Center for
Quantum Networks
NSF Engineering Research Center

The Physics Behind the Quantum Internet: A Gentle Introduction

Instructor: Michael G. Raymer
– University of Oregon

Co-Instructor: Abby Gookin
— University of Arizona

This work is supported primarily by the Engineering Research Centers Program of the National Science Foundation. Any opinions, findings and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect those of the National Science Foundation.

CQN Winter School on Quantum Networks

Funded by National Science Foundation Grant #1941583

Center for
Quantum Networks
NSF Engineering Research Center

https://cqn-erc.org/

Building the Quantum Internet

CQN is developing the entire technology stack to reliably carry quantum data across the globe, serving diverse applications across many user groups simultaneously... spurring new technology industries and a competitive marketplace of quantum service providers and application developers.

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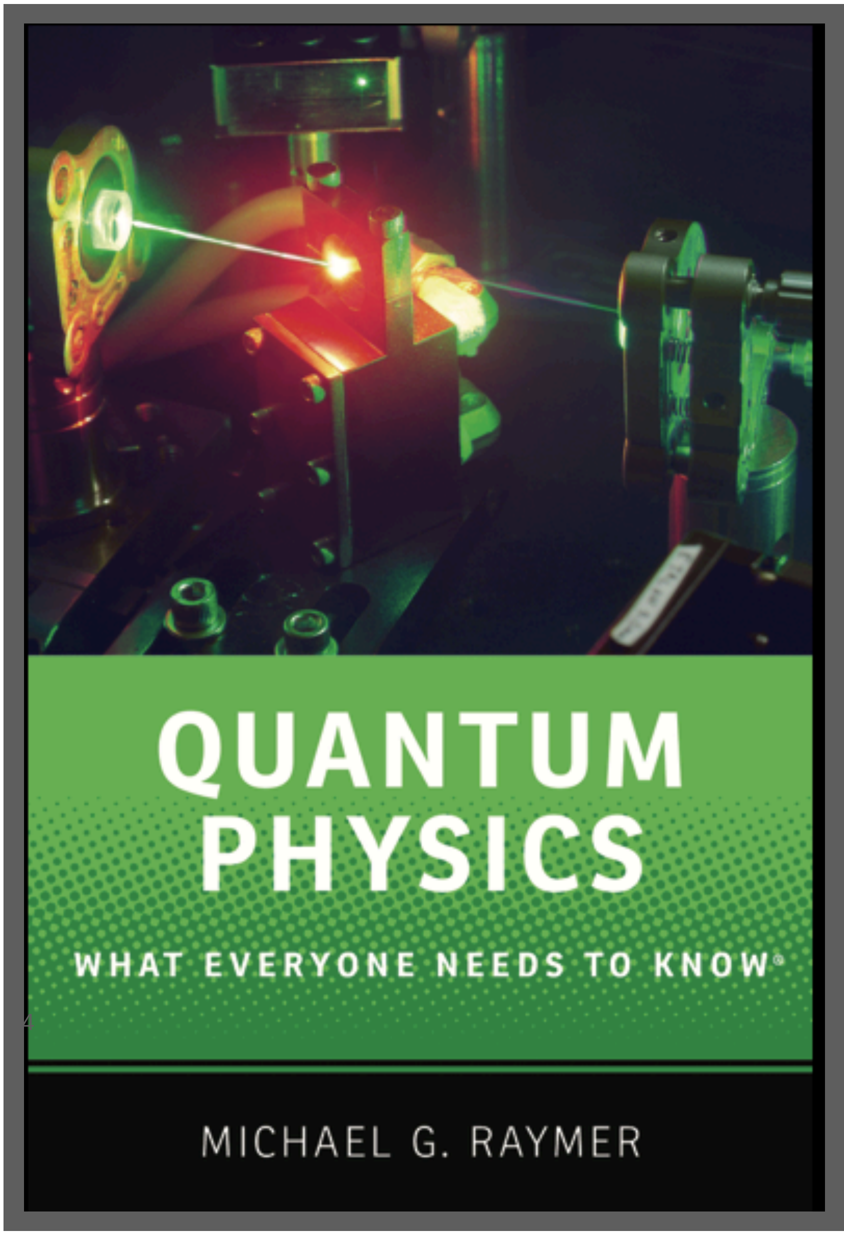
Textbook for non-experts

Concept of measurement
Probability
Photon polarization
Quantum cryptography
Path interference
Quantum States
Gravity sensors
Waves
Born rule
Bell inequalities
Entanglement
Teleportation
Quantum computing



UNIVERSITY OF OREGON

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POLL QUESTION 1

What is your highest level exposure to quantum theory?

A: None
B: High school
C: College
D: Self-taught

This short course can be useful for:

- Those completely new to quantum theory
- Those who learned the Schrodinger equation but not quantum information
- Those curious about effective ways to teach quantum information to non-experts

SHORT COURSE (4 HR) OUTLINE

PART 1: Quantum information science

The Center for Quantum Networks
The National Quantum Initative
What is *information*?
Bits and qubits
Superposition and entanglement

PART 2: Encoding and transmitting quantum information

Communication systems
Distributing Entangled states (e.g.. in Space)
Ways of encoding qubits
Ways of encoding qubits in photons (Flying qubits)
Quantum state teleportation
Space-based quantum networks

PART 3: Bell State measurements

Photon polarization revisited
Quantum measurement - Born's Rule
Correlations and the Bell inequality
Bell-Test experiments

PART 4: The Quantum Internet

Application #1: Quantum Cryptography
Bell-State Creating and Measuring
Quantum memories
Application #2: Memory-Assisted Teleportation
Entanglement Swapping with Quantum Memories
Quantum repeater networks
What could a quantum Network do?
Perspectives and misconceptions

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The Physics Behind the Quantum Internet

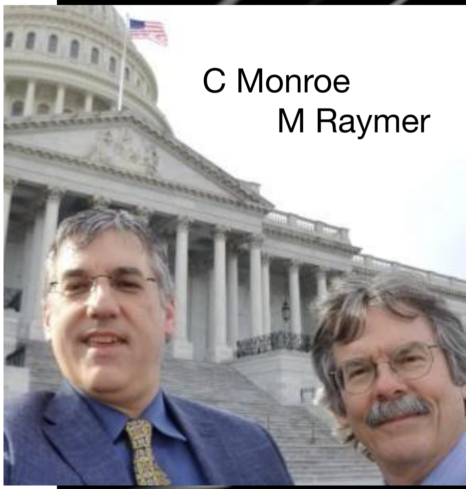
PART 1

QUANTUM INFORMATION SCIENCE

One Hundred Fifteenth Congress of the United States of America

AT THE SECOND SESSION

Begun and held at the City of Washington on Wednesday, the third day of January, two thousand and eighteen



An Act

To provide for a coordinated Federal program to accelerate quantum research and development for the economic and national security of the United States.

Be it enacted by the Senate and House of Representatives of the United States of America in Congress assembled,

SECTION 1. SHORT TITLE; TABLE OF CONTENTS.

(a) SHORT TITLE.—This Act may be cited as the "National Quantum Initiative Act".

(b) TABLE OF CONTENTS.—The table of contents of this Act is as follows:

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Quantum Science & Technology Pillars

Quantum Computing

- Optimization
- Designer molecules
  (drugs, solar cells..)
- Materials design
- Pattern recognition
  (Traffic patterns)
- Machine learning
- Artificial intelligence
- Decryption

Quantum Sensing

- Magnetic fields
- Gravitational fields
- Biomedical imaging
- Materials engineering
- GPS-free navigation
- Distributed sensing

Quantum Communication

- Secure data encryption
- Remote Q computing
- Distributed Q computing
- Distributed sensing
- Multiparty entangled protocols

Quantum Communication enables and links together diverse quantum technologies

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What is ‘Classical’ Information?*

- Two types of “Information”:
  - *Semantic Information* is the meaningful knowledge that a message is to impart at the destination.
  - *Technical Information* is the set of *symbols* that are sent.

Information Theory answers questions like:

How much information can be carried by a given number of symbols?

8 bits = 1 byte

Encoding decimal numbers using binary numbers (bits)

0	00000000
1	00000001
2	00000010
3	00000011
4	00000100
5	00000101
6	00000110
7	00000111
8	00001000
9	00001001
10	00001010

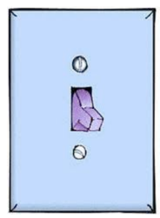
* Claude Shannon, “A Mathematical Theory of Communication” Bell Telephone Labs 1948

What is a Bit?

A single memory element in a conventional computer can store 1 bit:

Ordinary bit:

or



1 or 0

The value of the bit is represented in a physical object.

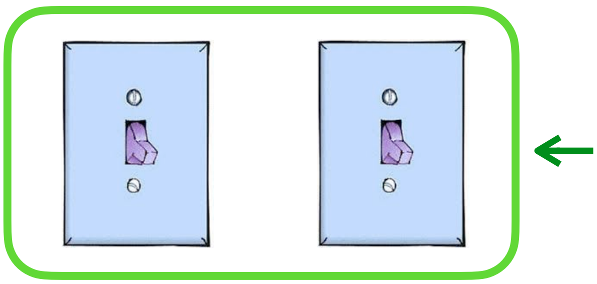
We call the <u>condition</u> of the switch its ***STATE***

The position of a light switch is an example of a *Classical State*

POLL QUESTION 2

A Memory Cell containing Two classical bits:

memory cell



Green Box = Classical Memory Cell

How many possibilities for switch settings (states) are there?

A: 2

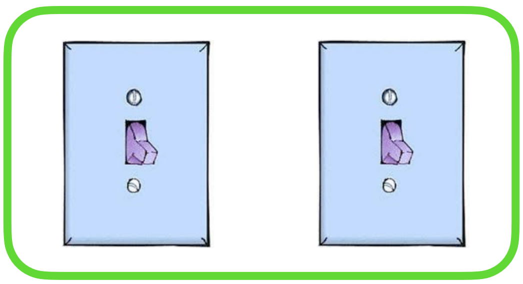
B: 4

C: 8

POLL QUESTION 2

A Memory Cell containing Two classical bits:

memory cell



Green Box = Classical Memory Cell

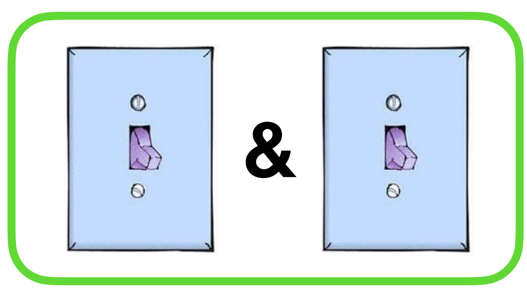
How many possibilities for switch settings (states) are there?

A: 2

→ B: 4

C: 8

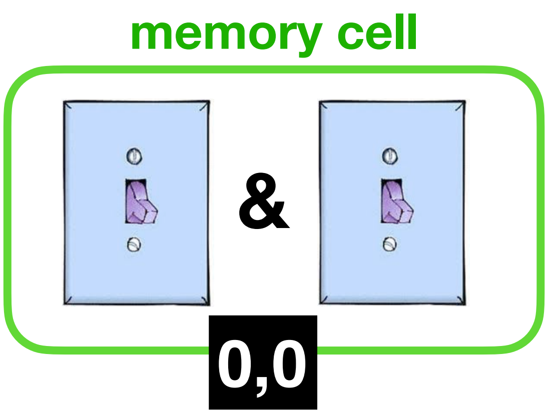
These possibilities are called "Combined States"



& means "and" (combined with)

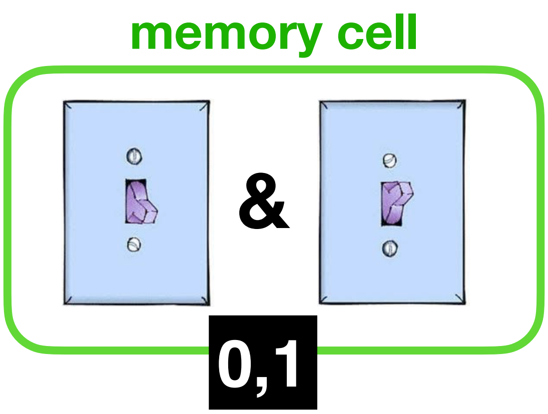
Two Ordinary bits:

4 possibilities



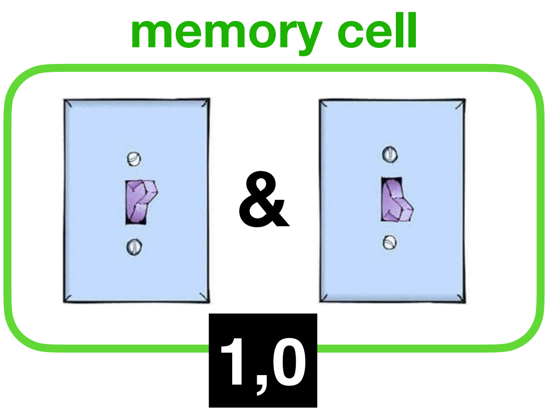
Two Ordinary bits:

4 possibilities



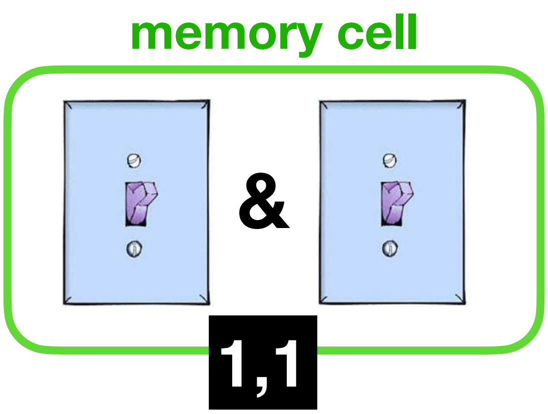
Two Ordinary bits:

4 possibilities



Two Ordinary bits:

4 possibilities



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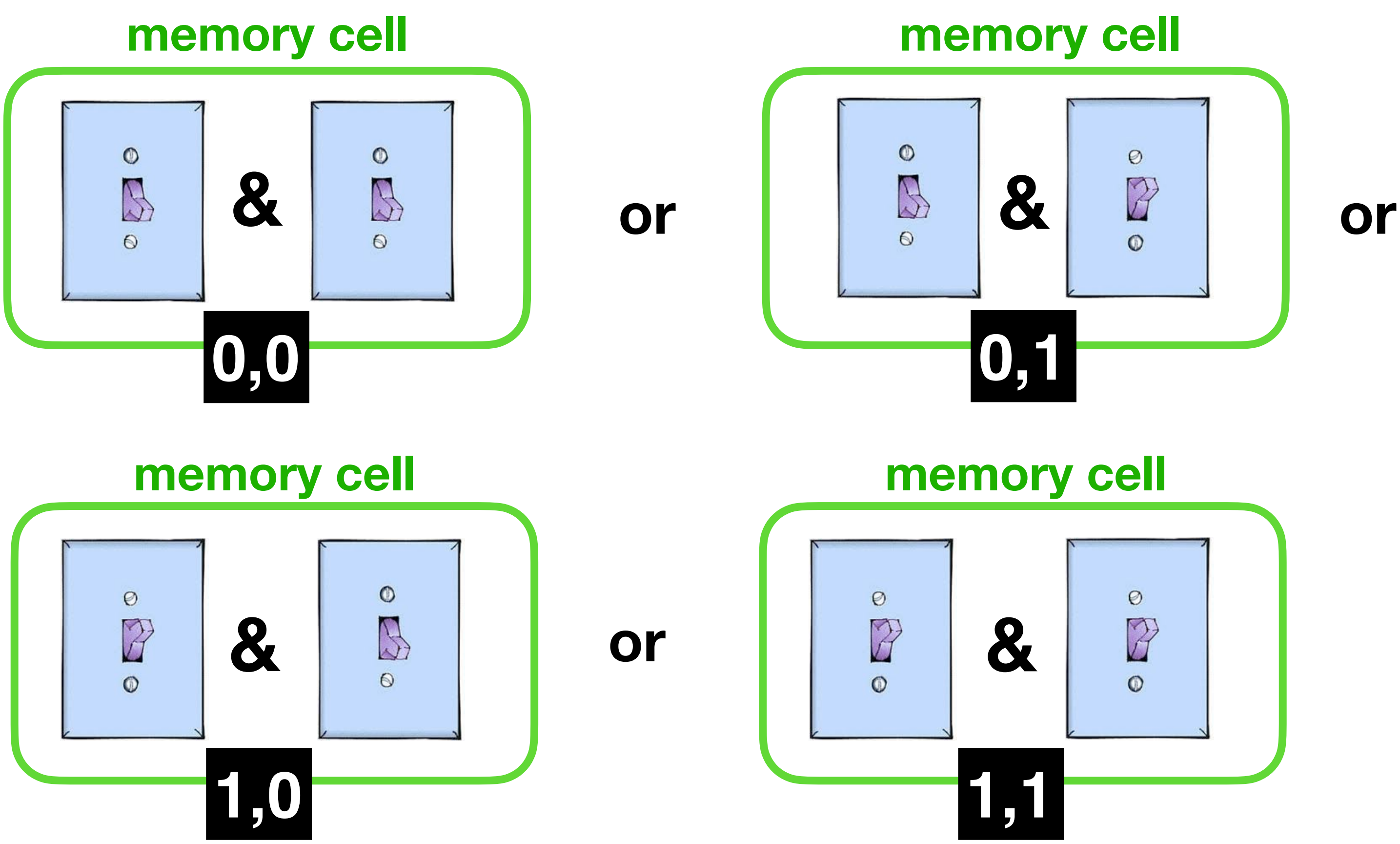
Two Ordinary bits:

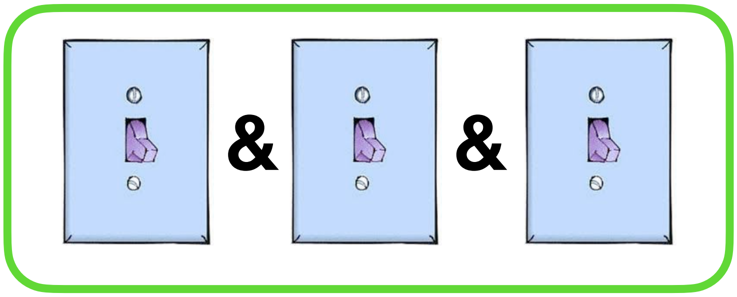
All 4 possibilities



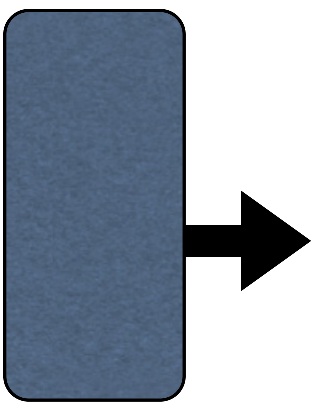
Can represent and store only a <u>single combination</u> of values in a single memory cell at a given time.

POLL QUESTION 3

If there are 3 switches, how many unique combinations are there?



memory cell



A: 3

B: 6

C: 8

D: 9

$$2x2x2 = 2^3 = 8$$

There are 8 unique “combined classical states”

If there are *N* switches, how many unique combinations are there?

Number of switches	Number of distinct combinations possible
1	2
2	2x2 = 4
3	2x2x2 = 8
4	2x2x2x2 = 16
5	2x2x2x2x2 = 32
6	2x2x2x2x2x2 =64
7	2x2x2x2x2x2x2 = 128
8	2x2x2x2x2x2x2x2= 256
9	2x2x2x2x2x2x2x2x2x2= 512
10	2x2x2x2x2x2x2x2x2x2x2= 1024

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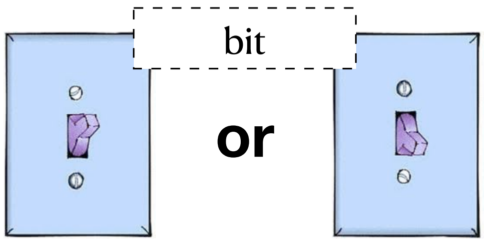
Concept of Quantum Bit (Qubit)

Recall: A memory element in a conventional computer: “Either-Or”

Ordinary bit:



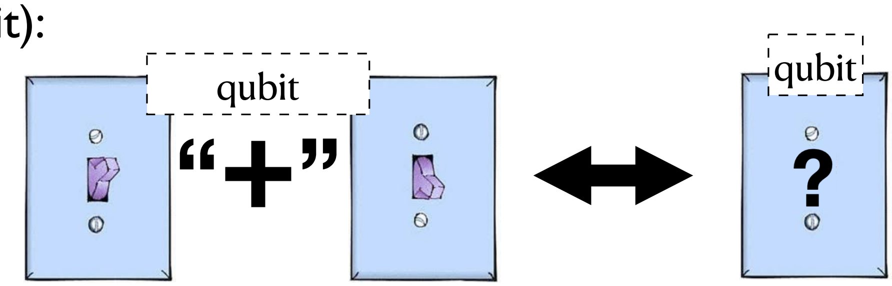
1 or 0

classical bit states

A memory element in a quantum computer: “Quantum Superposition”

Quantum bit (qubit):

“+” means
“in superposition with”



(1) + (0)

qubit states

“two possibilities upon measurement”

Dirac Notation: $|1\rangle + |0\rangle$

Measuring the qubit gives either 1 or 0 (true randomness)

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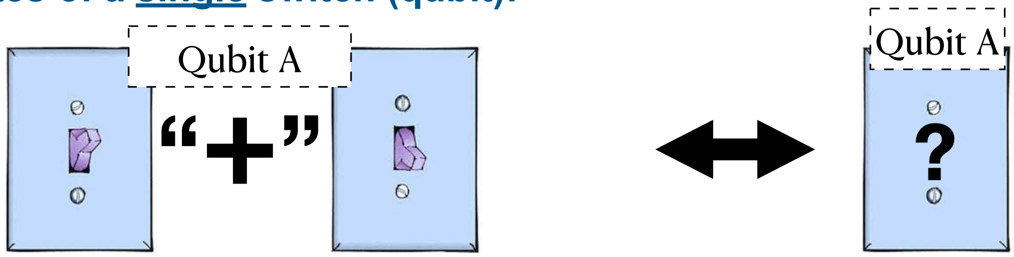
Quantum Information Science is enabled by State Superposition and Entanglement

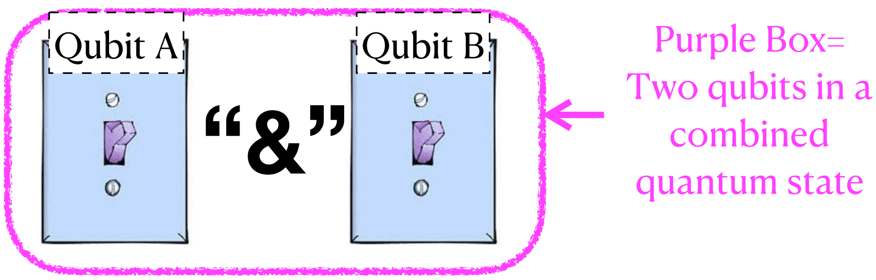
Superposition of States of a single switch (qubit):

"+" means
"in superposition with"

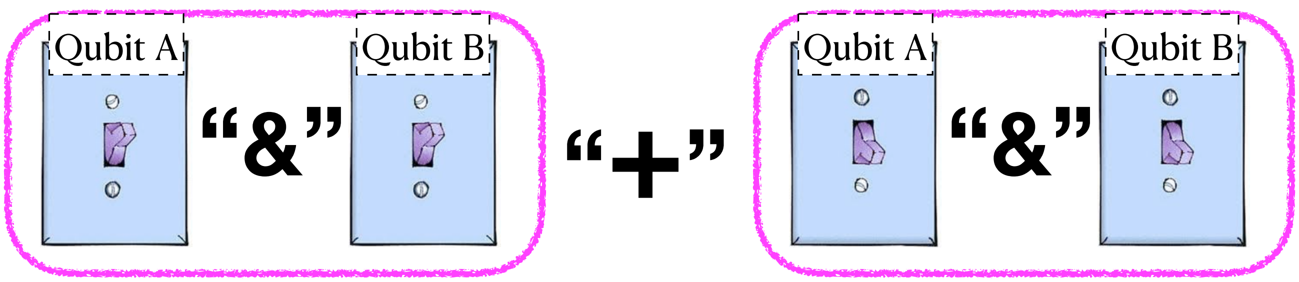


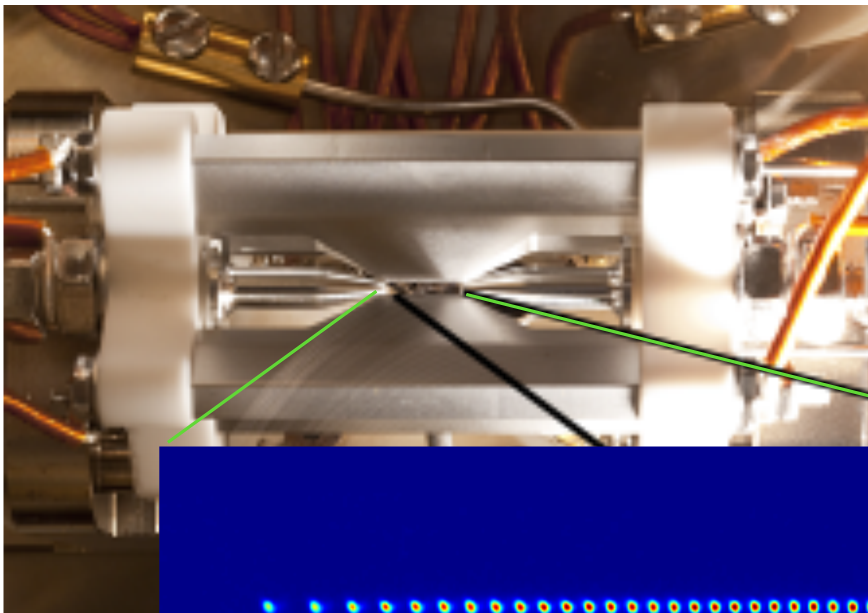
Combined State of two qubits:

& means "and"



Entangled Combined State of two qubits (example):

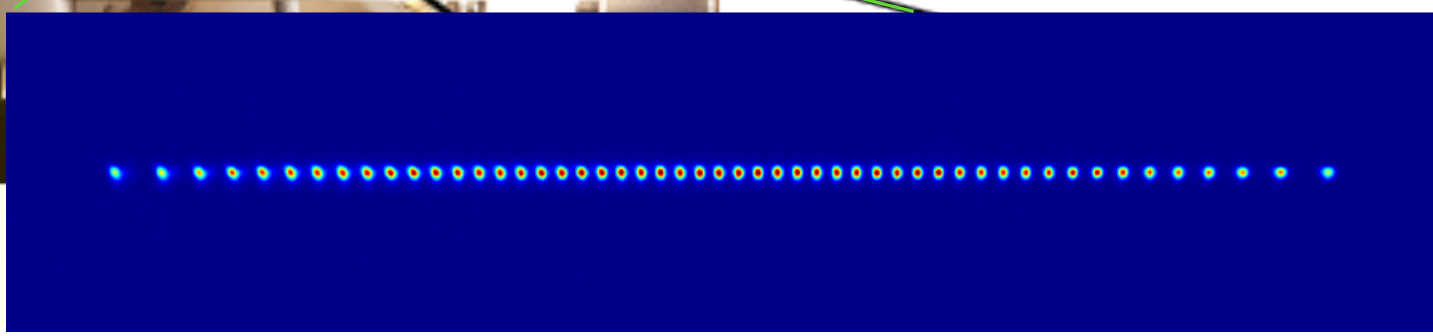




How to represent entangled states in elementary objects?

A line of 51 individual atoms (ions) trapped in vacuum

Atoms are not classical, they are quantum!
Their state is not well described using classical physics theory.



each ion has
electron spinning
cw or ccw

How to represent entangled states in elementary objects?

