Title: Enrichment Presentation on Quantum Theory and Quantum Information

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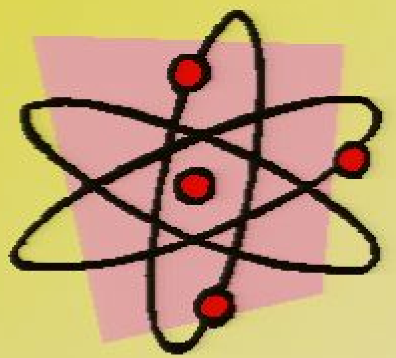
URL: http://pirsa.org/06070004

Abstract:

Core concepts of quantum theory



PERIMETER INSTITUTE
FOR THEORETICAL PHYSICS

Purpose of enrichment presentations

- For you, not (directly for) your students.

GOALS

1. Give you a deeper, richer understanding of the modern physics you teach.

2. Increase your confidence

Summary

- Purpose of enrichment presentations

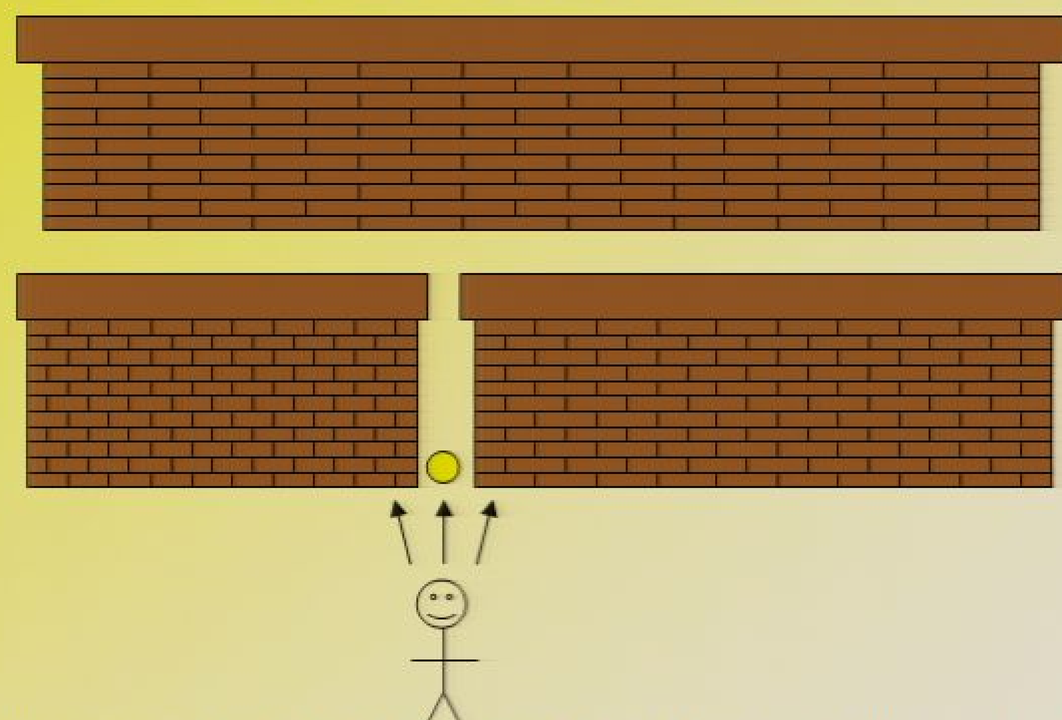
- double-slit experiment

- Four of the most important features of quantum theory
  1. wave-particle duality
  2. superposition
  3. genuine randomness
  4. Heisenberg's uncertainty principle

- Why is quantum theory sometimes so tough to understand?

Double-slit experiment

Imagine a brick wall with a narrow vertical slit. Behind it is a solid brick wall.

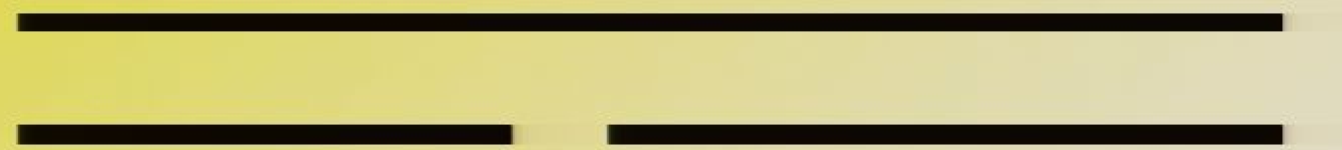


What would happen if we had a bucket full of tennis balls, picked them up one by one, dipped them in black paint, and then threw them *haphazardly* (i.e. the balls do *not* follow identical trajectories) at the first wall from in front of it?

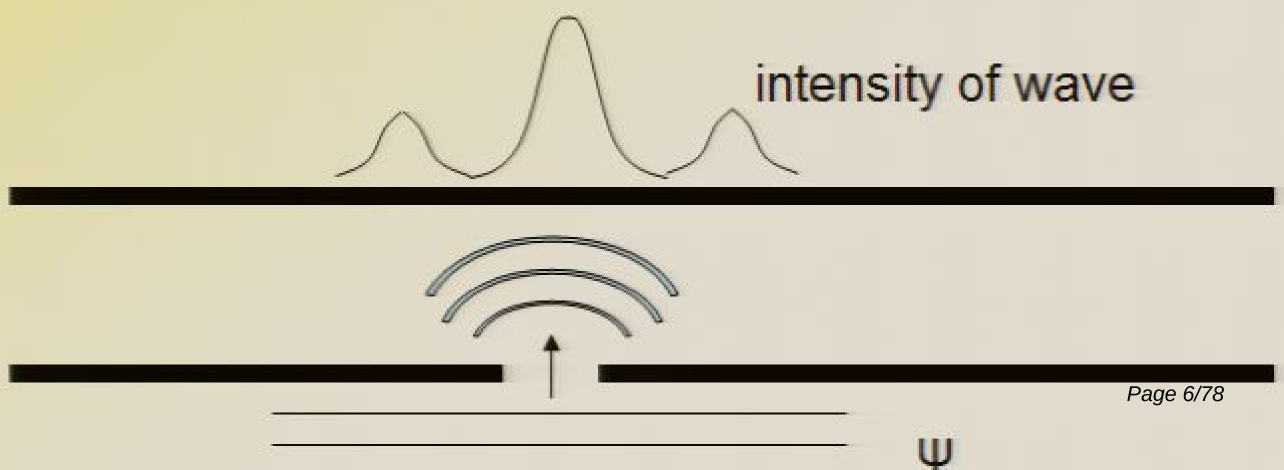
After we've thrown, say, 1000 tennis balls, what would the rear wall look like (roughly speaking)?

Waves

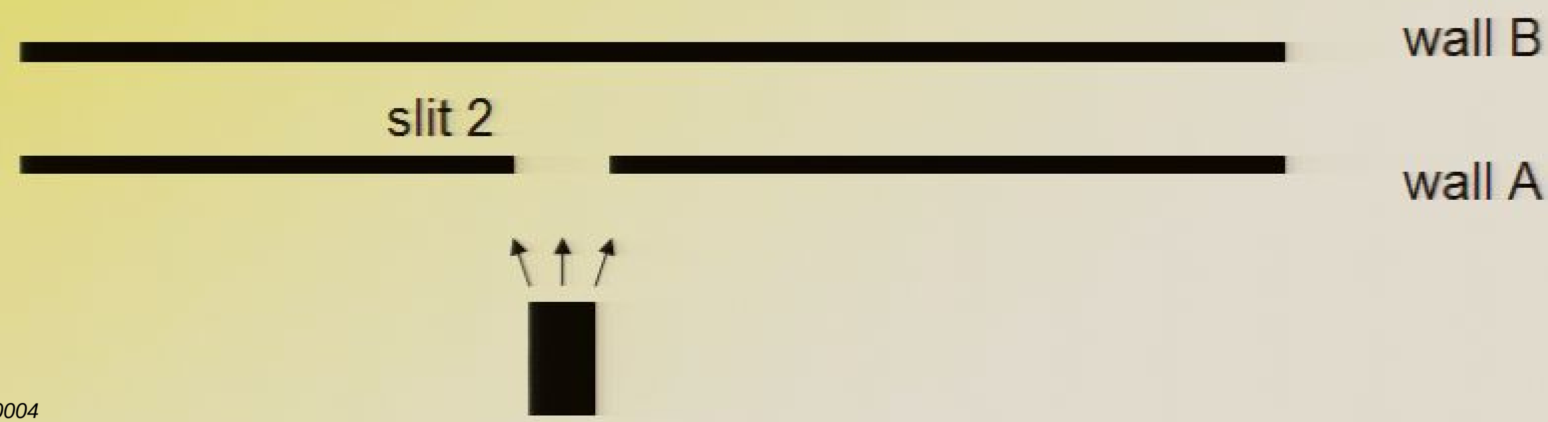
- Consider a similar sort of set up (in essence) but with water waves replacing the tennis balls.
- eg. a sea wall with a gap



- Imagine a plane wave incident at right angles hits the wall. What happens?
- wave represented by specifying the amplitude everywhere (scalar field ψ)
- Diffraction
  (N.B. Details of pattern depend on wavelength, slit width & distance between the two walls)



- Close slit 1 and open up slit 2 and we see the same pattern as before, but just shifted to the left somewhat



What happens when both slits are open?

- Many students think of electrons as kind of like tiny, scaled-down tennis balls (minute solid spheres).
- Given this intuition, would we pattern would we see at wall B with both slits open?
- ANSWER: (Consult with someone next to you and then draw a rough sketch.)

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

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

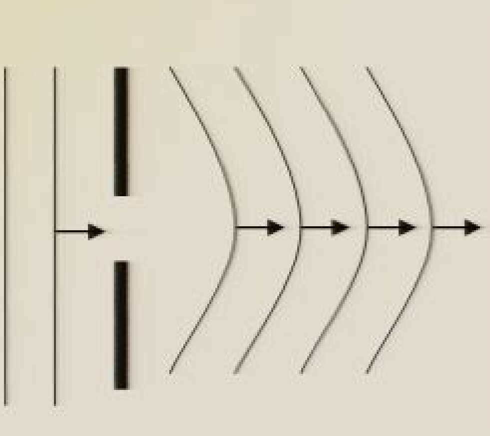
Destructive interference: explains why we can detect fewer electrons with both slits open

Can also get constructive interference, just as with water waves

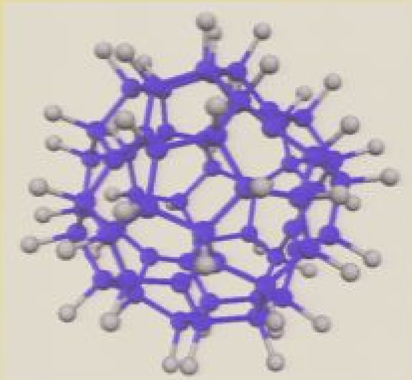
All quantum entities exhibit wave-like properties, not just electrons

- 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
- $m \approx 1{,}300{,}000$ times mass of electron!
- $v \approx 210\ ms^{-1}$



- 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

- 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. 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

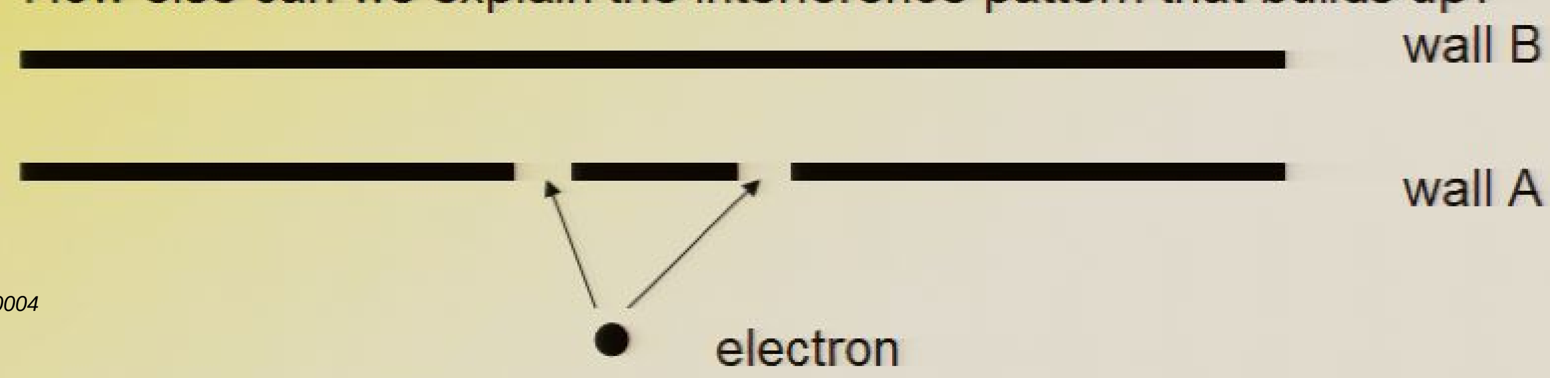
- Electrons are simply electrons.

