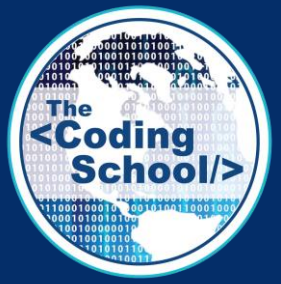


INTRO TO QUANTUM COMPUTING

Week 12 Lab

QUANTUM MECHANICS - 2

Corbin McElhanney

January 26, 2021

PROGRAM FOR TODAY

- Canvas attendance quiz
- Pre-lab zoom feedback
- Lab content
- Post-lab zoom feedback

CANVAS ATTENDANCE QUIZ

- Please log into Canvas and answer your lab section's quiz

Lab Number: 1 | Quiz Password: 3250

- Thinking back to the first semester, how would you describe your experience learning the math that was introduced?
- On a scale of 1-5, how did you feel about the pace of the math content?

- **This quiz not graded, but counts for your lab attendance!**

PRE-LAB ZOOM FEEDBACK

On a scale of 1 to 5, how would you rate your understanding of this week's content?

- 1 –Did not understand anything
- 2 – Understood some parts
- 3 – Understood most of the content
- 4 – Understood all of the content
- 5 – The content was easy for me/I already knew all of the content

LEARNING OBJECTIVES FOR LAB 12

- Answered and unanswered questions in quantum mechanics
- Understanding measurement in quantum mechanics
  - Double-silt experiment with electrons
  - Which slit does the electron go through?
  - Classical vs quantum measurement
- Demystifying the Stern-Gerlach (SG) experiment
  - Electron spin
  - SG experiment setup
  - SG experiment examples
- Two-level systems*

*Optional content

WHAT DO WE NOT KNOW?

The why questions

- Why do electrons seem to interfere with themselves in the double-slit experiment?
- Why can’t we know for sure the results of some types of experiments?
- Why do electrons have spin?
- …..

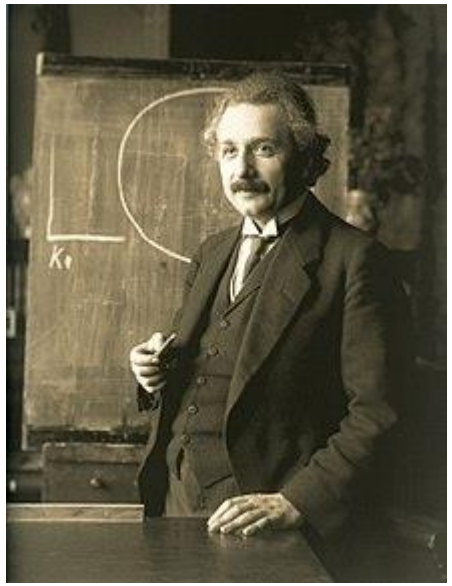
WHAT DO WE KNOW?

- What are the **possible** results we can get in an experiment with electrons/atoms/ions etc.?
- What is the **probability** of getting each of the possible results?
- How can we manipulate the probability of getting the result we want?
- ……

SO WHAT DO WE DO NOW?

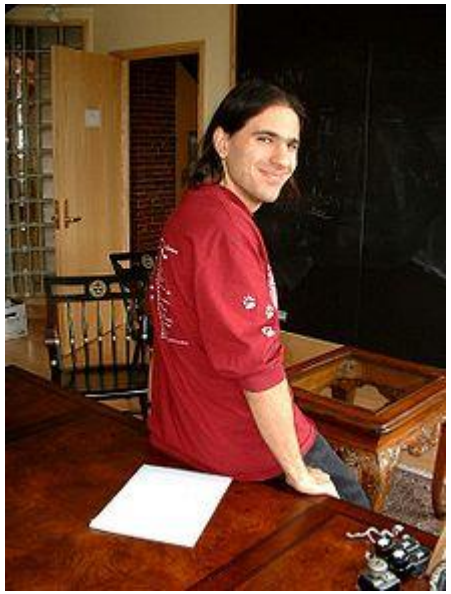
Do the unanswered questions make you uncomfortable?

- **Yes, and I need to know the answers** – Become a physicist and work on the foundations of quantum theory



Albert Einstein

Fabiola Gianotti



Nima Arkani-Hamed

SO WHAT DO WE DO NOW?

Do the unanswered questions make you uncomfortable?

- **Maybe, but I want to work on applications** – Become a physicist/engineer and develop uses of quantum theory (such as quantum computing!)

Clarice D. Aiello

Subir Sachdev

....and some of the TAs!

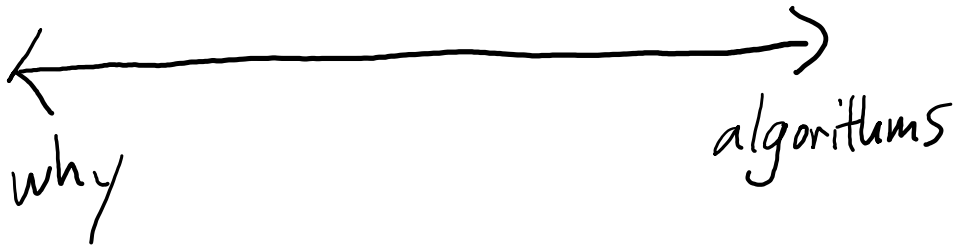
SO WHAT DO WE DO NOW?

Do the unanswered questions make you uncomfortable?

- **No, I just want to run Shor's algorithm** – Become a quantum computer scientist!

Peter Shor

Lov Grover

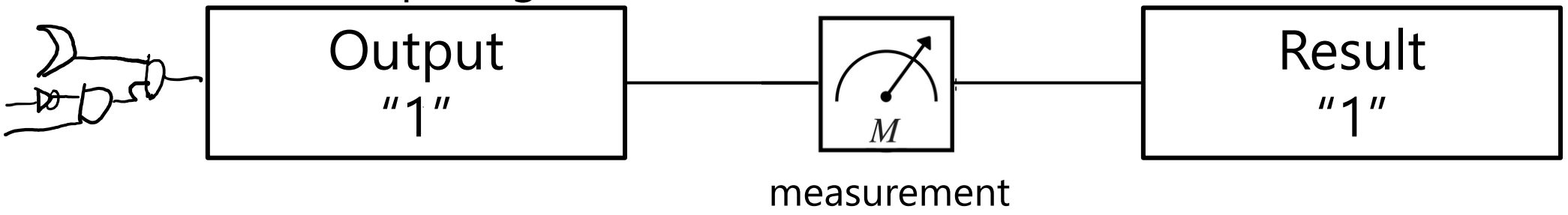


....and some of the TAs!

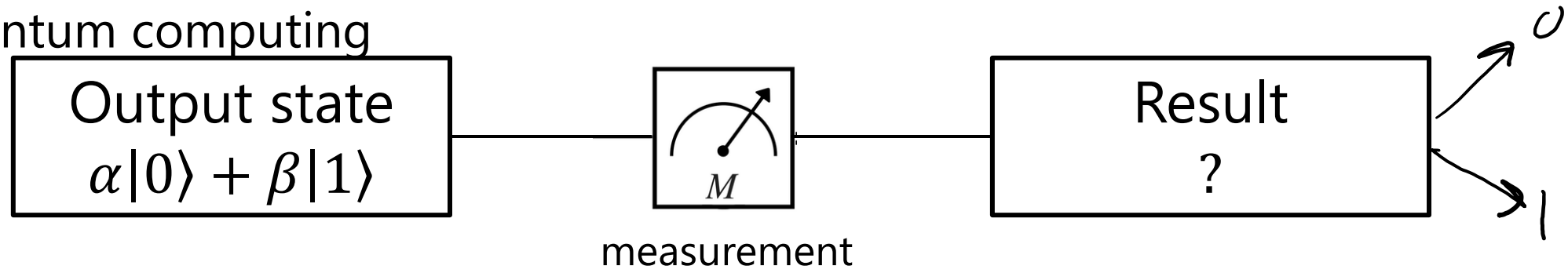
MEASUREMENT IN COMPUTING

Measurement is the final step of any computation (classical or quantum)