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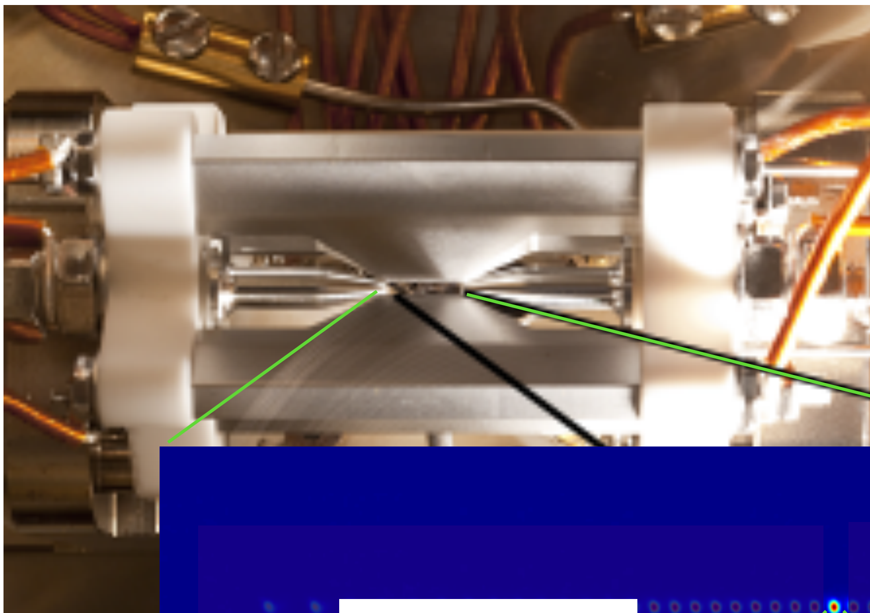

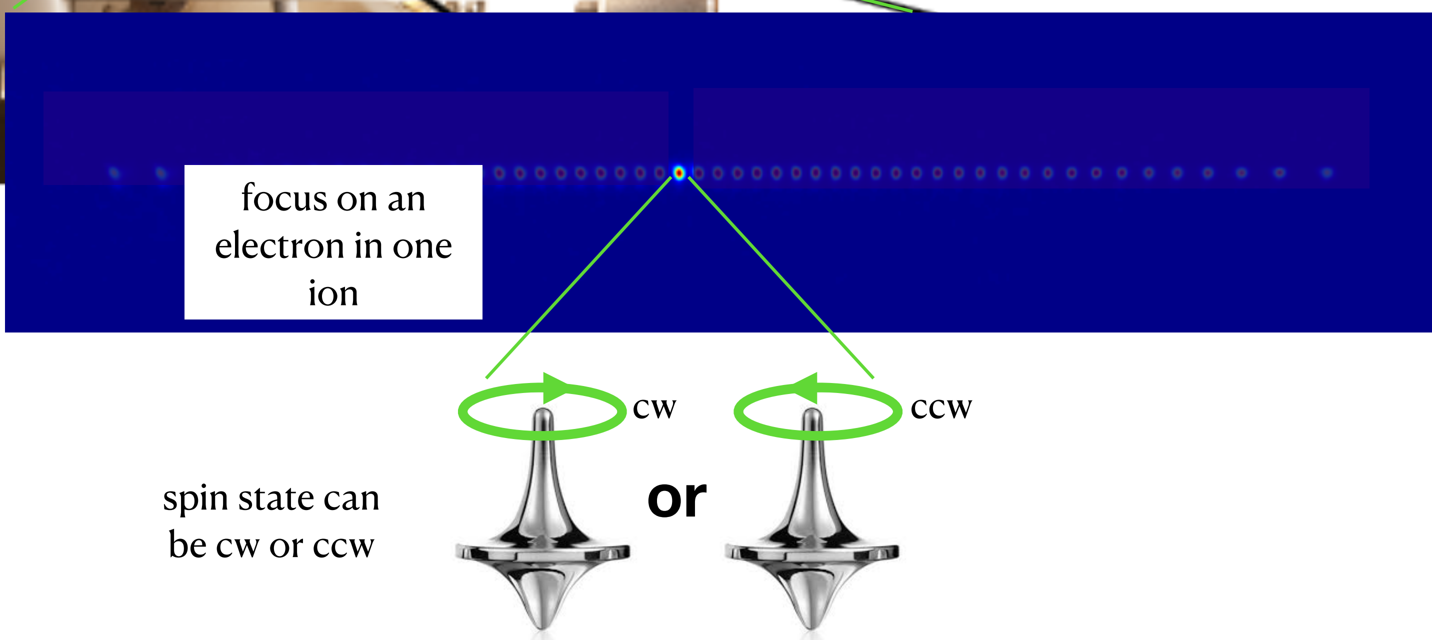

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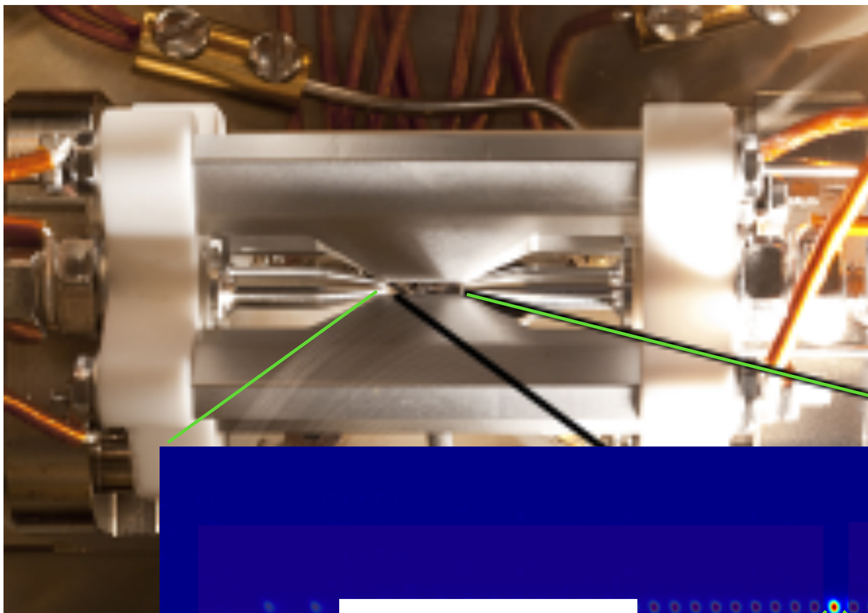
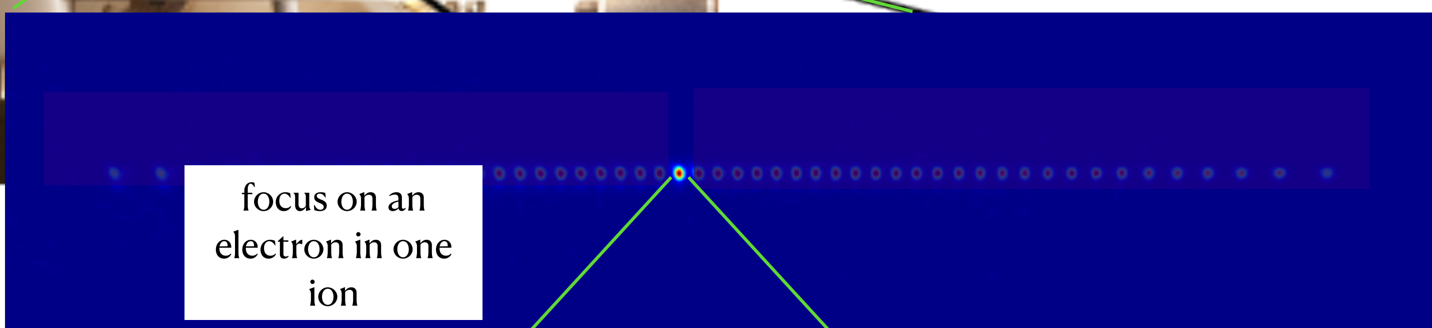
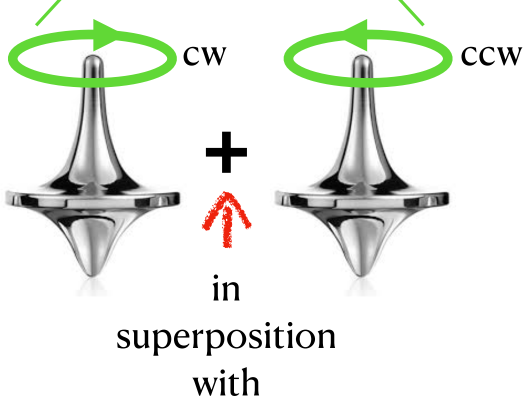




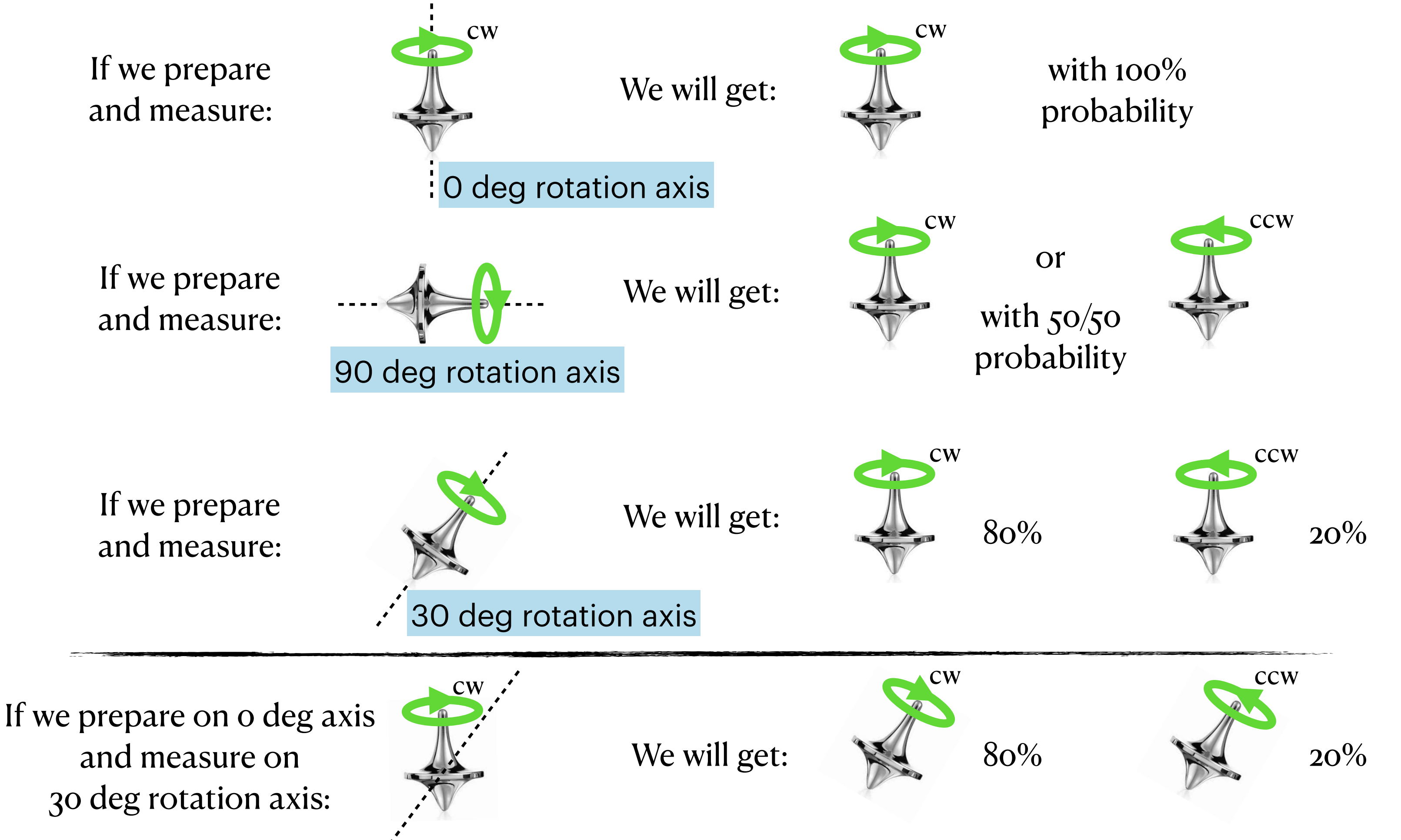
superposition states are possible



same possibilities for every ion

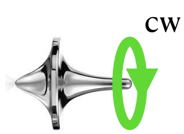
foreverspin.com

What does superposition mean?
It does not mean ‘both at the same time’. It does not mean ‘or’.



Superposition means that a range of “Measurement Outcomes” are possible, depending on how you measure it. (No classical system behaves like this.)

What does superposition mean?
It does not mean 'both at the same time'. It does not mean 'or'.

Evidentally, 

means 

in superposition with 

50% 50%

Evidentally, 

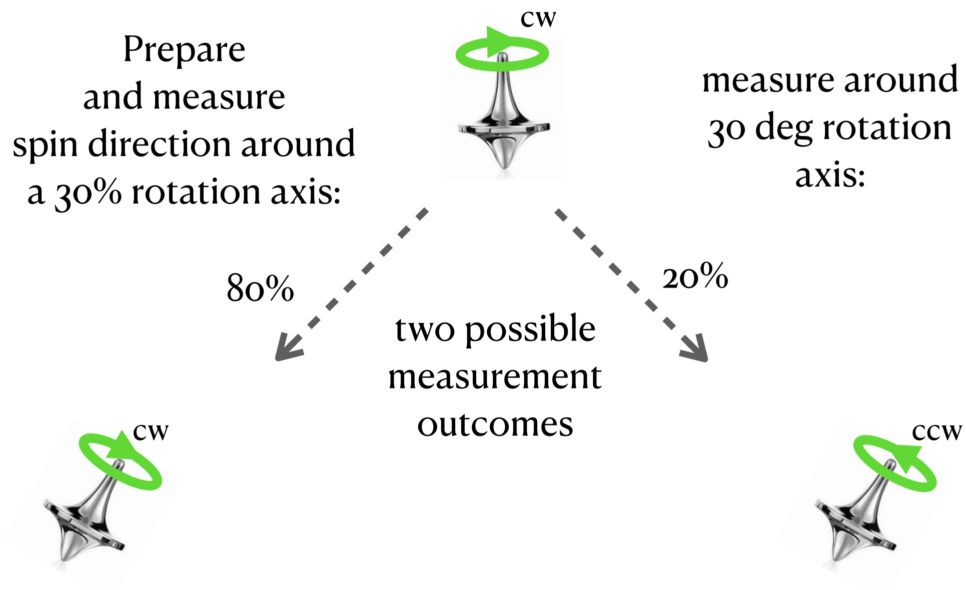
means 

in superposition with 

80% 20%

The observed results are called "Measurement Outcomes"

What if we repeat the same measurement on the same spin?



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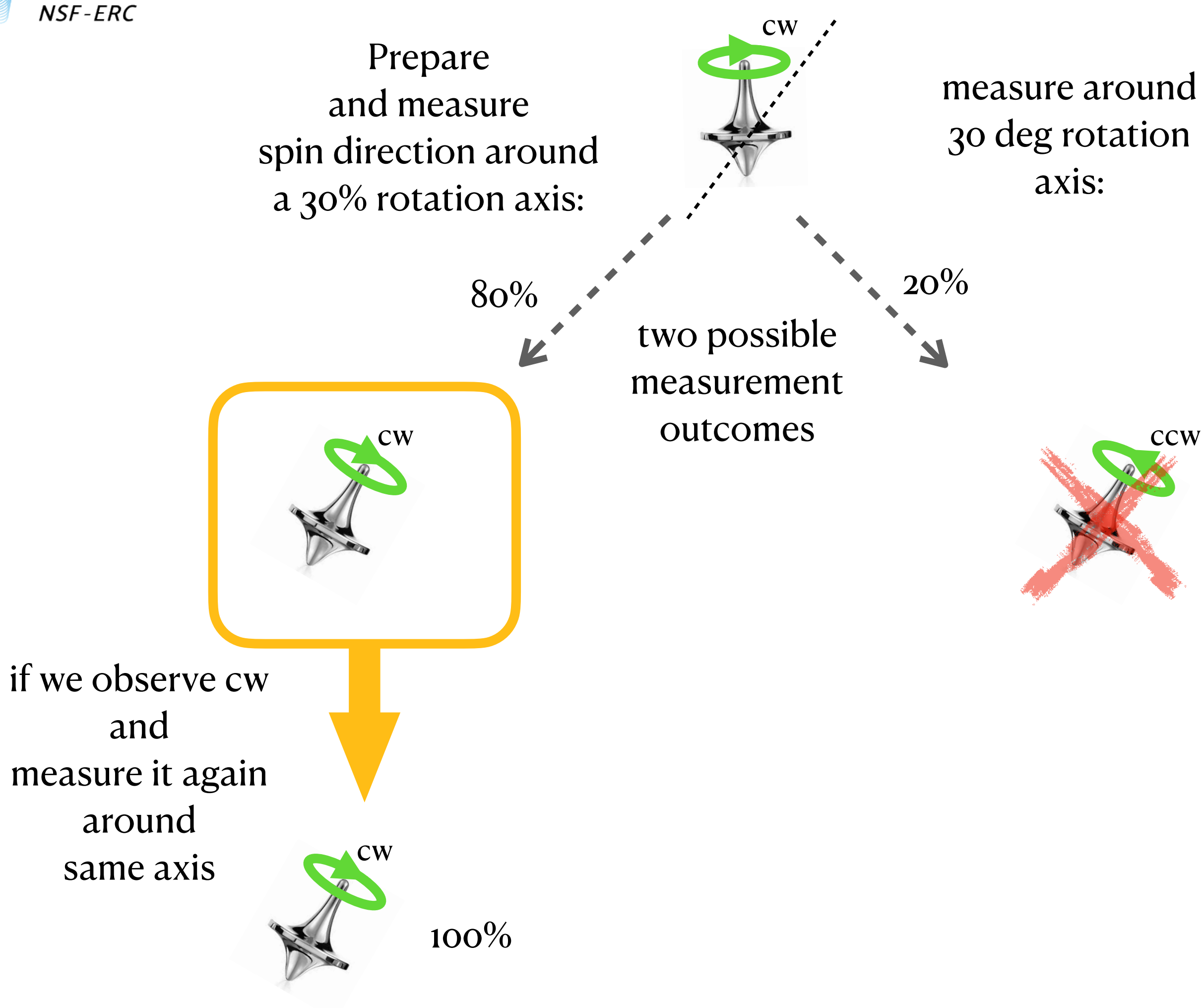
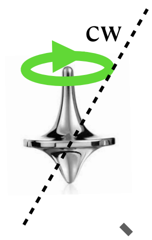
What if we repeat the same measurement on the same spin?



Conclude: The state has been changed by the first measurement!

POLL QUESTION 4

Prepare
spin as clockwise

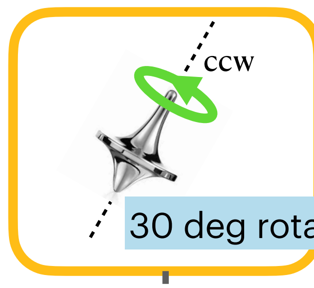


measure around 30
deg rotation axis

80%

20%

if we observe ccw
and then
measure it again
around the
same 30 deg axis



?

What will we observe?

A: ccw 100%
B: ccw 20%, cw 80%
C: ccw 50%, cw 50%
D: Don't know

Repeated like
measurements give the
same outcome

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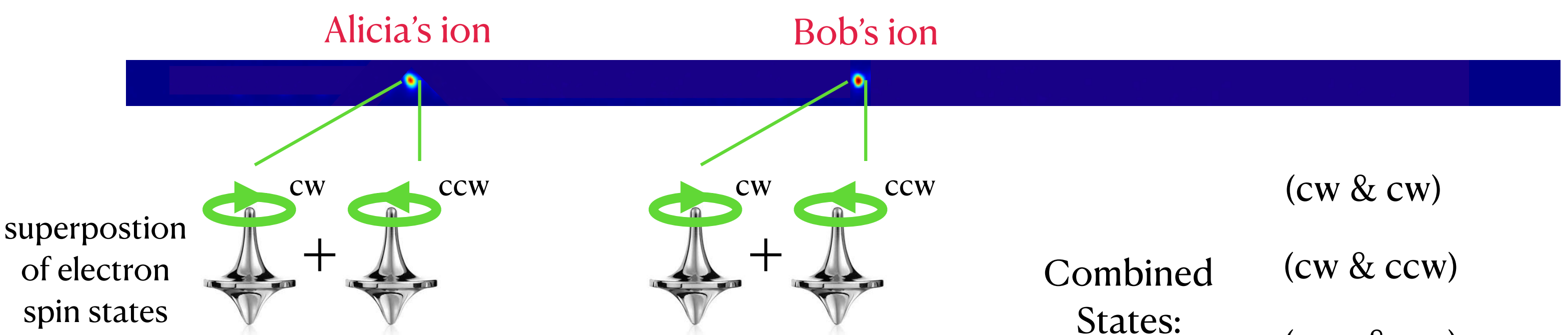
Consider an **ENTANGLED** state of two ions.



"+" means in superposition with

Combined States:

(cw & cw)

(cw & ccw)

(ccw & cw)

(ccw & ccw)

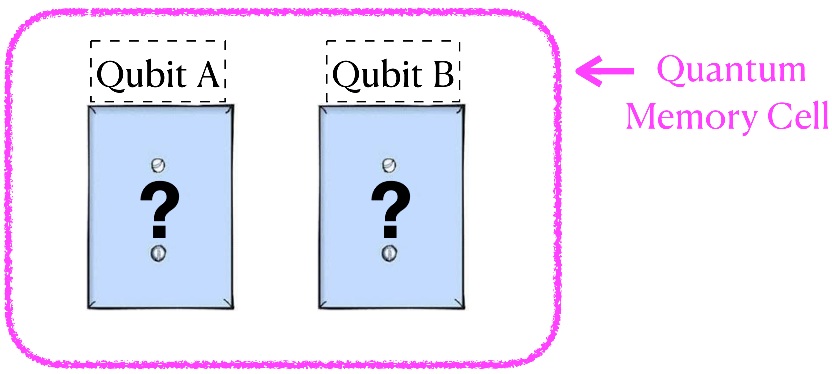
Example of a combined superposition state: $(\text{cw}_A \,\&\, \text{cw}_B) + (\text{ccw}_A \,\&\, \text{ccw}_B)$

A more general entangled state: $(\text{cw}_A \,\&\, \text{cw}_B) + (\text{cw}_A \,\&\, \text{ccw}_B) + (\text{ccw}_A \,\&\, \text{cw}_B) + (\text{ccw}_A \,\&\, \text{ccw}_B)$

If we measure the spinning direction (cw or cw) of each ion,
we can obtain any one of the four possible combinations.

Two Quantum bits: Entanglement

Let's make a measurement!

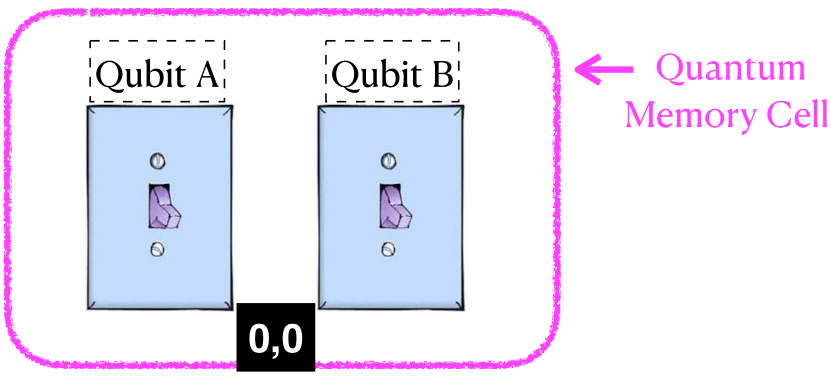


State = x (0_A & 0_B) + y(0_A & 1_B) + z(1_A & 0_B) + w(1_A & 1_B)

x, y, z, w are numbers (between 0 and 1) that correspond to probabilities

Two Quantum bits: Entanglement

Let's make a measurement!



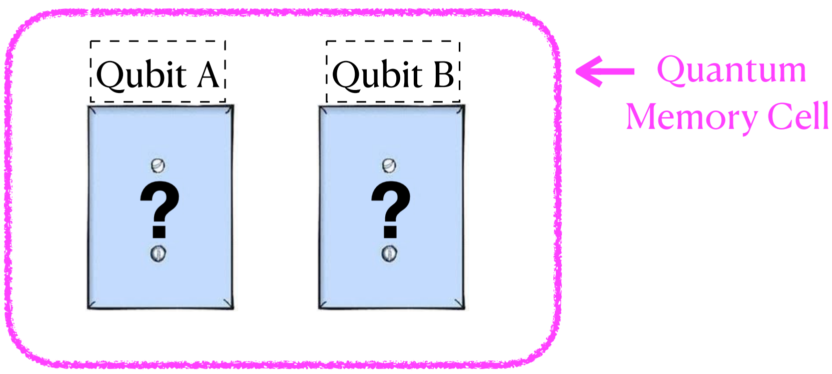
$$\text{State} = x\,(0_A \,\&\, 0_B) + y(0_A \,\&\, 1_B) + z(1_A \,\&\, 0_B) + w(1_A \,\&\, 1_B)$$

x, y, z, w are numbers (between 0 and 1) that correspond to probabilities

Two Quantum bits: Entanglement

Let's re-prepare the state and make a measurement

RESET!



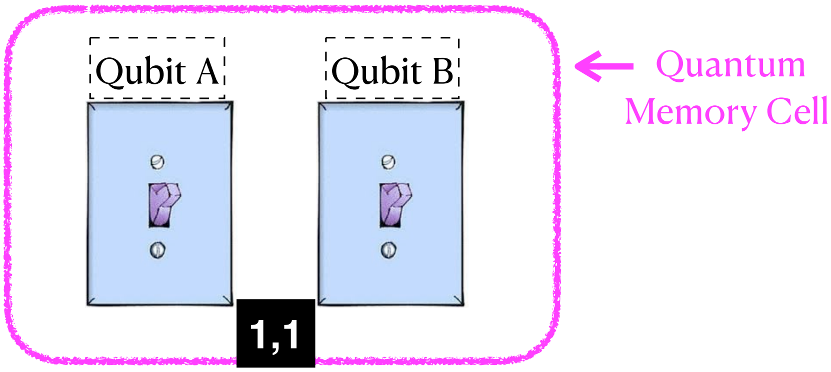
$$\text{State} = x\,(0_A \,\&\, 0_B) + y(0_A \,\&\, 1_B) + z(1_A \,\&\, 0_B) + w(1_A \,\&\, 1_B)$$

x, y, z, w are numbers (between 0 and 1) that correspond to probabilities

Two Quantum bits: Entanglement

Let's re-prepare the state and make a measurement

RESET!



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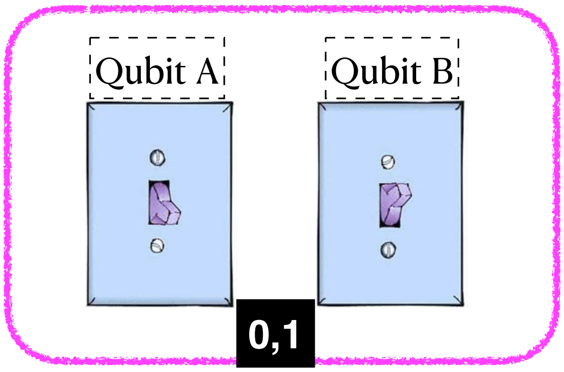
Two Quantum bits: Entanglement

Let's re-prepare the state and make a measurement

RESET!



← Quantum Memory Cell

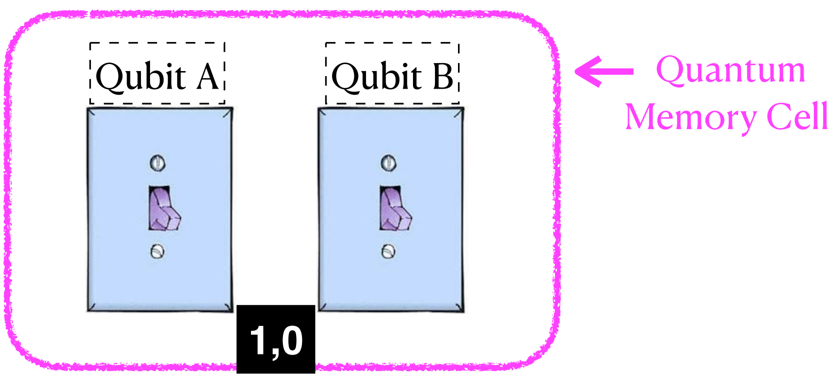
$$\text{State} = x\,(0_A \,\&\, 0_B) + y(0_A \,\&\, 1_B) + z(1_A \,\&\, 0_B) + w(1_A \,\&\, 1_B)$$

x, y, z, w are numbers (between 0 and 1) that correspond to probabilities

Two Quantum bits: Entanglement

Let's re-prepare the state and make a measurement

RESET!



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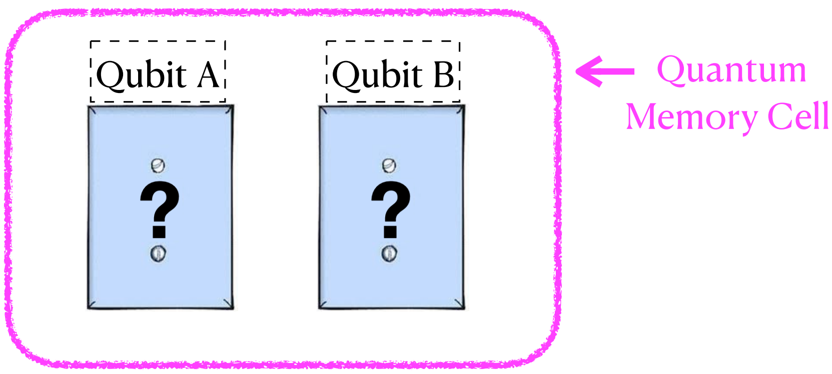
x, y, z, w are numbers (between 0 and 1) that correspond to probabilities

Two Quantum bits: Entanglement

in the general case, what are the probabilities for outcomes?



$$\text{State} = x\,(0_A \,\&\, 0_B) + y(0_A \,\&\, 1_B) + z(1_A \,\&\, 0_B) + w(1_A \,\&\, 1_B)$$

x, y, z, w are numbers (between 0 and 1) that correspond to probabilities

Born's Rule

The probability to observe $(0_A \,\&\, 0_B)$ equals x^2

The probability to observe $(0_A \,\&\, 1_B)$ equals y^2

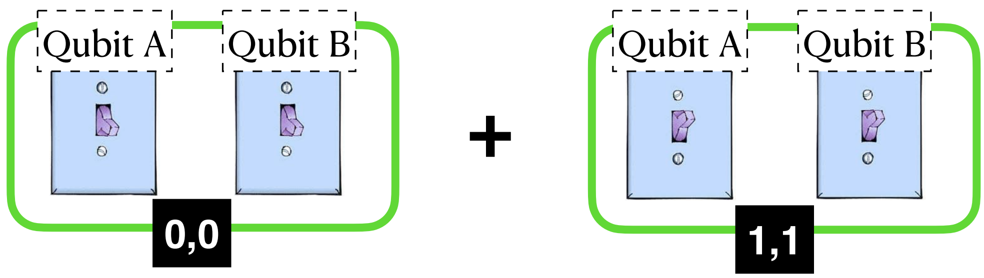
The probability to observe $(1_A \,\&\, 0_B)$ equals z^2

The probability to observe $(1_A \,\&\, 1_B)$ equals w^2

Max Born

Example: Entangled state of two qubits

NON-POLL QUESTION



State = $(0_A \& 0_B) + (1_A \& 1_B)$

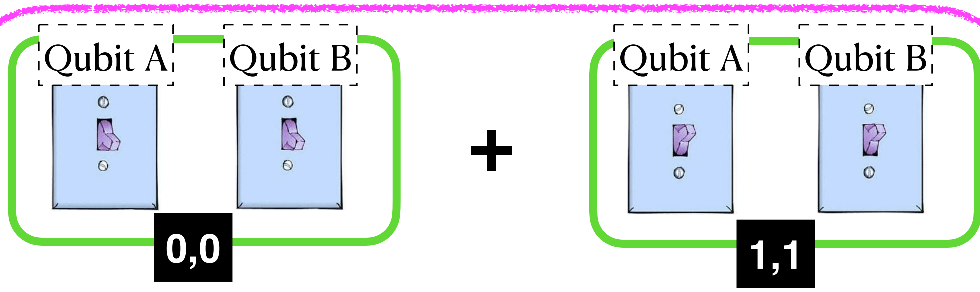
← Quantum Memory Cell

Say you measure the qubit A and obtain 1.
What will a measurement of qubit B then yield?