- Wavicles?

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

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?



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

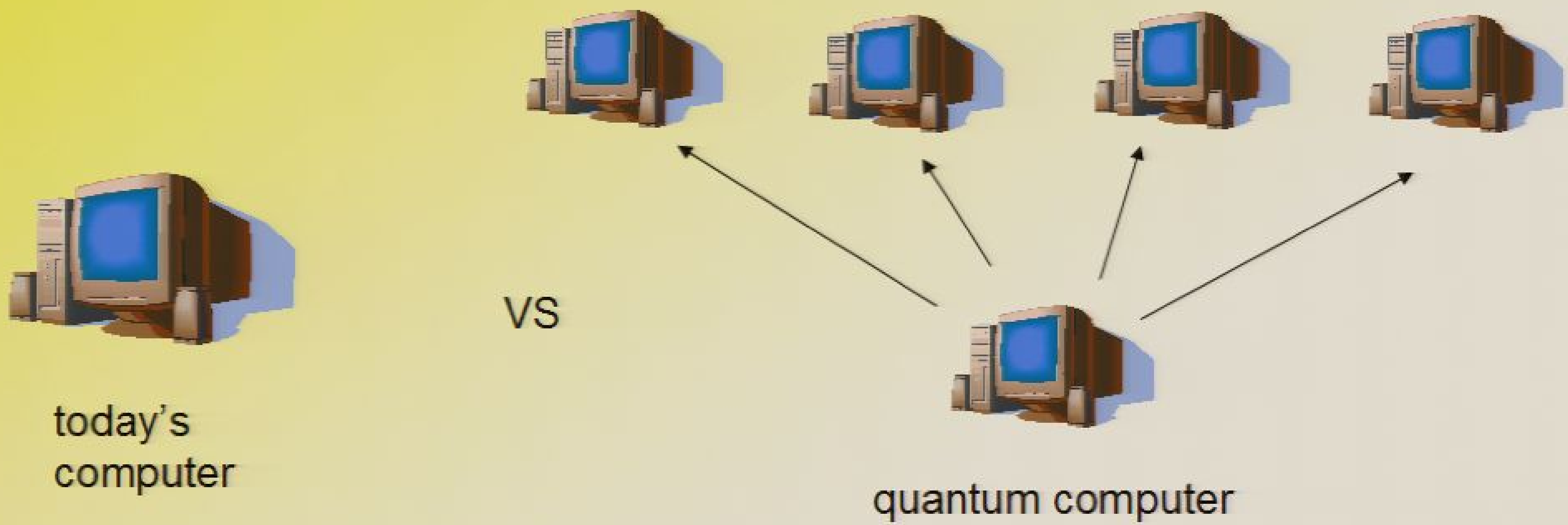
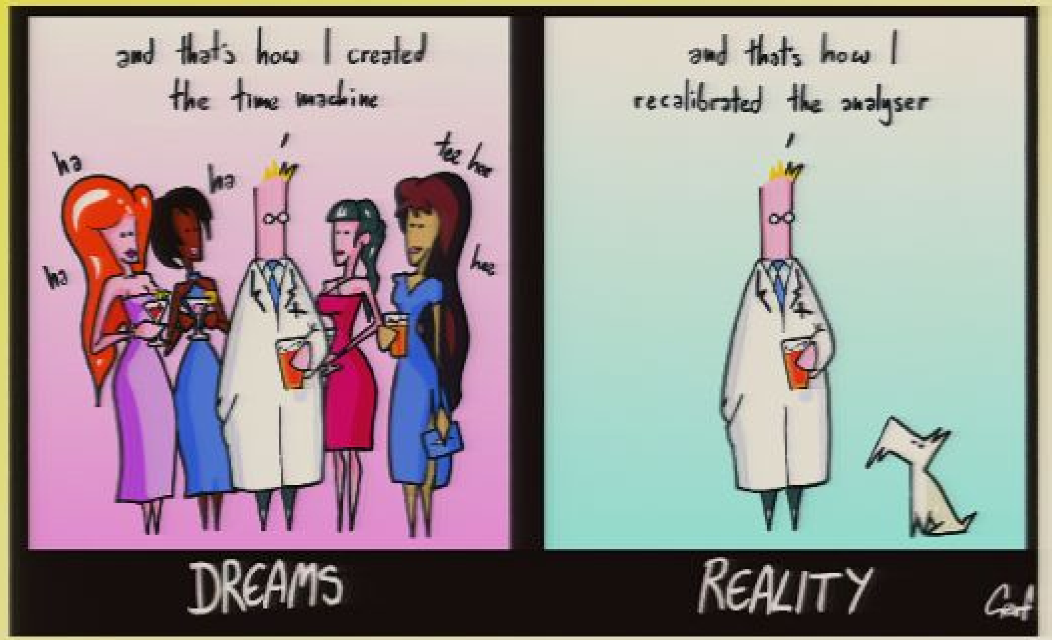


Image of physics



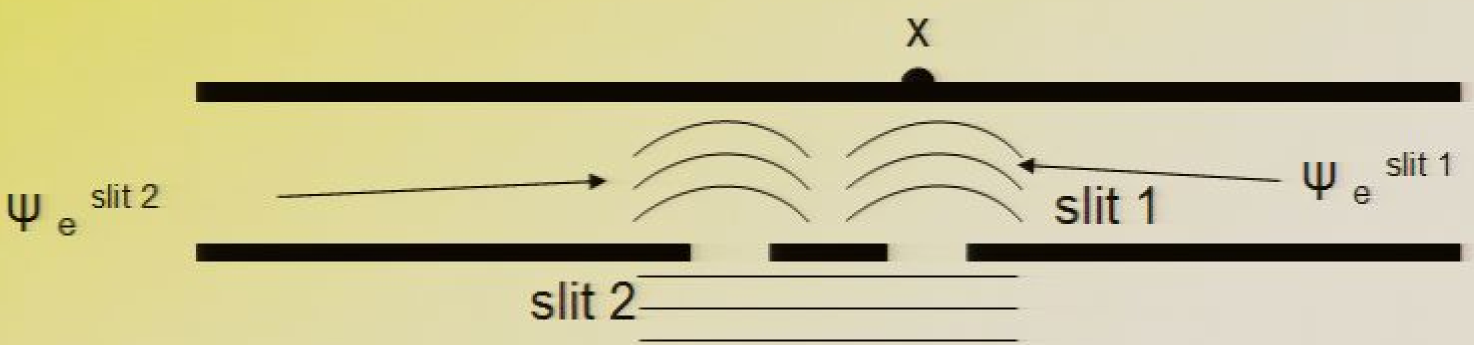
Cartoon courtesy *Physics World* magazine, Institute of Physics, UK

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

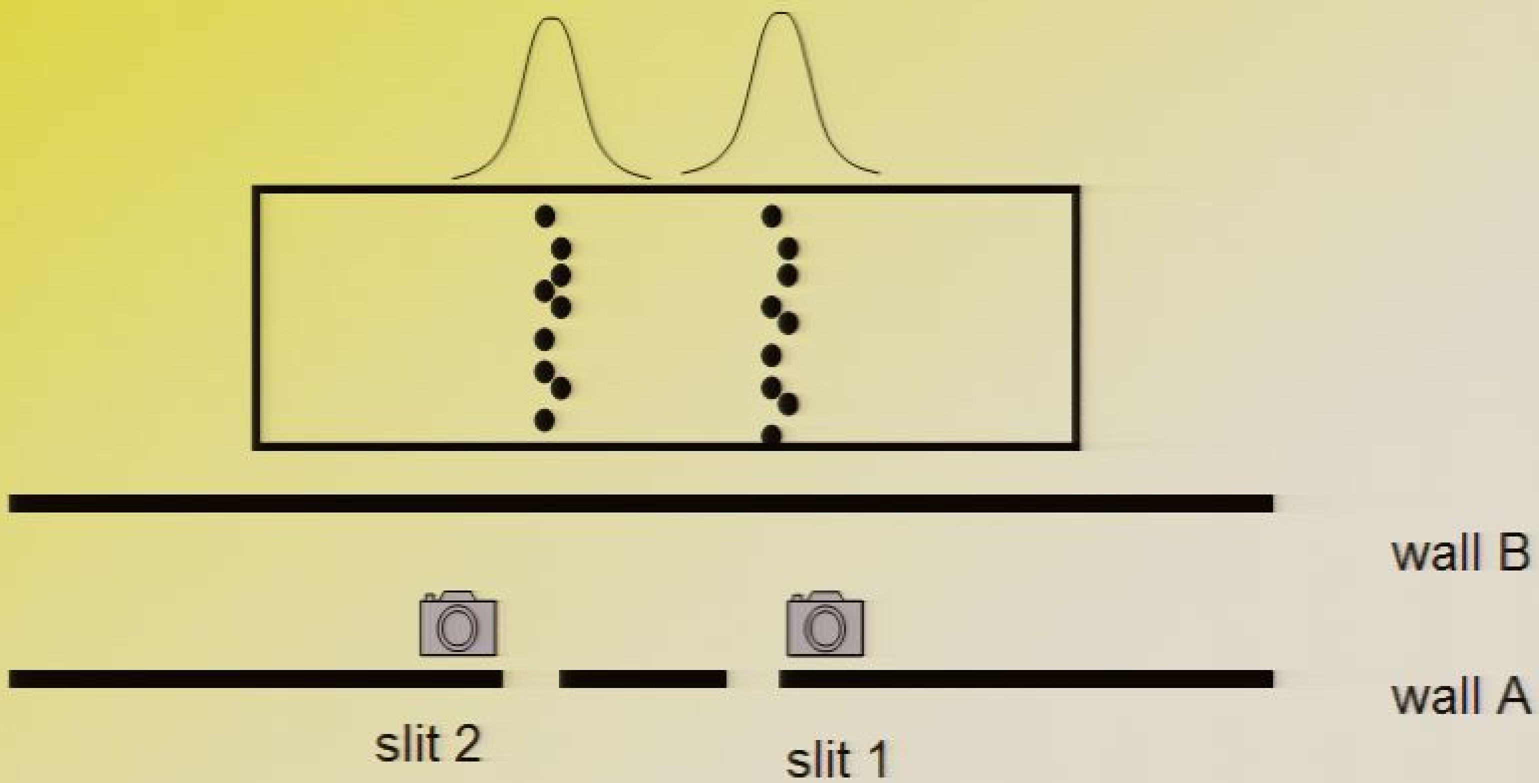
- General rule is that when there are two or more ways of detecting a particle at a certain location and these two ways are *distinguishable*, then we add the individual probabilities for each.

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



http://www.vega.org.uk/video/programme/47

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



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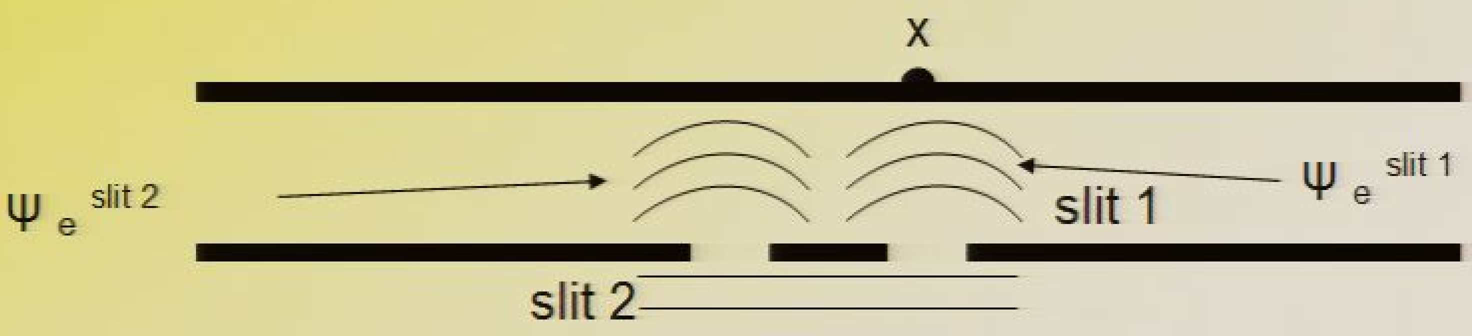

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- Let us think about, say, the 467th electron to pass through wall A.
- Can we predict whether it will go through slit 1 or 2?