Classical computing



Quantum computing



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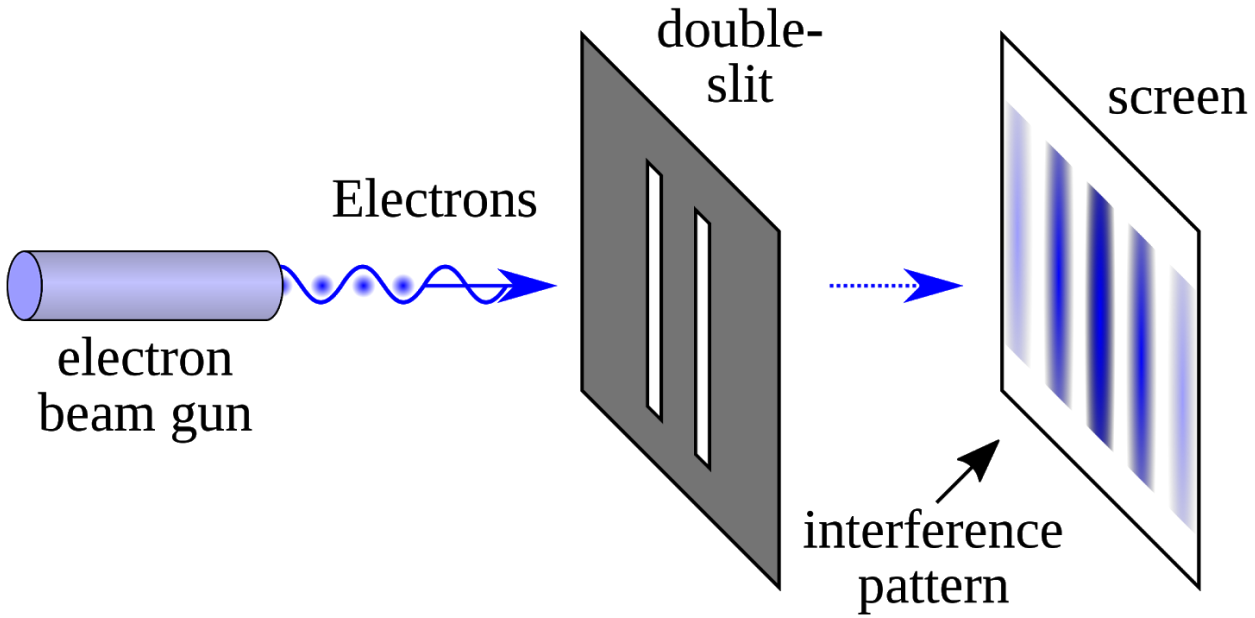
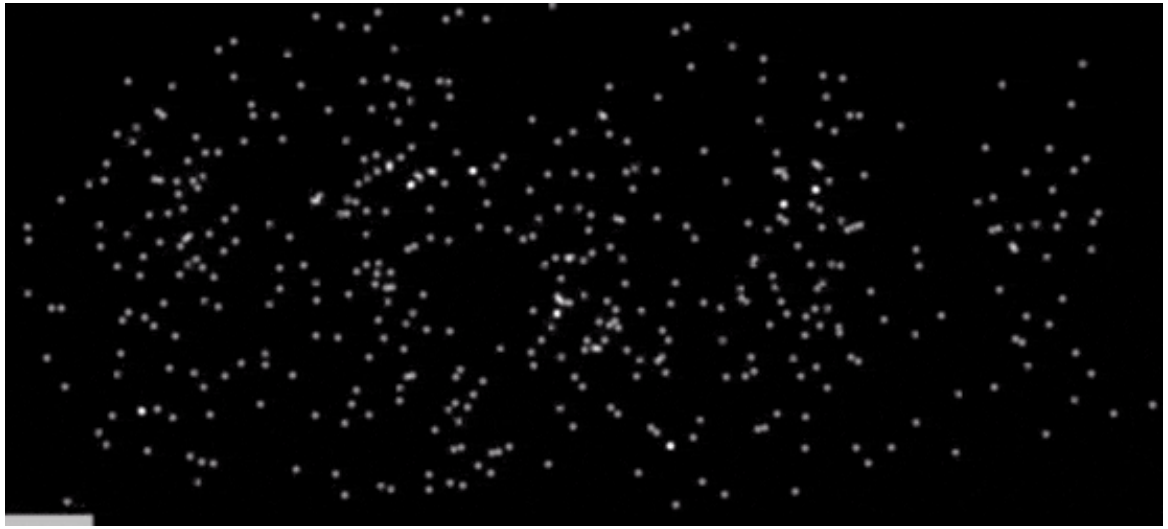
DOUBLE-SLIT EXPERIMENT REVISITED



- We can send the electrons one-by-one through the double slit
- We still get the interference pattern!

Screen



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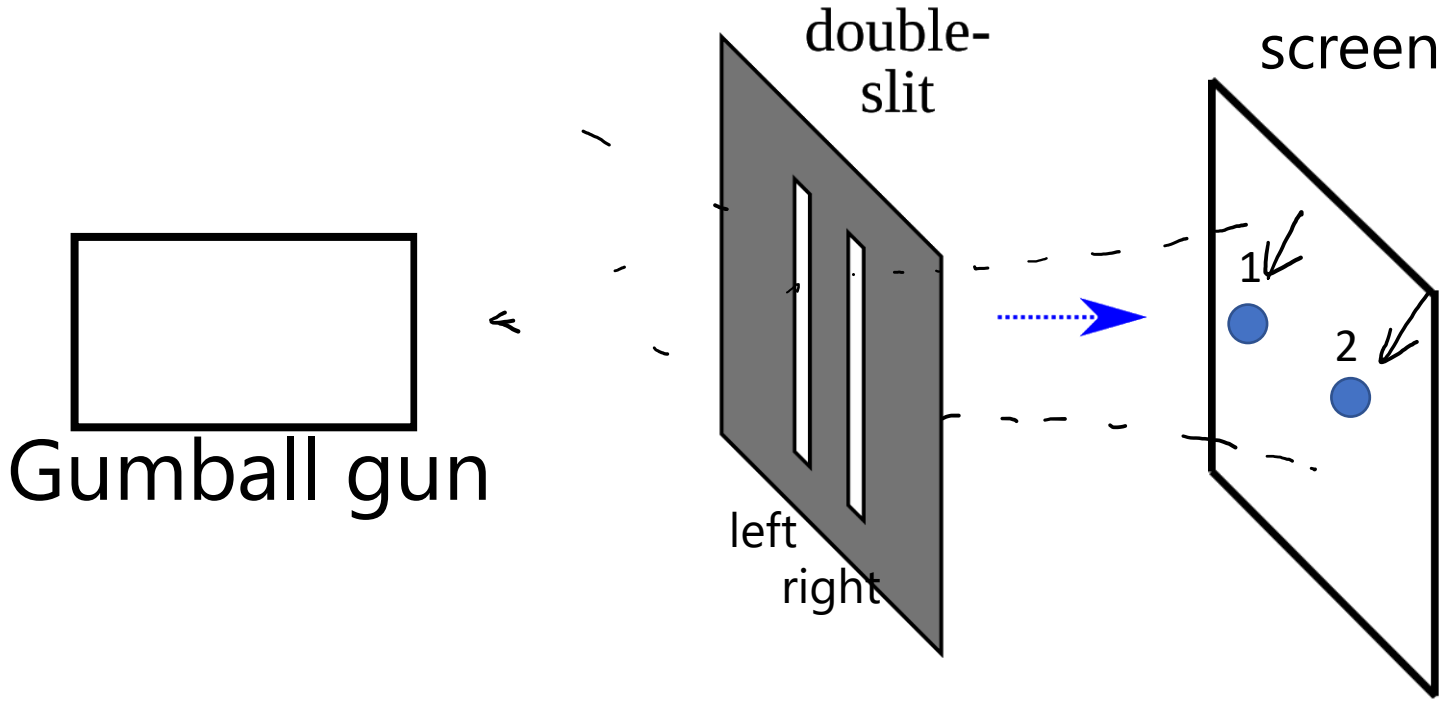
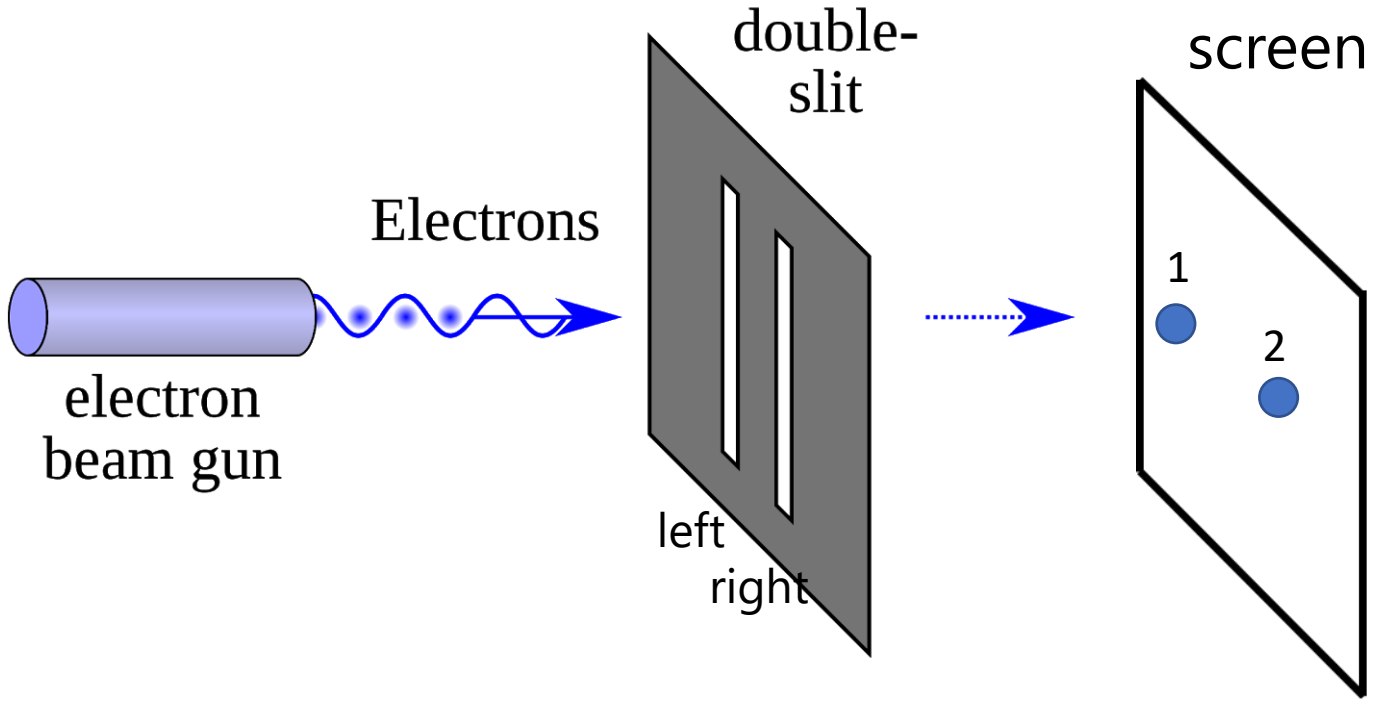
WHICH PATH DOES THE MARBLE TAKE?