A: 0
B: 1
C: 0 or 1 with equal probabilities
D: I don’t know

POLL QUESTION 5

Say you measure the qubit A and obtain 1.
Then you know that if qubit B is measured it must yield 1.
What statement is true?



State = (0 & 0) + (1 & 1)

A: The observed outcome of A caused B to be in the 1 state.
B: The observed outcome of A allows you to infer that B is in the 1 state
C: The observed outcome for B is independent of that for A
D: I don't know

Correlation does not not imply Causation!

If measurement of A were a causal operation, we could send information instantaneously (impossible).

END PART 1

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5 minute break

The Physics Behind the Quantum Internet

PART 2

Encoding and Transmitting Quantum Information

SHORT COURSE (4 HR) OUTLINE

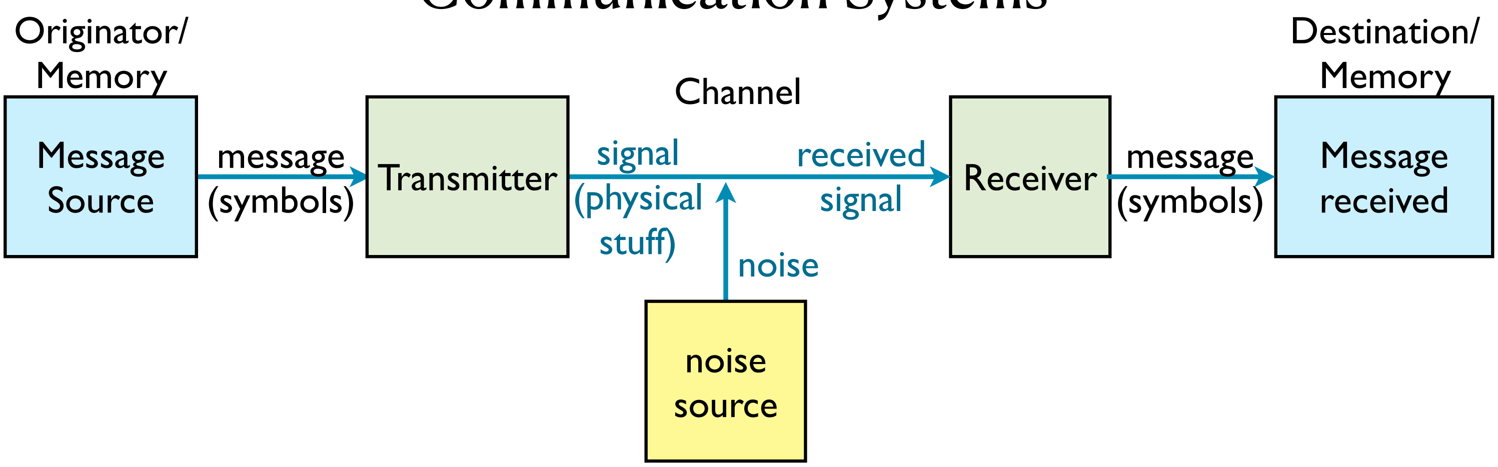
PART 1: Quantum information science
The Center for Quantum Networks
The National Quantum Initative
What is *information*?
Bits and qubits
Superposition and entanglement

PART 2: Encoding and transmitting quantum information
Communication systems
Distributing Entangled states (e.g.. in Space)
Ways of encoding qubits
Ways of encoding qubits in photons (Flying qubits)
Quantum state teleportation
Space-based quantum networks

PART 3: Bell State measurements
Photon polarization revisited
Quantum measurement - Born's Rule
Correlations and the Bell inequality
Bell-Test experiments

PART 4: The Quantum Internet
Application #1: Quantum Cryptography
Bell-State Creating and Measuring
Quantum memories
Application #2: Memory-Assisted Teleportation
Entanglement Swapping with Quantum Memories
Quantum repeater networks
What could a quantum Network do?
Perspectives and misconceptions

Communication Systems

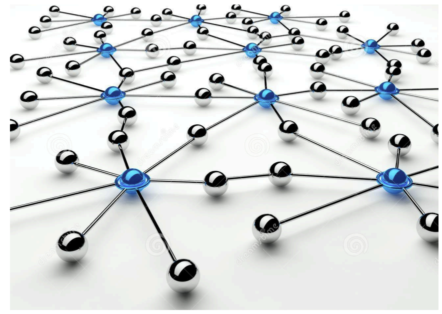


Information Theory answers these types of questions:

Q1. How much information can be carried by a certain number of symbols?

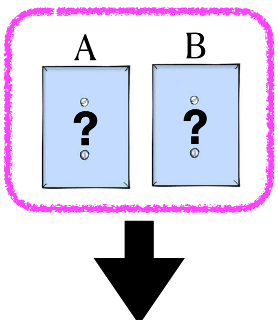
Q2. What new capabilities are made possible using quantum-state encoding?

What is a <u>Quantum</u> Communication Network?
a network of channels and nodes that transmits or shares quantum information



What is quantum information?
information encoded in quantum states of physical objects

How can we transform entanglement between nearby qubits to entanglement between far-separated qubits?

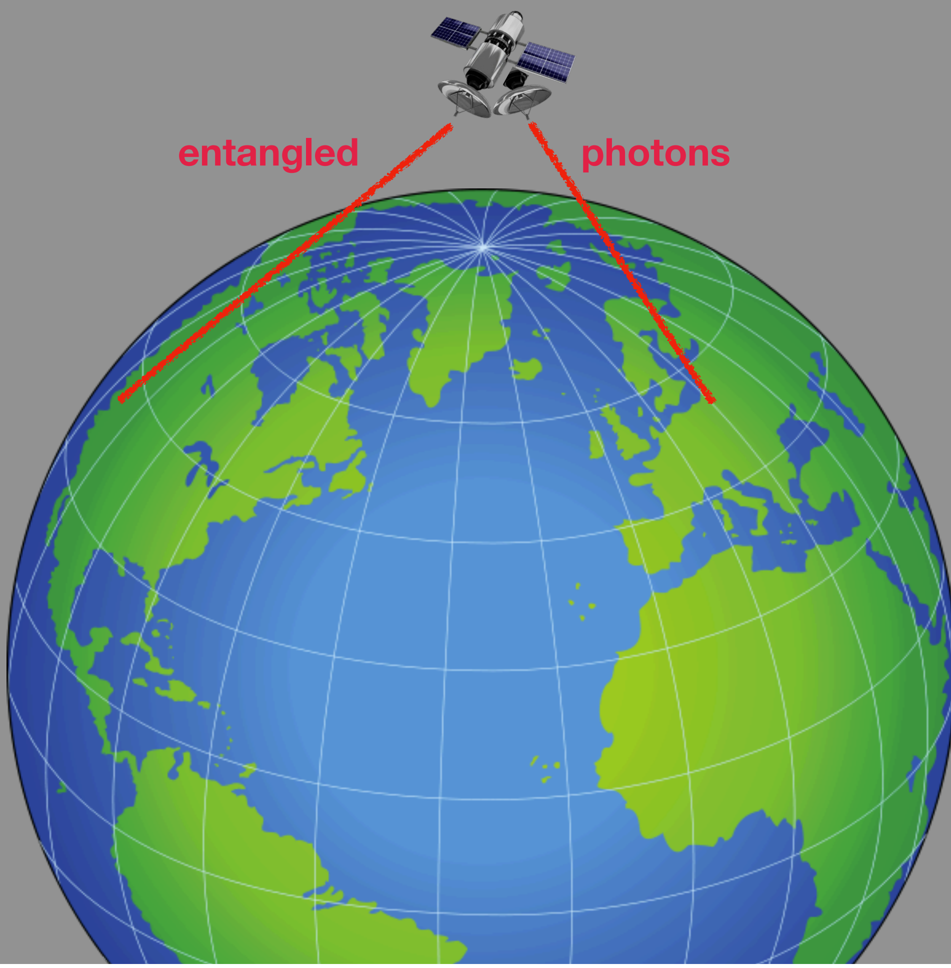


State = $(0_A \;\&\; 0_B) + (1_A \;\&\; 1_B)$

Entangled qubits separated by arbitrarily long distance!

Distributing Entangled States

Space-Based Quantum Communication



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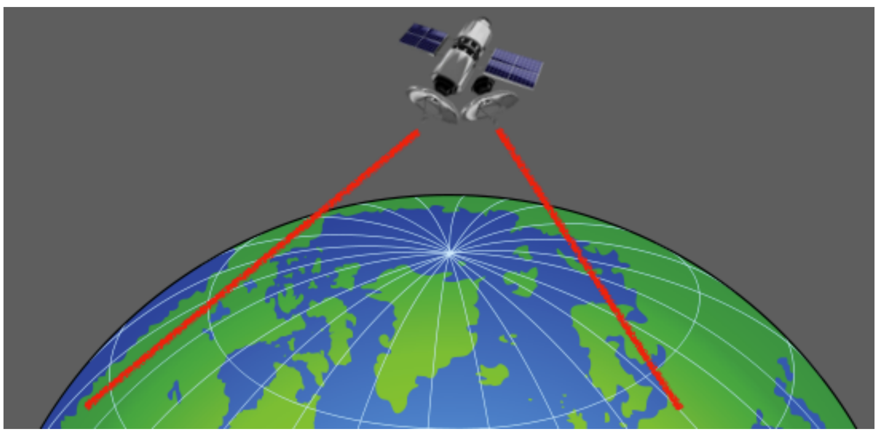
POLL QUESTION 7

State = $(0_A \ \& \ 0_B) + (1_A \ \& \ 1_B)$



Alicia

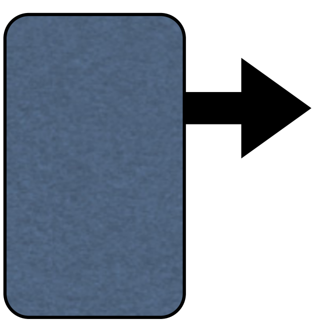
Bob

qubit A

qubit B

At 12:00 noon Alicia observes qubit A to have value 0.

At what time does **Alicia** know the state of qubit B, **without** observing it?



A: Immediately
B: Never
C: At 12:00 plus the time it takes light to travel from A to B
D: I don't know

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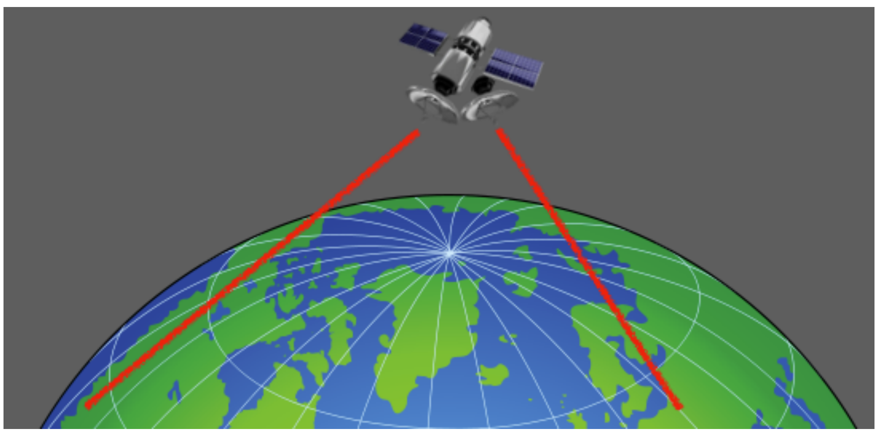
Followup QUESTION (no poll)

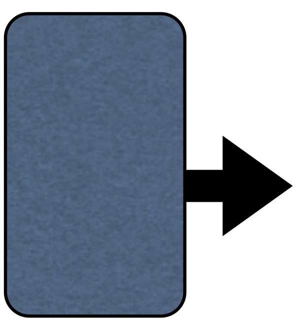
State = $(0_A \ \& \ 0_B) + (1_A \ \& \ 1_B)$



Alicia qubit A　　　　　　　　　　Bob qubit B

At 12:00 noon Alicia observes qubit A to have value 0.

At what time does **Bob** know the state of qubit B, **without** observing it?



A: Immediately
B: At 12:00 plus the time it takes light to travel from A to B
C: Never, unless Alice tells him what she observed
D: I don't know

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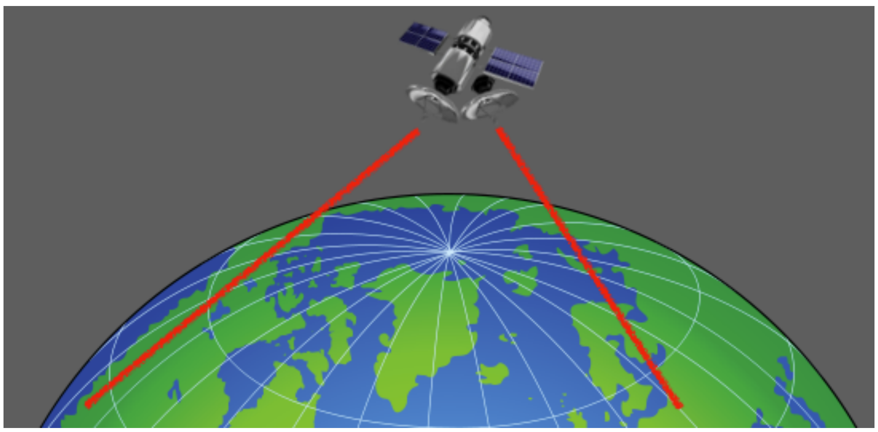
State = (0_A & 0_B) + (1_A & 1_B)



Alicia qubit A   Bob qubit B

At 12:00 noon Alicia observes qubit A to have value 0.

Alicia knows the state of qubit B immediately, but Bob does not.

Alicia can phone Bob and tell him, but there is a time lag limited by the speed of any information signal (speed of light)

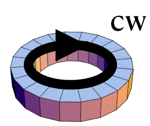
Whatever Alicia observes or does to qubit A in **no way** affects qubit B.

No faster-than-light communication

Qubits can be encoded in various ways

Electron spin states

The states of superconductor current



Stationary qubits

Most useful for storing quantum information

Photon polarization states

Photon times of arrival (time-bin states)

Photon frequency

Photon beam path

Flying qubits

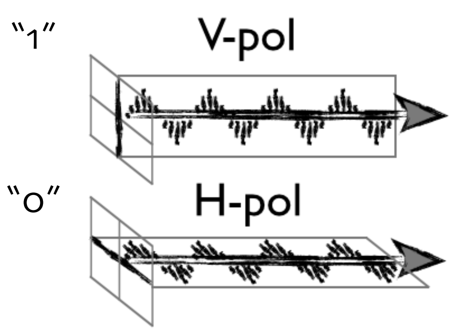
Most useful for transmitting quantum information

Ways to encode information into single photons

1. polarization
2. location in space or time

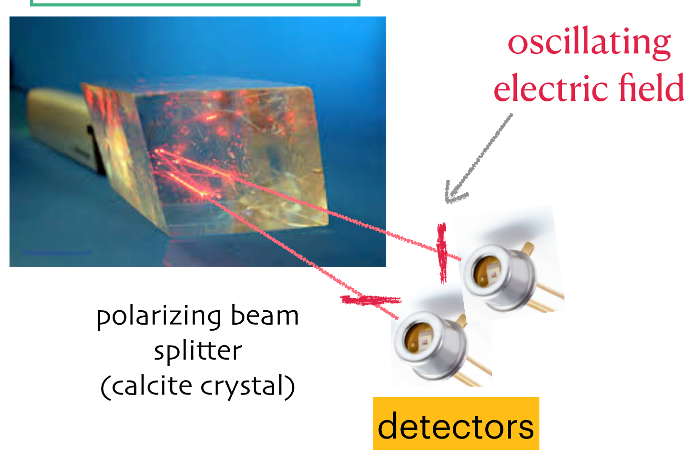
Encoding in Polarization

Polarization can be oriented in various directions perpendicular to the direction of light's travel:



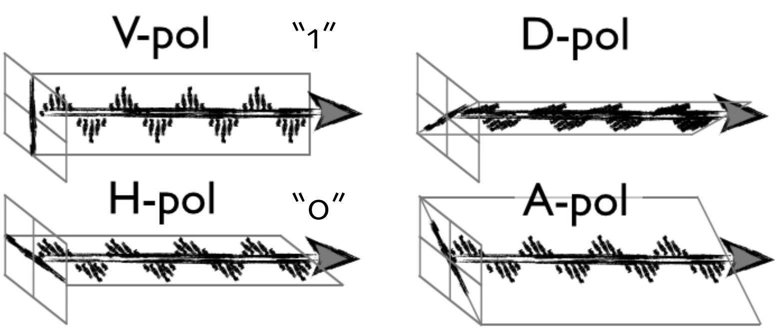
"0" and "1" are Logical Values
Single photon encodes a "qubit"

Qubit Measurement

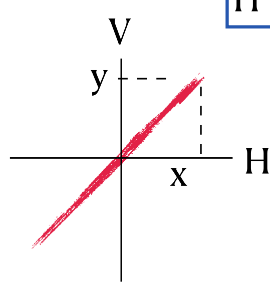


Superposition

V + H = D (diagonal)   V - H = A (anti-diagonal)

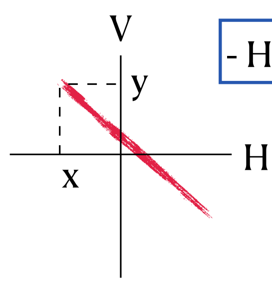


H + V   "0" + "1"

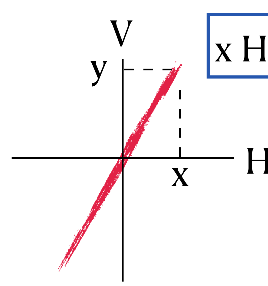


+ means "in superposition with"

- H + V   "-0" + "1"



x H + y A



Polarization can be oriented in **any** direction perpendicular to the direction of travel

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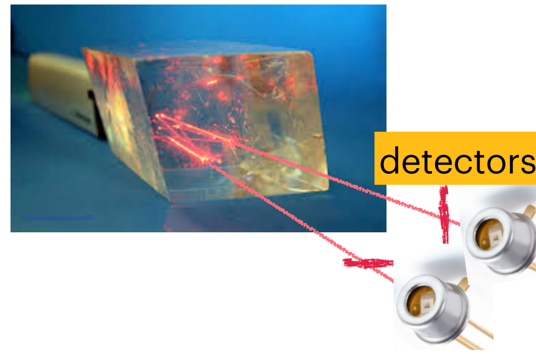
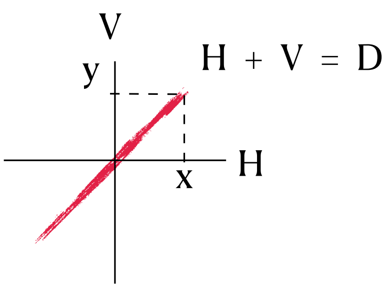
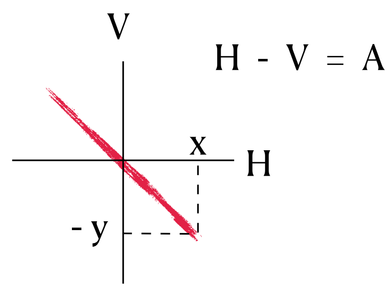
Fragility: A simple phase change can change the state drastically



H + V   "0" + "1"



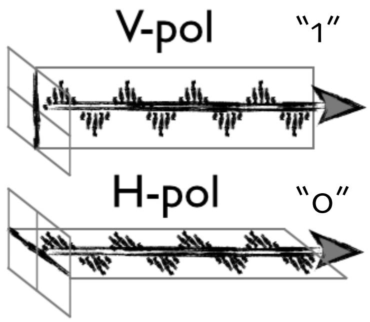
y ➡ - y



Phase changes (called "**Decoherence**") will lead to errors.

Entangled Polarization state of two photons

One photon:



Two photons A, B: Example State = (0_A & 0_B) + (1_A & 1_B)

= (H_A & H_B) + (V_A & V_b)

Sometimes we denote polarization states using arrows:

(H) = (➔)

(V) = (🡅)

(D) = (🡕)

(A) = (🡔)

Example Two-Photon State

= ($➔_A$ & $➔_B$) + ($🡅_A$ & $🡅_B$)

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Entangled Polarization State of two photons

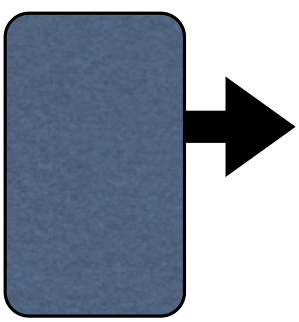
POLL QUESTION 8

Two photons are in the entangled state:

$$\text{State} = (H_A \,\&\, V_B) + (V_A \,\&\, H_B)$$

The A photon goes to Alice and the B photon to Bob

Bob measures his photon and obtains H.
What will Alice observe if she measures her photon using a polarizer that separates H and V?



A: H
B: V
C: H or V with equal probabilities
D: I don’t know

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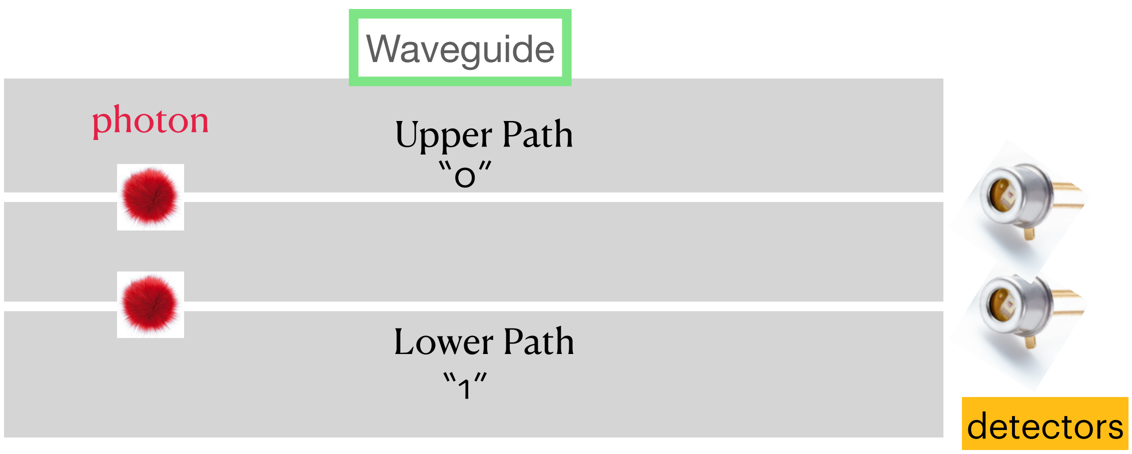
How to encode information into single photons?

1. polarization
2. location in space or time

Encoding in Location



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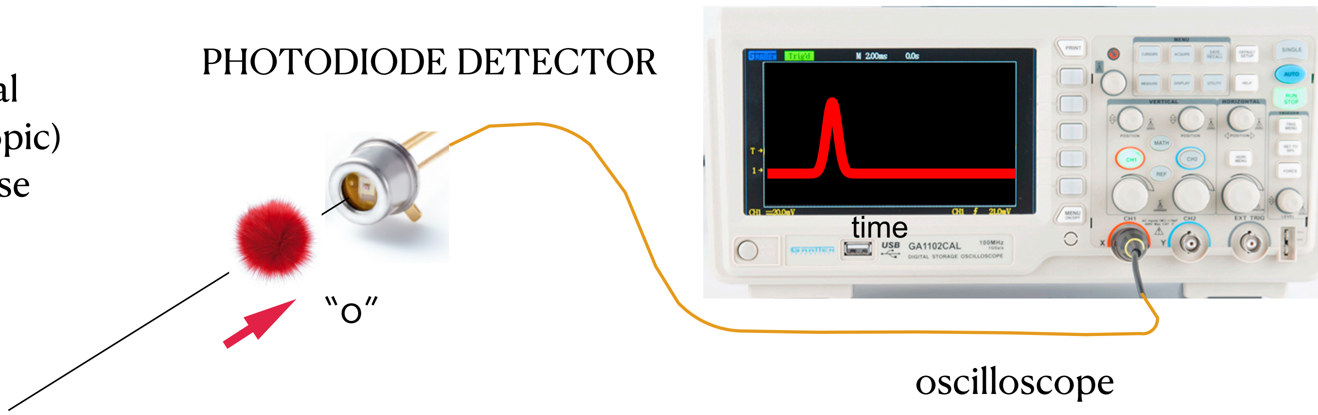
Encoding in Time of Arrival

Classical
(macroscopic)
light pulse

PHOTODIODE DETECTOR

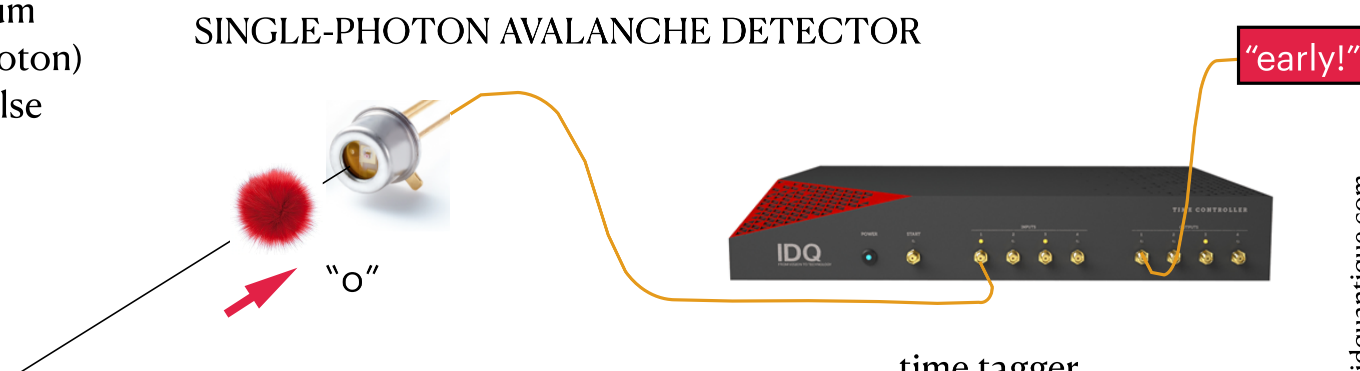


oscilloscope

sparkfun.com

Quantum
(single-photon)
light pulse

SINGLE-PHOTON AVALANCHE DETECTOR



time tagger

idquantique.com

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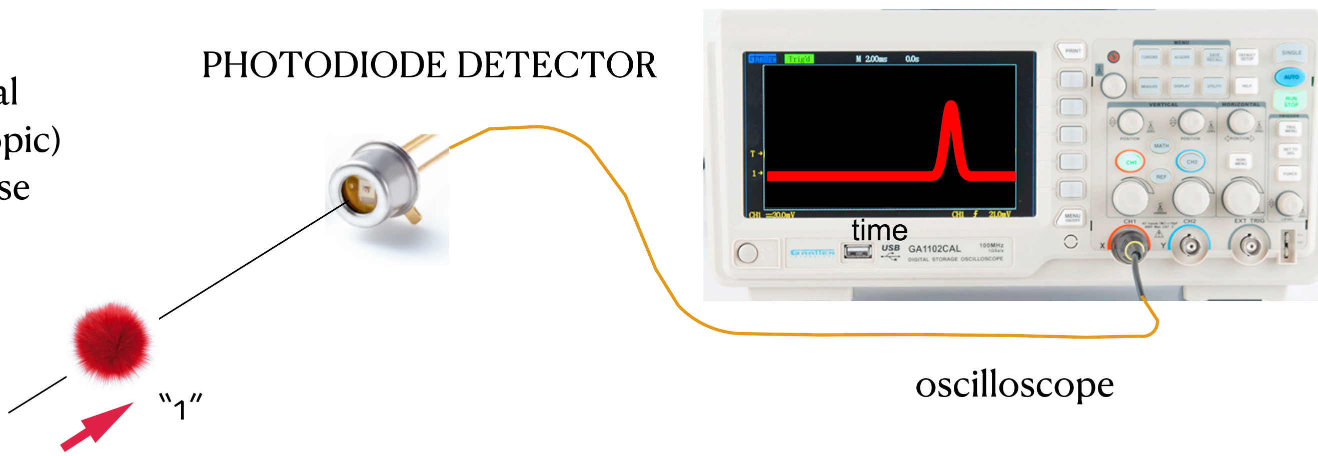
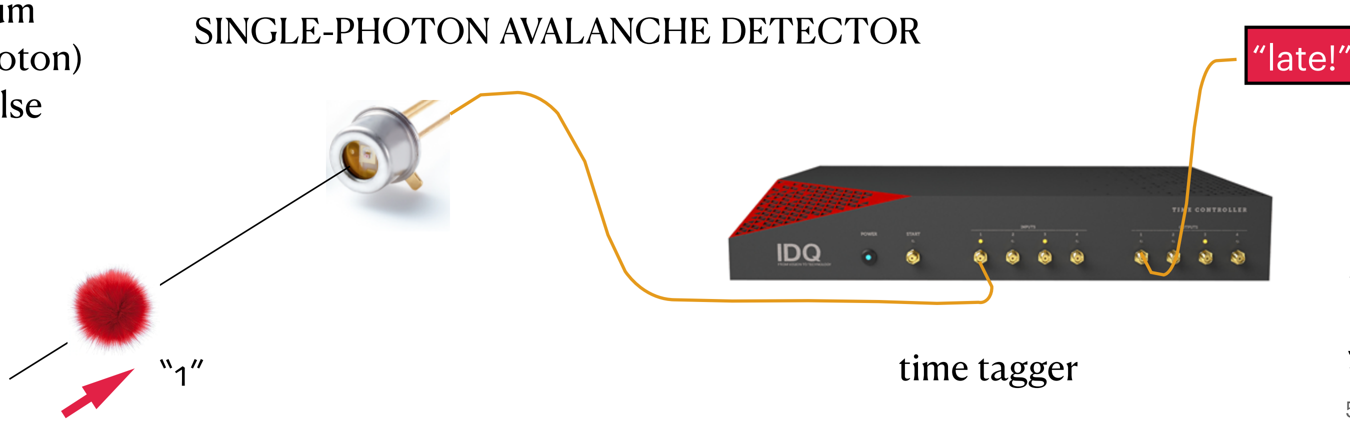
Encoding in Time of Arrival

