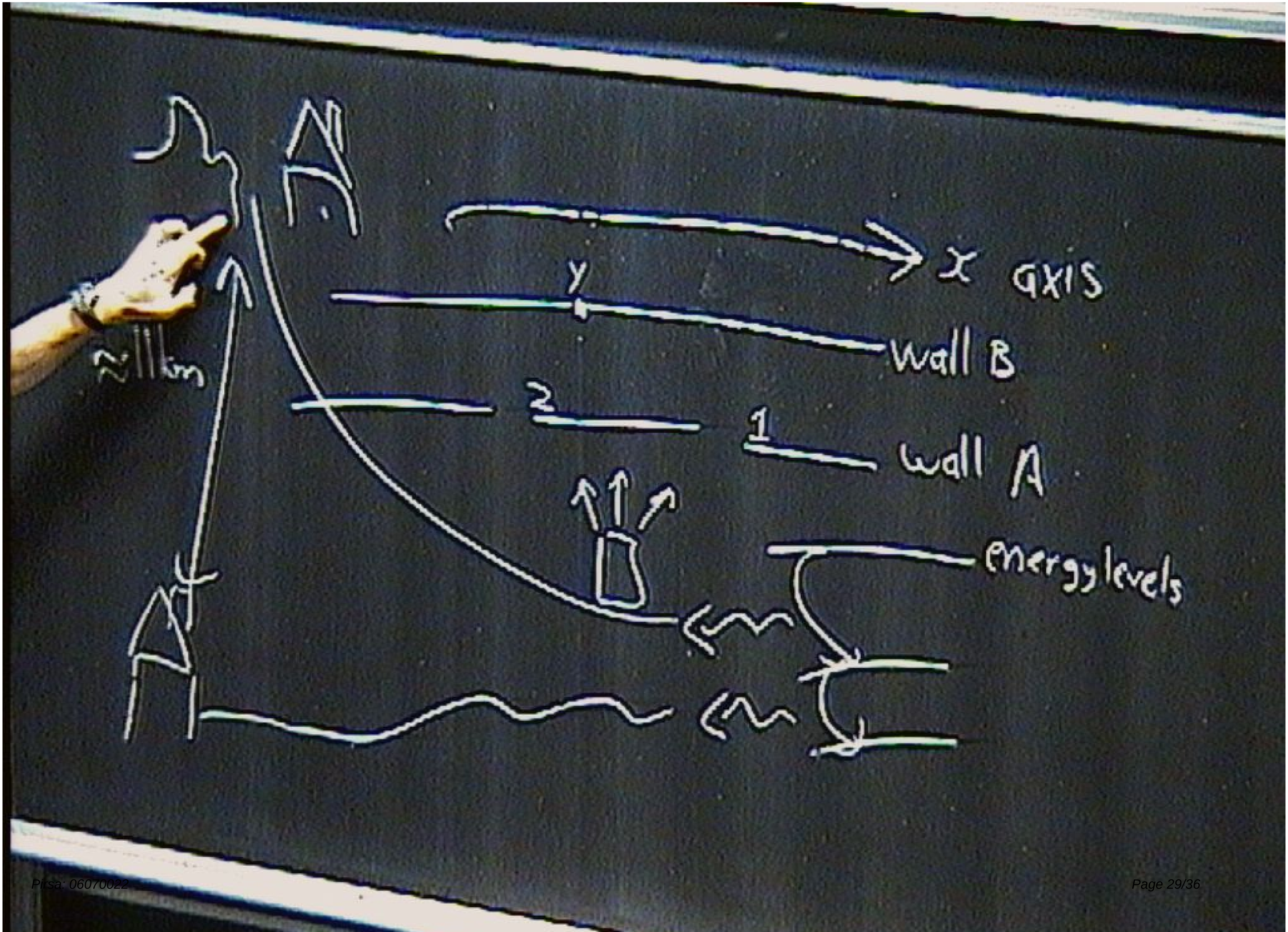

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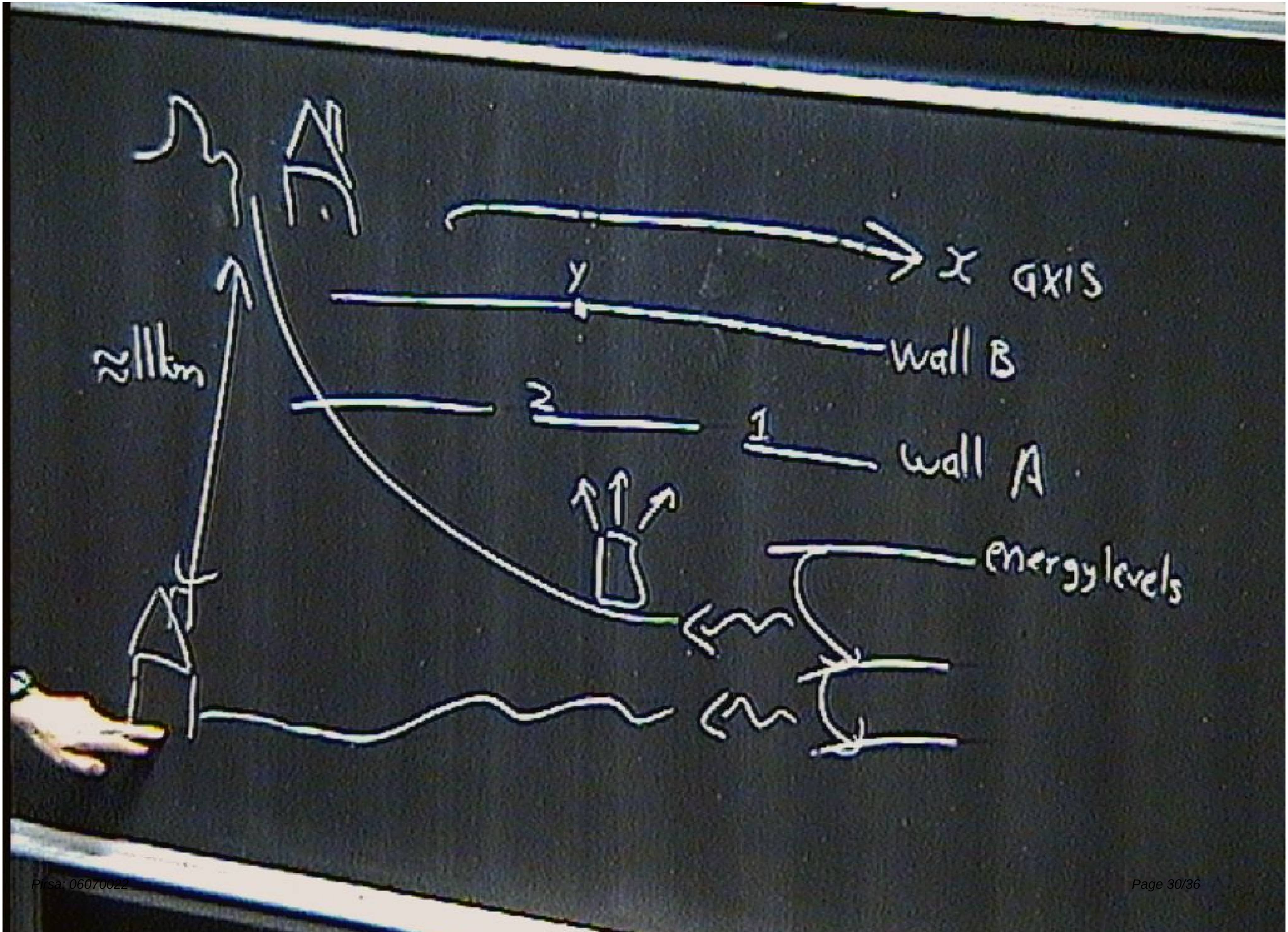
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