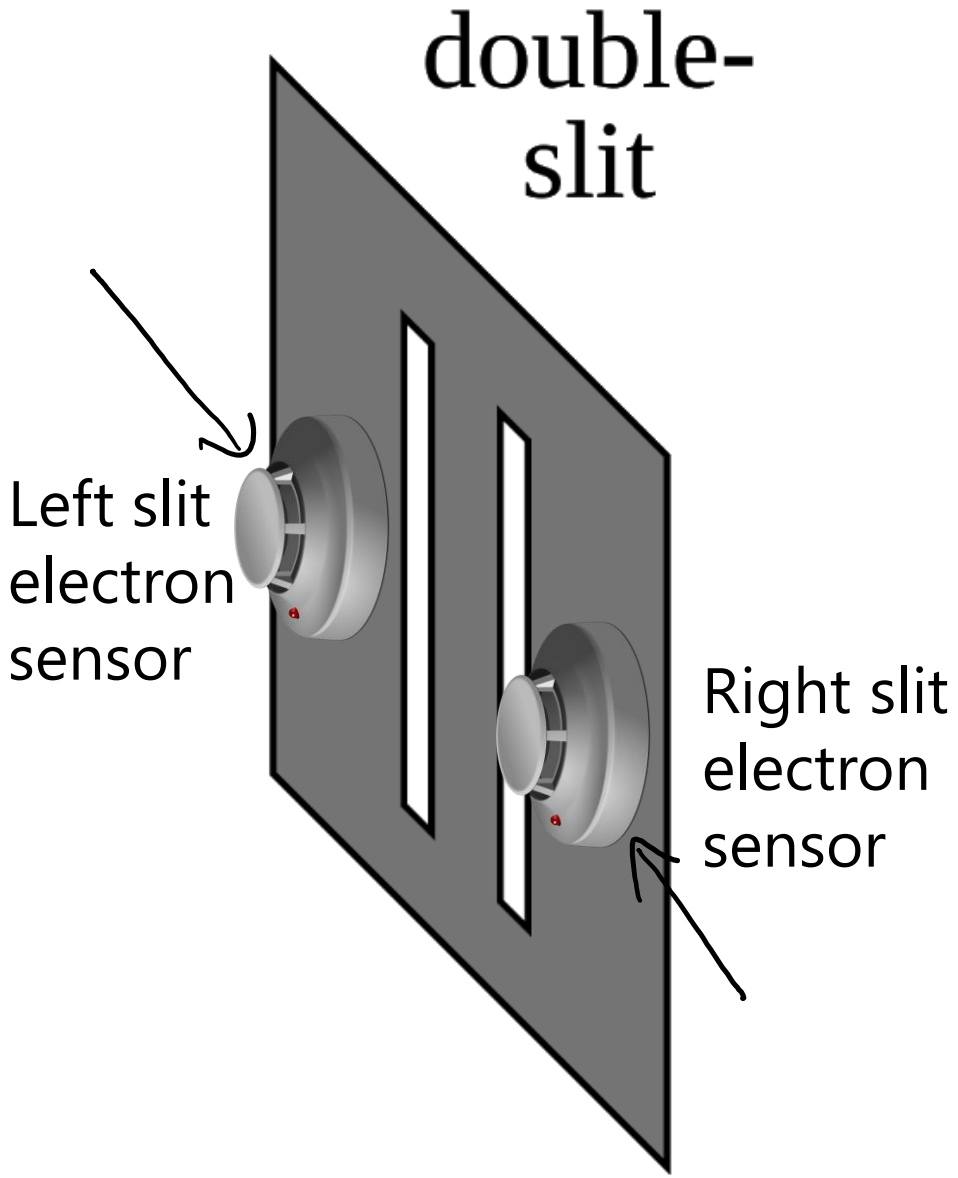
Did the gumballs go through the left slit or the right slit?

WHICH PATH DOES THE ELECTRON TAKE?



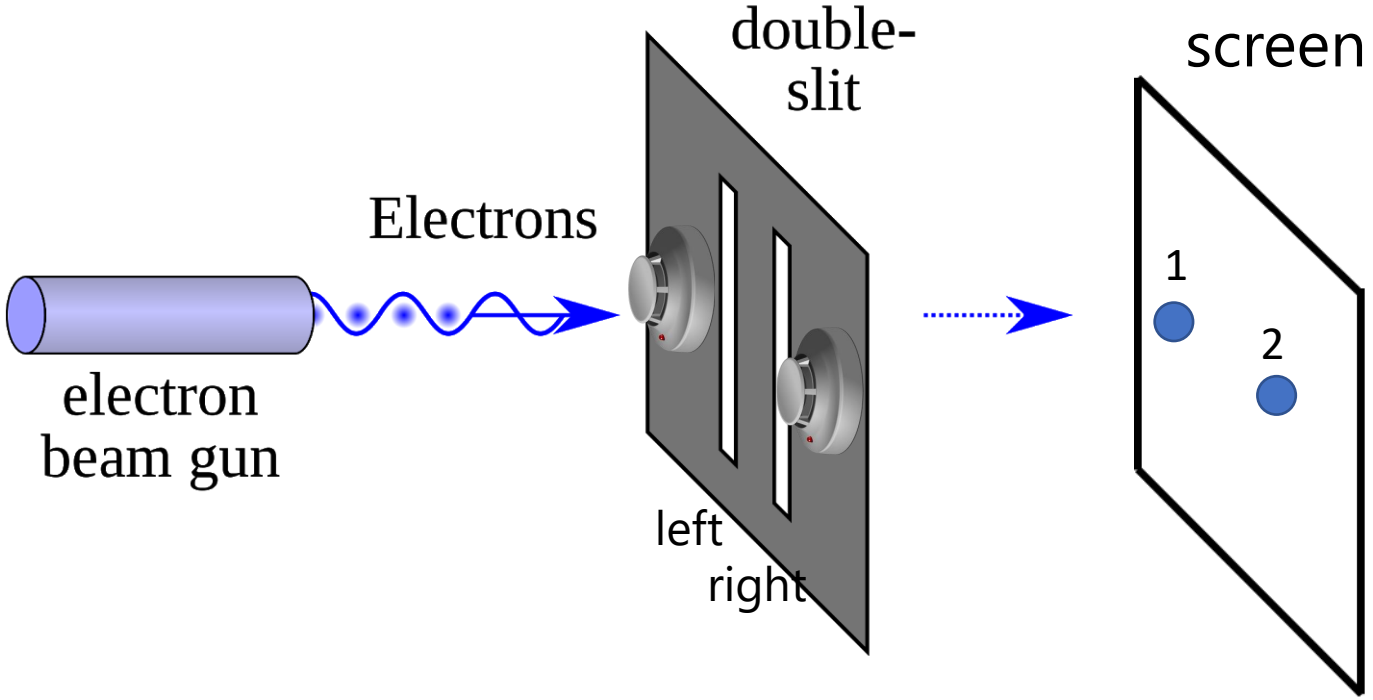
Did the electrons go through the left slit or the right slit?

LET'S FIND OUT!



- If the left slit electron sensor senses an electron zipping by, it beeps
- If the right slit electron sensor senses an electron zipping by, it beeps

LET'S FIND OUT



- As each electron goes through the slits, either the left slit or the right slit detector beeps
- Yay! We did it! We can now tell for sure which slit each electron goes through