Classical
(macroscopic)
light pulse



sparkfun.com

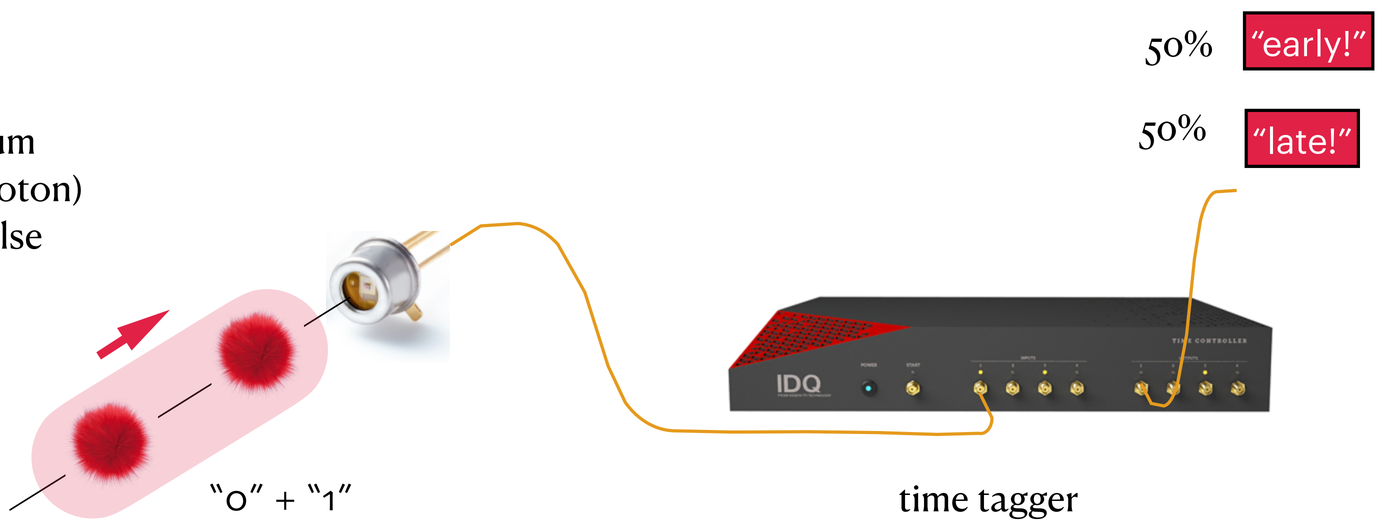
Quantum
(single-photon)
light pulse



idquantique.com

Encoding in Time of Arrival

Superposition



could be: "0" - "1" Same probabilities , but the minus state is distinct from the plus state.

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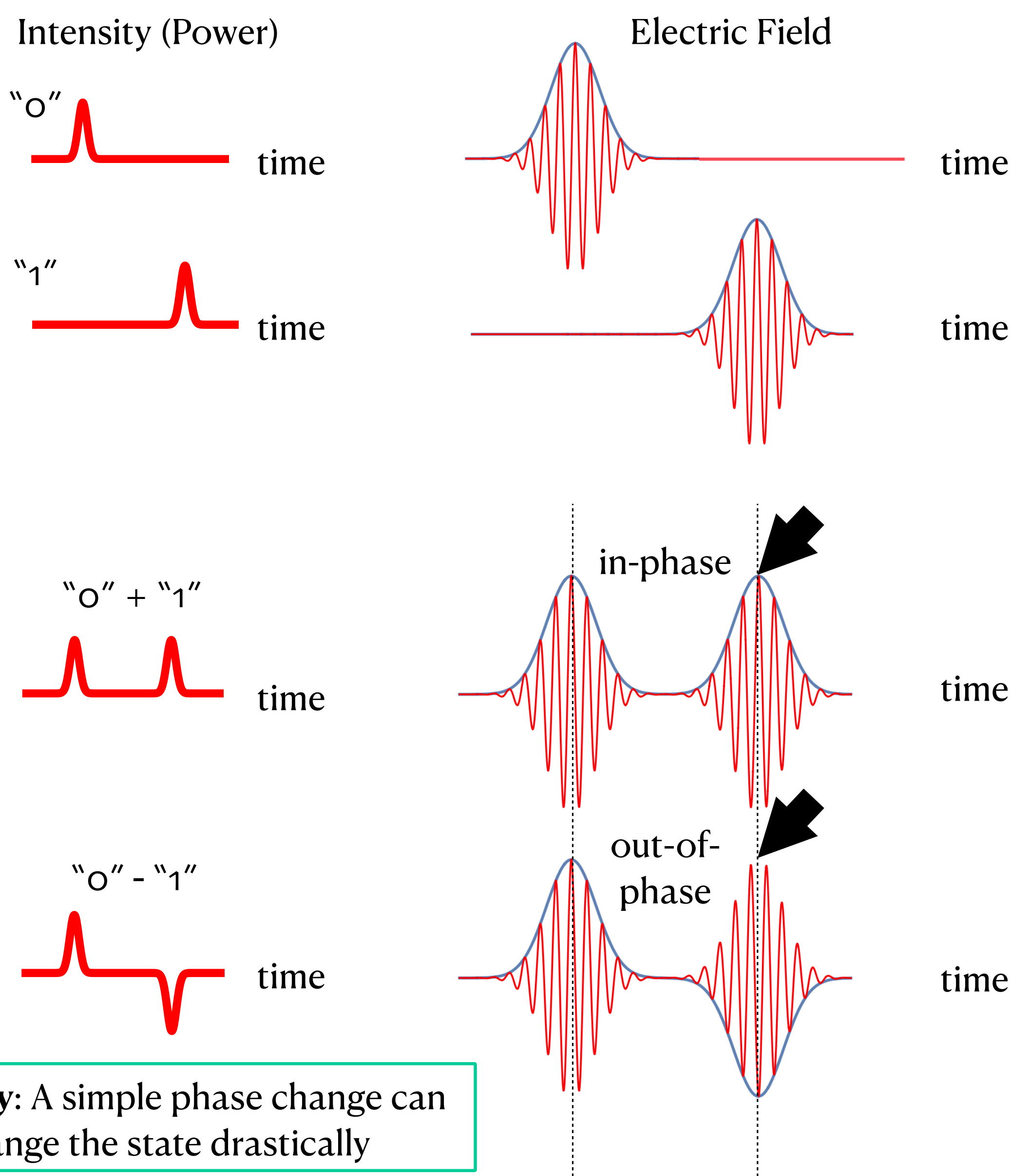
Encoding in Time of Arrival



Superposition

Fragility: A simple phase change can change the state drastically

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Encoding in Time of Arrival

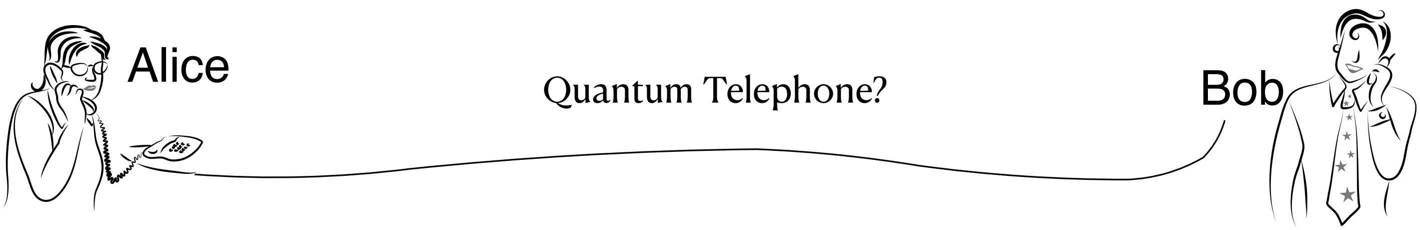
Recall
One photon:

Entangled State of Two photons:

Example State = (0 & 0) + (1 & 1)

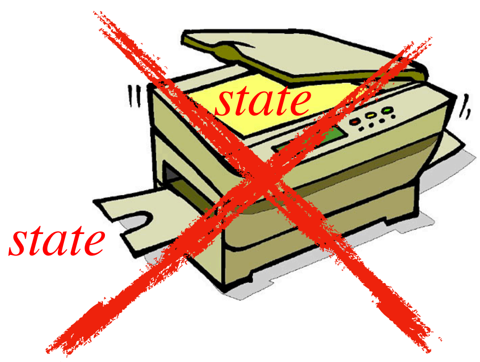
State = (Early & Early) + (Late & Late)

How to transmit a quantum state from one place to a place far away?



No Copying of Qubit States Allowed:

You can't make a copy of a state without destroying the state of the original object.



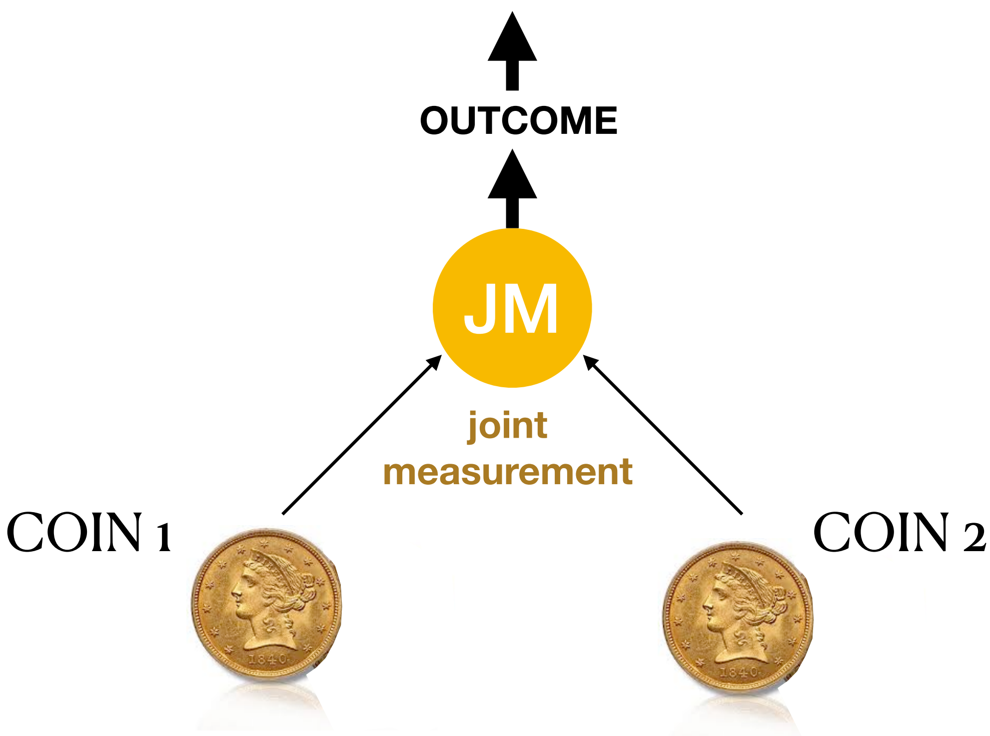
A quantum communication network must transmit the state of the physical systems, although it may do so by state teleportation.

https://clipartstation.com/wp-content/uploads/2017/11/xerox-machine-clipart-8.jpg

A Useful Tool: Joint Measurement

Joint Measurement gives information about the pair, but not full information about each member

They are the same
(H, H) or (T,T)
can't say which



Joint Qubit Measurement

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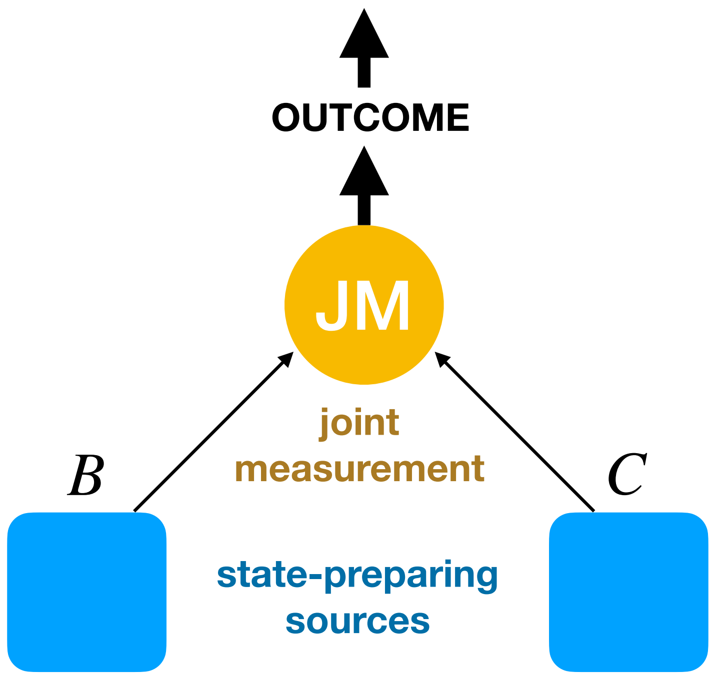
Joint Measurement gives information about the pair, but not full information about each member

example outcome #1

They are the same
(0, 0) or (1,1)
can't say which



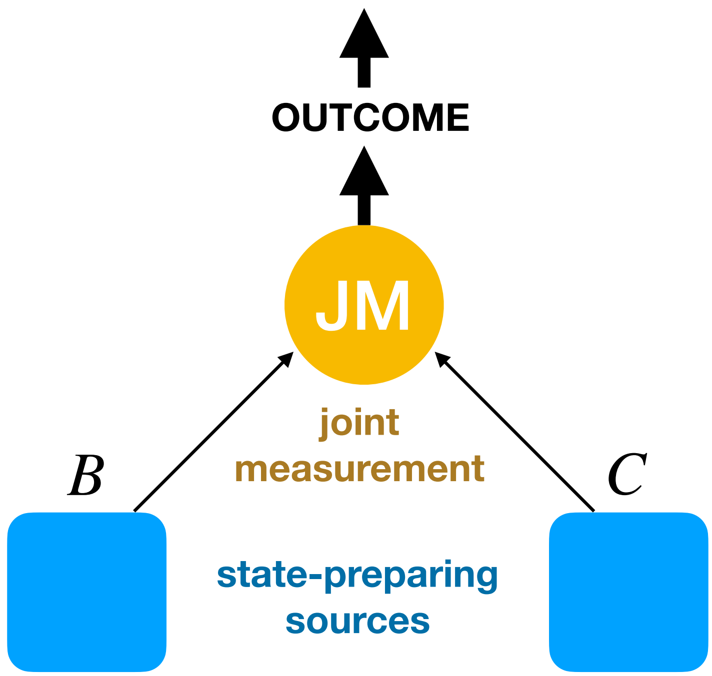
$\text{State}_B = (0_B) + (1_B)$ $\text{State}_C = (0_C) + (1_C)$

Joint Qubit Measurement

Joint Measurement
gives information
about the pair,
but not full information
about each member

example outcome #2

They are different
(0, 1) or (1,0)
can't say which



$State_B = (0_B) + (1_B)$ $State_C = (0_C) + (1_C)$

Entanglement Swapping

start with two separate entangled states

entangled state of A and B

A,B

C,D

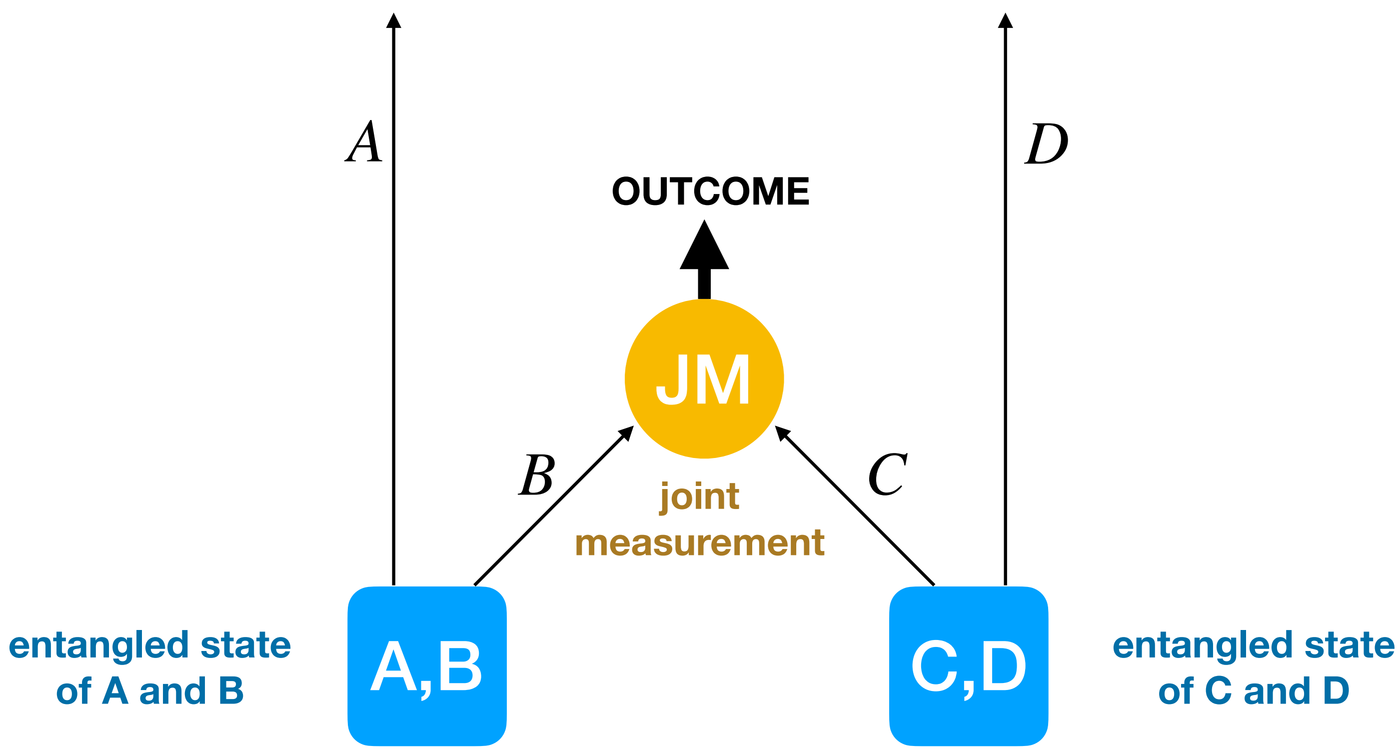
entangled state of C and D

$(0_A \ \& \ 1_B) + (1_A \ \& \ 0_B)$ & $(0_C \ \& \ 1_D) + (1_C \ \& \ 0_D)$

↑ "and"

Entanglement Swapping

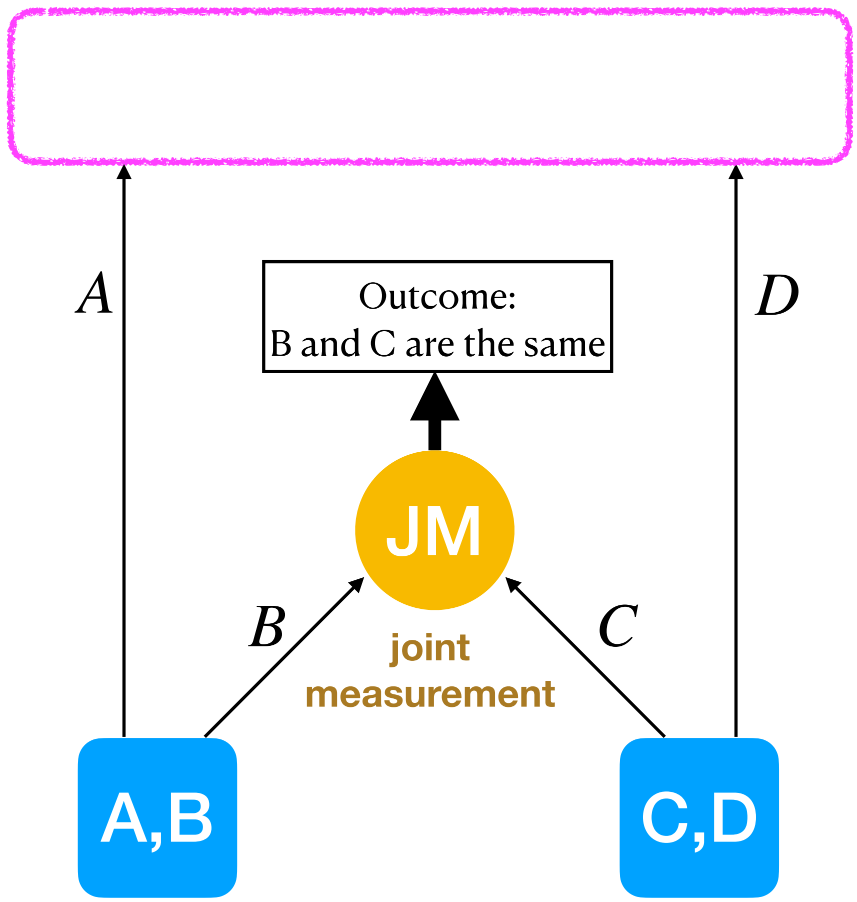
Send B and C into a Joint Measurement.
Outcome determines entangled state of A and D



$(0_A \,\&\, 1_B) + (1_A \,\&\, 0_B) \quad \& \quad (0_C \,\&\, 1_D) + (1_C \,\&\, 0_D)$

EXAMPLE A,B and C,D are initially in the state as shown

The joint measurement yields that B and C are the same. What is the state then created for A and D?



$(0_A \,\&\, 1_B) + (1_A \,\&\, 0_B)$ & $(0_C \,\&\, 1_D) + (1_C \,\&\, 0_D)$

Two possible cases:

B = C = 1
Then

$(0_A \,\&\, 1_B) +$ ~~$(1_A \,\&\, 0_B)$~~

&

~~$(0_C \,\&\, 1_D)$~~ $+ (1_C \,\&\, 0_D)$

in superposition with
B = C = 0

~~$(0_A \,\&\, 1_B)$~~ $+ (1_A \,\&\, 0_B)$

&

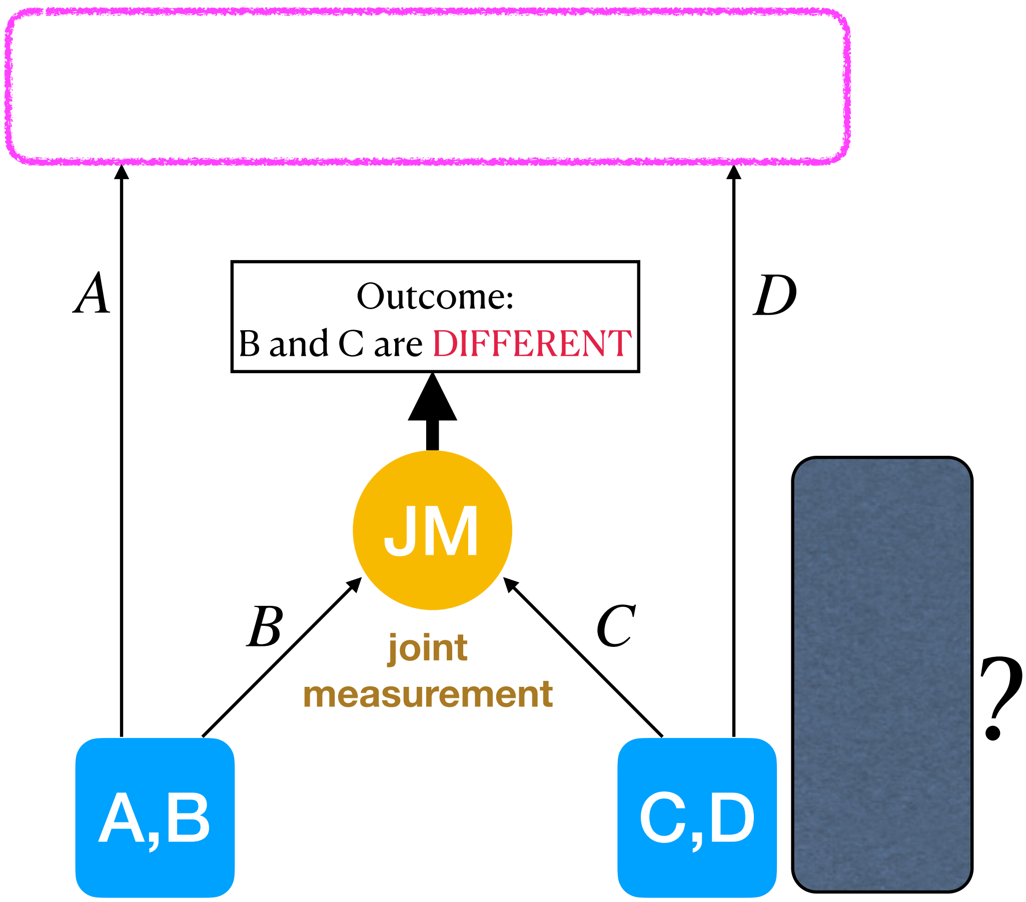
$(0_C \,\&\, 1_D) +$ ~~$(1_C \,\&\, 0_D)$~~

Final State:

$(0_A \,\&\, 0_D) + (1_A \,\&\, 1_D)$

POLL QUESTION 9 A,B and C,D are initially in the state as shown

The joint measurement yields that B and C are **DIFFERENT**.
What is the state then created for A and D?



$(0_A \,\&\, 1_B) + (1_A \,\&\, 0_B)$ & $(0_C \,\&\, 1_D) + (1_C \,\&\, 0_D)$

A. $(1_A \,\&\, 0_D) + (0_A \,\&\, 1_D)$

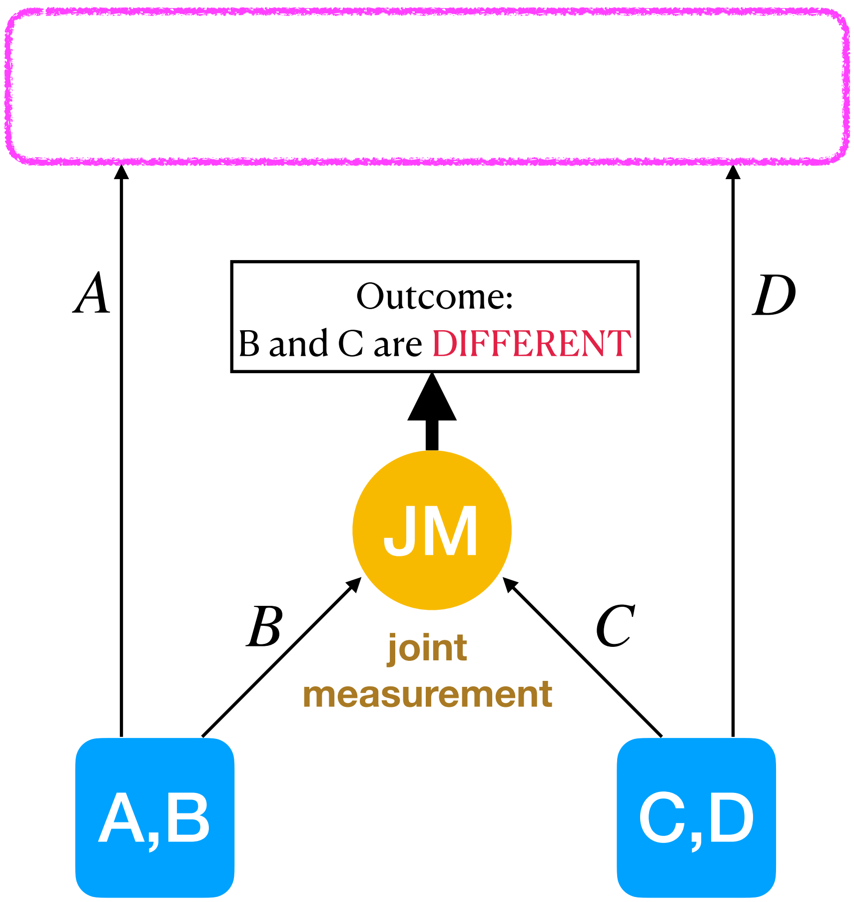
B. $(1_A \,\&\, 0_B) + (0_C \,\&\, 1_D)$

C. $(1_A \,\&\, 1_D) + (0_A \,\&\, 0_D)$

D. I don't know

ANSWER A,B and C,D are initially in the state as shown

The joint measurement yields that B and C are **DIFFERENT**.
What is the state then created for A and D?