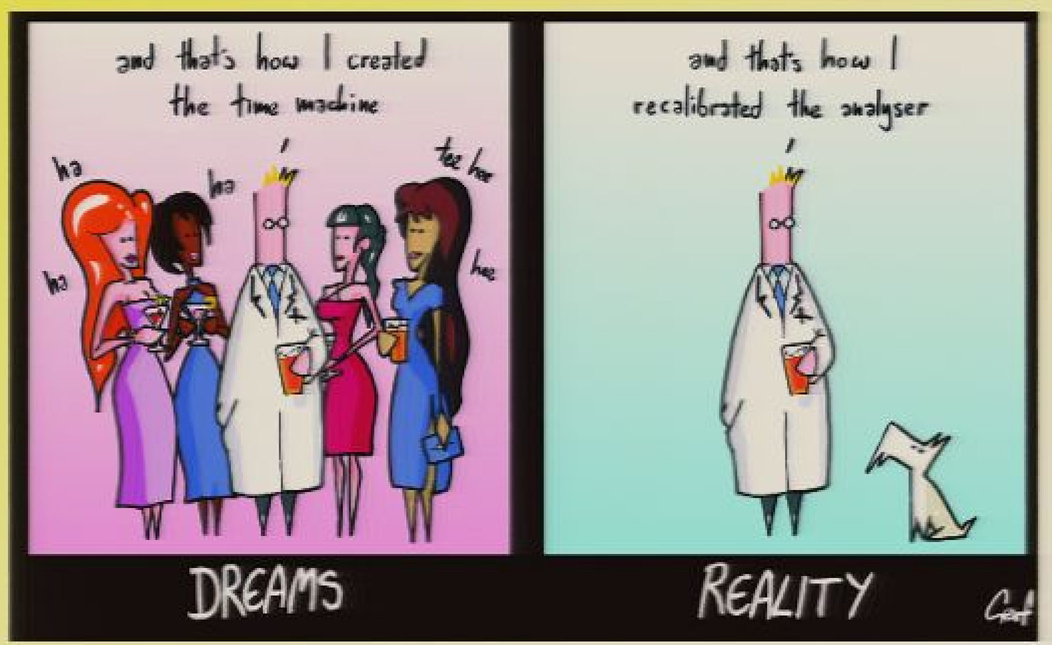
- Everyday wave analogies exist for many *quantum superposition* phenomena (But not all — eg. entanglement and Bell violations).