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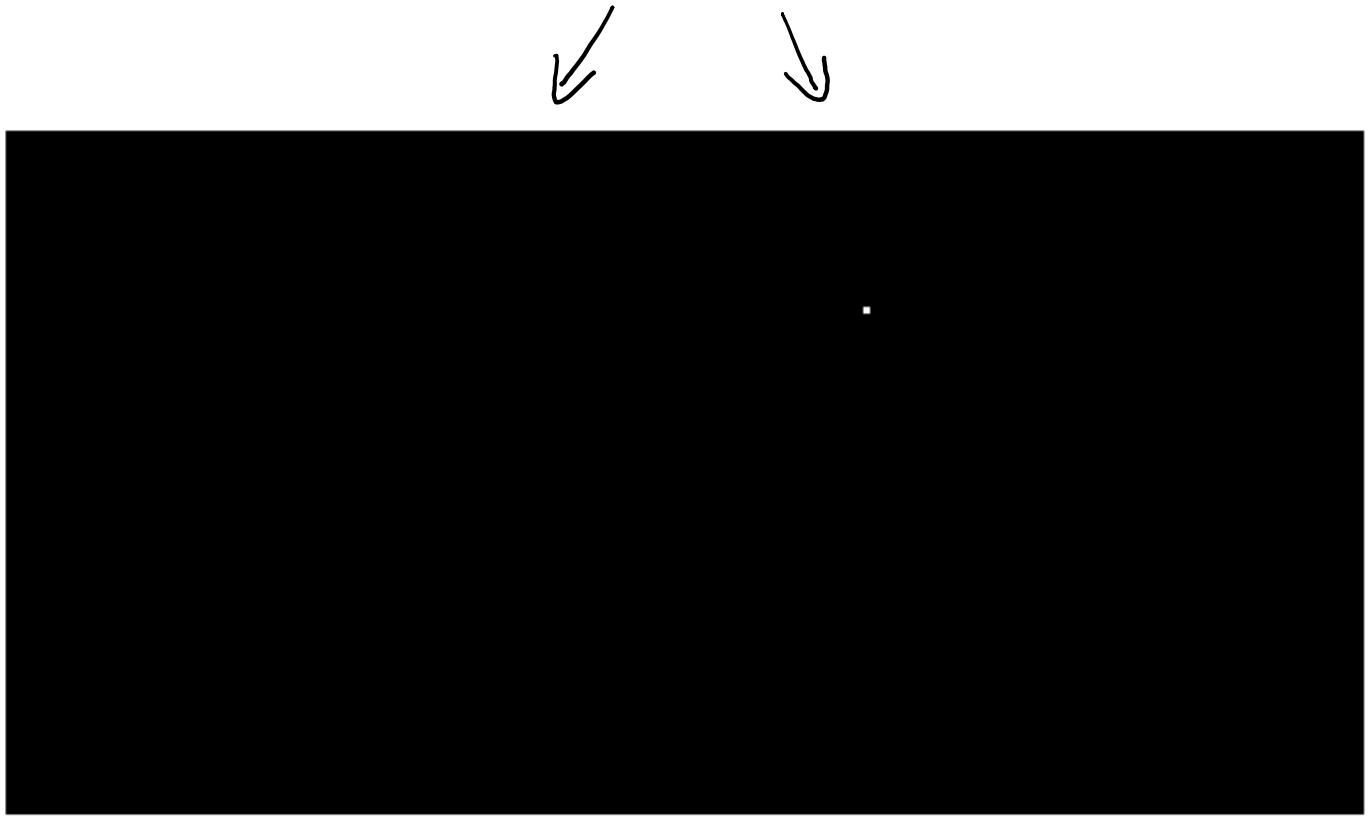
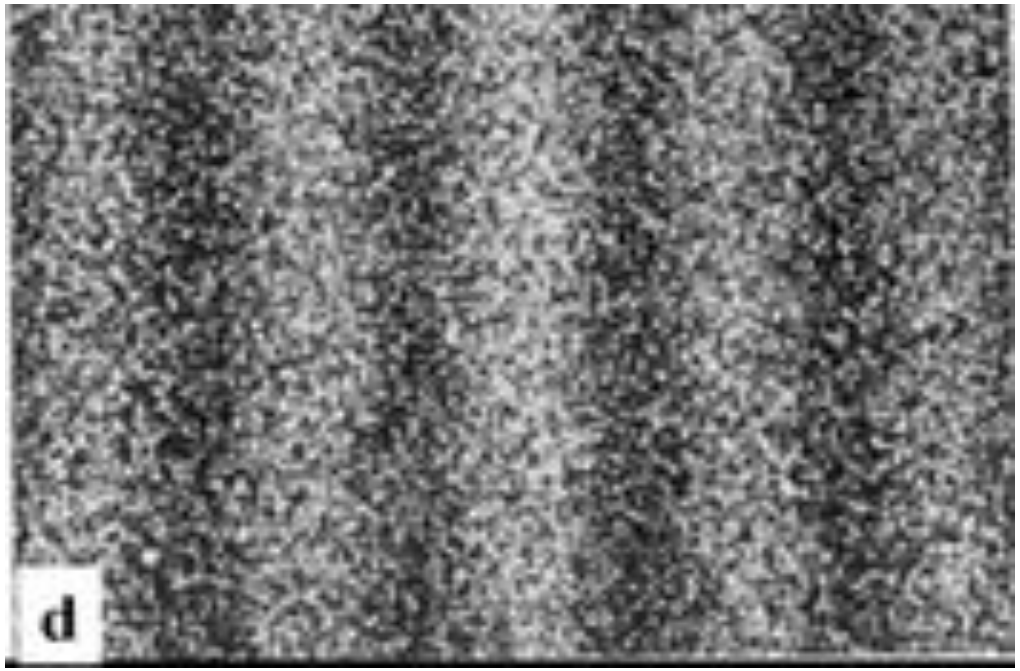
...AND WHAT HAPPENS AT THE SCREEN?



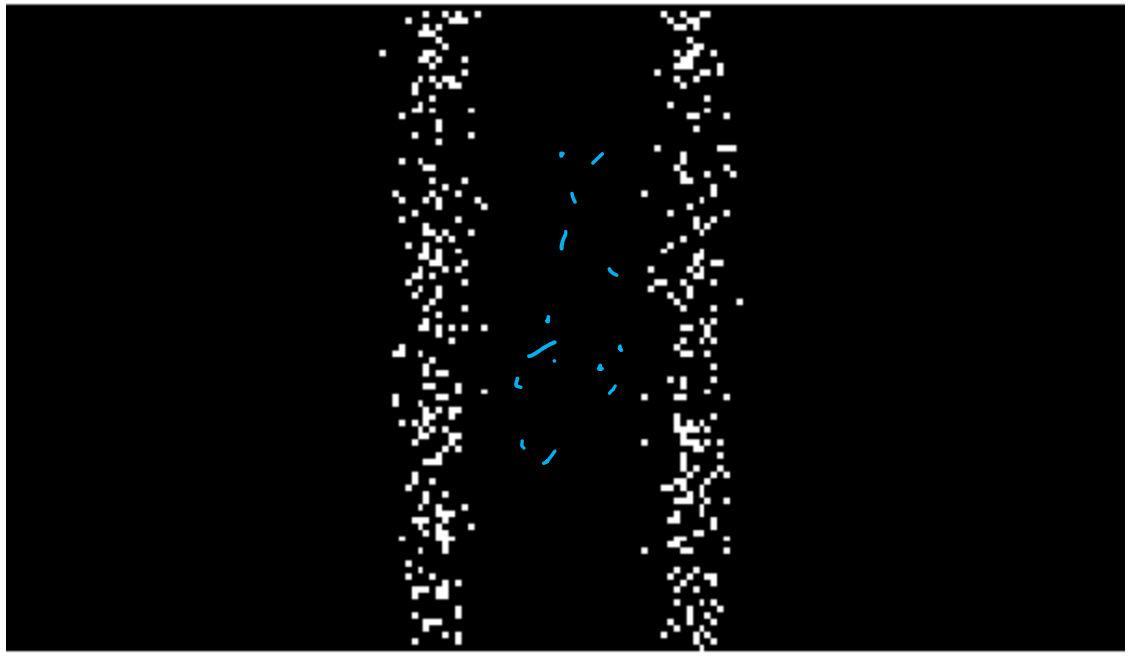
What do you notice?

MEASUREMENT CHANGES THE OUTCOME!!