$(0_A \& 1_B) + (1_A \& 0_B)$ & $(0_C \& 1_D) + (1_C \& 0_D)$

Two possible cases:

B = 0, C = 1
Then

~~$(0_A \& 1_B)$~~ $+ (1_A \& 0_B)$
&
~~$(0_C \& 1_D)$~~ $+ (1_C \& 0_D)$

in superposition with
B = 1, C = 0

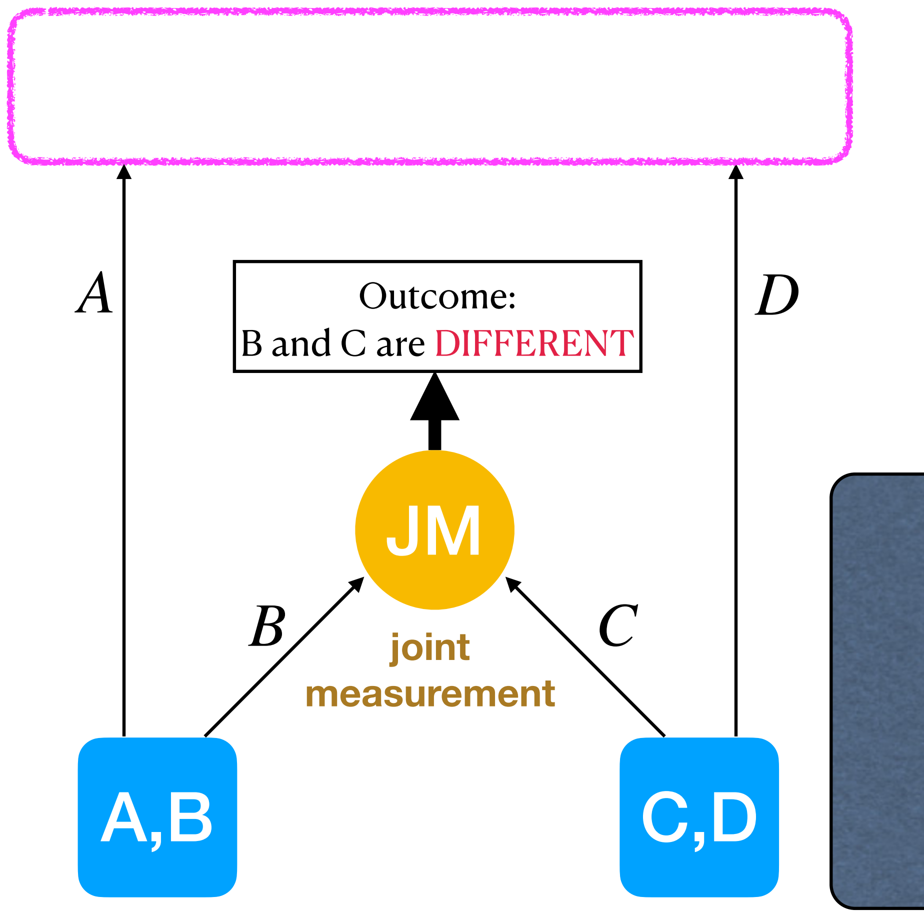
$(0_A \& 1_B) +$ ~~$(1_A \& 0_B)$~~
&
$(0_C \& 1_D) +$ ~~$(1_C \& 0_D)$~~

Final State:

$(1_A \& 0_D) + (0_A \& 1_D)$

POLL QUESTION 9 A,B and C,D are initially in the state as shown

The joint measurement yields that B and C are **DIFFERENT**.
What is the state then created for A and D?



$(0_A \ \& \ 1_B) + (1_A \ \& \ 0_B)$ & $(0_C \ \& \ 1_D) + (1_C \ \& \ 0_D)$

A. $(1_A \ \& \ 0_D) + (0_A \ \& \ 1_D)$

B. $(1_A \ \& \ 0_B) + (0_C \ \& \ 1_D)$

C. $(1_A \ \& \ 1_D) + (0_A \ \& \ 0_D)$

D. I don't know

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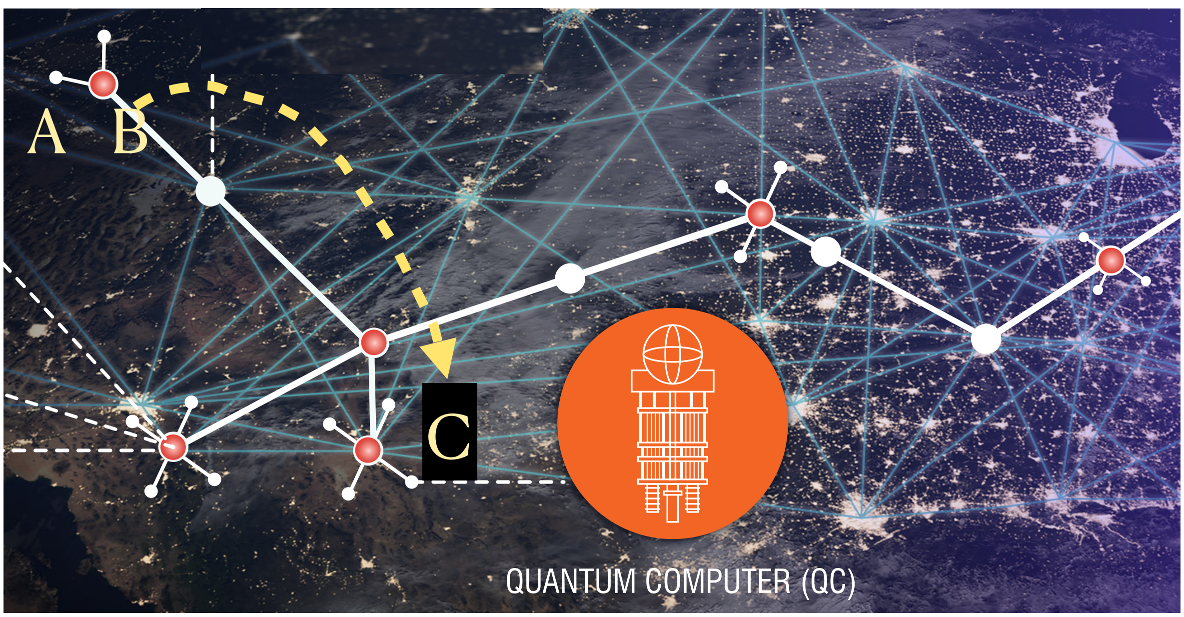
Quantum State Teleportation

Say you have an entangled pair of qubits A and B.
You want to transfer the state of B over to C so you have entanglement between A and C, leaving B unentangled.



Can be done by Quantum State Teleportation

If the distance is greater than ~ 100 km, you will need Quantum Repeaters, which have not yet been built

Quantum State Teleportation

Bob

Prof Xavier wants to send the quantum state of particle X to Bob without sending particle X

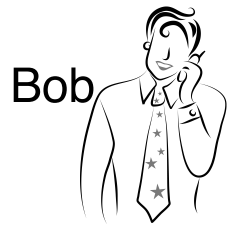
$$\text{State}_X = x(0_X) + y(1_X)$$

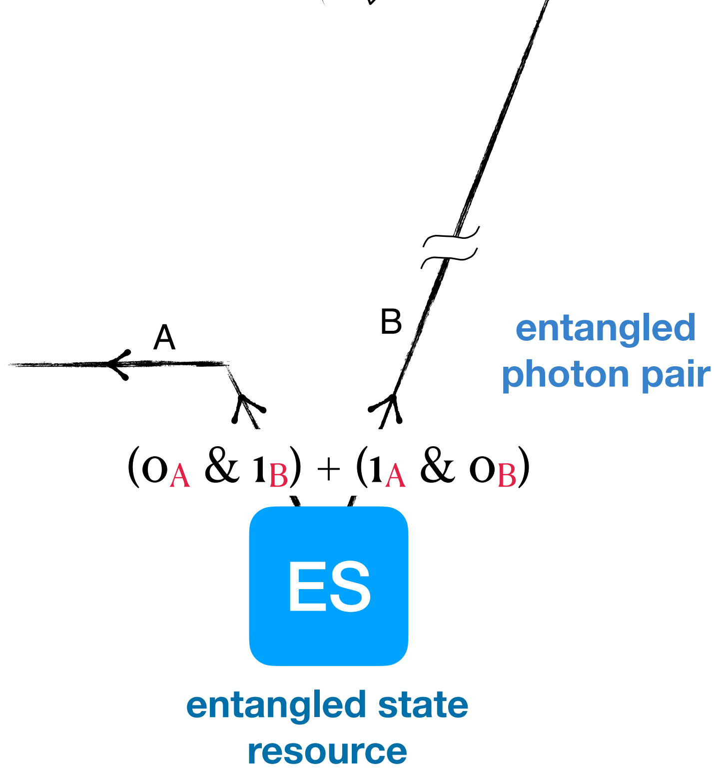
X

Prof Xavier

Quantum State Teleportation

Prof Xavier recruits Alice to help. They arrange to acquire an entangled photon pair. They send B to Bob and A to Alice,



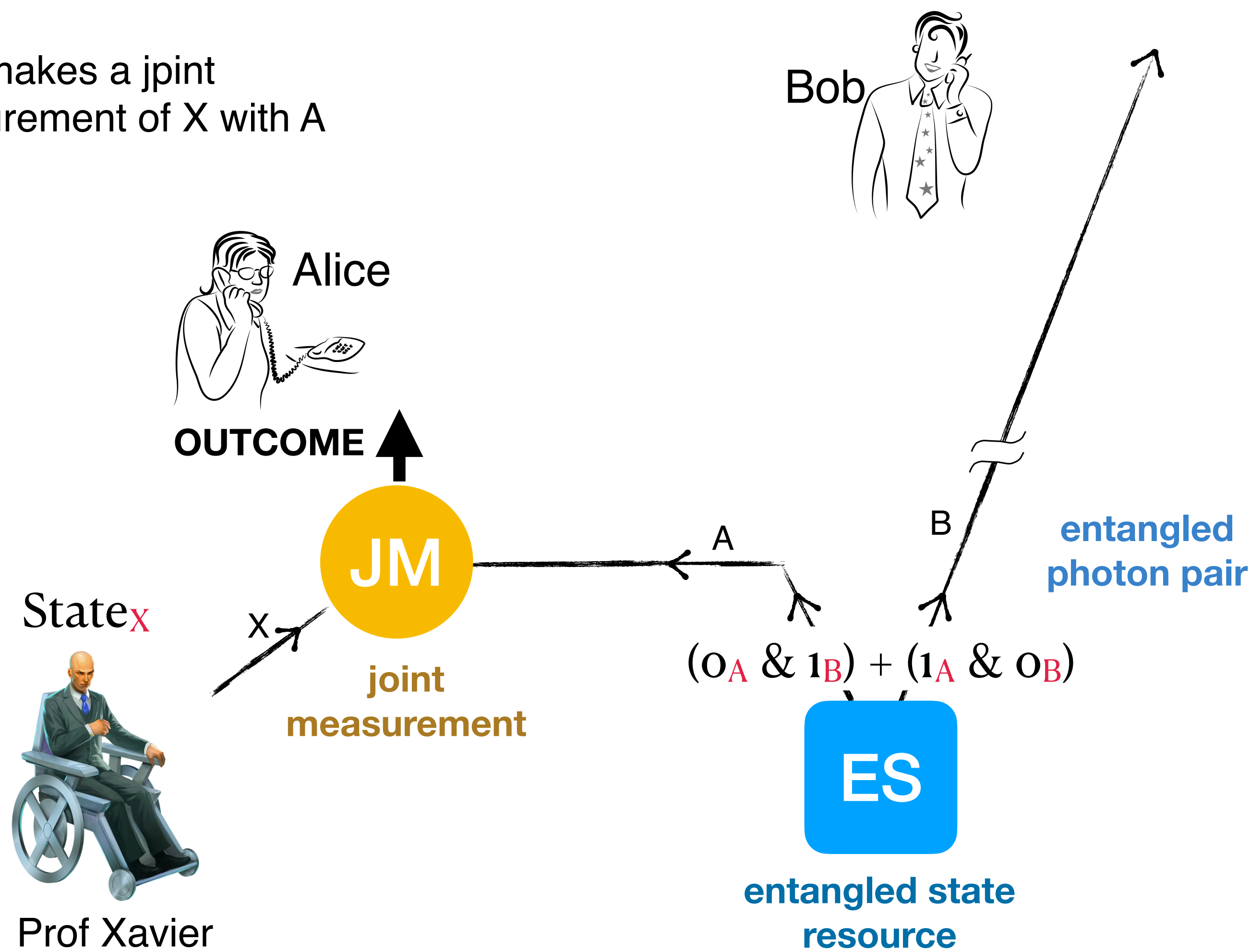


$$State_X = x(0_X) + y(1_X)$$

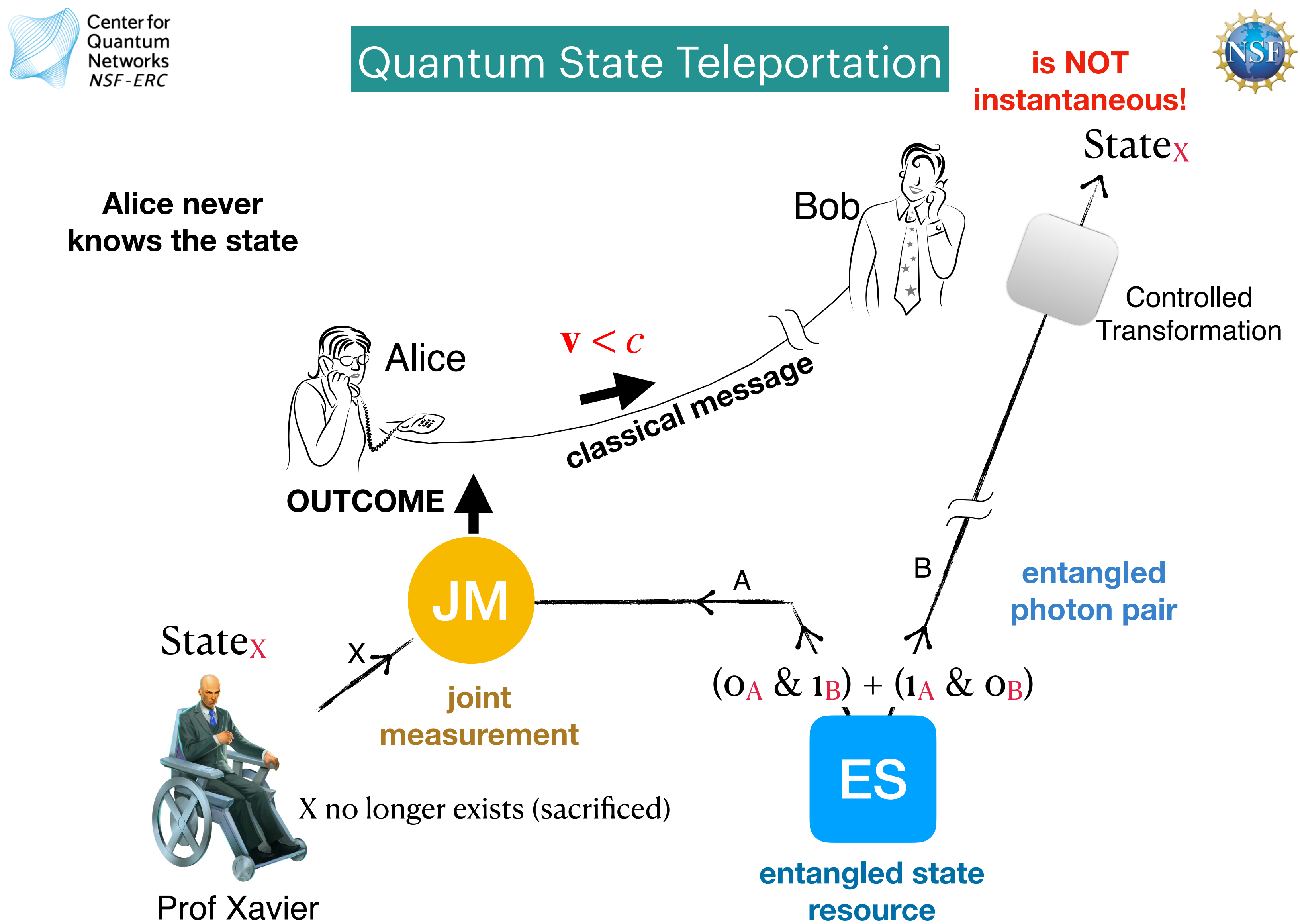
Prof Xavier

Quantum State Teleportation

Alice makes a jpint measurement of X with A

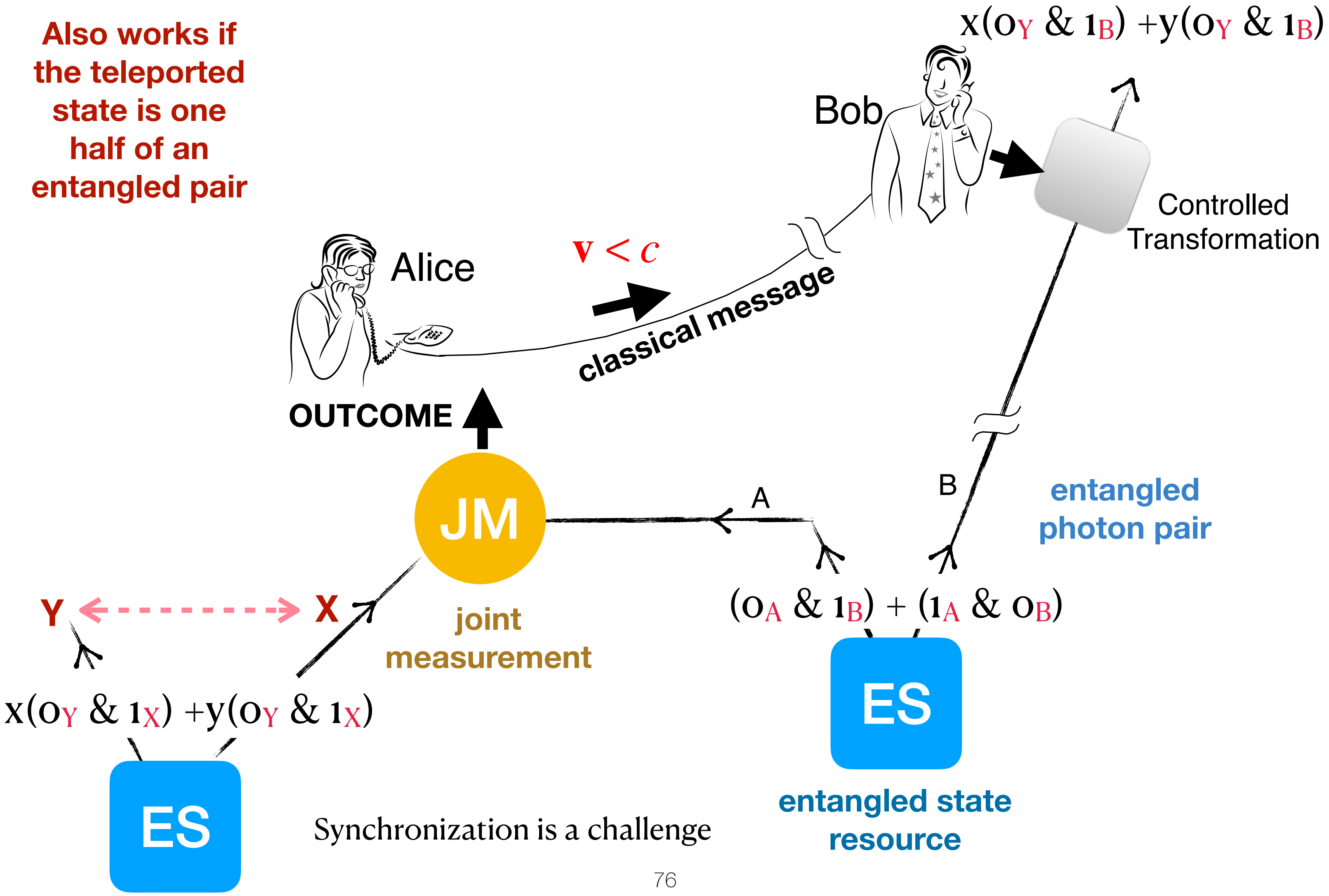


Quantum State Teleportation



Quantum State Teleportation

Also works if the teleported state is one half of an entangled pair

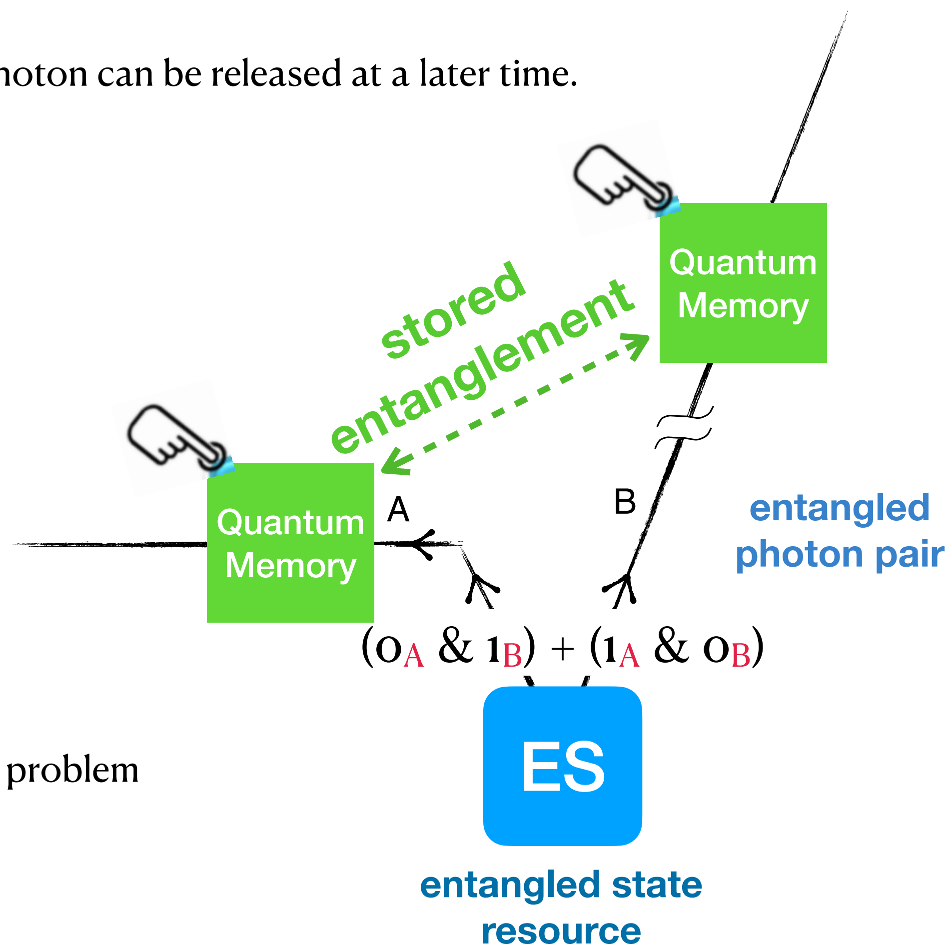


Synchronization is a challenge

Optical Quantum Memories

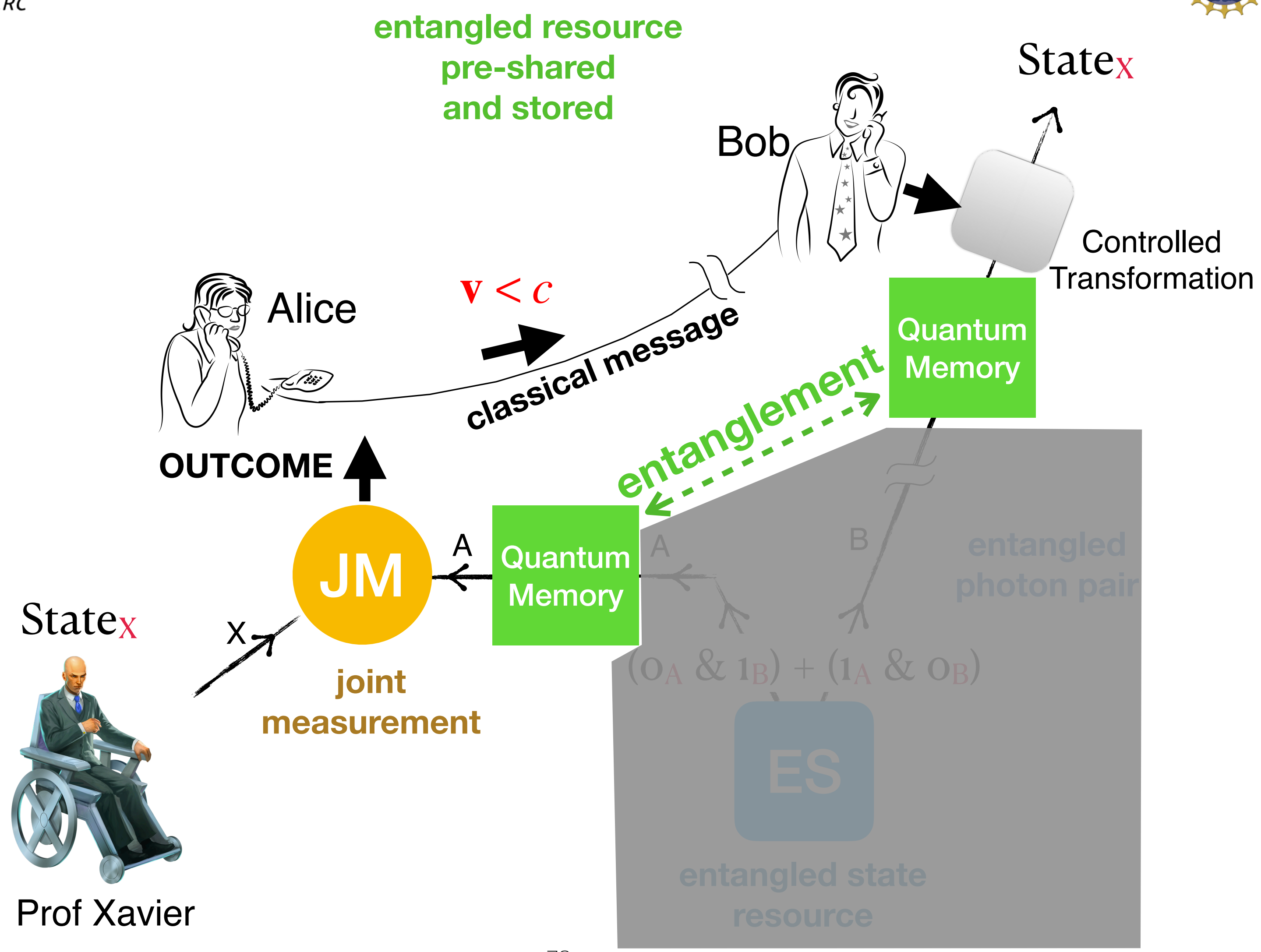
A photon is absorbed in a material medium in a way that its state is preserved.

The photon can be released at a later time.