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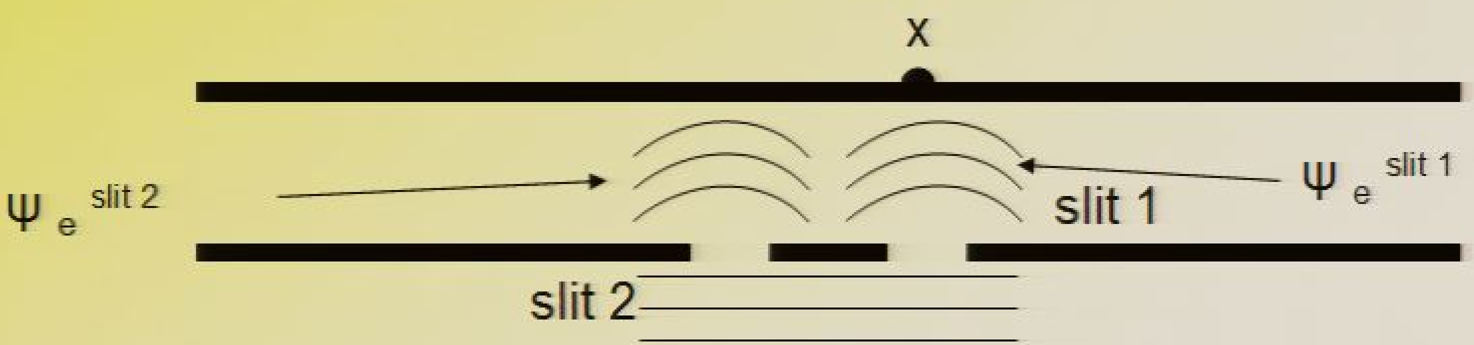

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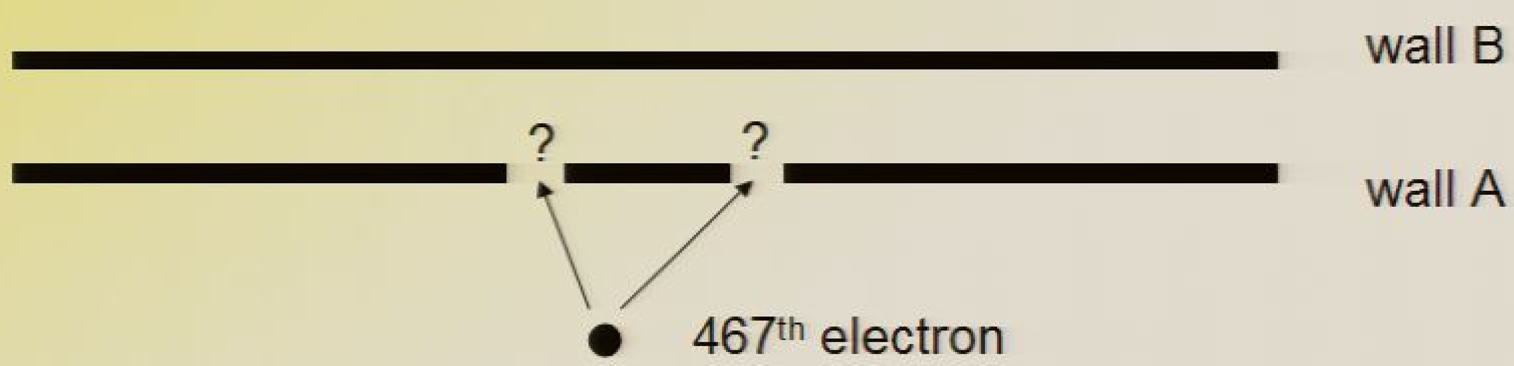
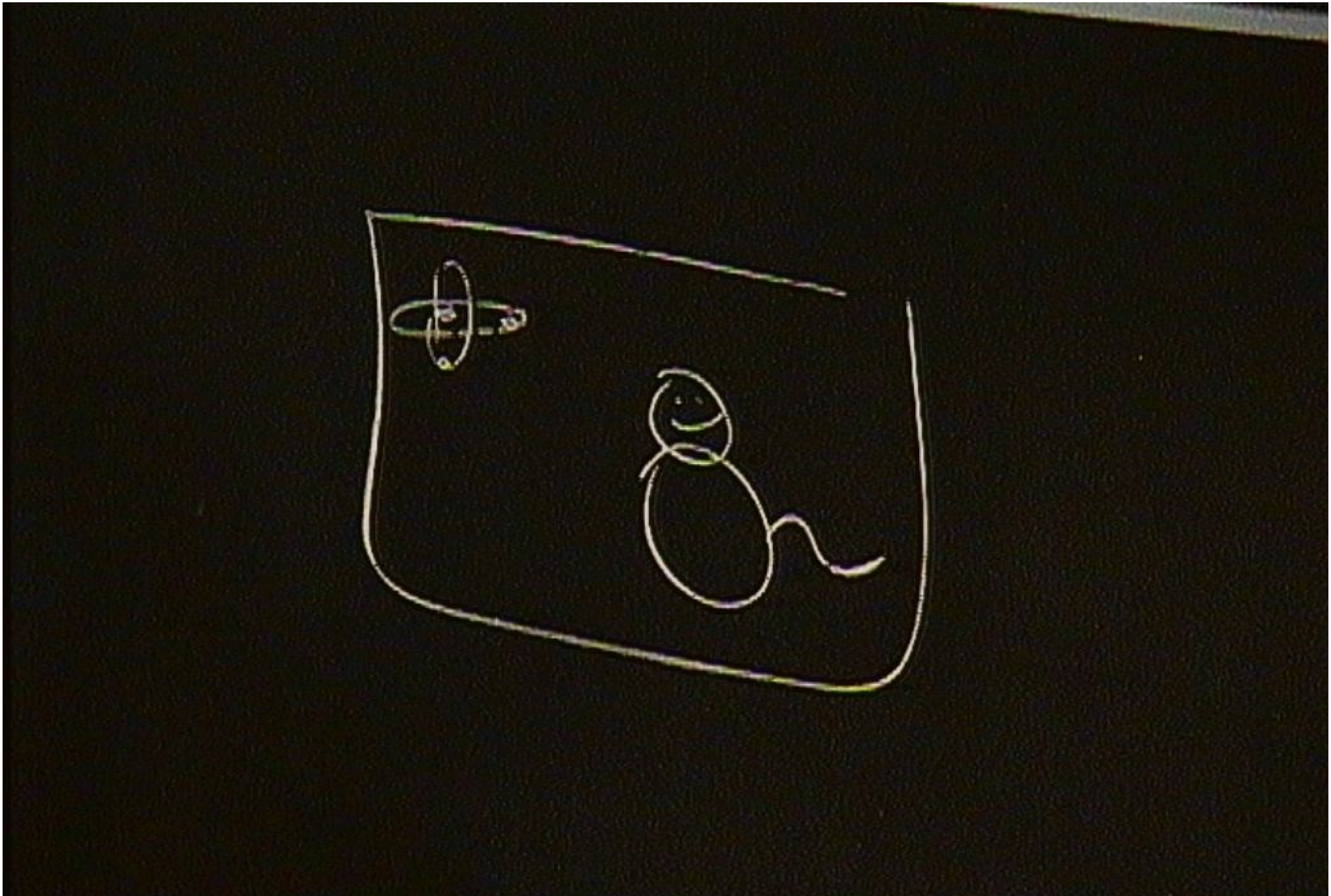
- Let us think about, say, the 467th electron to pass through wall A.

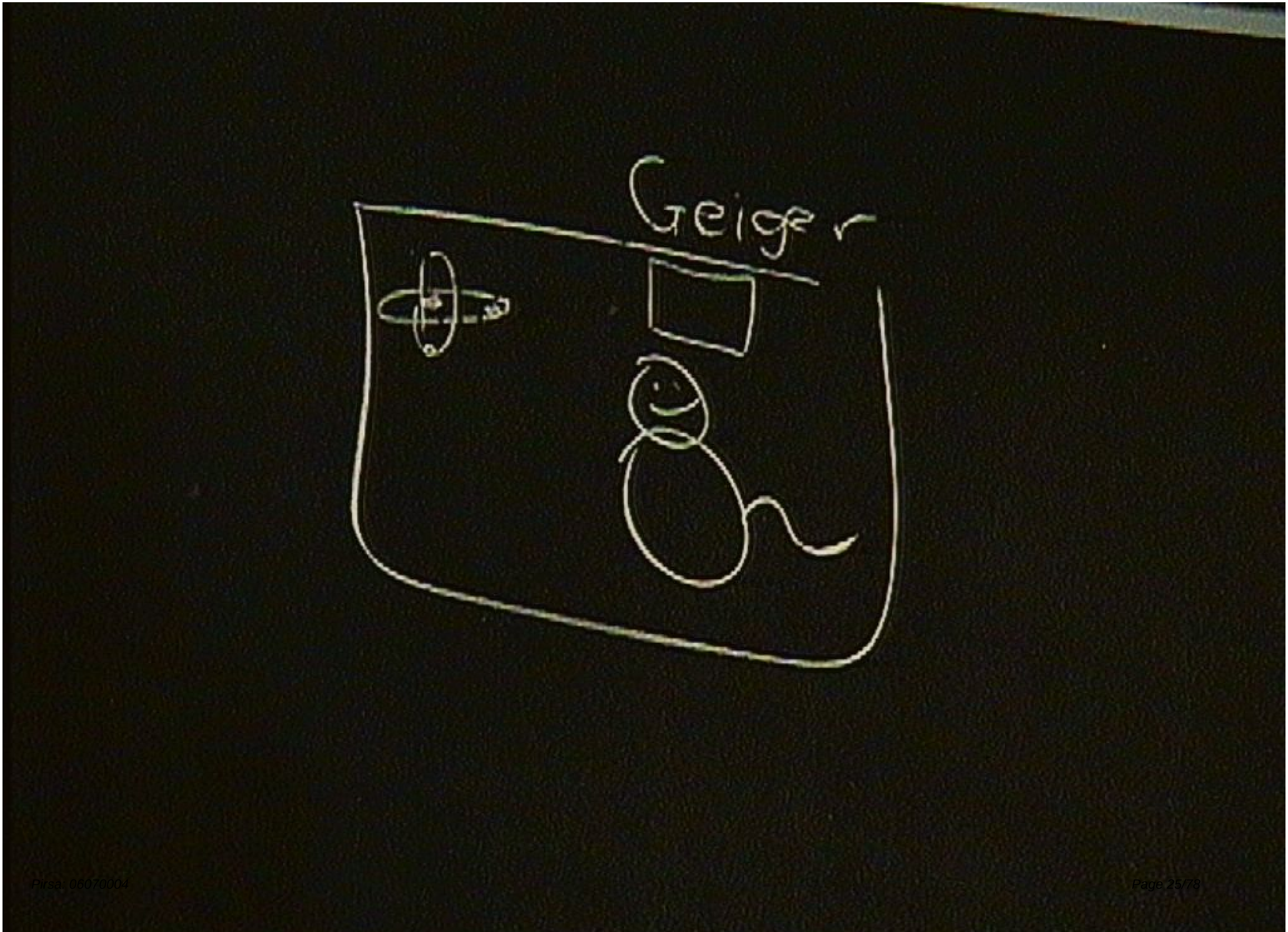
- Can we predict whether it will go through slit 1 or 2?

- Impossible to predict which slit the 467th electron (or any other) will pass through.
- 50-50 probability that it will pass through each slit. *Genuinely random event.*
- Another example of genuine randomness in quantum theory: We cannot predict with certainty whether we will see Schroedinger's cat as being dead or alive upon opening the box.

- A more familiar example: An individual radioactive decay event. Eg. inside your smoke detector
- Genuine randomness is core defining feature that runs throughout quantum theory.
- "The quantum casino."
- $|\psi|^2$ gives the probability (density)