Without electron sensors



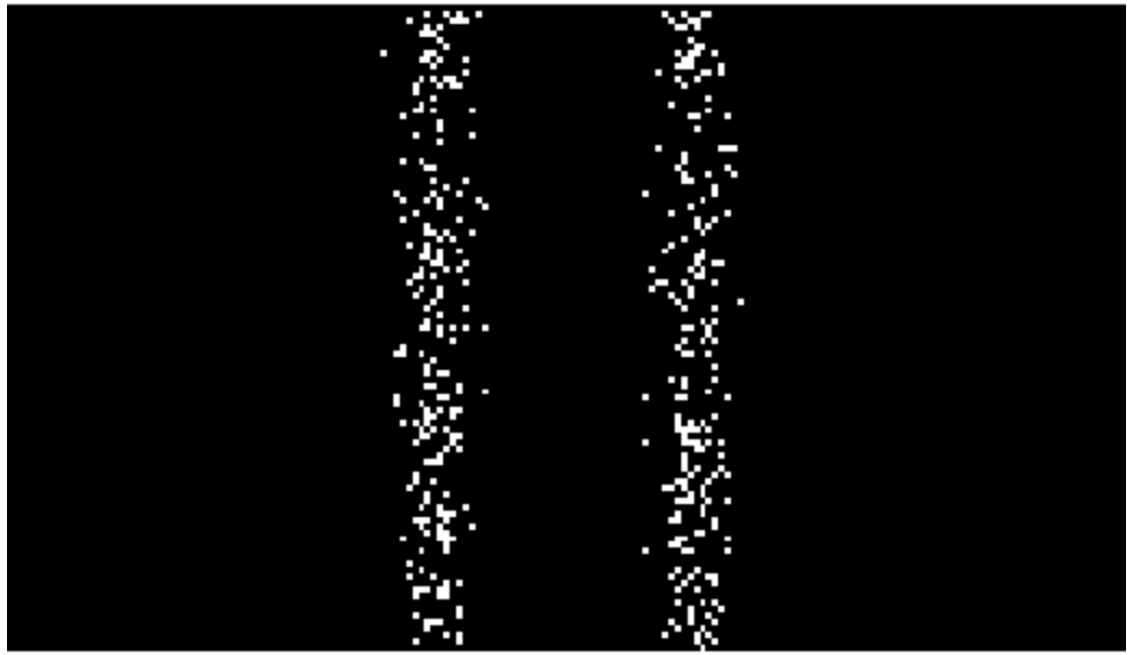
With electron sensors



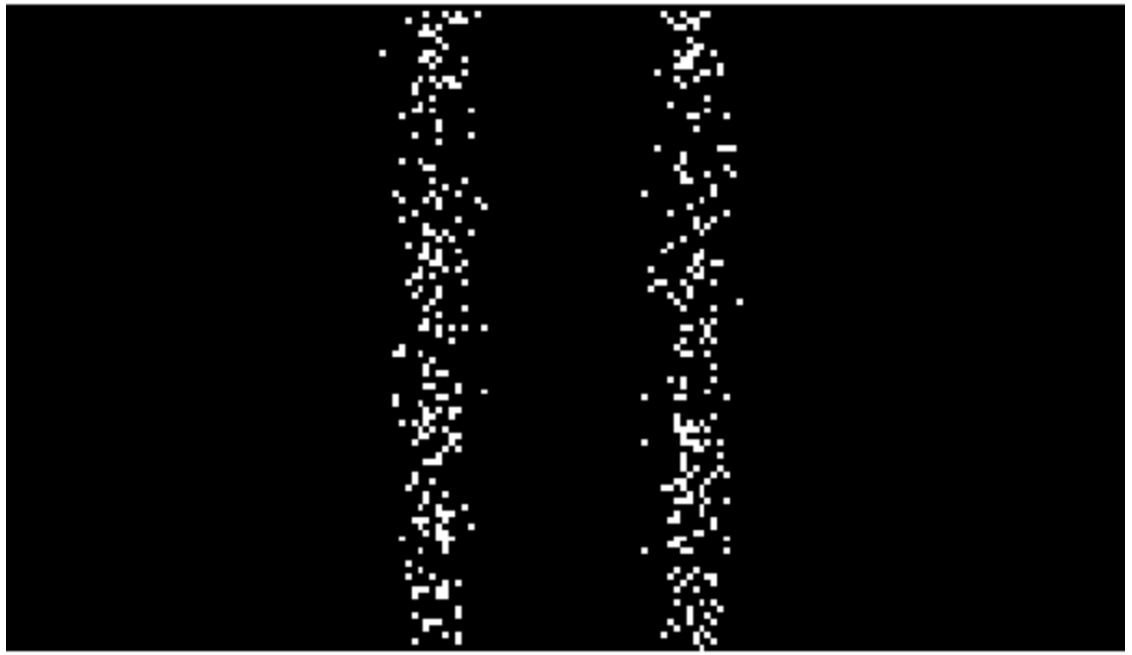
- Trying to find out which slit the electrons went through changed the outcome of the experiment!
- Measurement changes the **state** of each electron

WITH GUMBALLS

Without gumball sensors



With gumball sensors

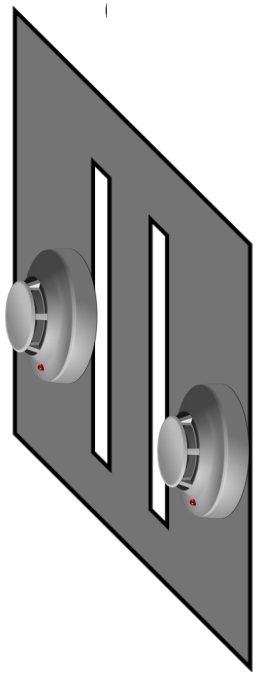


No change in outcome of experiment if you check which slit the gumball takes

EVERYDAY LIFE VS QUANTUM

Everyday life

Quantum



Measurement does not affect the thing being measured – everyday objects

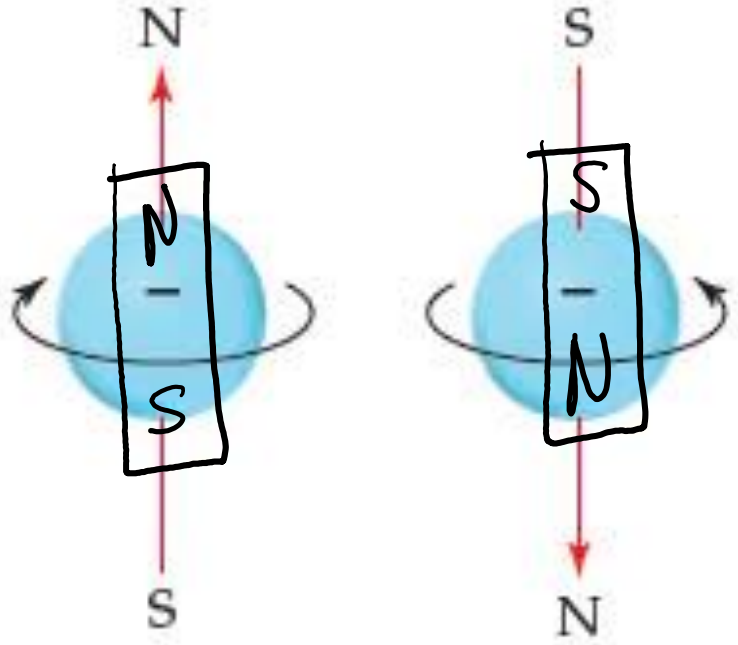
Measurement can affect the state of the thing being measured – quantum objects (qubits)

QUESTIONS?

Questions on content so far?

ELECTRON SPIN

- Fundamental properties of an electron (and other particles):
  - Mass
  - Charge
  - Magnetic field (spin)
  - ….
- Spin does **not** correspond to actual spinning

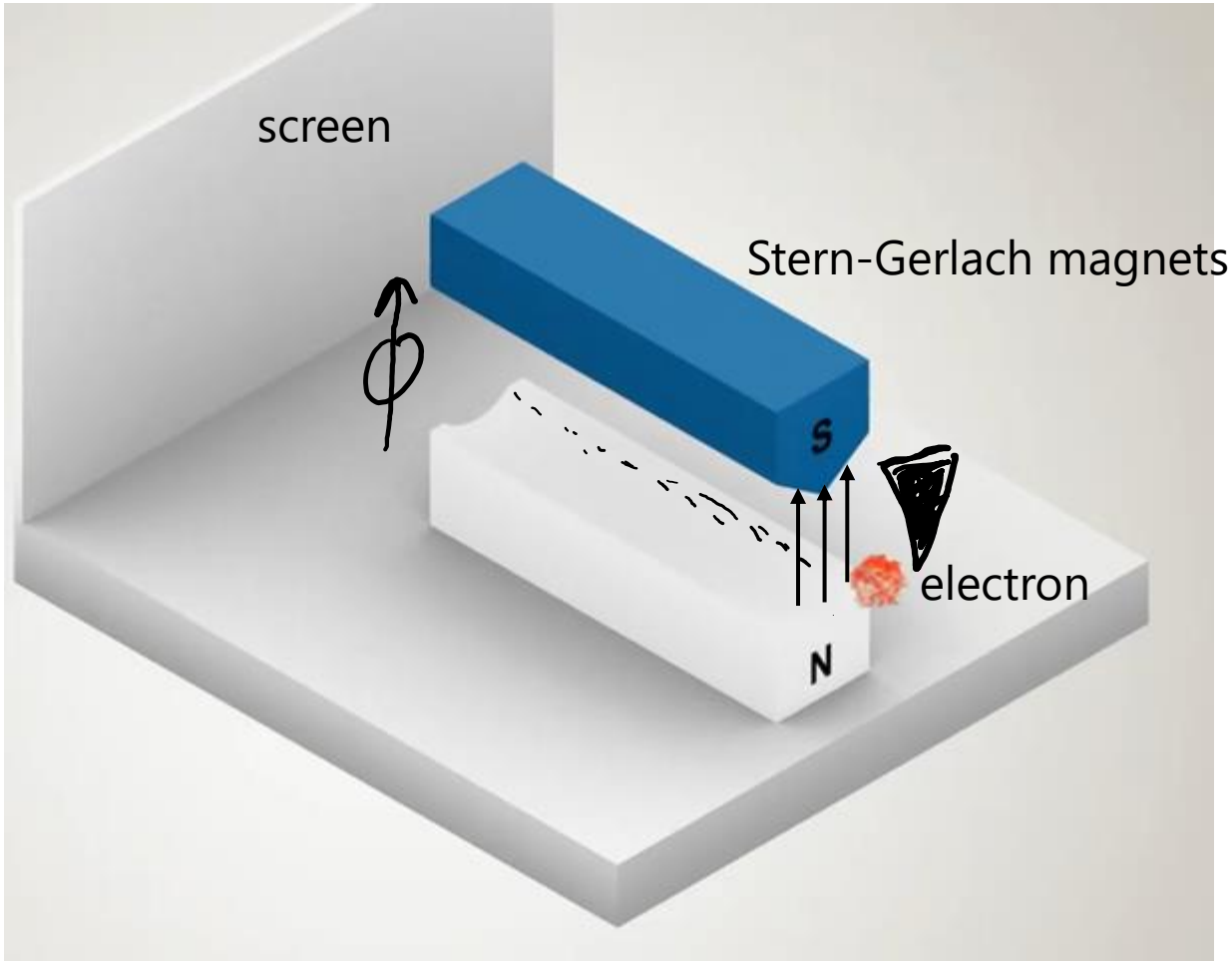


….misleading

MEASURING SPIN – THE STERN GERLACH EXPT.

- Since spin corresponds to a small magnetic field, we can use another magnet to measure it!