Solves the synchronization problem

Memory-Assisted Quantum State Teleportation



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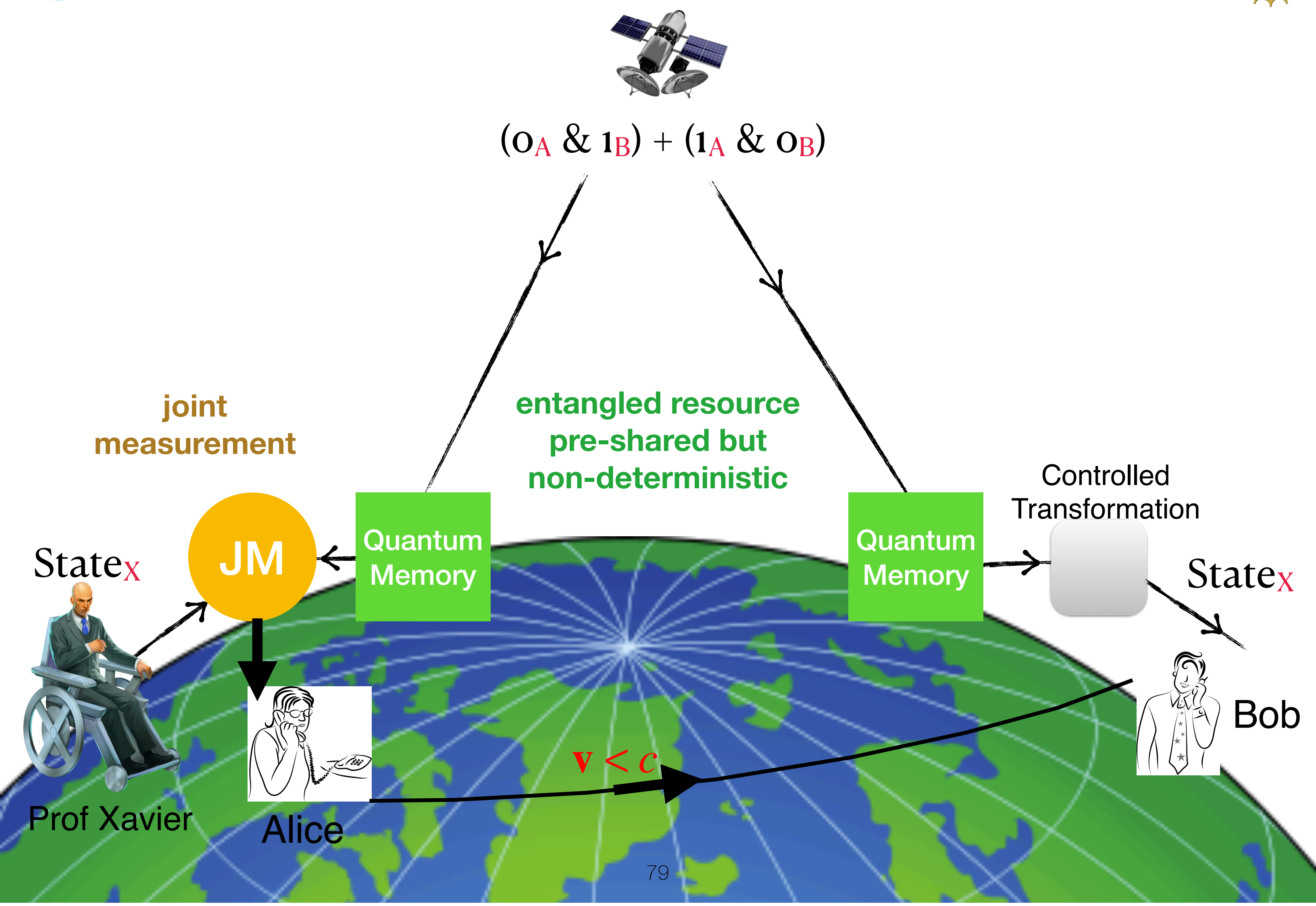
Satellite-Assisted Quantum State Teleportation



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Why Quantum Entanglement Distribution in Space?

Short-term path to long-distance Quantum Internet -

-Remote/blind quantum computing

- Distributed quantum computing

- Secure Communications

Very long baseline interferometery

Entangled clock network

Quantum enhanced sensor network: e.g. planetary science, Earth science

Quantum enhanced fundamental physics, Quantum gravity / new physics

END PART 2

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5 minute break

The Physics Behind the Quantum Internet

PART 3

BELL STATE MEASUREMENTS

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SHORT COURSE (4 HR) OUTLINE

PART 1: Quantum information science
The Center for Quantum Networks
The National Quantum Initative
What is *information*?
Bits and qubits
Superposition and entanglement

PART 2: Encoding and transmitting quantum information
Communication systems
Distributing Entangled states (e.g.. in Space)
Ways of encoding qubits
Ways of encoding qubits in photons (Flying qubits)
Quantum state teleportation
Space-based quantum networks

PART 3: Bell State measurements
Photon polarization revisited
Quantum measurement - Born's Rule
Correlations and the Bell inequality
Bell-Test experiments

PART 4: The Quantum Internet
Application #1: Quantum Cryptography
Bell-State Creating and Measuring
Quantum memories
Application #2: Memory-Assisted Teleportation
Entanglement Swapping with Quantum Memories
Quantum repeater networks
What could a quantum Network do?
Perspectives and misconceptions

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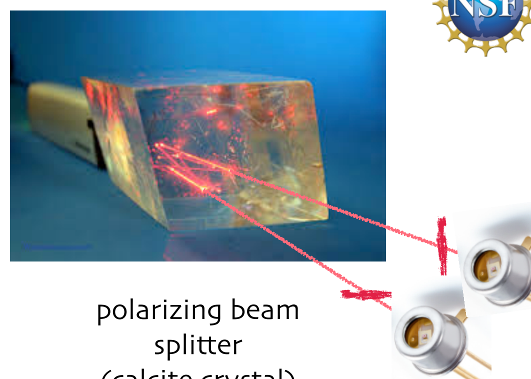
REVIEW:
Photon Polarization

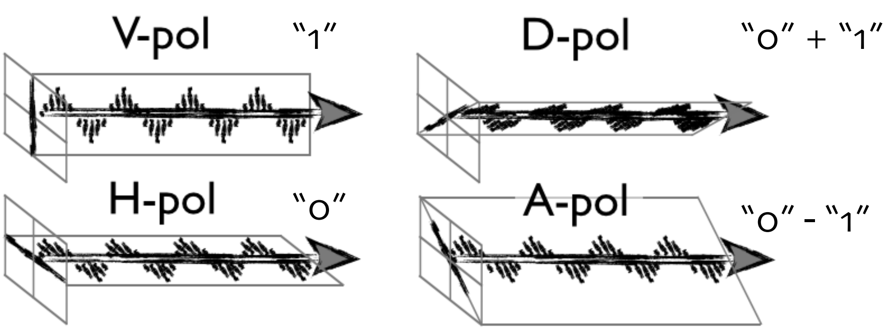


Superposition

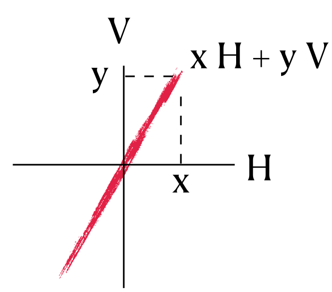
V + H = D (diagonal)

V - H = A (anti-diagonal)

Polarization can be oriented in **any** direction perpendicular to the direction of travel

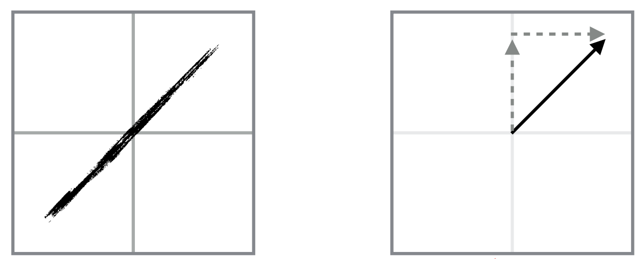


Most general possibility:

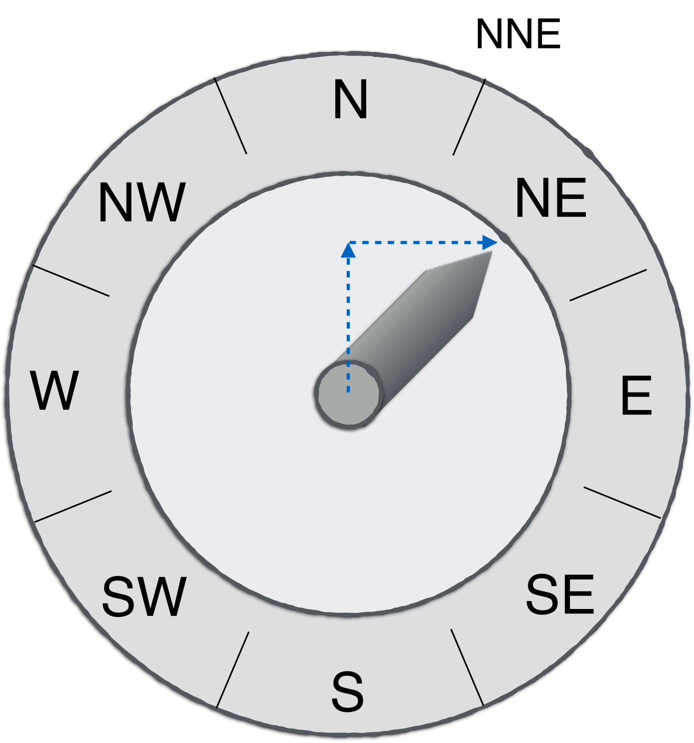


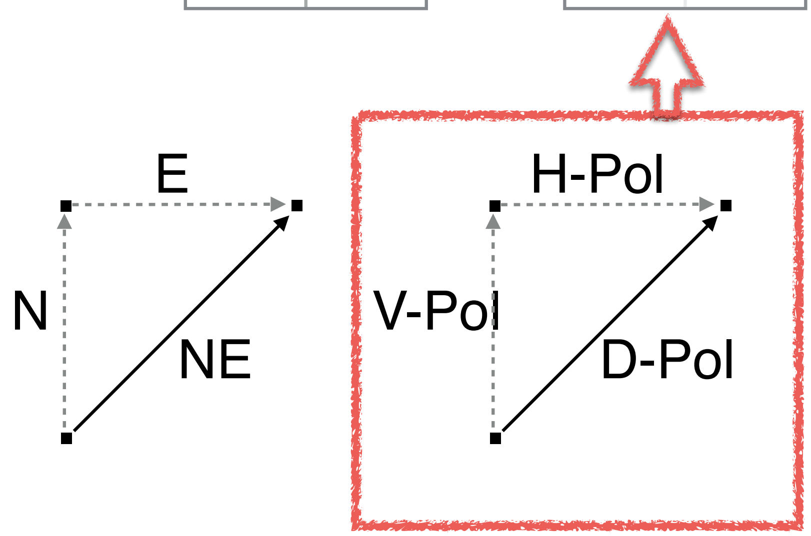
"0" and "1" are Logical Values

D-pol is a special combination of H-pol and V-pol



‘Direction Indicator’





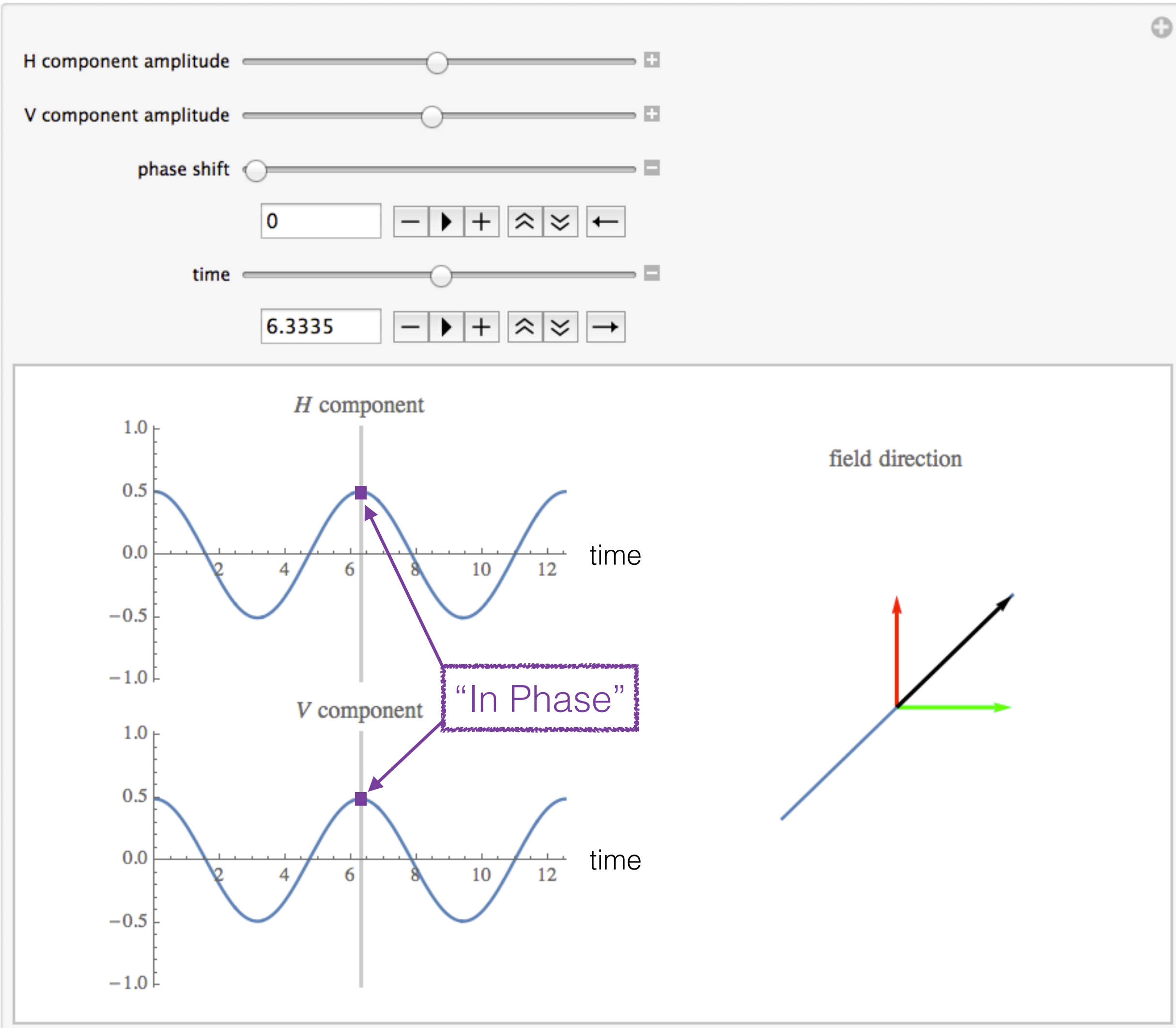
‘Vectors” or “Arrows”

Initialize:

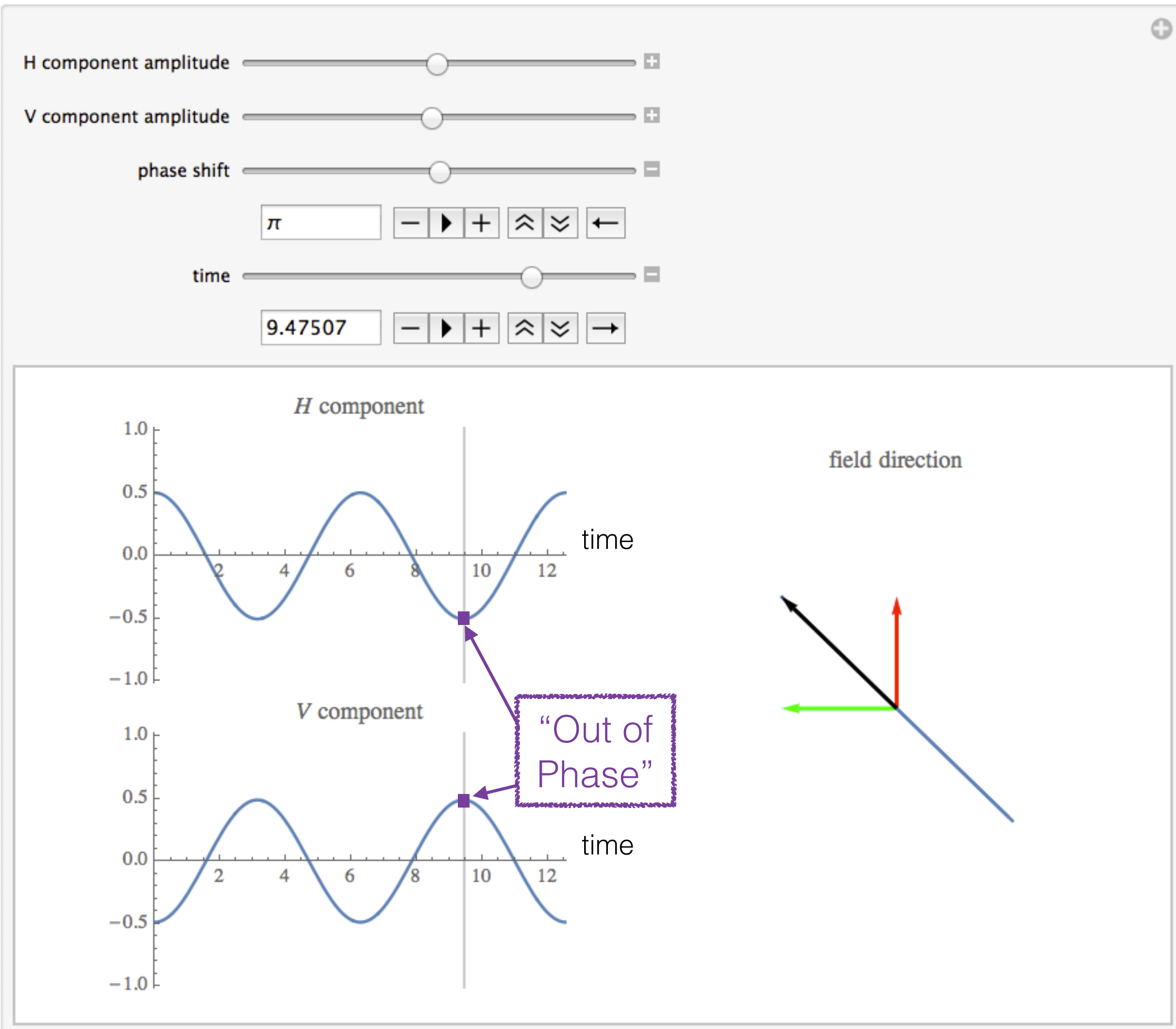

H component amplitude
0.
V component amplitude
0.
phase shift
0
time
0.0001
H component
field direction
V component

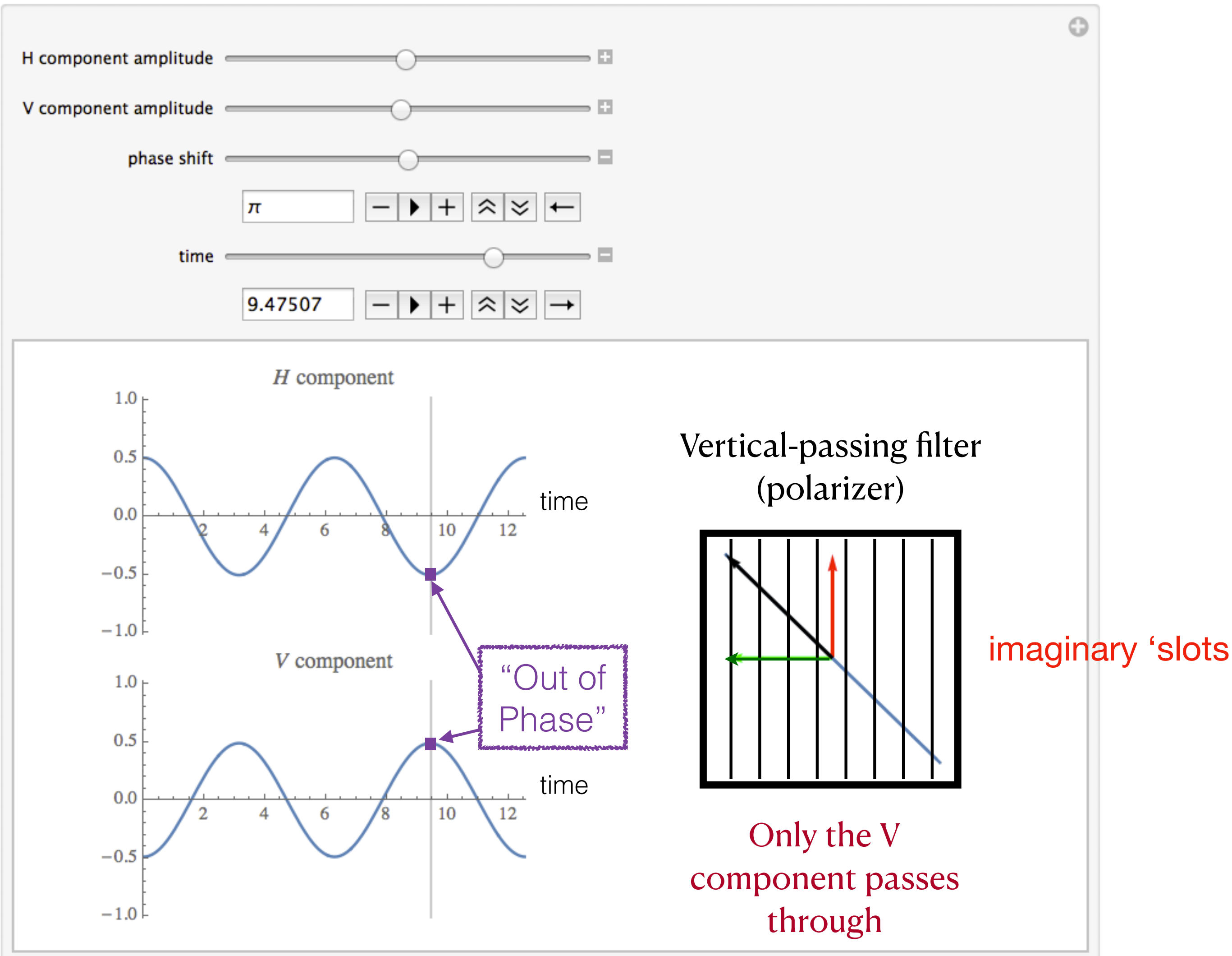
AddingPolarizationsWithPhaseShifts-Demonstrations Project.nb

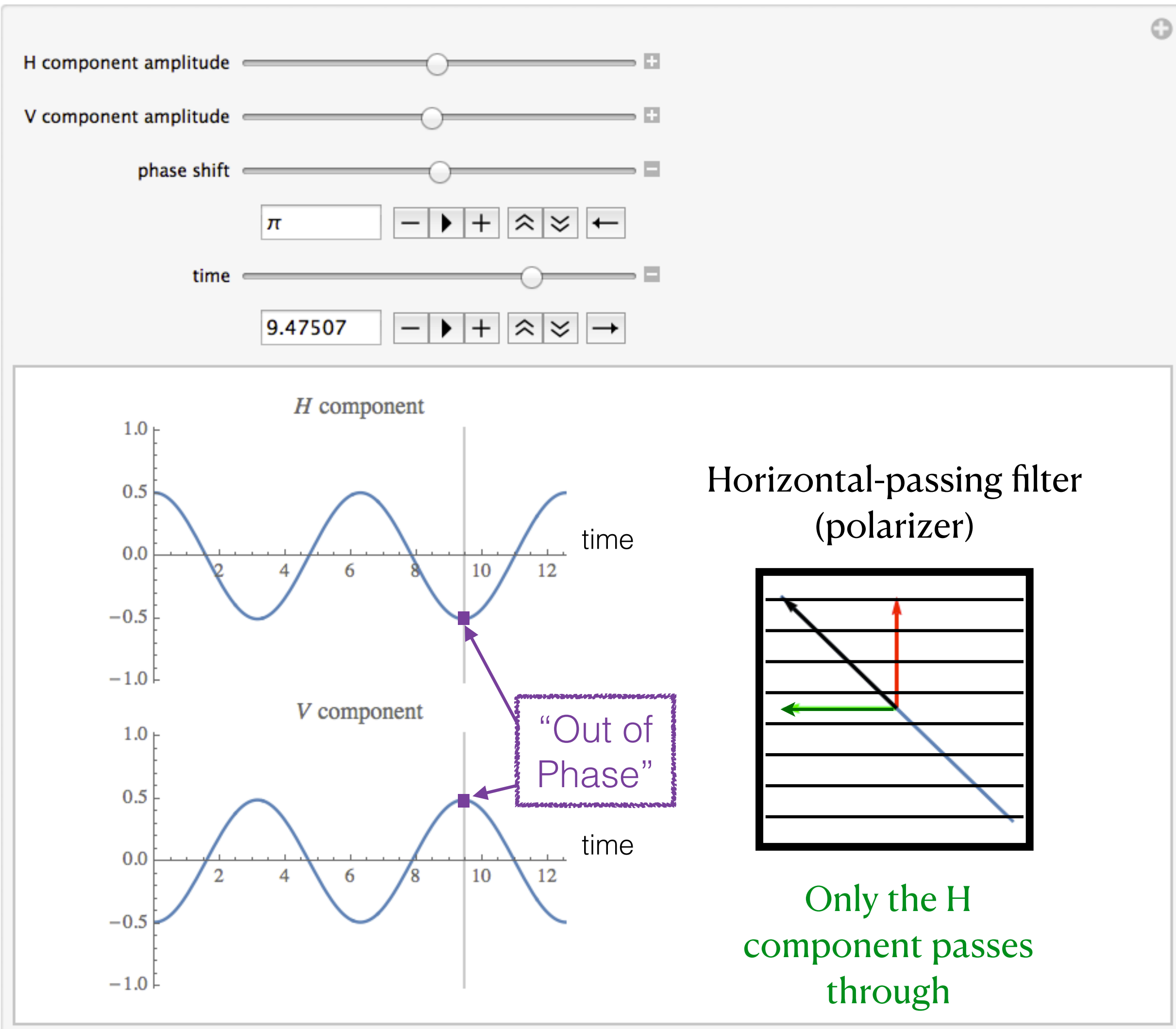
1.



2.


H component amplitude
V component amplitude
phase shift
π
time
9.47507
H component
1.0
0.5
0.0
−0.5
−1.0
2
4
6
8
10
12
time
V component
1.0
0.5
0.0
−0.5
−1.0
2
4
6
8
10
12
time
"Out of Phase"
field direction


H component amplitude
V component amplitude
phase shift
π
time
9.47507
H component
V component
1.0
0.5
0.0
−0.5
−1.0
2
4
6
8
10
12
time
"Out of Phase"
Vertical-passing filter (polarizer)
imaginary 'slots'
Only the V component passes through


H component amplitude
V component amplitude
phase shift
π
time
9.47507
H component
time
V component
time
"Out of Phase"
Horizontal-passing filter (polarizer)
Only the H component passes through

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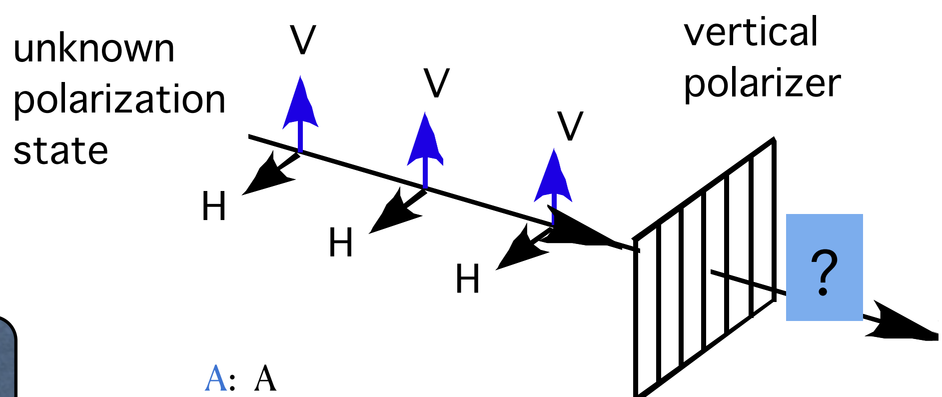
POLL QUESTION 10

What is the polarization of transmitted light after the vertical polarizer?