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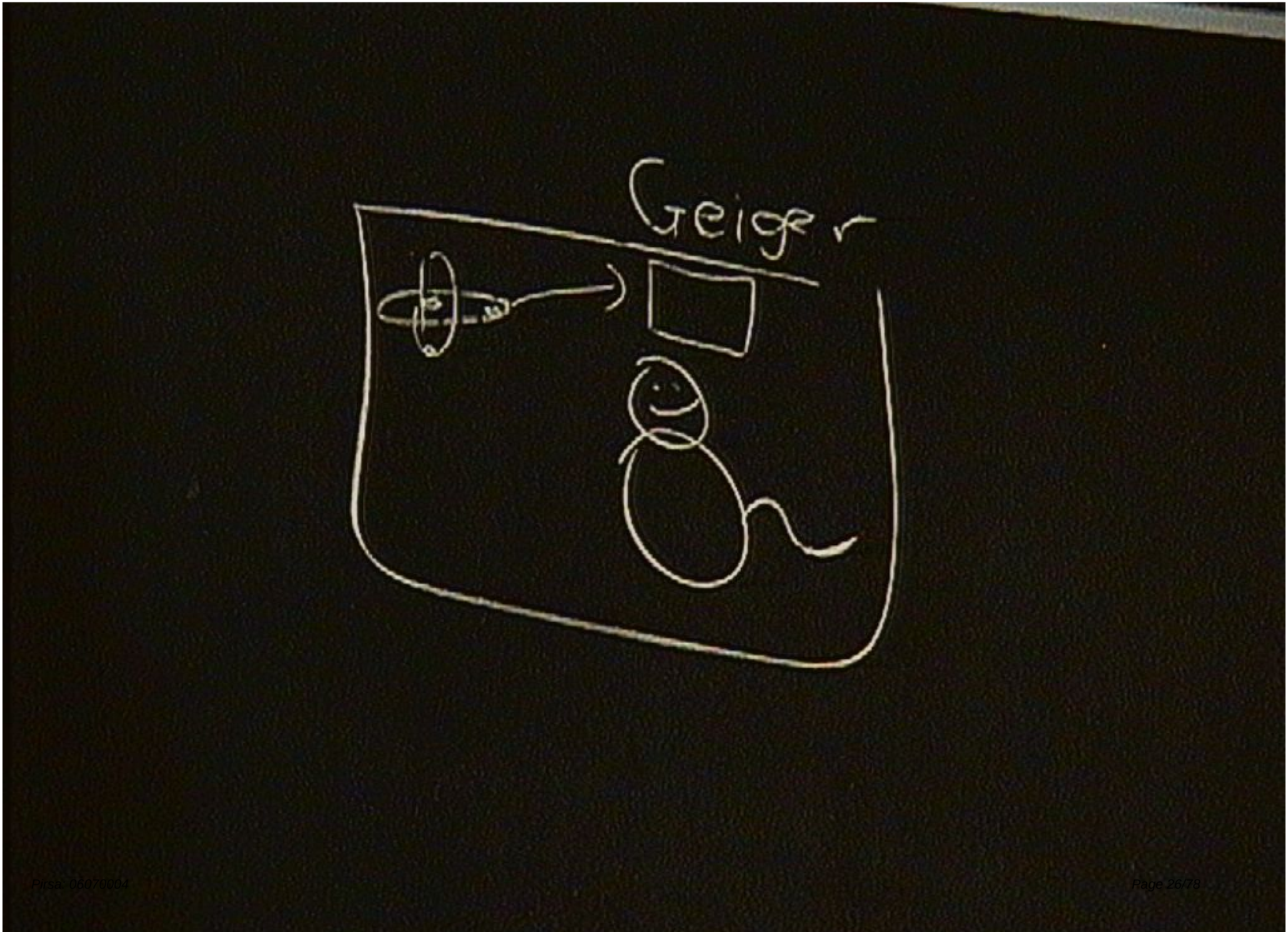
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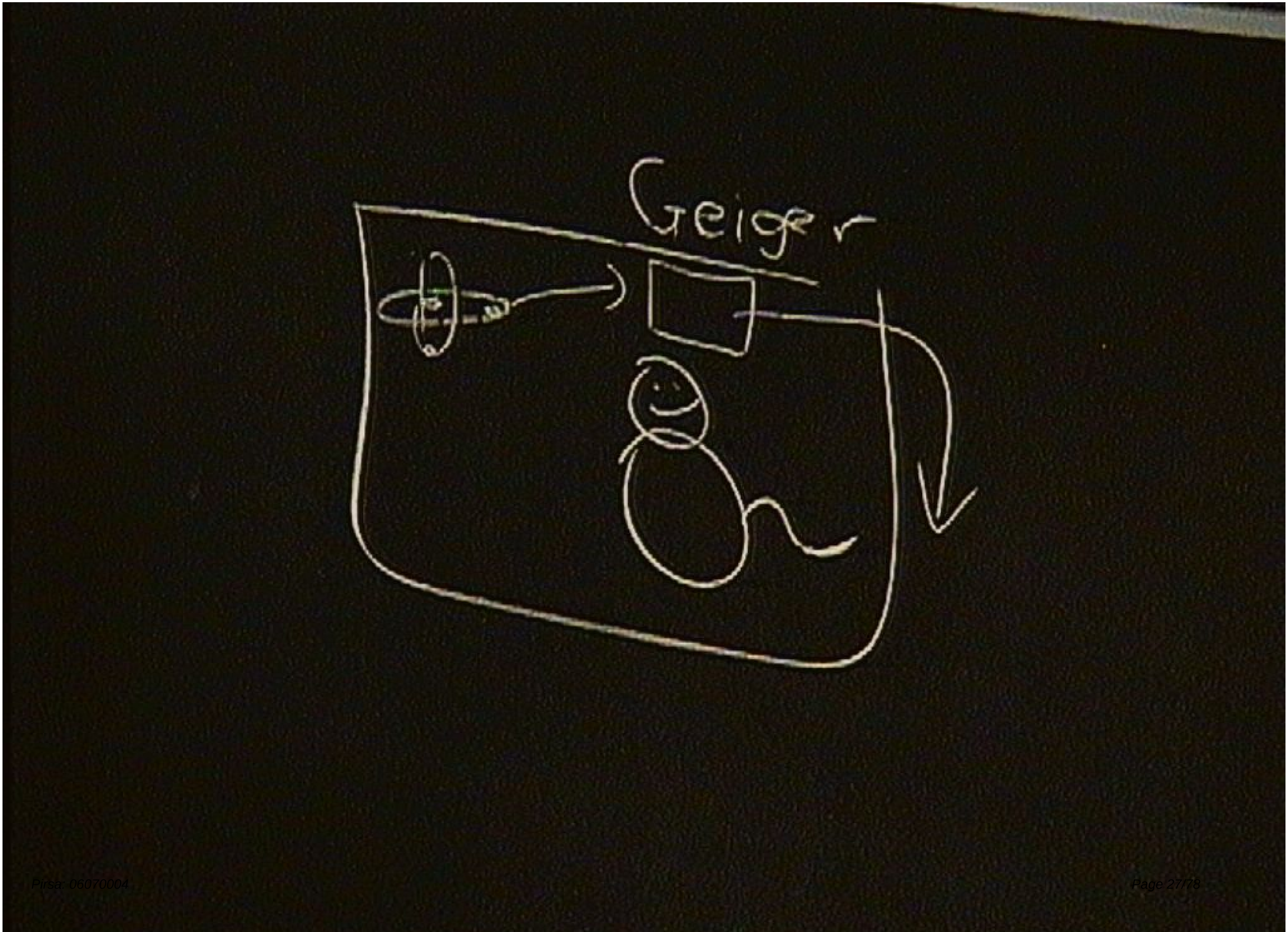
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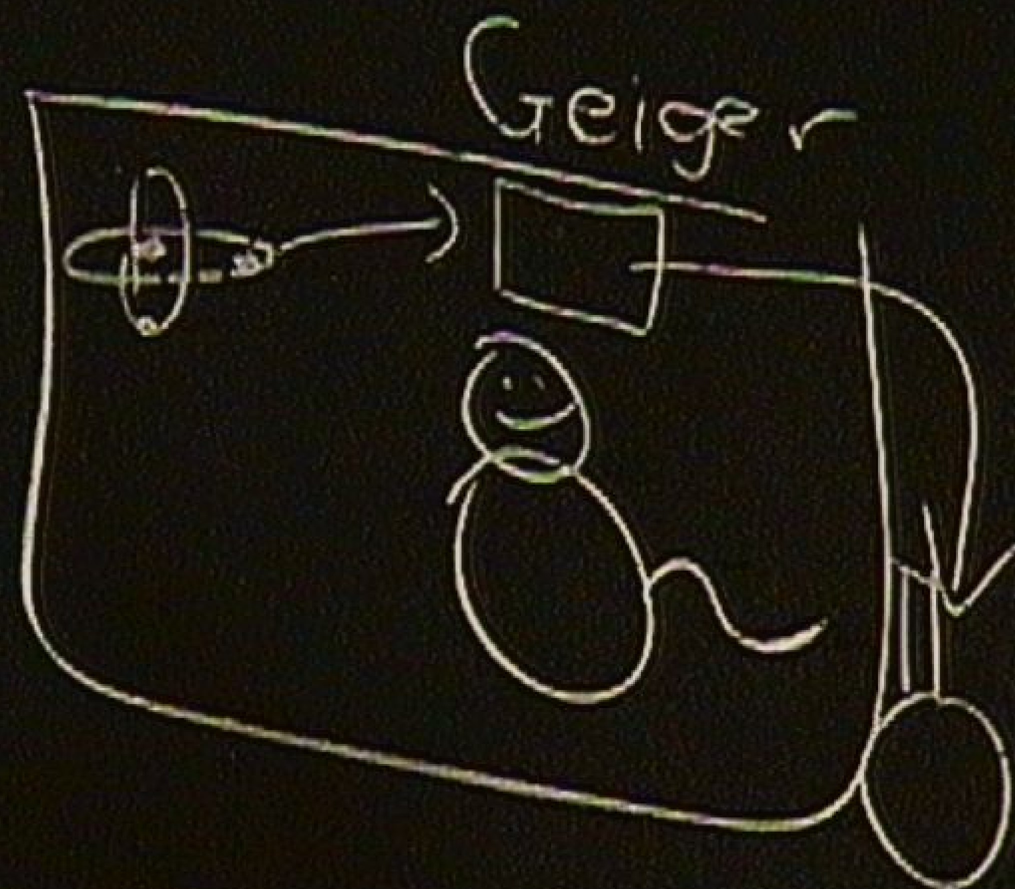
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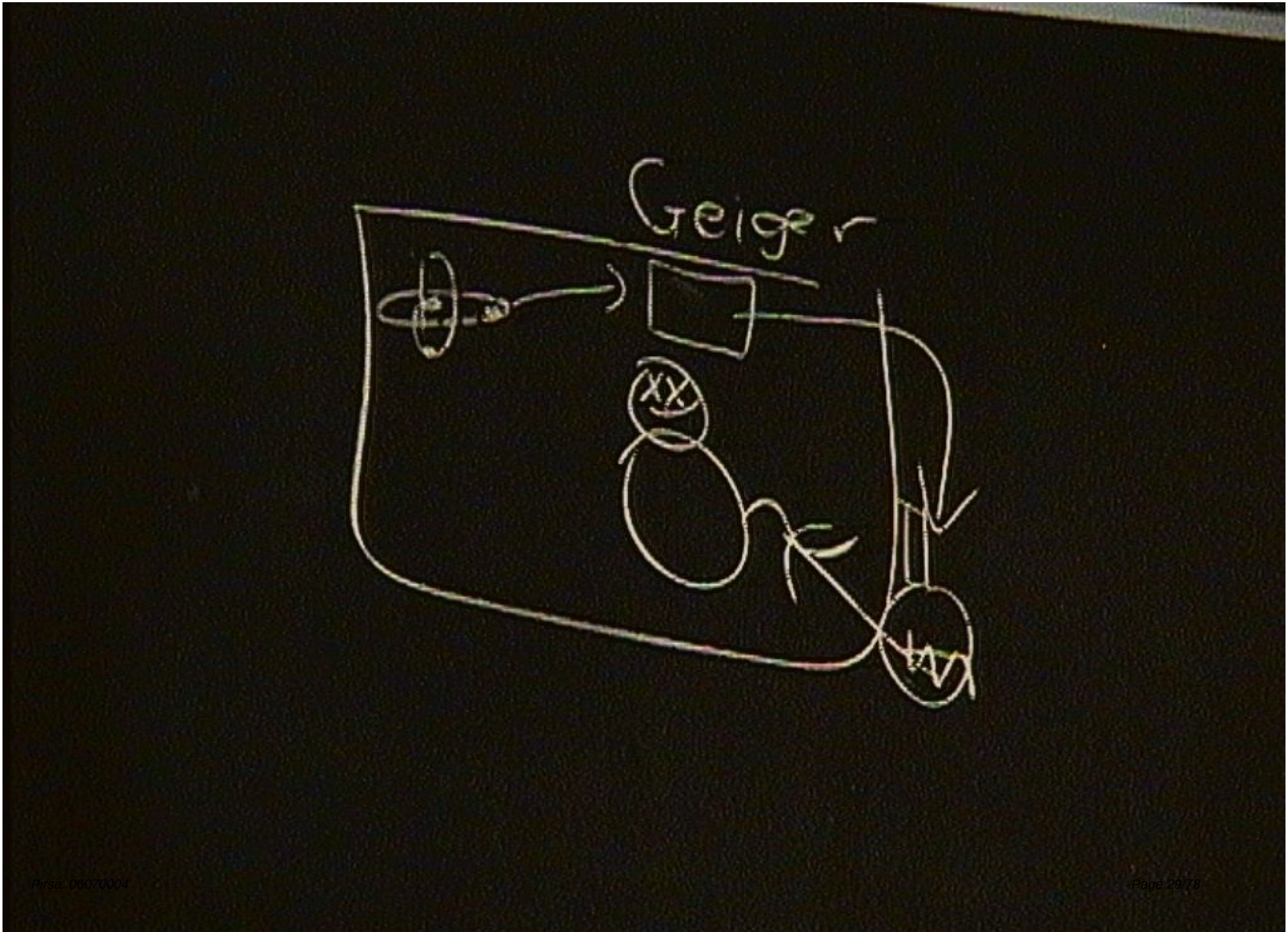
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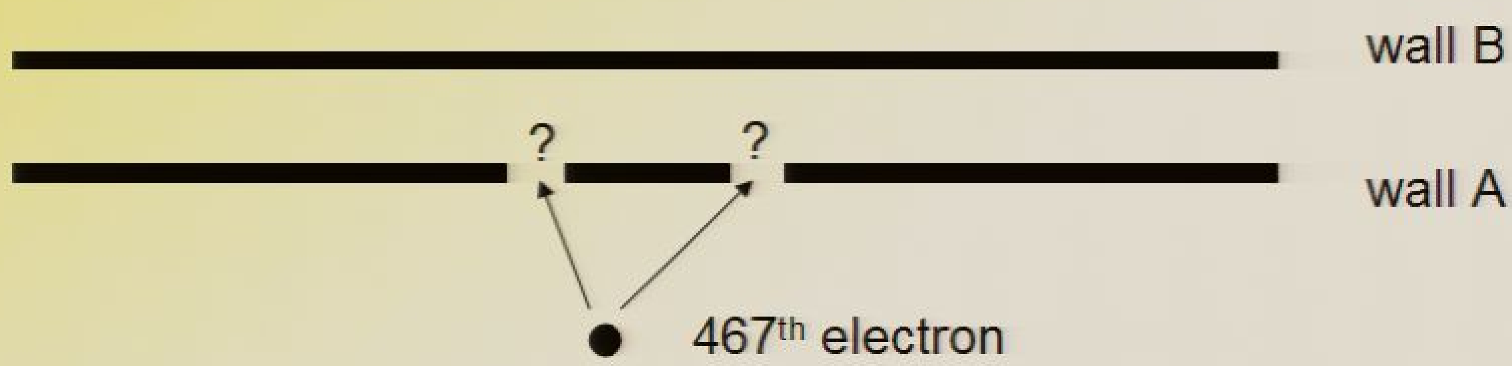
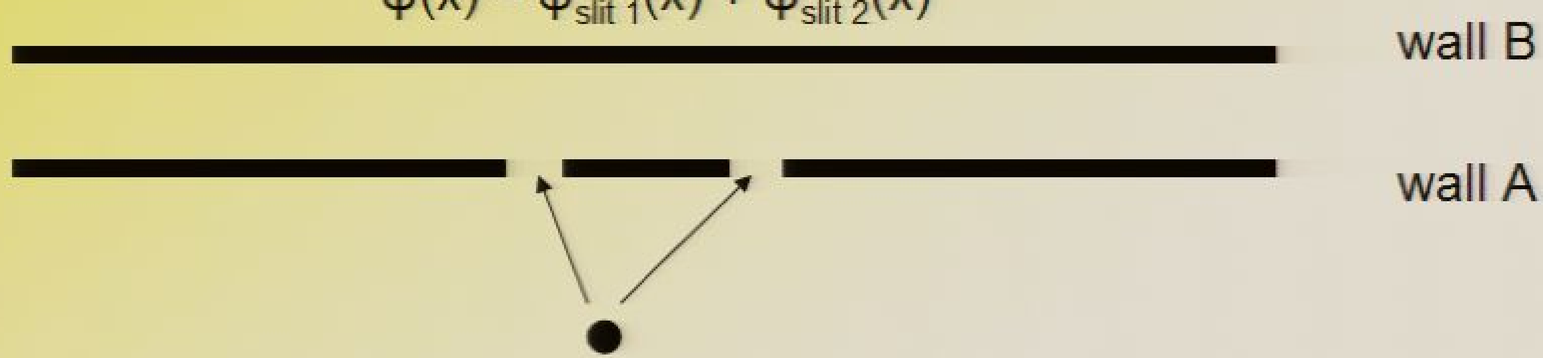