- There are differences between ‘ordinary’ (called ‘classical’ by physicists) superposition with, say, water waves and quantum superposition.
- When we measure quantum entities, they’re always localized in one spot.
- Eg. we detect electrons at specific locations along wall B rather than being spread out like water waves and other classical waves.
- “As if electrons and other quantum entities are acting like waves when we’re not looking at them but particles when we are.”
- *Collapse of the wavefunction*. This does not happen with classical waves.
- Also (more technically), classical waves exist in 3-dimensional space. Wave(function)s in quantum theory are objects in a 3n-dimensional space (configuration space), where n is the number of particles we’re considering.

Image of physics



Cartoon courtesy *Physics World* magazine, Institute of Physics, UK

Core feature No. 3: Genuine Randomness

- Imagine doing the double-slit experiment with electrons, but with a slight variation.

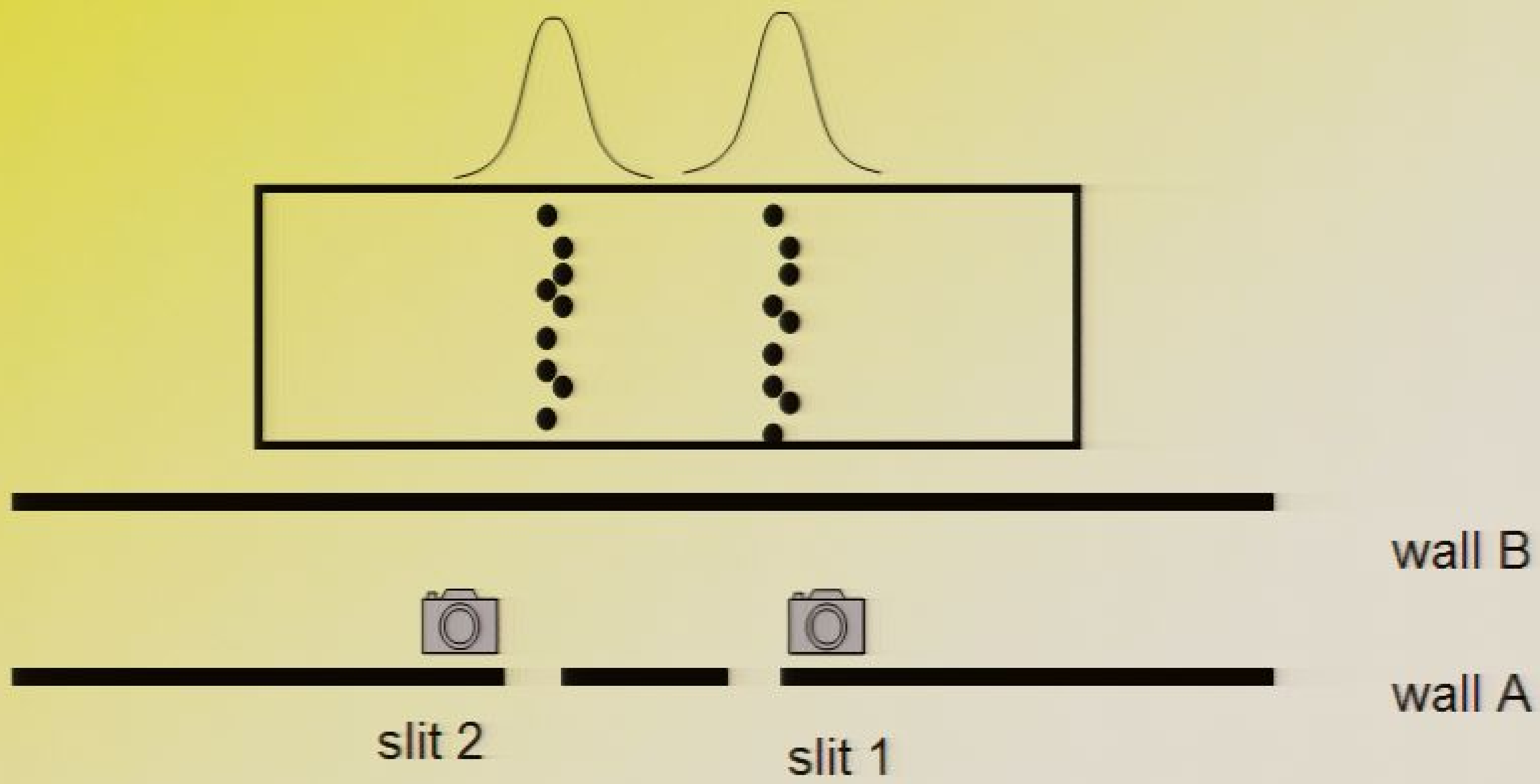
- Place detectors right next to both slits to watch which slit each electron passes through.