A: A
B: D
C: V
D: H
E: No light comes through

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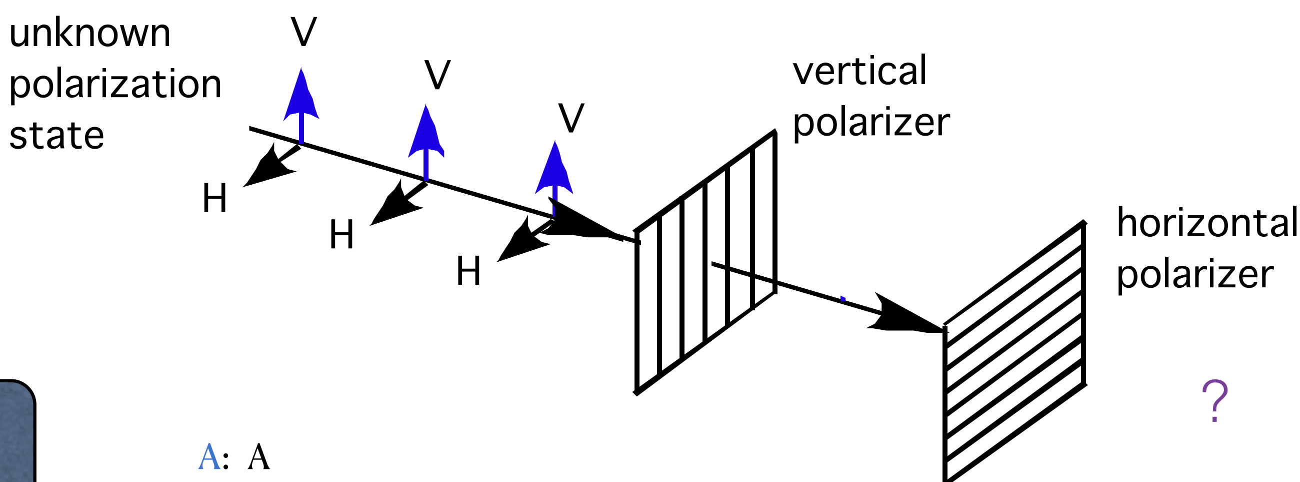
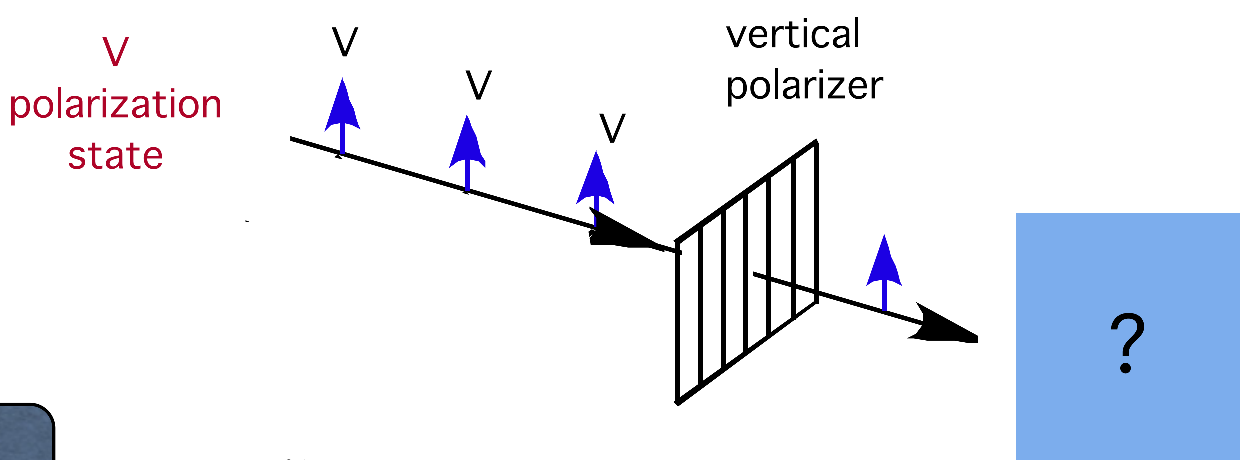
POLL QUESTION 11

What is the polarization of transmitted light after the <u>horizontal</u> polarizer?



A: A
B: D
C: V
D: H
E: No light comes through

If only a **Single Photon** is sent into this polarizer, what is the probability it will make it through?



: 0%
: 25%
: 50%
: 100%

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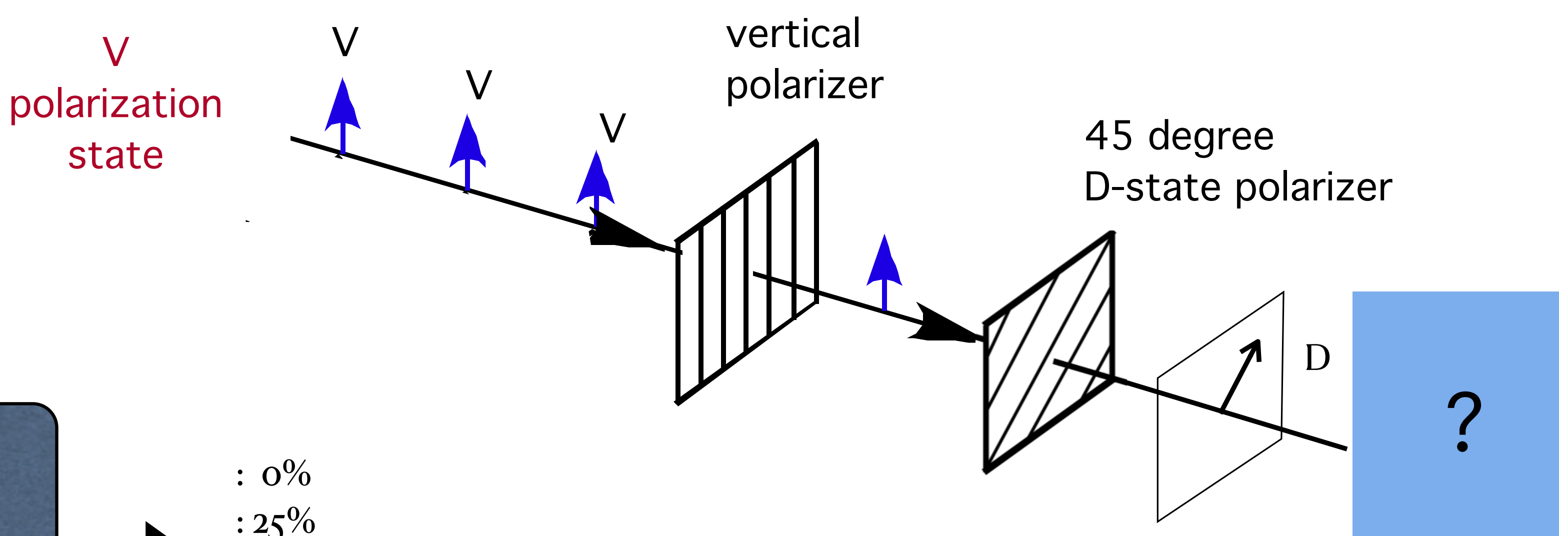
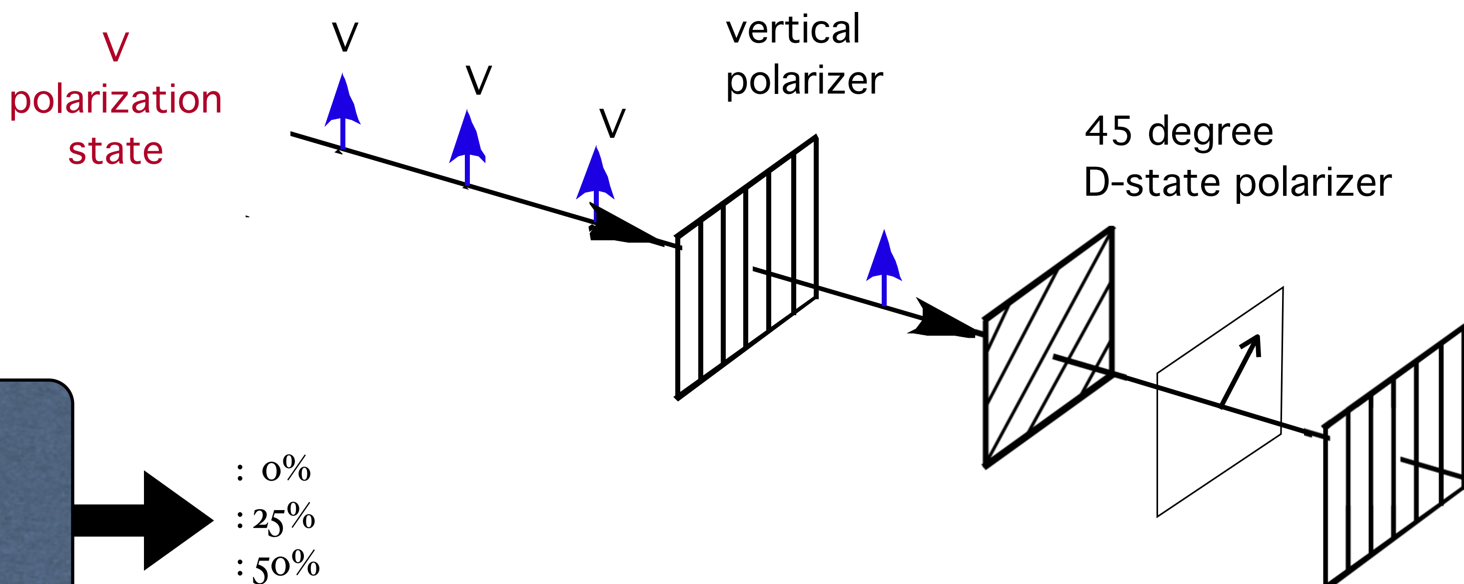
If only a **Single Photon** is sent into this series of polarizers, what is the probability it will make it through?



: 0%
: 25%
: 50%
: 100%

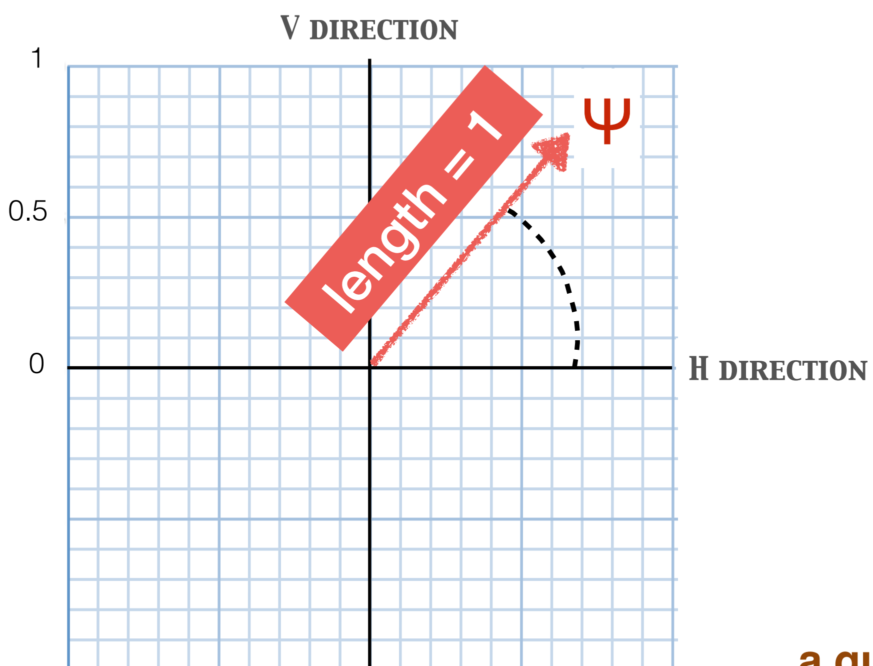
If only a **Single Photon** is sent into this series of polarizers, what is the probability it will make it through?



: 0%
: 25%
: 50%
: 100%

50% at each polarizer

For a *single photon*, the **quantum state of polarization** is represented by a **polarization arrow (vector)**.



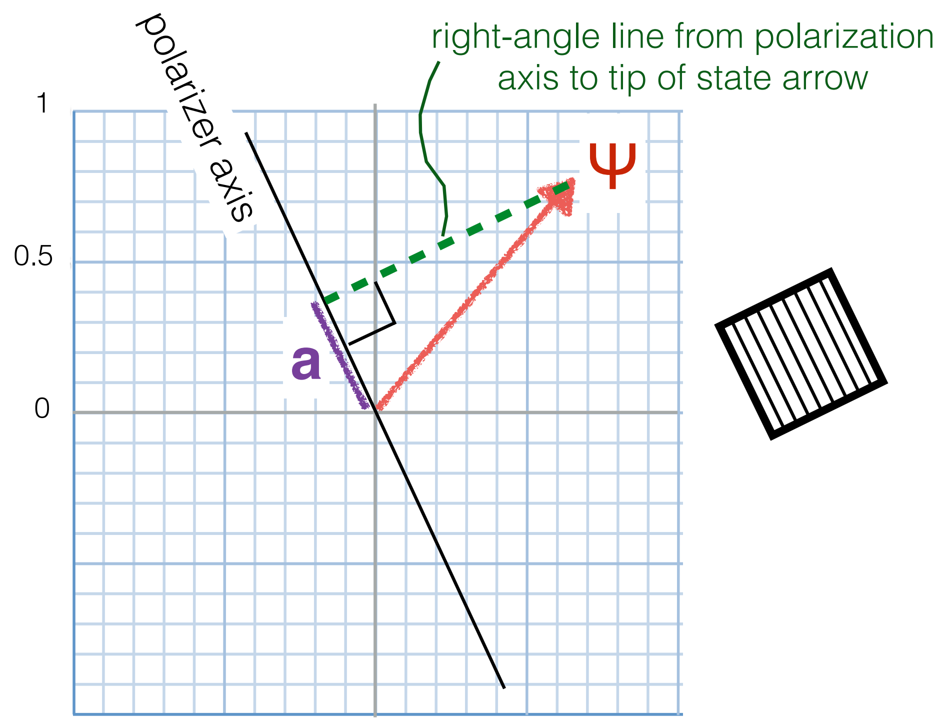
symbol: **Ψ**
name: psi

a quantum state is not a property of the photon; it is a description of the photon

Max Born

Born's Rule

To find the **probability** for a photon to be observed passing through a polarizer set for any given measurement scheme, **project** the photon's polarization arrow onto the polarizer axis, then **square** the length of the projection.



a = length of projection

Probability = $\mathbf{a}^2$

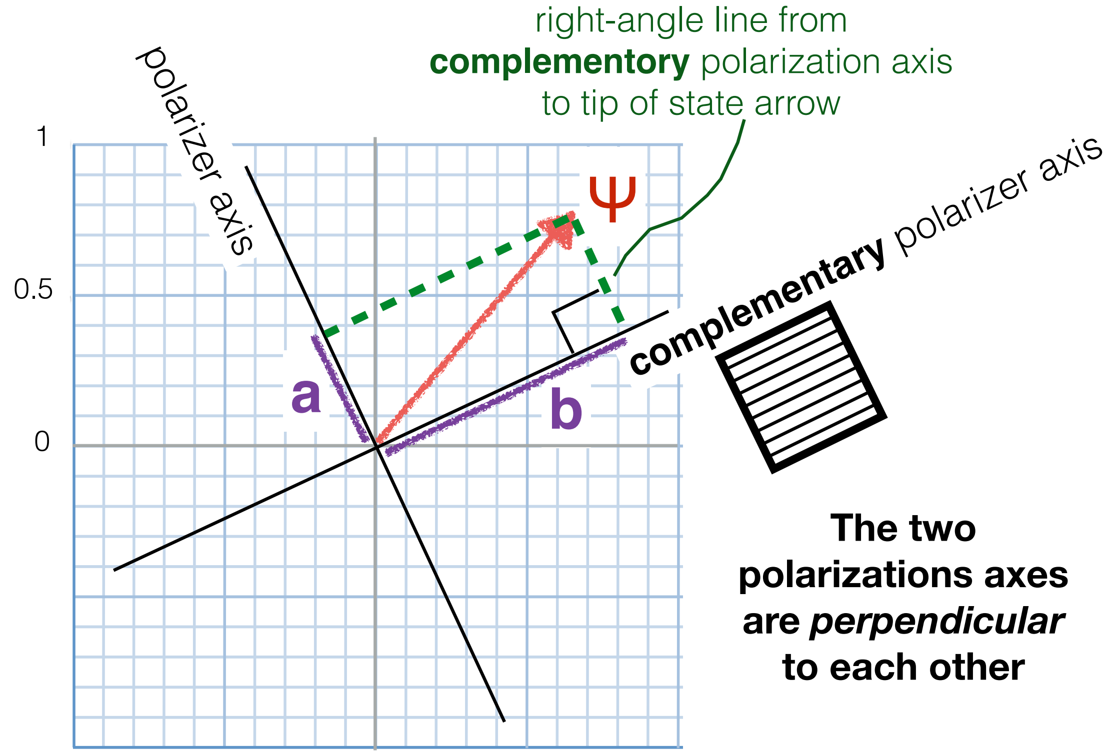
Born's Rule

What about the other polarization axis?

Probability = **a^2**

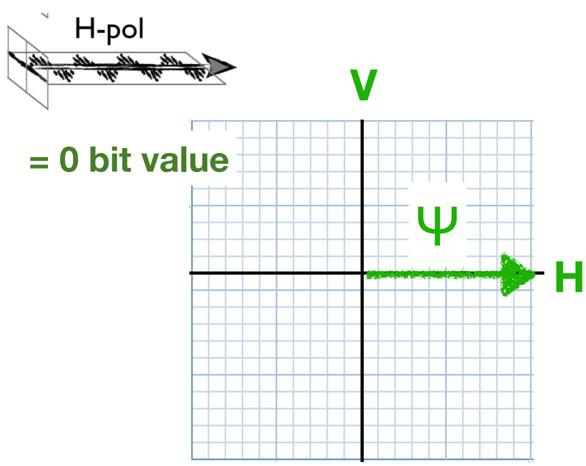
Complementary Probability = **b^2**

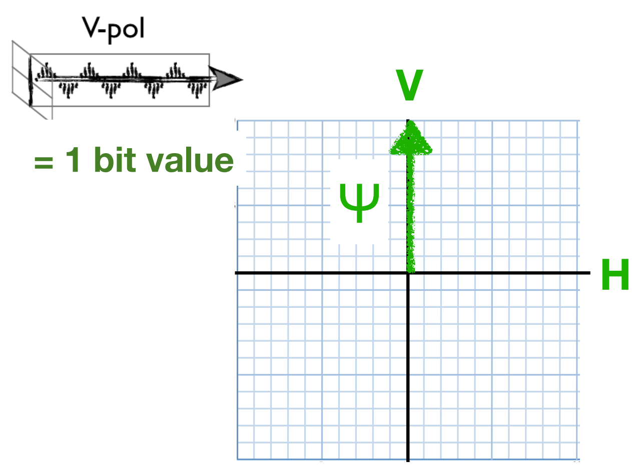
$$a^2 + b^2 = 1^2$$

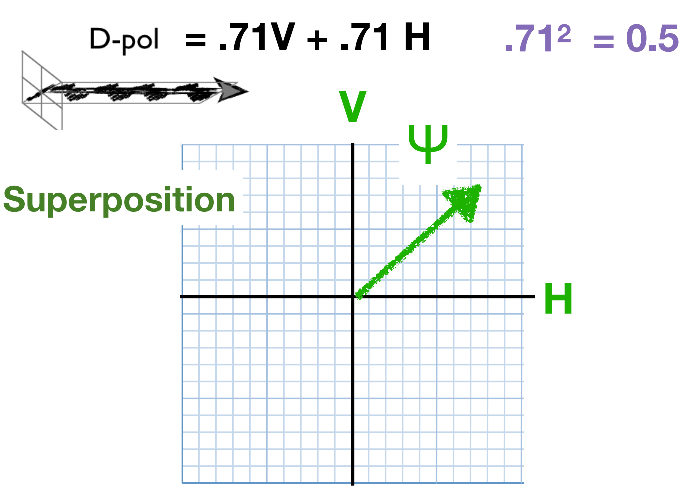


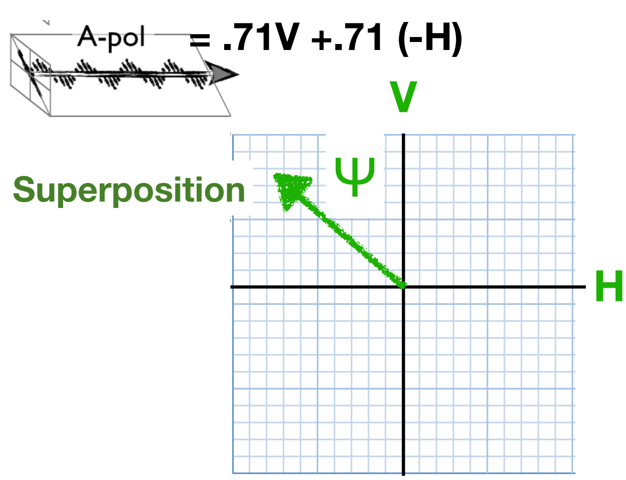
The two polarizations axes are *perpendicular* to each other

State Arrow (vector) representation of Polarization Qubit









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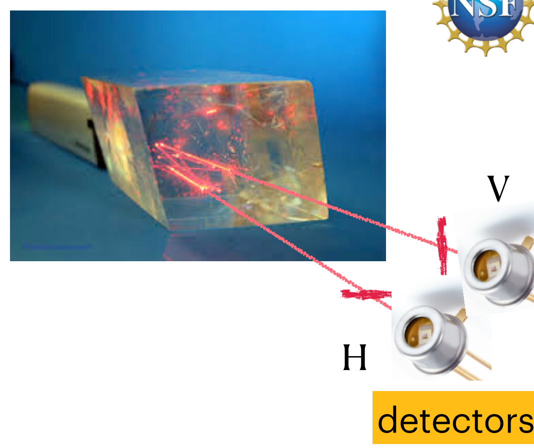
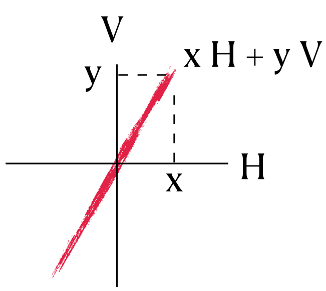
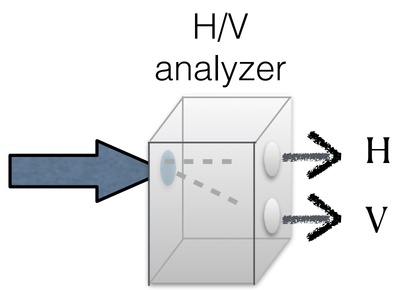
Calcite crystals as Polarization Analyzers (Sorters)

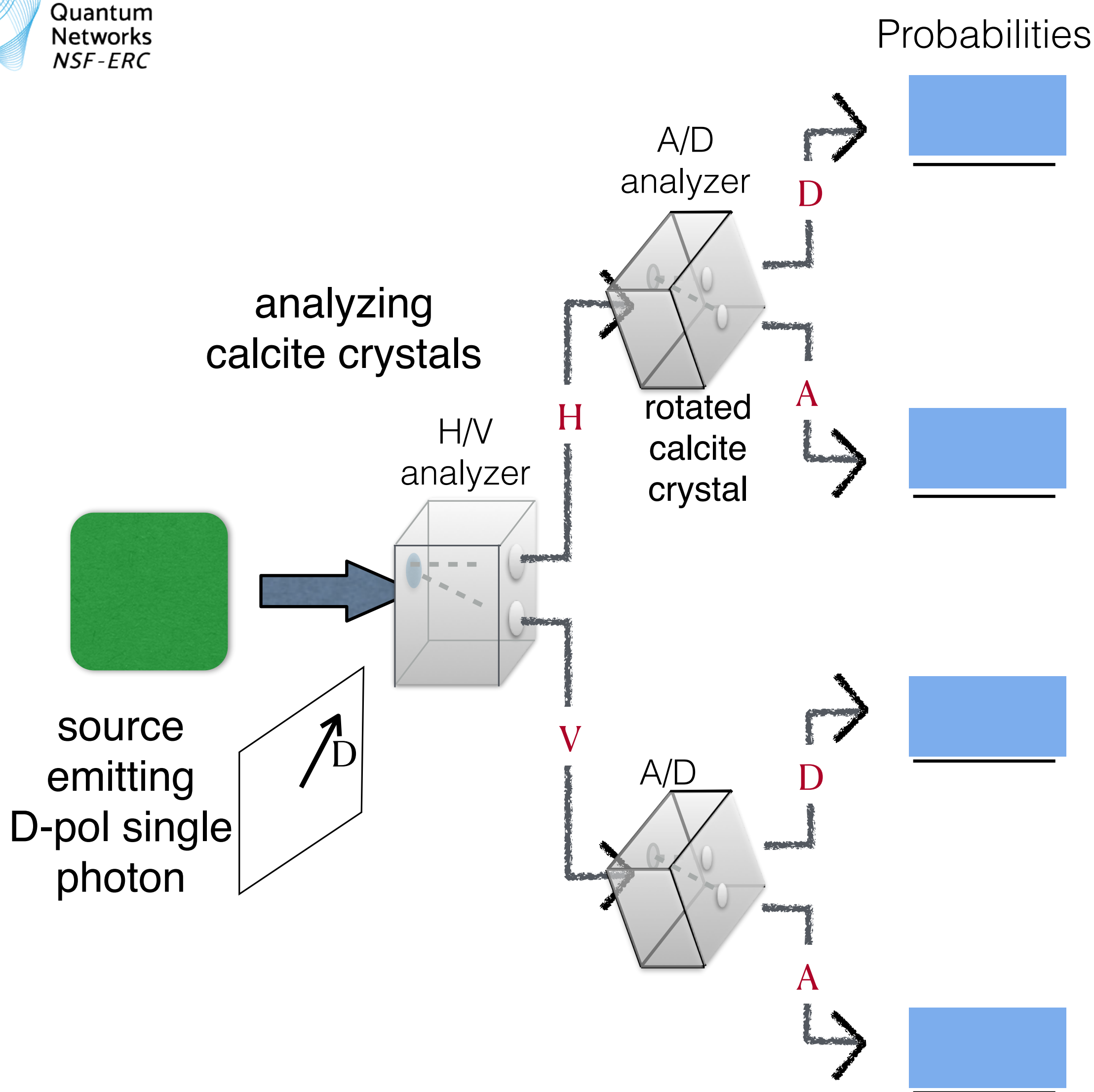


Arbitrary state of polarization:





probabilities = x^2 and y^2



QUESTION

write the probabilities on paper

(30 seconds)

INHERENT PROPERTY LIST OR INSTRUCTIONS LIST (A CLASSICAL-PHYSICS ***MODEL*** FOR CORRELATIONS)

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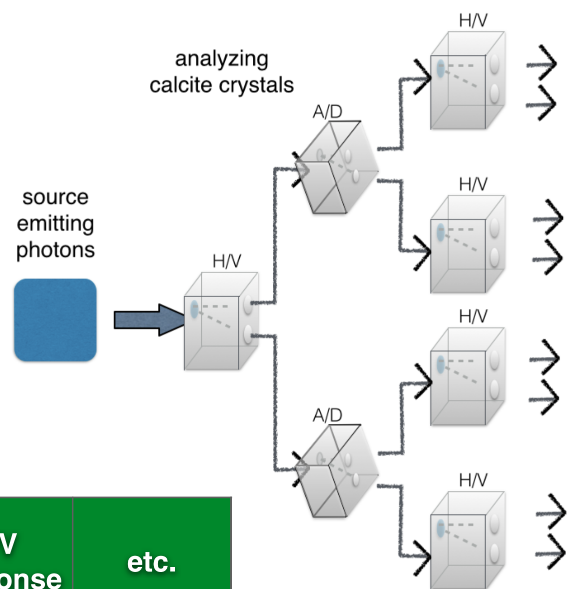
A chain of POLARIZATION ANALYZERS

Imagine each photon having its own set of instructions. The inherent properties list gets longer.. could this be the way the world works??? (if so then there is no deeper physics theory beyond the list.)
Can we design an experiment that rules this out?



photon	H/V Response	A/D Response	H/V Response	etc.
1	H	D	V	
2	H	A	V	
3	V	A	V	
4	H	D	H	
5	V	D	H	

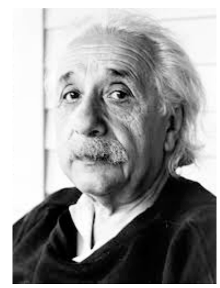
The size of the initial instructions list would be exponentially large.

Single-particle experiments cannot rule out the possibility that nature follows inherent properties or inherent instruction tables.

The Bell Inequality -
Does classical common-sense theory describe the world correctly?

Two quantum particles can have "spooky" *correlations*.

"Spooky"



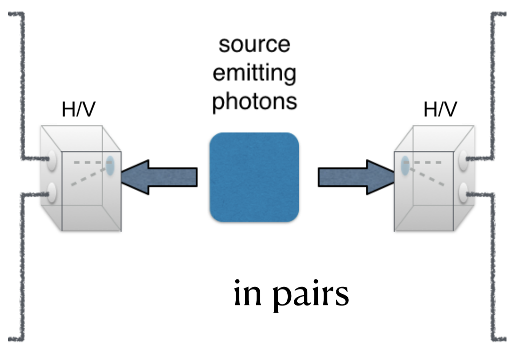
Correlations in Classical Probability

http://en.wikipedia.org/wiki/Correlation_and_dependence

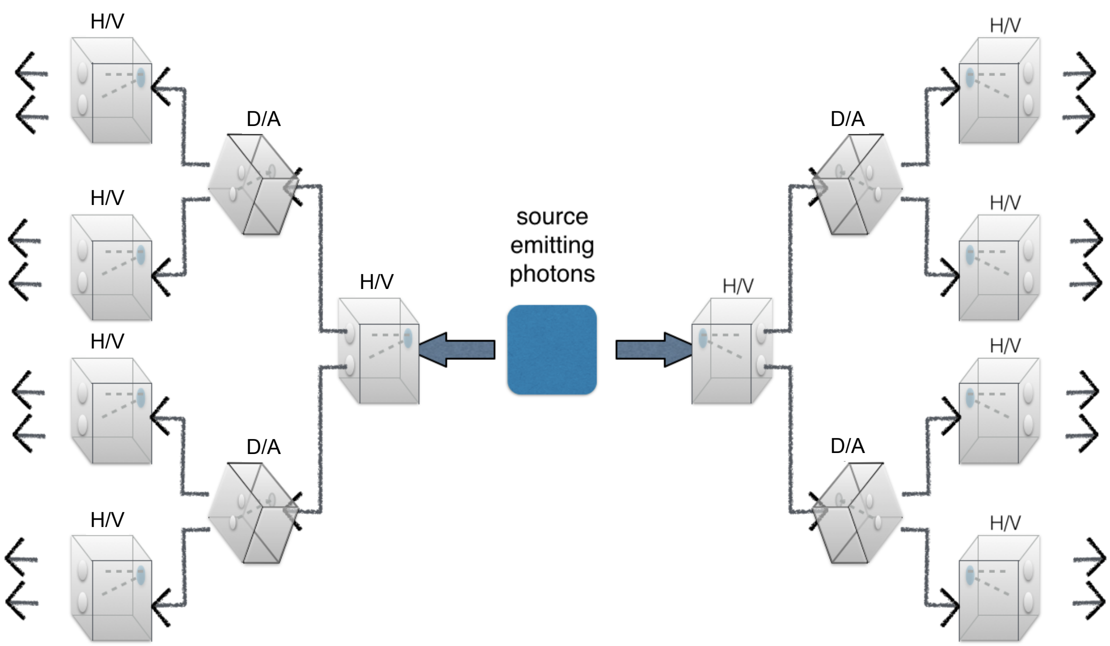
"**Correlation** refers to any … statistical relationships involving dependence. …

A correlation between age and height in children .
… A correlation can be taken as evidence for a possible *causal relationship*, but cannot indicate what the causal relationship, if any, might be."