- Everyday objects such as baseballs, cars and trees are constrained to only exist in one place at any given time.

- 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

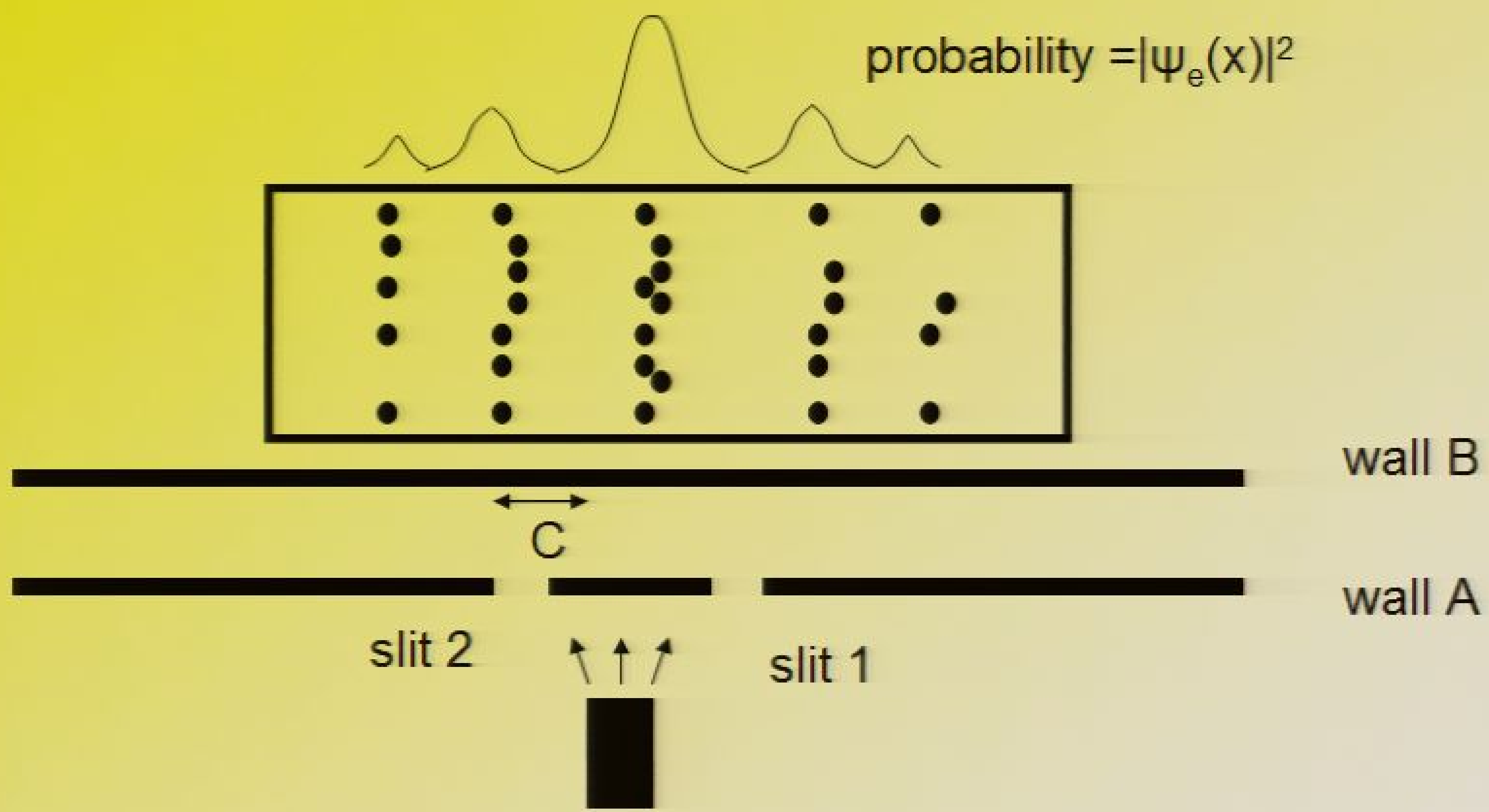
- Eg. the quantum state ψ in the double-slit experiment

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



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

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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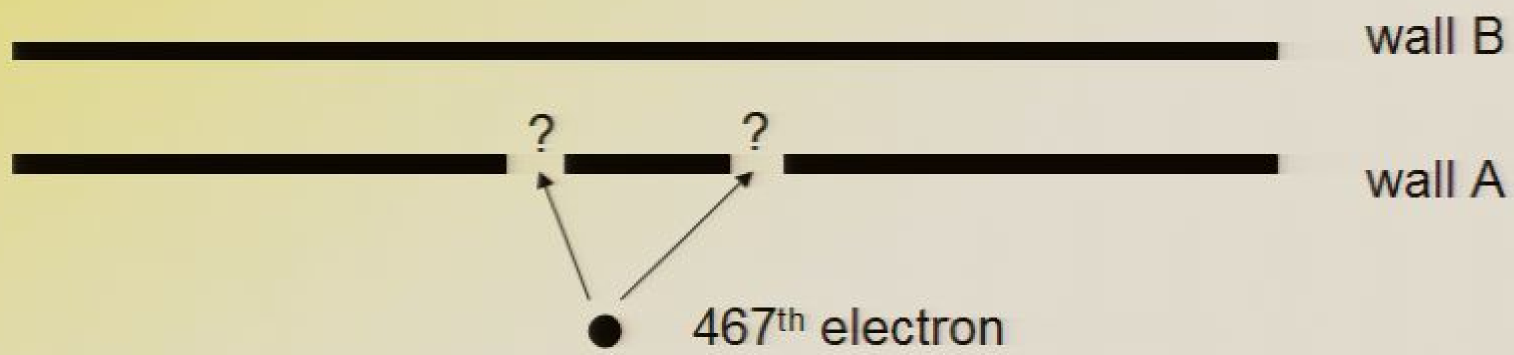

Practical applications?

- Commerically available quantum random number generators. Genuinely random numbers.

- Idquantique, Geneva, Switzerland.
- http://www.idquantique.com
- "When random numbers cannot be left to chance!"
- Uses include "gambling, lotteries"
- Also quantum cryptography (tour of Institute for Quantum Computing on Wednesday)

image from http://www.idquantique.com

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image from http://www.idquantique.com

- Deep philosophical consequences.
  Is the world, fundamentally, one big casino?

- Hard to get one's head around the idea of things just happening for no reason whatsoever.

- Spontaneously occurrences (acausal)

- Is this really possible philosophically (metaphysically)?

Who do you think is right?

DAVID: “Physics must be deterministic as it’s impossible for things to just happen for without any reason. There must be a deeper, hidden cause underlying why each electron goes through the slit that it does that we haven’t yet discovered.”

ANDREA: “We must take quantum theory at face value and trust what it seems to be telling us because it’s been proven by experiment after experiment. Therefore, we should accept that electrons goes through the slit that it does in a fundamentally random fashion.”

JOANNE: “Physics is just a collection of artificial models; a set of convenient fictions that we use. Thus, it can never tell us whether or not the world is really random or deterministic. Only philosophy or religion can answer such a question.”

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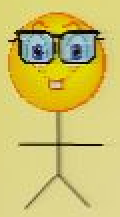

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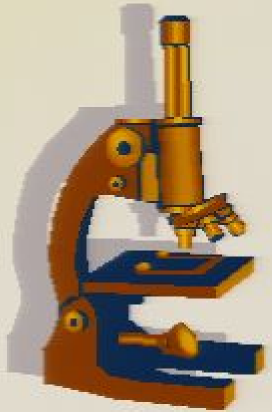
Core feature No. 4: Heisenberg's uncertainty principle

- In Newtonian physics, can we can measure both the position and the velocity of any object precisely. Eg. we can know exactly both the position and the velocity of a speck of dust drifting across a room.

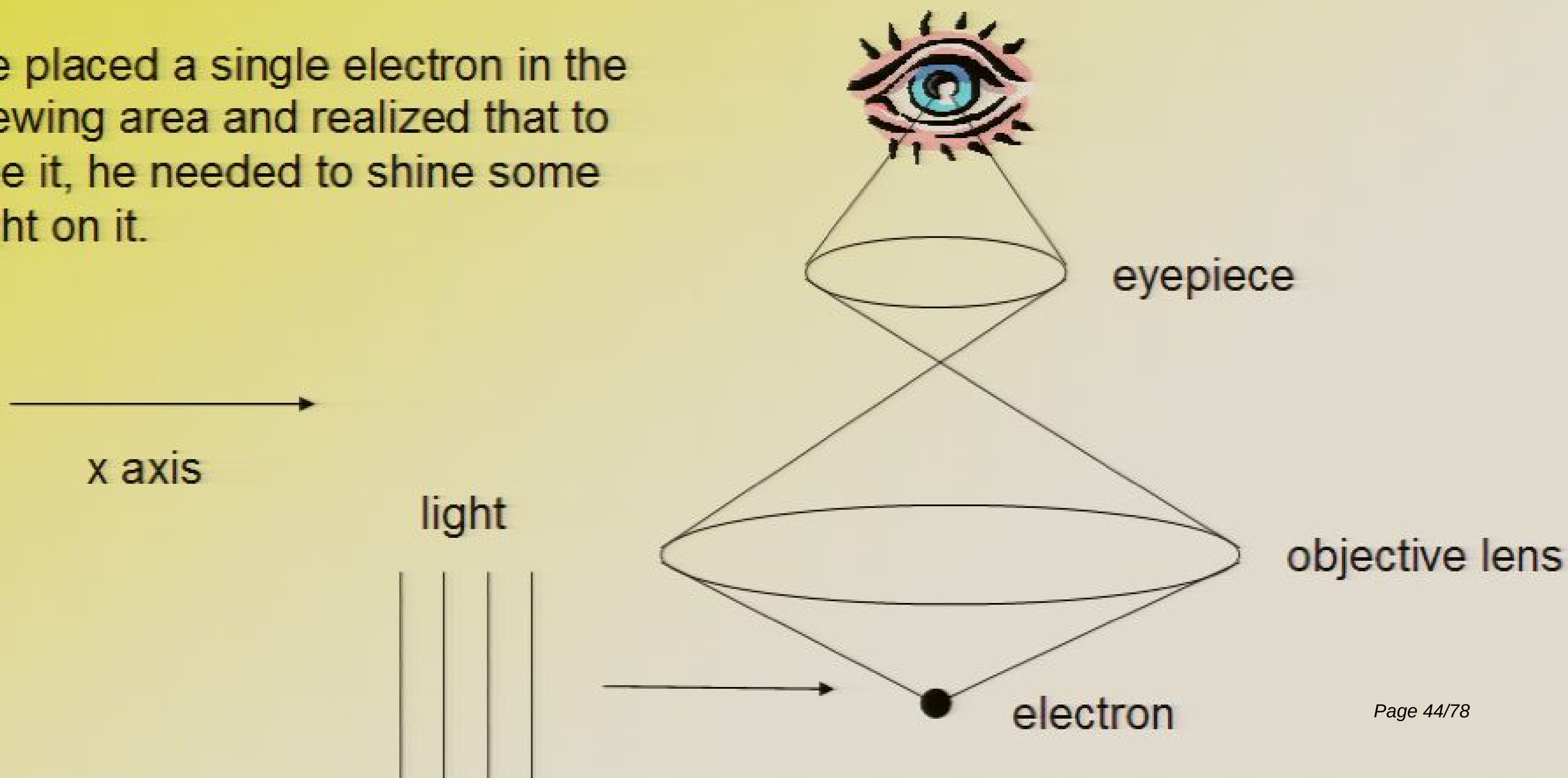
- Not true for quantum entities. Heisenberg's uncertainty principle places a fundamental, 'hardwired' limit on what how much we can simultaneously know about these two properties.