- **When measured**, spin always has two directions – one along the direction of the magnetic field and one opposite to it



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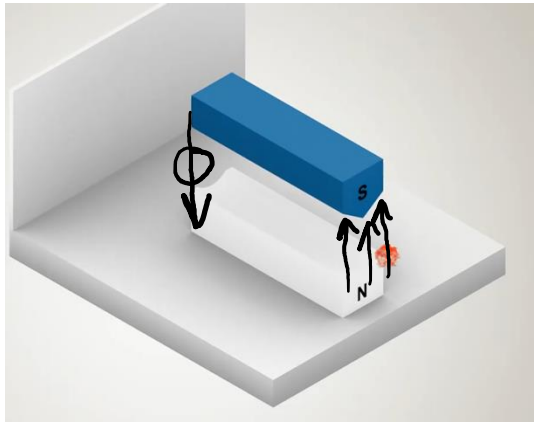
NOTE ON NOTATION

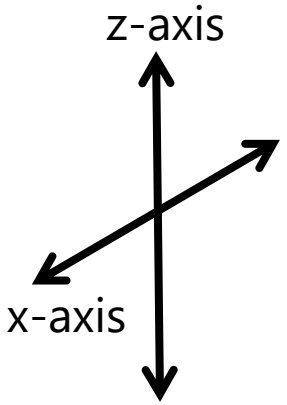
Measurement along z (vertical) axis:



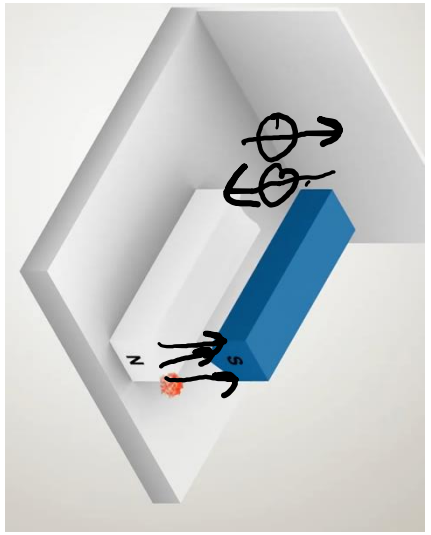
$$|0\rangle = |\uparrow\rangle = \begin{pmatrix} 1 \\ 0 \end{pmatrix}$$ "spin-up"

$$|1\rangle = |\downarrow\rangle = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$ "spin-down"

basis = aka possible outcomes



Measurement along x (horizontal) axis:

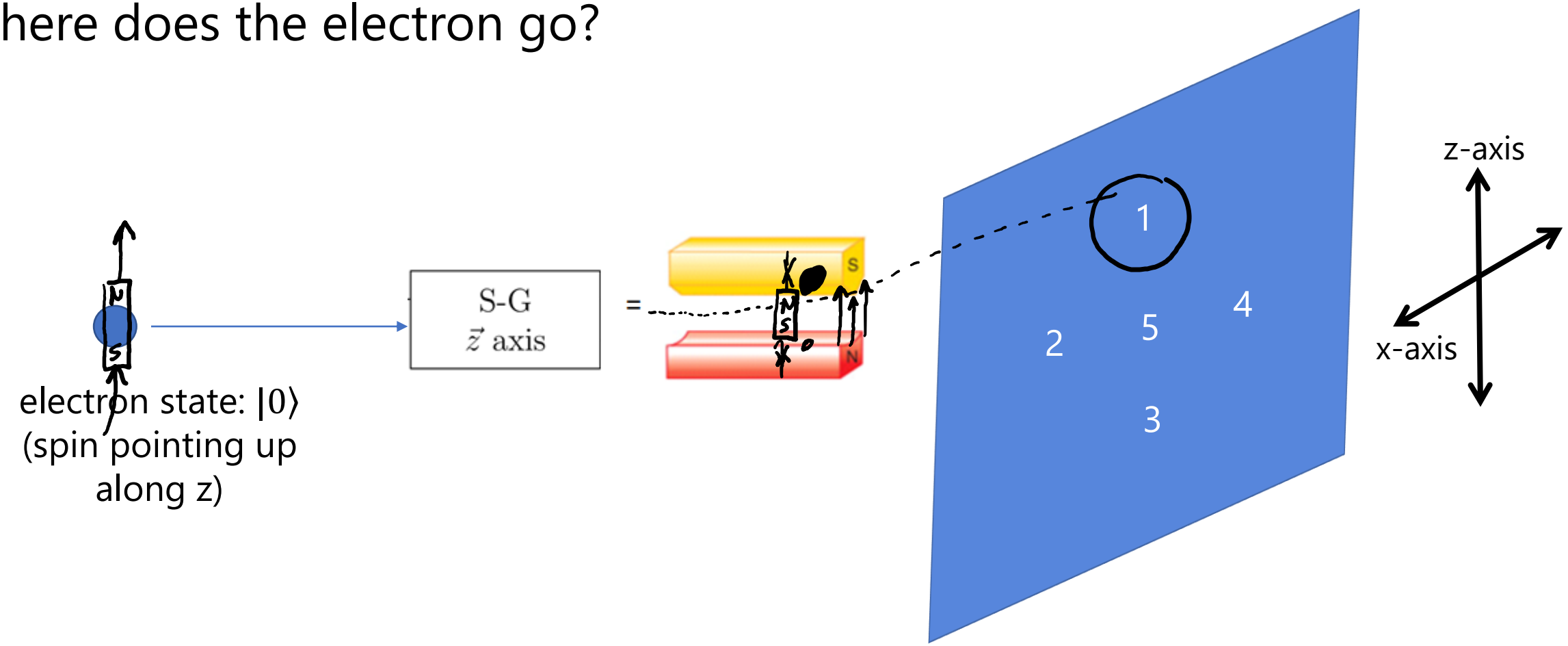


$$|+\rangle = |\rightarrow\rangle = \begin{pmatrix} 1/\sqrt{2} \\ 1/\sqrt{2} \end{pmatrix}$$ "spin-right"

$$|-\rangle = |\leftarrow\rangle = \begin{pmatrix} 1/\sqrt{2} \\ -1/\sqrt{2} \end{pmatrix}$$ "spin-left"

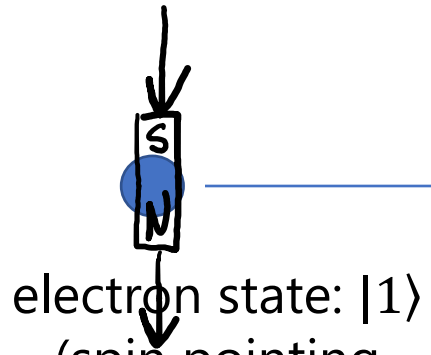
STERN GERLACH EXPERIMENT

Where does the electron go?

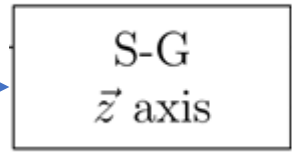


STERN GERLACH EXPERIMENT

Where does the electron go?



electron state: $|1\rangle$
(spin pointing
down along z)



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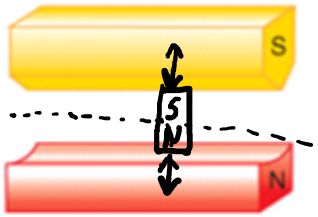
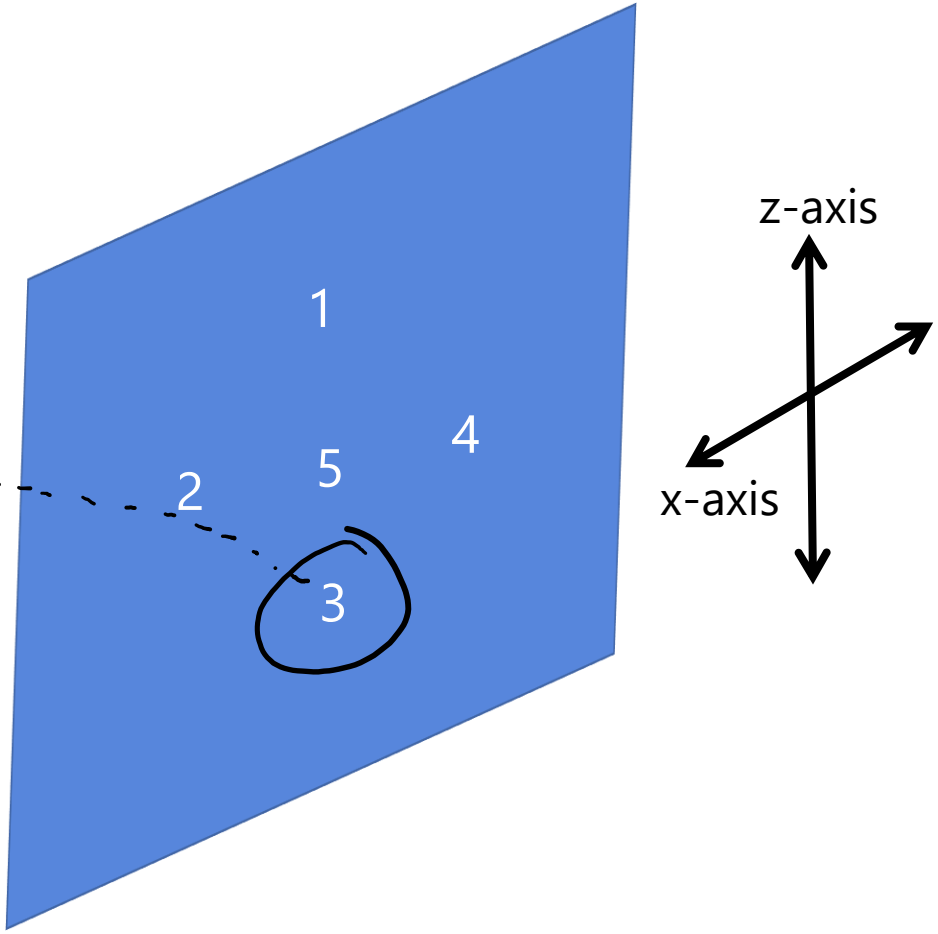
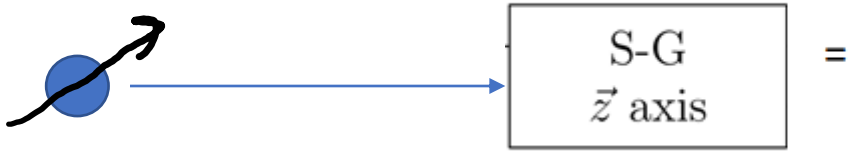




STERN GERLACH EXPERIMENT

Where does the electron go?