  (The detectors do not absorb the electrons. They simply register whether or not they pass through the slit next to which they are located.)

- Surely, we will still see the trademark interference pattern at wall B?

  No.

- We see the two single-slit electron patterns added together. i.e.

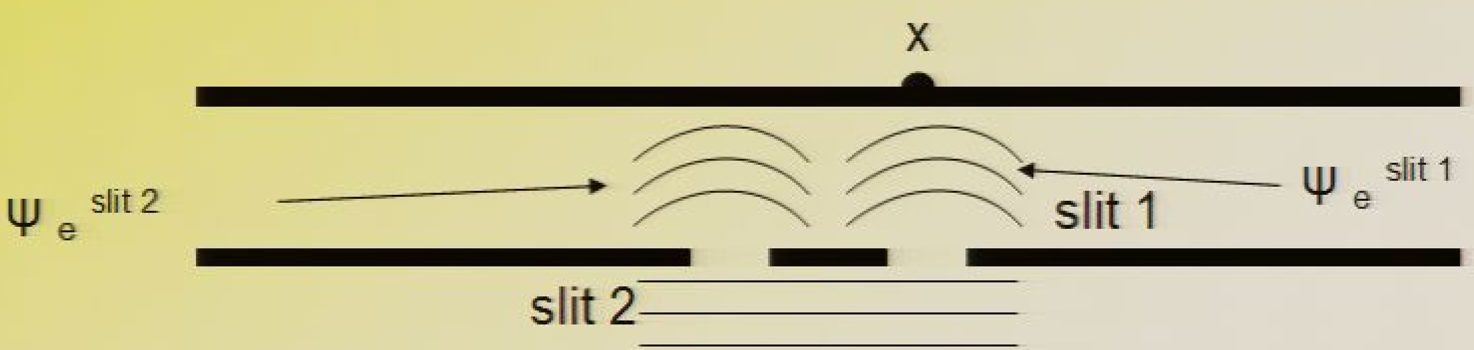


- Somehow, the act of measuring the electrons has destroyed the wave-like interference. Related to *Heisenberg's uncertainty principle*.

  Probability (slits 1 & 2 open) (x) $= |\psi_e^{\text{slit 1}}(x)|^2 + |\psi_e^{\text{slit 2}}(x)|^2$

- General rule is that when there are two or more ways of detecting a particle at a certain location and these two ways are *distinguishable*, then we add the individual probabilities for each.

- N.B. Different to when the ways are *indistinguishable* in which case we add the amplitudes first.



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