- Let us consider the story of (Werner) Heisenberg trying to measure the position and the velocity of an electron using his 'gamma-ray microscope'



- Heisenberg walked into his lab one day and set up an idealized microscope.

- He placed a single electron in the viewing area and realized that to see it, he needed to shine some light on it.



- As Heisenberg was intimately familiar with Einstein's photon hypothesis, he knew that he could think of the light as consisting of a large collection of particle-like photons.

- He also knew that, as he had made sure that the light was travelling parallel to the x axis, the momentum in the x direction p_x of each photon was given by the equation $p_x=h/\lambda$, where h is Planck's constant (6.63×10^{-34}Js) and λ is the photon's wavelength.

- Of course, because he was good friends with Compton, he knew that the photons collided with the electron in particle-particle collisions modelled by the Compton effect

- While Heisenberg was fine-tuning his microscope, he suddenly thought "Aha! I must ensure that at least one photon collides with the electron if the microscope is to be of any use."

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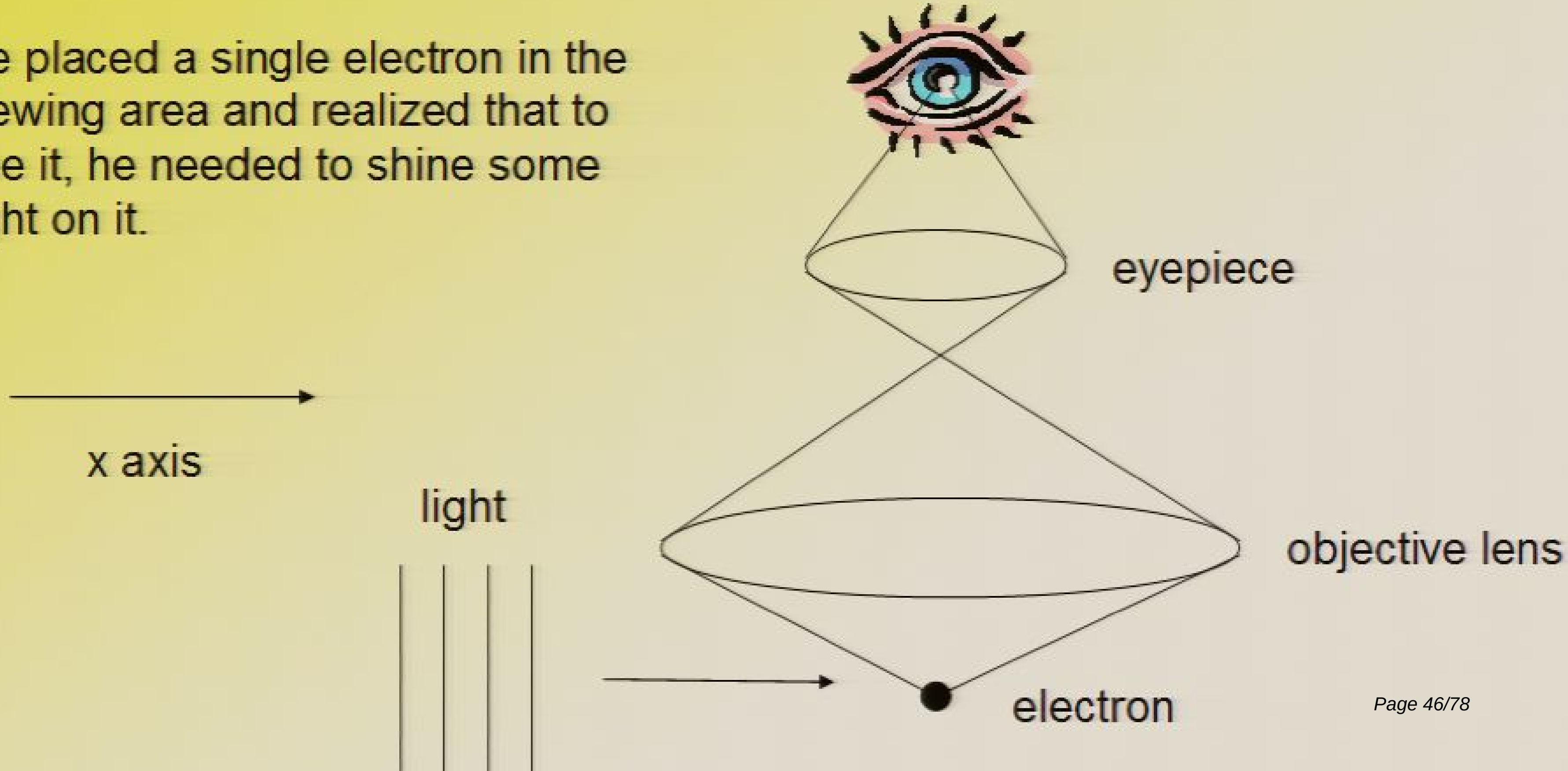

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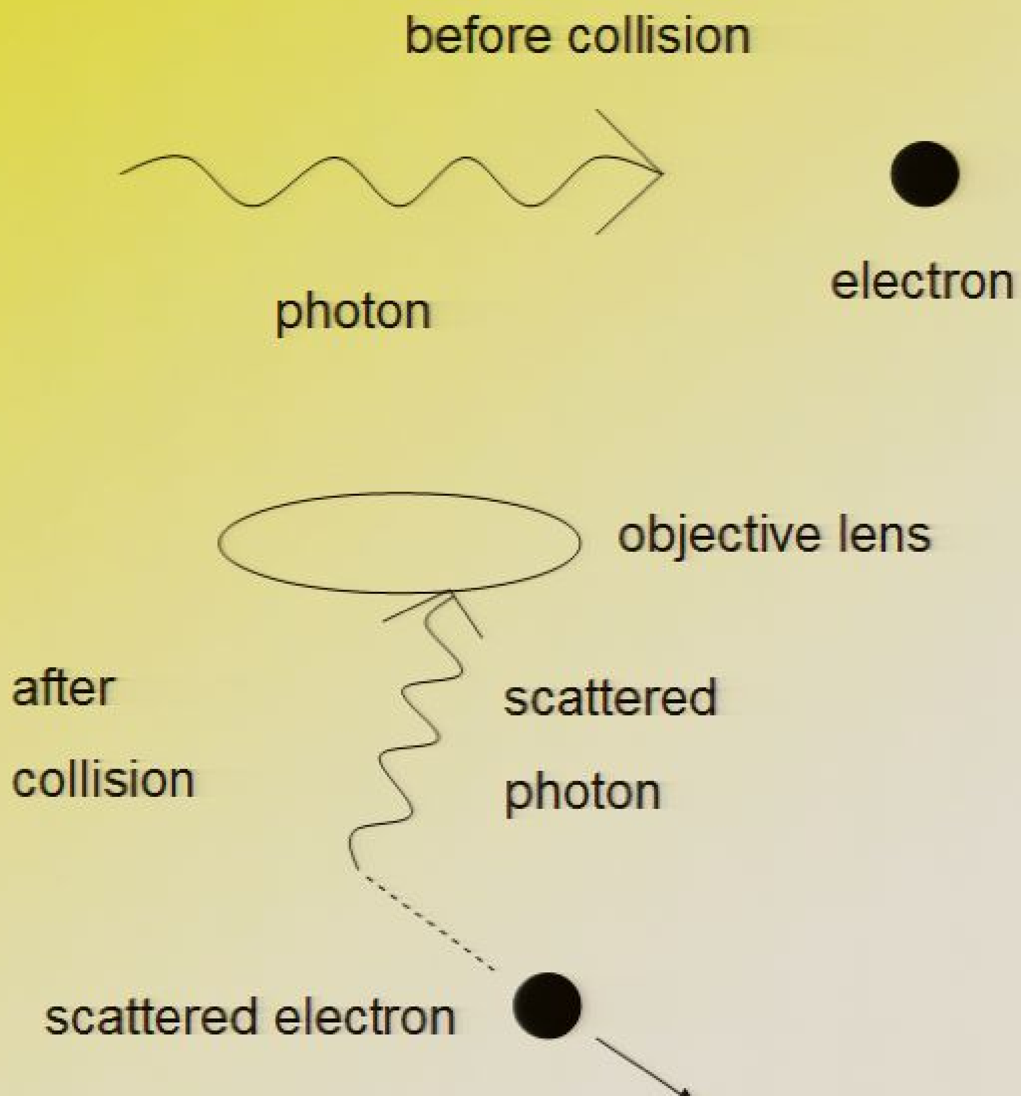
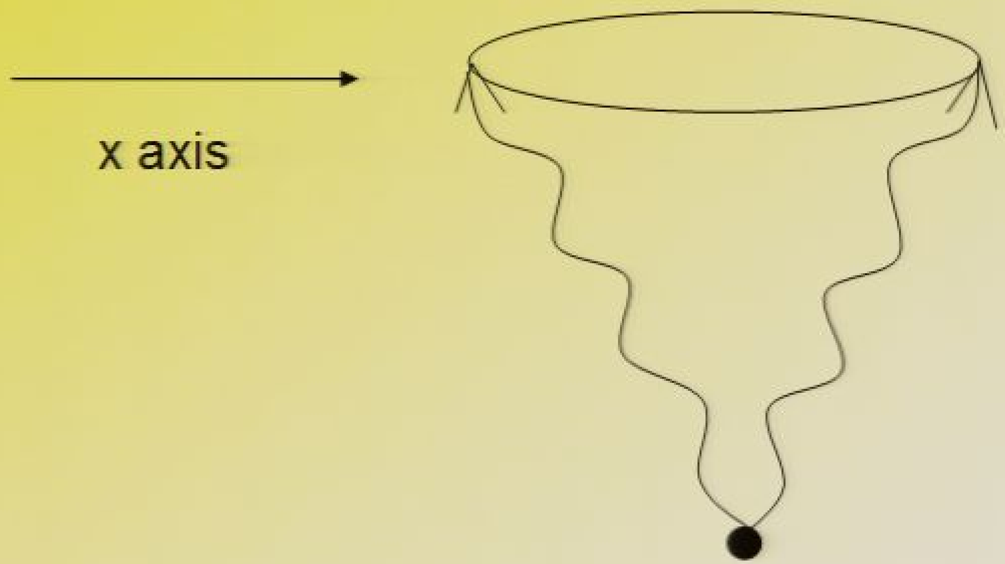
- While Heisenberg was fine-tuning his microscope, he suddenly thought "Aha! I must ensure that at least one photon collides with the electron if the microscope is to be of any use."

- He then begin to visualize what would happen during and after each collision.



- He realized that each photon could enter the objective lens at any point along it but that, looking through his microscope, he could not tell where the entry point was or what the angle between the photon's path and the x axis was.