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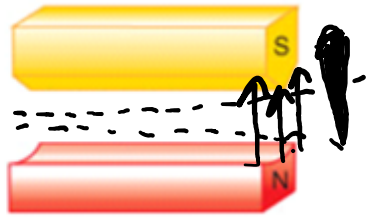
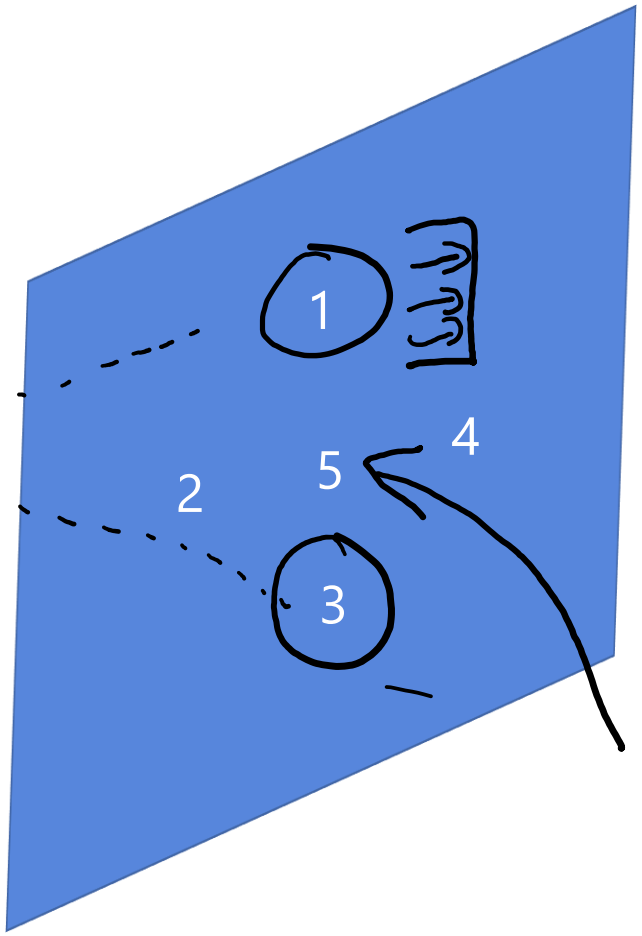
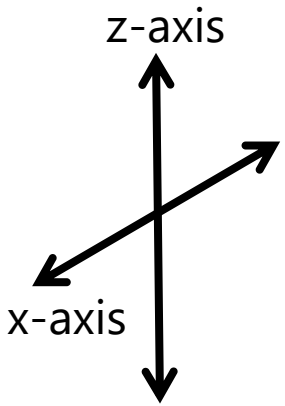






electron state:
$0.71|0\rangle + 0.71|1\rangle$
(spin combination of up and down along z)

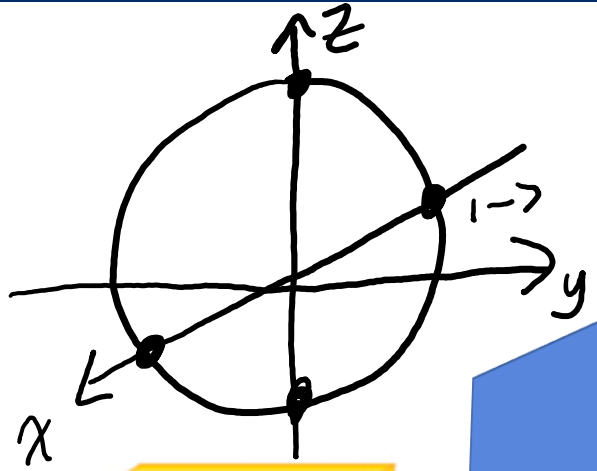
$= \frac{1}{\sqrt{2}}|0\rangle + \frac{1}{\sqrt{2}}|1\rangle$

$= |+\rangle = |\rightarrow\rangle$

STERN GERLACH EXPERIMENT

Where does the electron go?

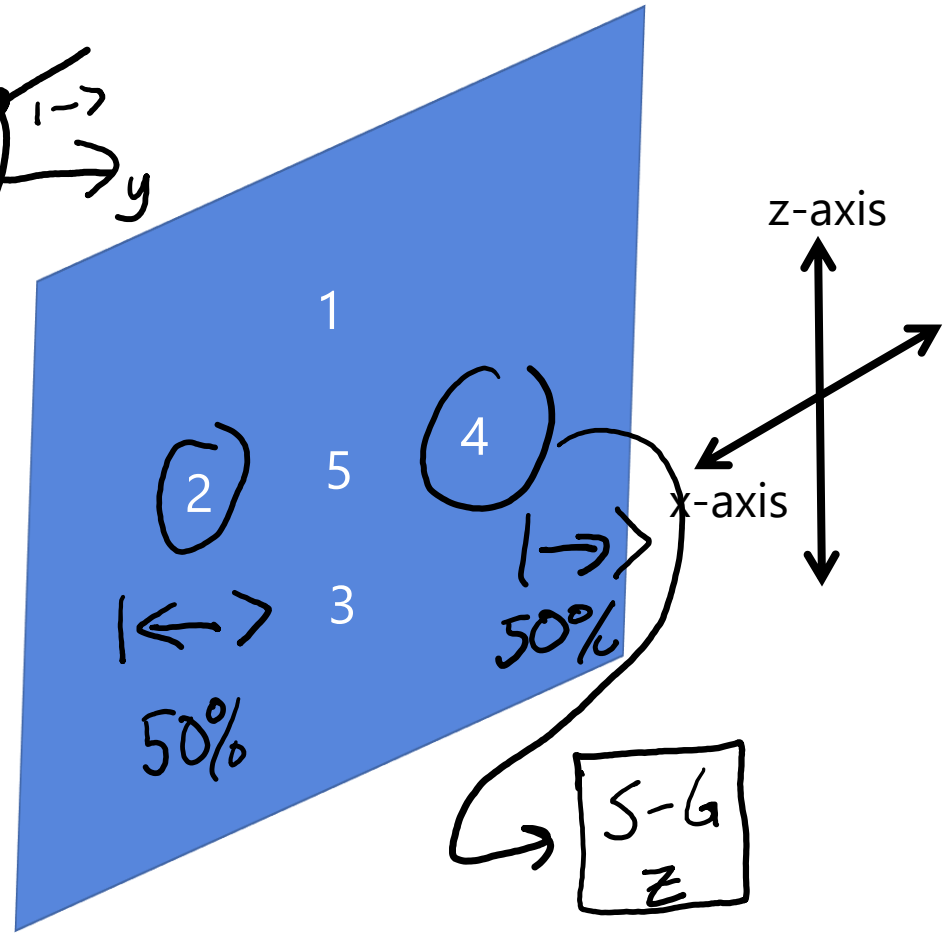
$$\begin{cases} |0\rangle = \frac{1}{\sqrt{2}}|+\rangle + \frac{1}{\sqrt{2}}|-\rangle \\ |1\rangle = \frac{1}{\sqrt{2}}|+\rangle - \frac{1}{\sqrt{2}}|-\rangle \\ |+\rangle = \frac{1}{\sqrt{2}}|0\rangle + \frac{1}{\sqrt{2}}|1\rangle \\ |-\rangle = \frac{1}{\sqrt{2}}|0\rangle - \frac{1}{\sqrt{2}}|1\rangle \end{cases}$$



electron state: $|0\rangle$ (spin pointing up along z)

$$= \frac{1}{\sqrt{2}}|+\rangle - \frac{1}{\sqrt{2}}|-\rangle$$

$$= |0\rangle = |\uparrow\rangle$$



KEY TAKEAWAYS

- Measurement in the quantum world is different from everyday life
  - Measurement affects the state of the quantum system being measured
  - Results from different ways of measurement may not always agree
  - Interference pattern disappears if you try to find out which slit the electron takes!

- The Stern-Gerlach experiment measures the spin of the electron/quantum system
  - When measured, spin always has two directions – one along the direction of the external magnetic field, and one opposite to the direction
  - The result depends on the orientation of the SG magnet!

FURTHER READING AND RESOURCES

- https://www.youtube.com/watch?v=b_ddt6J1Bio – Series of videos introducing quantum mechanics
- https://www.youtube.com/watch?v=NW7VUFgwqg8 – Quantum systems might aid bird navigation
- https://ocw.mit.edu/courses/physics/8-04-quantum-physics-i-spring-2013/lecture-videos/lecture-1/ - Lecture on measurement and its implications, with analogies from our everyday experience
- https://cp3.irmp.ucl.ac.be/~maltoni/PHY1222/mermin_moon.pdf - Accessible paper on measurement, entanglement, and their implications

QUESTIONS?

Questions on content so far?

POST-LAB ZOOM FEEDBACK

After this lab, on a scale of 1 to 5, how would you rate your understanding of this week's content?