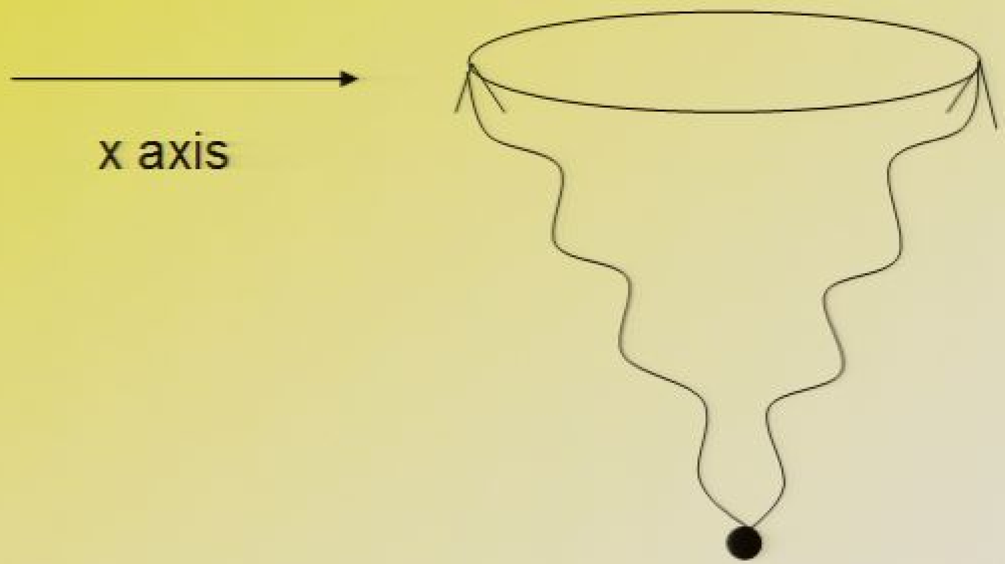
- Assuming that the objective lens is wide, Heisenberg could not even distinguish between the two extreme possibilities of a photon travelling in the negative x direction with momentum $p_x=-h/\lambda$ (head-on collision) and one travelling in the positive x direction with momentum $p_x=h/\lambda$ (glancing collision).

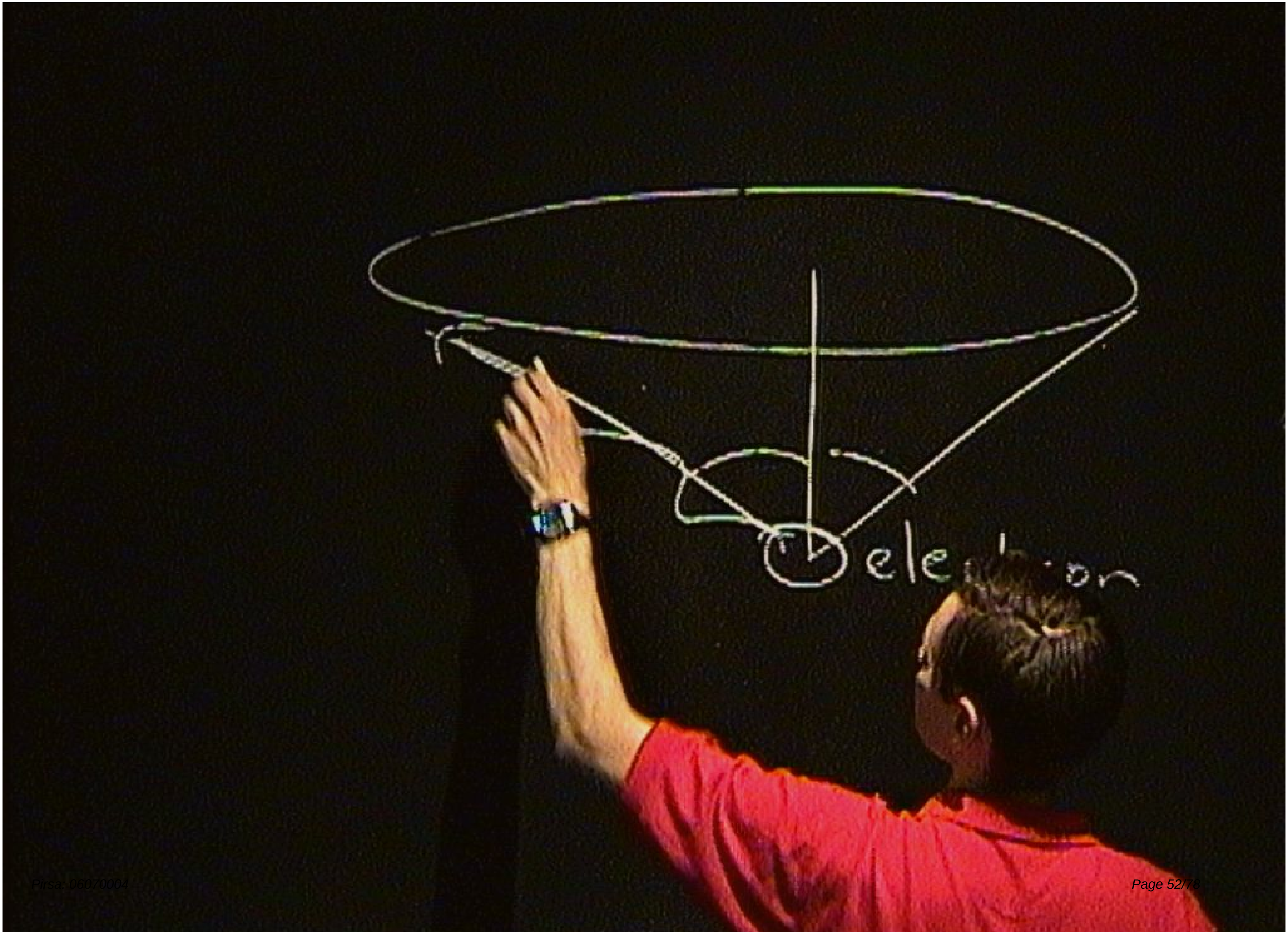
- Performing a quick mental calculation, Heisenberg realized that these two extreme possibilities corresponded to electron momenta of, respectively $p_x=p_{initial} + 2h/\lambda$ and $p_x = p_{initial}$.

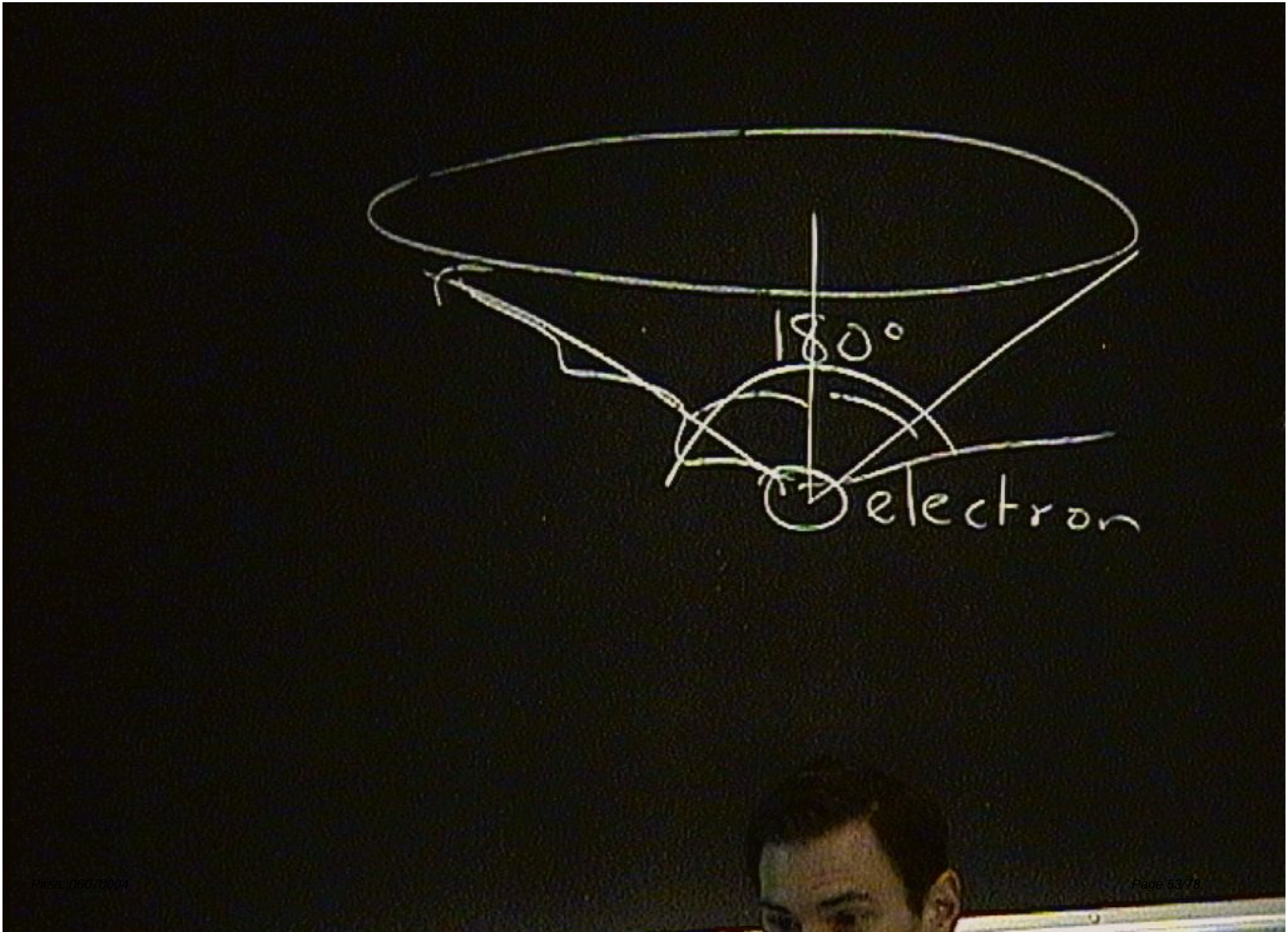
- Therefore, he concluded, for the electron $\Delta p_x = \frac{1}{2}\left(\frac{2h}{\lambda} - 0\right) = \frac{h}{\lambda}$

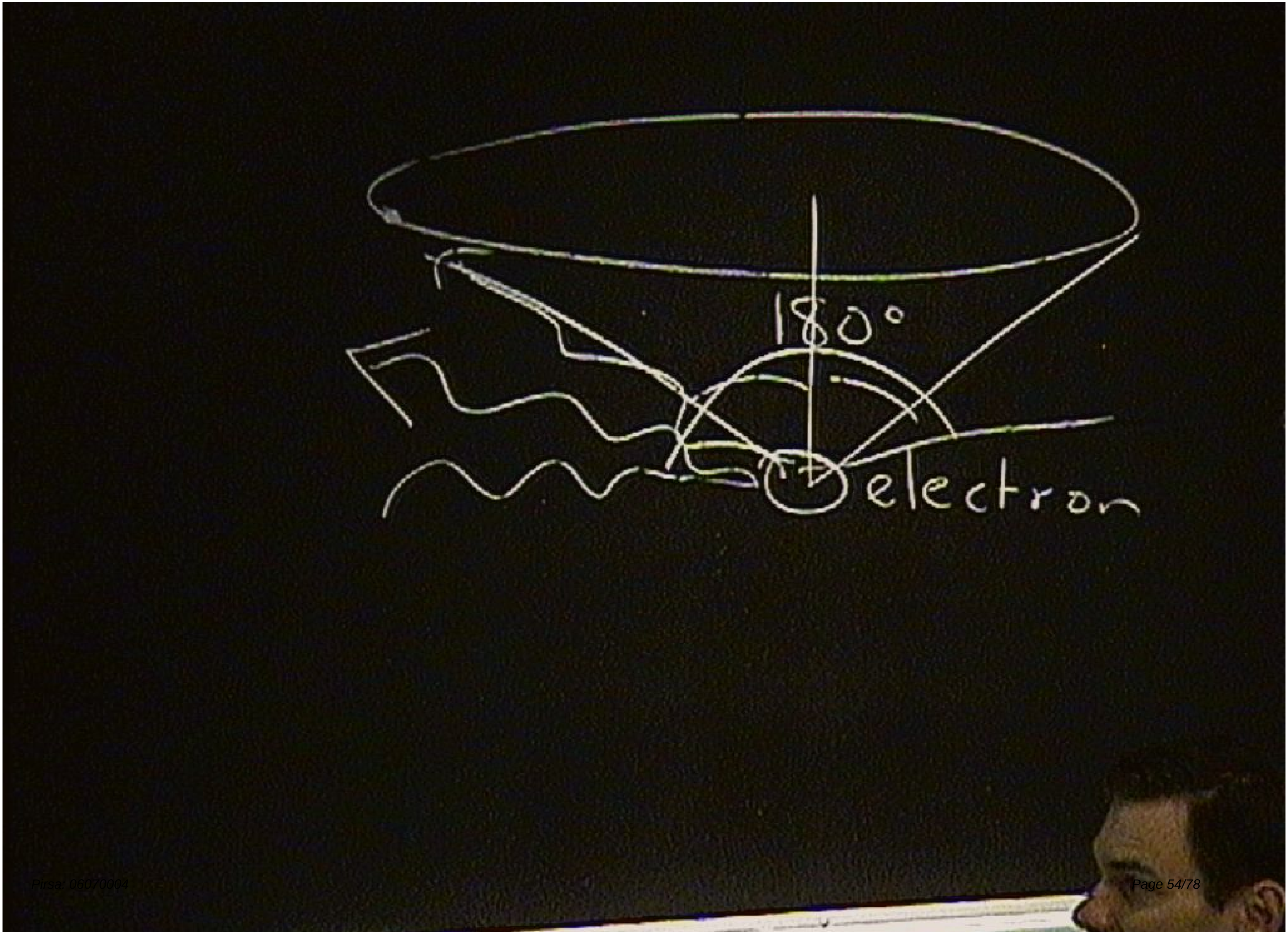
- As he looked out his lab's window at the crowd of students scurrying in different directions across the university courtyard, he reflected on the fact that, at the quantum level, all measurements necessarily disturb the quantum entities that they are trying to gain information about.