- 1 –Did not understand anything
- 2 – Understood some parts
- 3 – Understood most of the content
- 4 – Understood all of the content
- 5 – The content was easy for me/I already knew all of the content

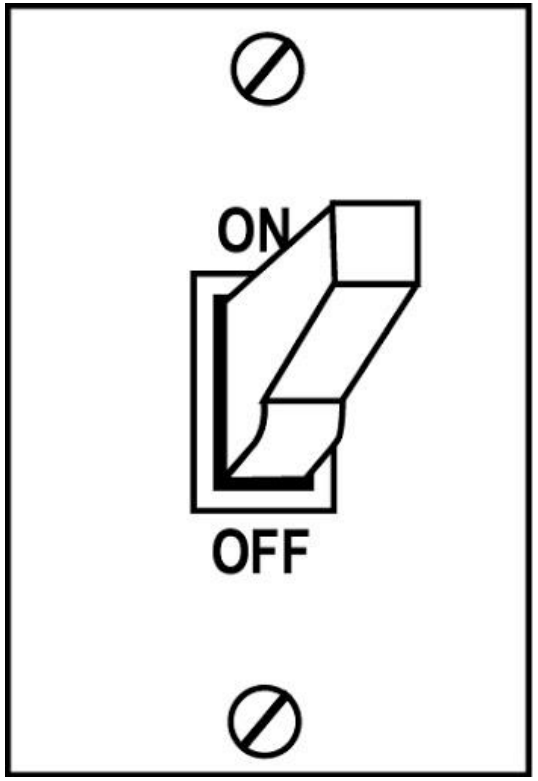
OPTIONAL CONTENT

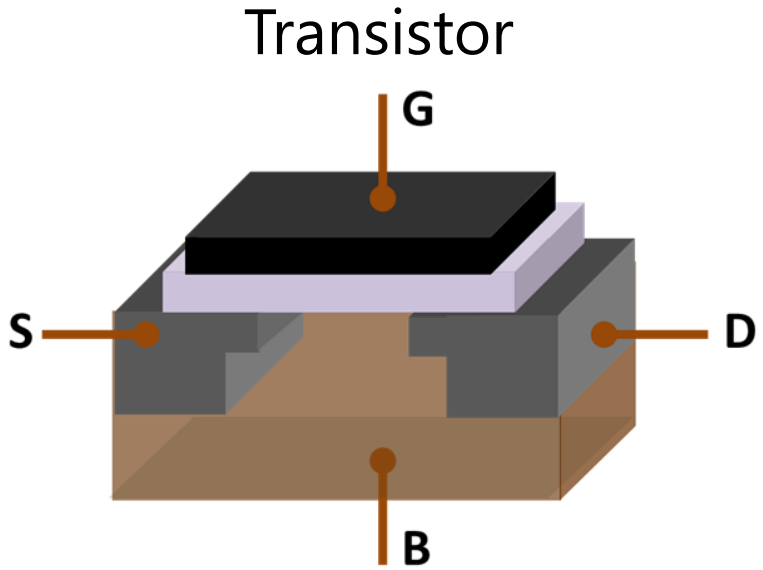
TWO-LEVEL SYSTEMS

Why do we care about two-level systems in quantum computing?

- Qubits are two-level systems!
- Analogous to classical bits, than can be 0 or 1
- **Wouldn't 3 or more-level systems be even better?** Yes! But really hard to control more than 2 states in experiments

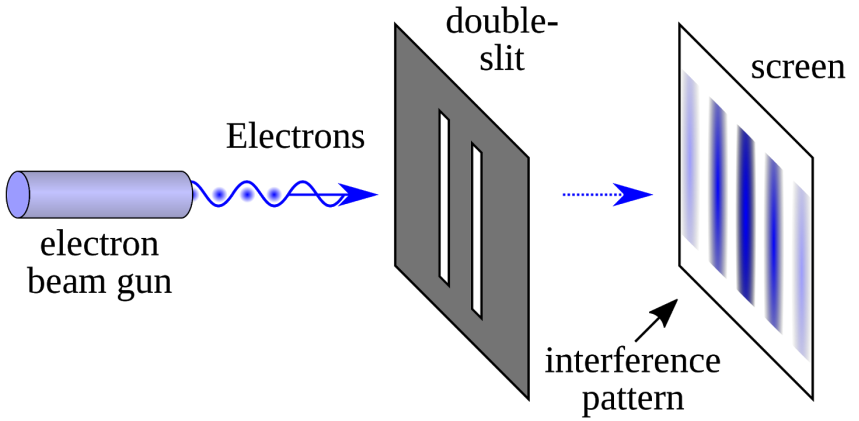
2 LEVEL-SYSTEMS AROUND US

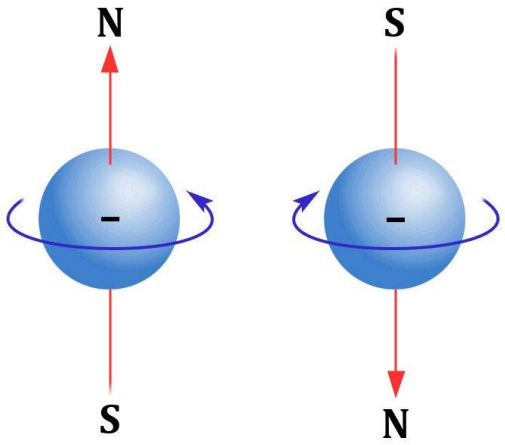




2 LEVEL SYSTEMS IN THE QUANTUM WORLD

- Double-slit experiment
- Current in a superconducting circuit
- Electron spin





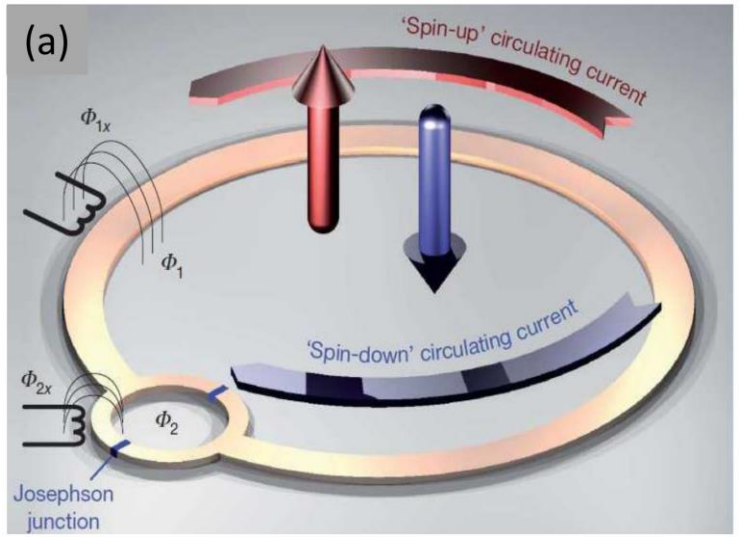


Image from Smelyanskiy et al., arXiv:1204.2821v2 **[quant-ph]**

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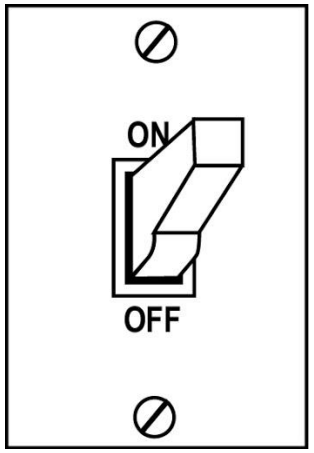
QUANTUM VS CLASSICAL 2 LEVEL SYSTEMS

Classical

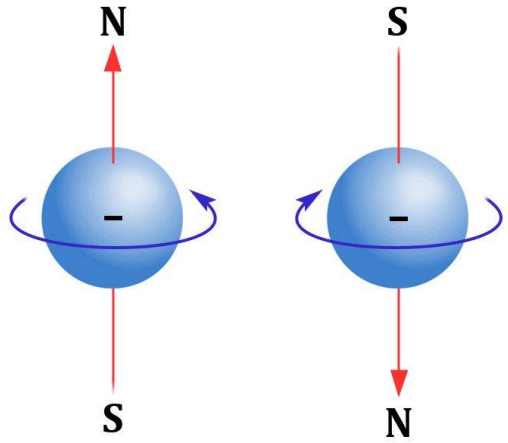


Either 1 or 0

ON: 1

OFF: 0

Quantum



Either 1, or 0, or a combination of both!

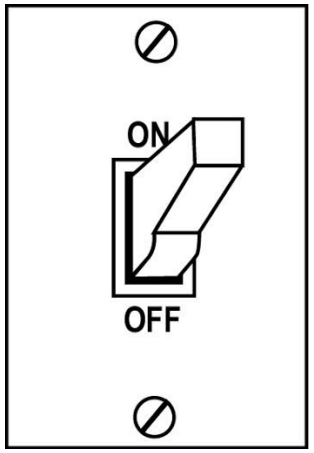
Only spin pointing down: $|1\rangle$

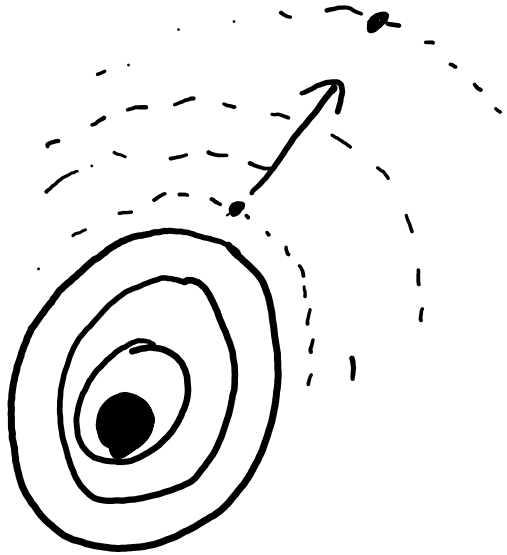
Only spin pointing up: $|0\rangle$

Combination of both: $\alpha|1\rangle + \beta|0\rangle$ ✓

QUANTUM VS CLASSICAL 2 LEVEL SYSTEMS

Classical





Quantum

Either 1 or 0

ON: 1

OFF: 0

Either 1, or 0, or a combination of both!

Only Shankar plays: $|1\rangle$

Only Menuhin plays: $|0\rangle$

Both play together: $\alpha|1\rangle + \beta|0\rangle$