- He realized that each photon could enter the objective lens at any point along it but that, looking through his microscope, he could not tell where the entry point was or what the angle between the photon's path and the x axis was.






180°
electron


180°
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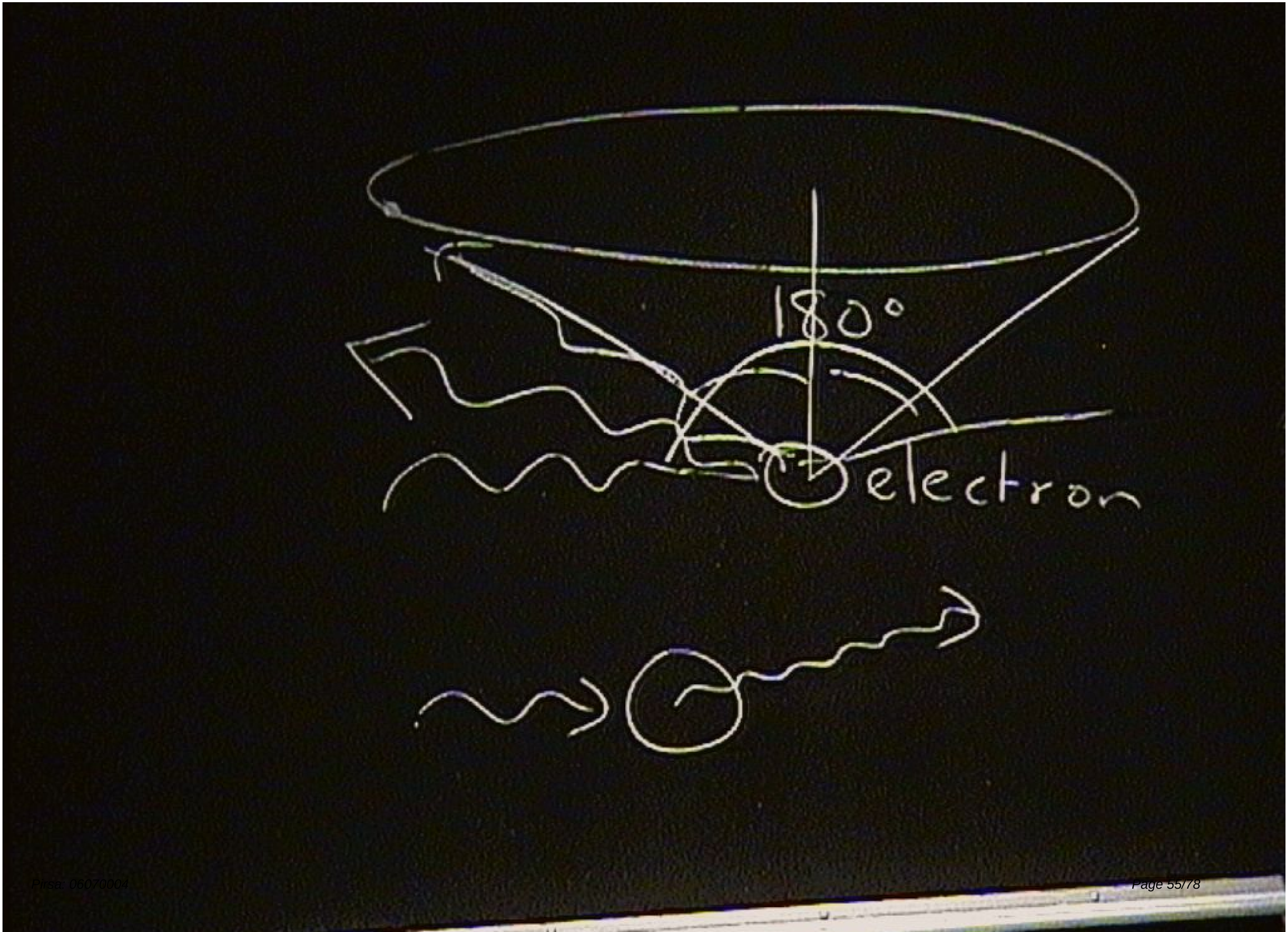
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- Assuming that the objective lens is wide, Heisenberg could not even distinguish between the two extreme possibilities of a photon travelling in the negative x direction with momentum p_x=-h/λ (head-on collision) and one travelling in the positive x direction with momentum p_x=h/λ (glancing collision).

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- Therefore, he concluded, for the electron $\Delta p_x = \frac{1}{2}\left(\frac{2h}{\lambda} - 0\right) = \frac{h}{\lambda}$

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- Diameter of disk roughly equal to λ (given certain assumptions)
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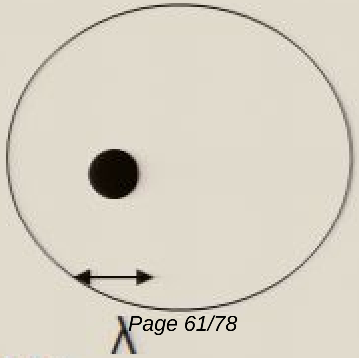

view through eyepiece

- He also vaguely seemed to remember the professor telling him that for each individual photon reaching the eyepiece, we detect it at a *random* location within the circle

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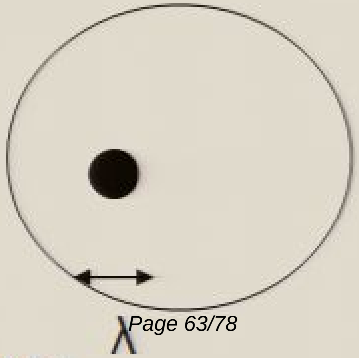

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$\Delta x \, \Delta p \geq h$

HEISENBERG'S UNCERTAINTY PRINCIPLE

- More detailed arguments lead to $\Delta x \Delta p \geq \frac{\hbar}{2}$

$$\hbar = \frac{h}{2\pi}$$

- Hardwired limit within nature (assuming quantum theory is true). Cannot measure both x and p with arbitrary accuracy

(Note: The modern (statistical) account of

Heisenberg's uncertainty principle

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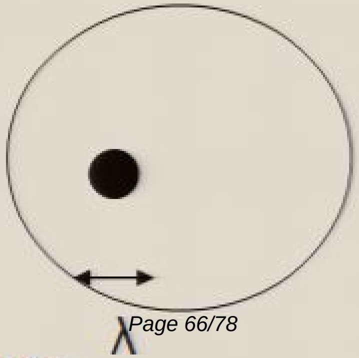

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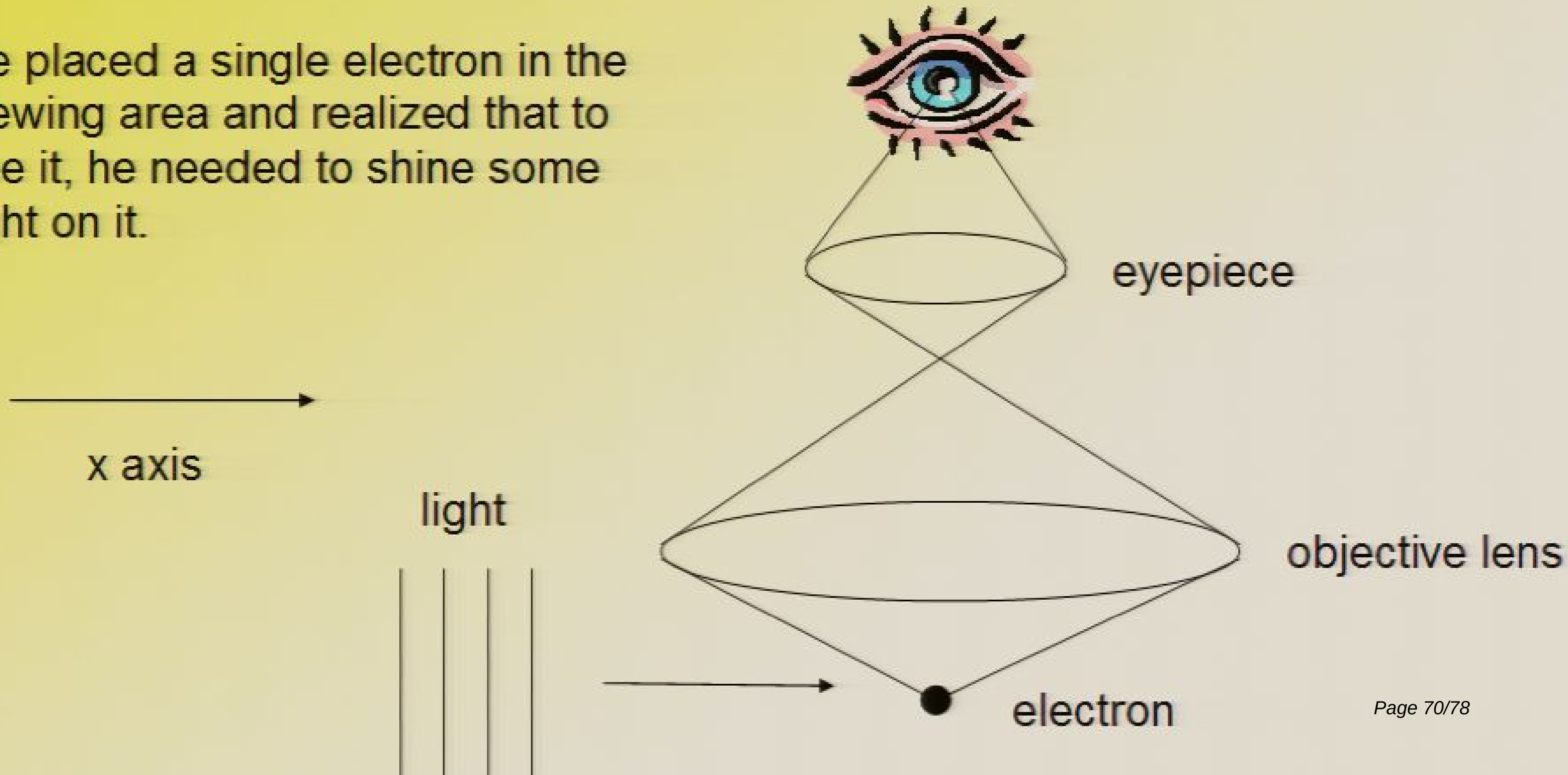
- Heisenberg walked into his lab one day and set up an idealized microscope.
- He placed a single electron in the viewing area and realized that to see it, he needed to shine some light on it.



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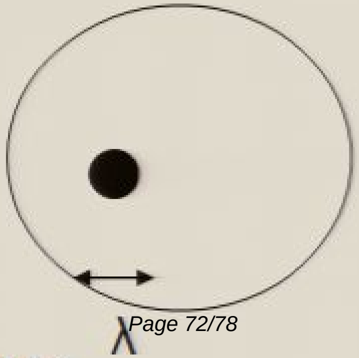

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- nothing to do with imperfect equipment or unskilled physicists.
- Defining trait of quantum theory
- x and p do not simultaneously exist?
- N.B. As it is an inequality $\Delta x \, \Delta p$ can be as large as we like
- Only certain states have $\Delta x \, \Delta p = h$ (minimum uncertainty states)
- Eg. Gaussian states. $\psi(x) = A \exp(-x^2)$, where A is a constant

- application: quantum cryptography.
- Want to set up a secret string of numbers
- Called a *cryptographic key*
- Hide information in, say, the position and momentum of an electron.
- Any attempt to snoop or eavesdrop on the electron by way of measuring it, will necessarily disturb in a noticeable way.
- Can always tell if someone is eavesdropping
- Commercial reality. Quantum internet currently running in Boston.
- http://www.magiqtech.com
- $US 50,000

- quantum theory is hard because it's difficult to get a picture of what's going on.

- abstract rules for 'turning the handle'

- A number of pictures have been proposed.

- More on this in Dr Hans Westman's keynote presentation *Cats, collapses and the nature of reality in quantum theory …*

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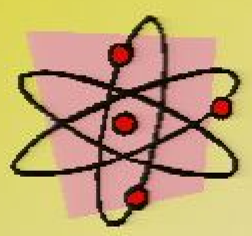
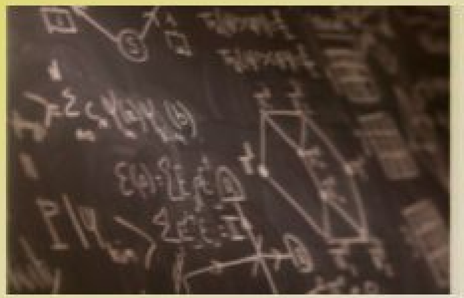
Microsoft PowerPoint - [Day 1 slides for me final Use this version]

Core concepts of quantum theory





Slide 1 of 57 Default Design English (U.S.)