A source emits correlated (entangled) pairs of photons



A source emits correlated (entangled) pairs of photons



Requires a lengthy list of possible correlations,
depending on all possible measurement combinations.

Even if you could make such a predictive list, could this describe successfully the observed statistics of outcomes?
NO!
The idea of inherent properties or instructions fails. Proof on next slides.

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Proof of the (classical) Bell Inequality

Given these Assumptions:

1. After the photons leave the common source, their inherent properties or instructions exist and don't change later. (Realism)

2. Causal effects cannot travel faster than light. (Causal Locality)

3. Alice and Bob are able to make independent choices about what measurement* each will make on each of their observed photons. (Measurement independence or 'Free Will')

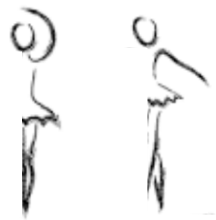
⇒ One can prove a limit on the possible outcomes of certain well-designed experiments. (Bell Inequality)

Experiments can be carried out to test the predicted limit. (Bell Tests)

* choice of polarizer angles

Averages of Products Quantify Correlations

e.g. Two dancers



Uncorrelated

Average of Bc

Avg(Bc)=0

Average of Ac

Ave(Ac)=0

Average of Product

Ave(Ac x Bc)=0

correlation = 0

Run	Alice c	Bob c	Ac x Bc
1	+1	-1	-1
2	-1	+1	-1
3	+1	-1	-1
4	-1	-1	+1
5	+1	-1	-1
6	-1	-1	+1
7	1	+1	1
8	+1	+1	+1
9	-1	+1	-1
10	+1	+1	+1
11	+1	-1	-1

Define the correlation of two lists as the <u>average of the products</u> of the corresponding list entries.

Perfectly correlated

Avg(Bc)=0

Average of Ac

Ave(Ac)=0

Ave(Ac x Bc)=1

correlation = 1

Run	Alice c	Bob c	Ac x Bc
1	+1	+1	+1
2	+1	+1	+1
3	+1	+1	+1
4	-1	-1	+1
5	+1	+1	+1
6	-1	-1	+1
7	-1	-1	+1
8	+1	+1	+1
9	-1	-1	+1
10	+1	+1	+1
11	+1	+1	+1

What if each ‘object’ has **TWO** properties that can be observed?

leg up = + 1

leg down = - 1

arm up = + 1

arm down = - 1

Two Dancers perform in separate halls, one observed by Alice the other by Bob.

Alice sees:

(leg) AL= +1 or -1 and
(arm) AA= +1 or -1

Bob sees:

(leg) BL= +1 or -1 and
(arm) BA= +1 or -1

There are only16 possible combinations of outcomes

There are many possible combinations of products we could invent, e.g.

$$Q = AA \times BA + AA \times BL + AL \times BA - AL \times BL$$

complete, systematic list of all combinations

Alice sees Arm AA	Alice sees Leg AL	Bob sees Arm BA	Bob sees Leg BL	Products AAxBA	AAxBL	ALxBA	ALxBL	"Curious Quantity" Q
1	1	1	1	1	1	1	1	2
1	1	1	-1	1	-1	1	-1	2
1	1	-1	1	-1	1	-1	1	-2
1	1	-1	-1	-1	-1	-1	-1	-2
1	-1	1	1	1	1	-1	-1	2
1	-1	1	-1	1	-1	-1	1	-2
1	-1	-1	1	-1	1	1	-1	2
1	-1	-1	-1	-1	-1	1	1	-2
-1	1	1	1	-1	-1	1	1	-2
-1	1	1	-1	-1	1	1	-1	2
							1	-2
							-1	2
							-1	-2
-1	-1	1	-1	-1	1	-1	1	-2
-1	-1	-1	1	1	-1	1	-1	2
-1	-1	-1	-1	1	1	1	1	2
							AVERAGE	≤ 2

"less than or equal to"

It turns out: by measuring Q we can distinguish between classical and quantum physics.

Theorem: If all data is recorded and analyzed, there is no way to have Q greater than 2

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In some experiments, only ONE of two possible measurements can actually be done on each single object.

Examples later

If the choices of quantity to be measured are chosen randomly (‘fair’ sampling)…

Ave Q =
Ave (AA×BA) + Ave (AA×BL) + Ave (AL×BA) – Ave (AL×BL)

RUN	AA Alice sees Arm	AL Alice sees Leg	BA Bob sees Arm	BL Bob sees Leg	AAxBA	AAxBL	ALxBA	ALxBL
	1		-1		-1			
		-1		1				-1
		1	1				1	
		-1	-1				1	
	1		1		1			
		-1		-1				1
	1			1		1		
		-1	1				-1	
	-1		1		-1			
		-1	1			1		
		1	-1			1		
		1		-1				-1
		1		1				1
		1	-1			1		
		1	1			1		
	-1		-1		1			
		-1		-1				1
	-1			1		-1		
		-1	-1			-1		
	-1		-1		1			
	1			1		1		
		-1	-1			-1		
		1		1				1
		-1		1				-1
etc.					0.25	0	0	0.083

example

Ave Q = ? 0.167

Assume we have thousands or millions of runs

we must average down instead of across.

…Ave Q is accurate (if the data set is large enough)

If the choices of quantity to be measured are NOT chosen randomly ('rigged' sampling)…

We could have:

Alice sees Arm AA	Alice sees Leg AL	Bob sees Arm BA	Bob sees Leg BL	Products AAxBA	AAxBL	ALxBA	ALxBL
	1		-1				-1
1		1		1			
1			1		1		
	1	1				1	
	1		-1				-1
1		1		1			
1			1		1		
	1	1				1	
	1		-1				-1
1		1		1			
1			1		1		
	1	1				1	
	1		-1				-1
1		1		1			
1			1		1		
	1	1				1	
	1		-1				-1
1		1		1			
1			1		1		
	1	1				1	
	1		-1				-1
1		1		1			
1			1		1		
	1	1				1	
			Averages:	1	1	1	-1

Ave Q = Ave AA×BA + Ave AA×BL + Ave AL×BA – Ave AL×BL

NON-POLL QUESTION

In this example, what is the average of Q?

A: -1
B: +1
C: 0
D: 4

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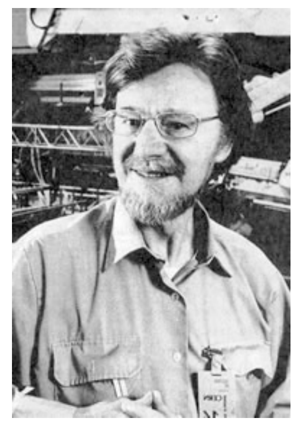
For *any* data set W, X, Y, Z

$$Q = W\times Y + W\times Z + X\times Y - X\times Z$$

$$\text{Ave } Q = \text{Ave } W\times Y + \text{Ave } W\times Z + \text{Ave } X\times Y - \text{Ave } X\times Z$$

Bell's Inequality

Under the assumptions of inherent properties or instructions, and fair sampling of measurement settings, No matter what state is prepared, and "no conspiracies" or "rigging", the Average(Q) cannot be greater than 2



John Bell

$$\text{Average}(Q) \leqslant 2$$

Under the Assumptions of:
- Realism
- Causal Locality
- Fair Random Sampling and Measurement independence or 'Free Will'

Testing classical assumptions and logic

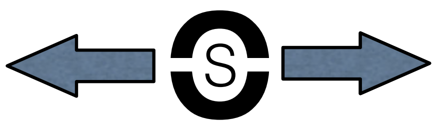
Correlations in **Photon Polarization** Experiments

Two photons are emitted from a common source. They might have correlated behavior.

Can Alice and Bob do a Bell test?

Pair of photons emitted by source S

"Alice"
Alicia Keys
famous musician



"Bob"
Nobel prize-winning Bob Dylan

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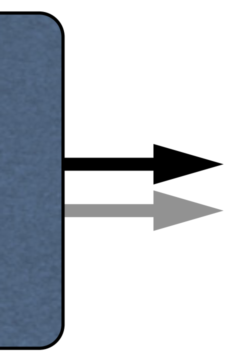
POLL QUESTION 12

For a given single photon, can you measure whether it is V or H and also measure whether it is D or A?



A: Yes, send it through a series of two polarizers
B: No, the first polarizer changes its state
C: Yes for classical light, no for quantum light
D: I'm not sure

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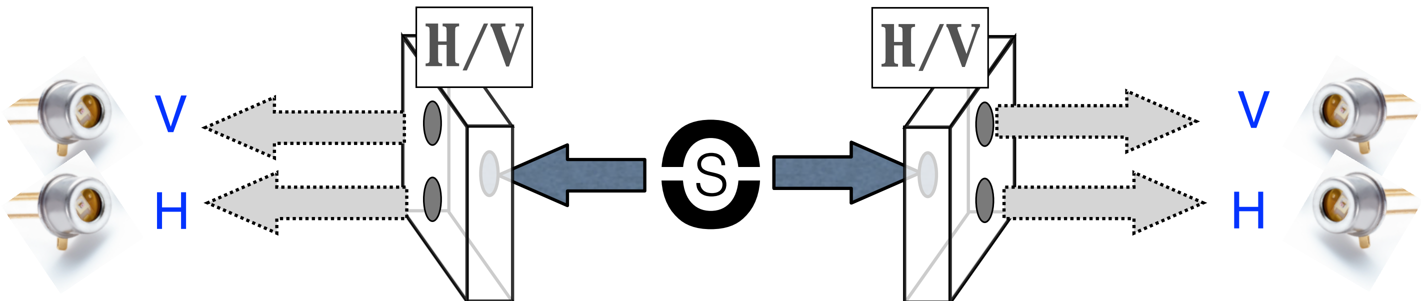
Correlations in **Photon Polarization** Experiments

Two photons are emitted from a common source. They might have correlated behavior.



"Alice"
Alicia Keys famous musician

"Bob"
Nobel prize-winning Bob Dylan

Do you expect correlations between Bob's and Alice's measurement outcomes?

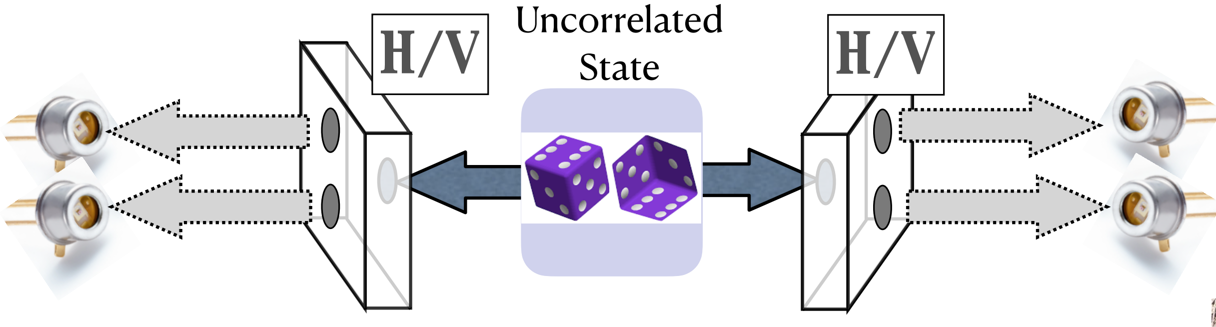
Consider a **quantum state** where the H/V-properties show **no correlation**: When Alice's shows V, Bob's shows H or V equally

Alice's outcome called W

W=-1

or +1

Random Uncorrelated State



Bob's outcome called Y

Y=-1

or +1

Inherent-property table
for Alice's and Bob's electrons

	Alice H/V	Bob H/V
Run	Alice W	Bob Y
1	+1	-1
2	+1	+1
3	+1	-1
4	-1	-1
5	+1	-1
6	-1	-1
7	-1	+1
8	+1	+1
9	-1	+1
10	+1	+1
11	+1	-1
12	U	D

The outcomes for
Alice and Bob separately
are perfectly random
(mean value = 0)

Compute correlations; denote
H as +1 and V as -1.

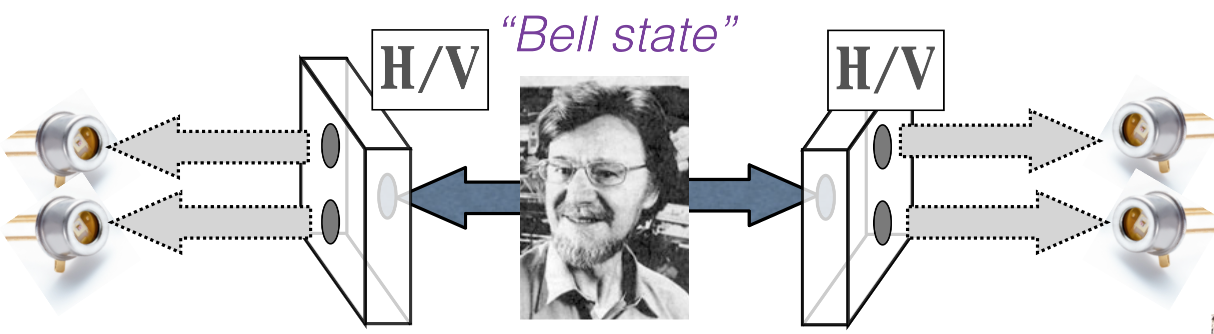
Average of Product
Ave(W x Y)=0

Now Consider a new state preparer *John Bell* who makes the H/V properties have **perfect anti-correlation**:
when Alice's shows V, Bob's shows H

Alice's outcome called W

W=-1

or +1



Bob's outcome called Y

Y=-1

or +1

Inherent-property table
for Alice's and Bob's electrons

Alice H/V   Bob H/V

Run	Alice W	Bob Y
1	+1	-1
2	+1	-1
3	+1	-1
4	-1	+1
5	+1	-1
6	-1	+1
7	-1	+1
8	+1	-1
9	-1	+1
10	+1	-1
11	-1	+1
12	U	D

The outcomes for
Alice and Bob separately
still appear perfectly <u>random</u>
(mean value = 0)

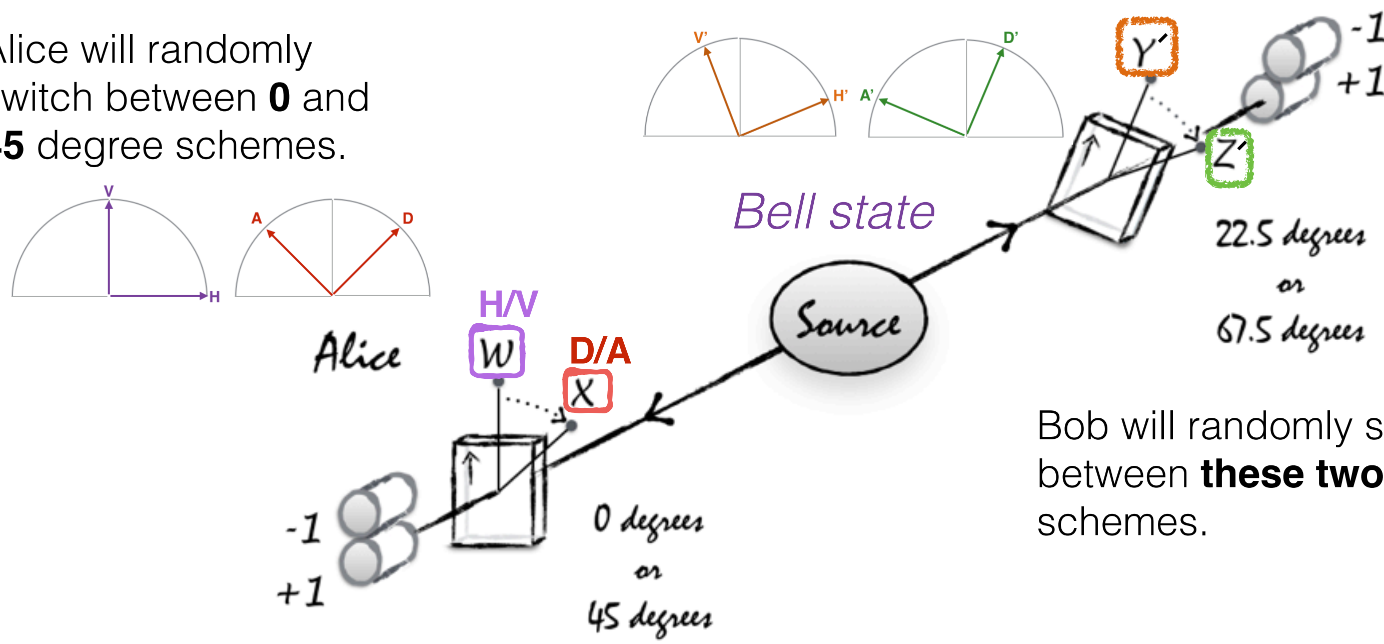
Compute correlations; denote
H as +1 and V as -1

Average of Product
Ave(W x Y)= **-1**

NOW FOR THE MAGIC TRICK

On a given run, Alice and Bob can measure only one property each, of their choice

Alice will randomly switch between **0** and **45** degree schemes.



Bob will randomly switch between **these two** schemes.

define: Ave Q = Ave W×Y' + Ave W×Z' + Ave X×Y' – Ave X×Z'

Alice H/V = W

Alice D/A = X

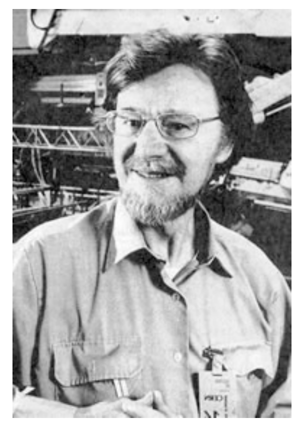
Bob H'/V' = Y'

Bob D'/A' = Z'

Ave Q = Ave W×Y' + Ave W×Z' + Ave X×Y' – Ave X×Z'

One might think:
Bell's Classical Inequality should hold for photon polarization

Under the assumptions of inherent properties or instructions, No matter what state is prepared, and "no conspiracies" or "rigging", the Average(Q) cannot be greater than 2

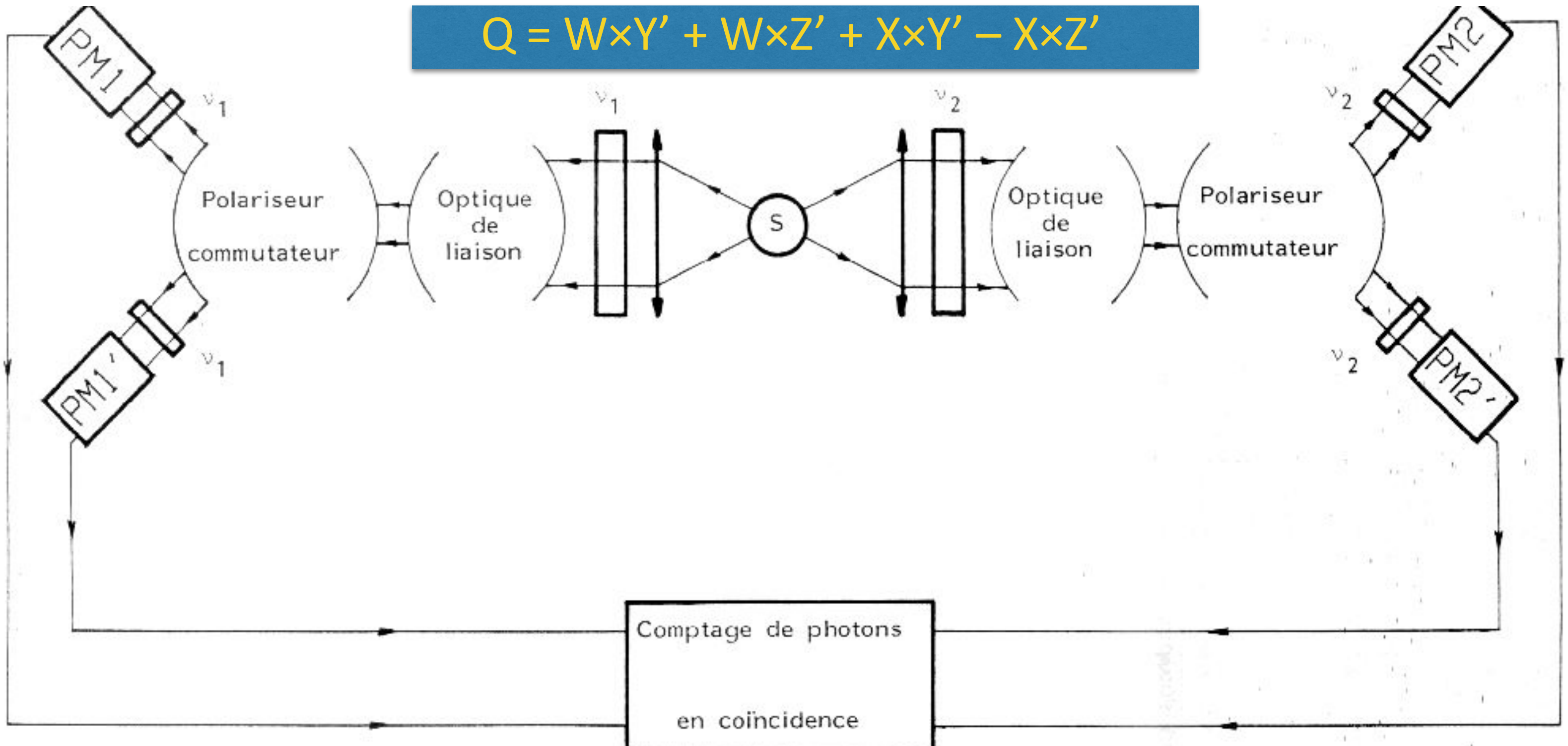


John Bell

pre-determined measurement outcomes

Bell-Test Experiments were carried out by a few groups: John Clauser in 1974. Alain Aspect 1982

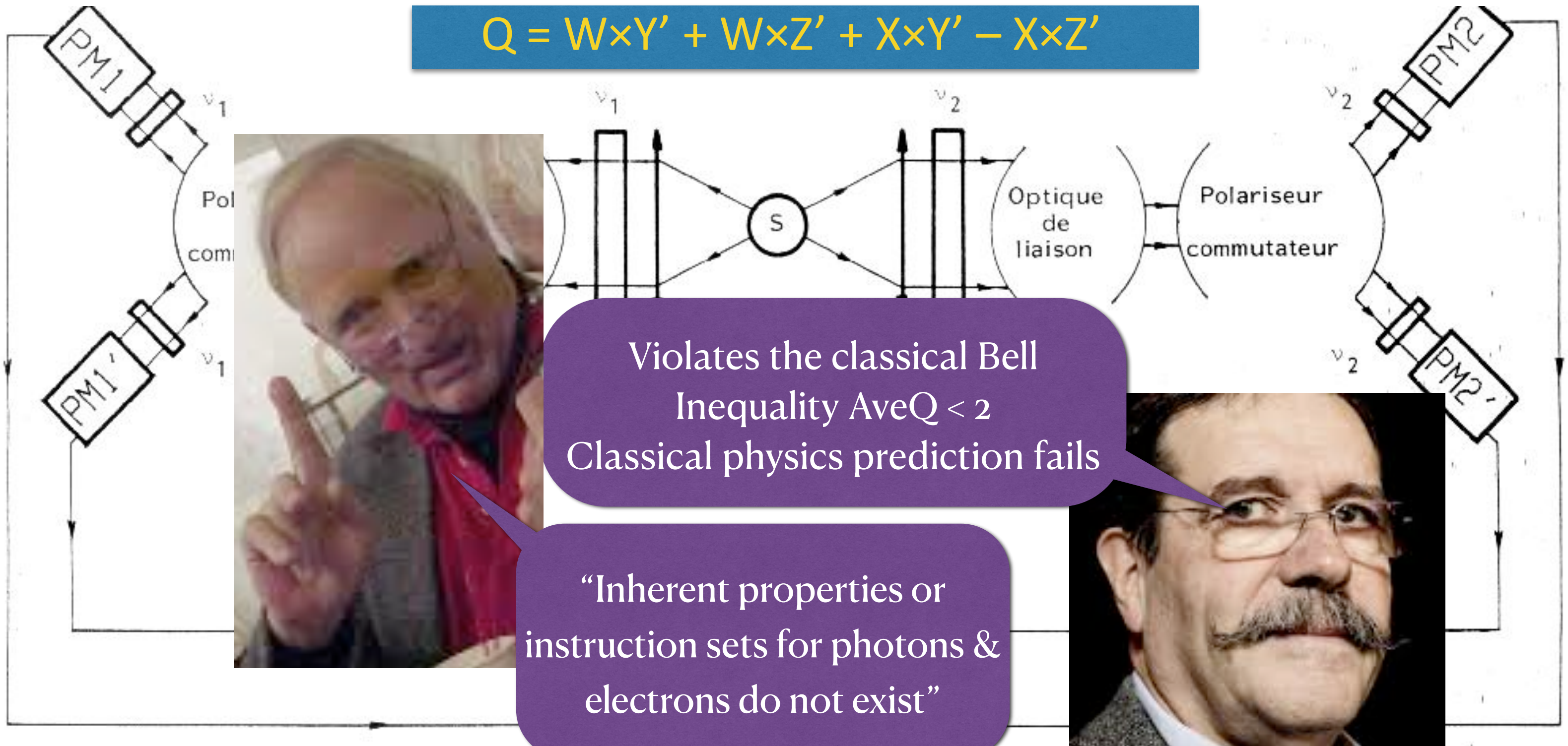
$$Q = W \times Y' + W \times Z' + X \times Y' - X \times Z'$$



W	X	Y'	Z'	W x Y'	W x Z'	X x Y'	X x Z'	Ave(Q)
	1		1				1	
1		-1		-1				
	-1		1				-1	
-1			-1		1			AveQ > 2
Experimental results for averages:				~0.7	~0.7	~0.7	~ - 0.7	2.8

Bell-Test Experiments were carried out by a few groups: John Clauser in 1974. Alain Aspect 1982

$$Q = W\times Y' + W\times Z' + X\times Y' - X\times Z'$$



W	X	Y'	Z'	W x Y'	W x Z'	X x Y'	X x Z'	Ave(Q)
	1		1				1	
1		-1		-1				
	-1		1				-1	
-1			-1		1			AveQ > 2
Experimental results for averages:				~0.7	~0.7	~0.7	~ - 0.7	2.8

2015-2017 UPDATE - Closing three possible "logical loopholes":

1. Maybe there is some unknown phenomenon that can send information between Alice's and Bob's setups, allowing a hidden coordination or 'conspiracy' unknown to physics.

Closing the loophole: Separate the two labs by a large distance and switch the measurement settings after the photons have departed from the source. (Light travels at 1 foot per ns.)

2. Maybe the detectors, which have limited detection efficiency (e.g. 80%), fail to detect photons under some 'conspiracy' scheme, selecting only those events that lead to 'rigged' results.

Closing the loophole: Use detectors with near 100% detection efficiency.

3. Maybe the experimenters' (or their computers') choices of measurement settings were being controlled by some external agent.

Closing the loophole: Switch the analyzer settings after the particles left the source in the experiment by using the random polarizations of photons from two distant stars. The starlight was created over 500 years ago, well before quantum theory was even invented!

In 2015 to 2017 all these experiments were done and they still observed Q = 2.8, violating the **classical prediction** the Bell Inequality (Q<2).

"Strictly speaking the experiments show that the combination of realism, causal locality, and measurement independence can't exist!"

Common Sense Questions That Look Easy ...
chartcons.com

"Obviously realism, causal locality, and measurement independence exist!"

I did the experiment.

"Strictly speaking the experiments show that the combination of realism, causal locality, and measurement independence can't exist!"

The Bell Inequality is based on common sense.
But careful scientific reasoning with experiments can override common sense.

Quantum Entanglement

Quantum theory provides an explanation for correlations that works!
The state description obeys local causality, but must be “global.”
(Holistic - the whole does not equal the sum of parts)

A pair of photons can be prepared in the entangled Bell state ψ = (V)&(H) + (-H)&(V), and quantum theory predicts exactly the correlations observed in the Bell Test experiments.

The experiments validate quantum theory and the fact that entangled states are an actual (‘real’) aspect of nature, which suggests that quantum states allow information processing and communication beyond what is possible with classical states.

NEXT: Bell-State Measurements provide the basis of Quantum Network operations.

END PART 3

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5 minute break

The Physics Behind the Quantum Internet

PART 4

THE QUANTUM INTERNET

UNIVERSITY OF OREGON

Center for Quantum Networks NSF-ERC

SHORT COURSE (4 HR) OUTLINE

PART 1: Quantum information science
The Center for Quantum Networks
The National Quantum Initative
What is *information*?
Bits and qubits
Superposition and entanglement

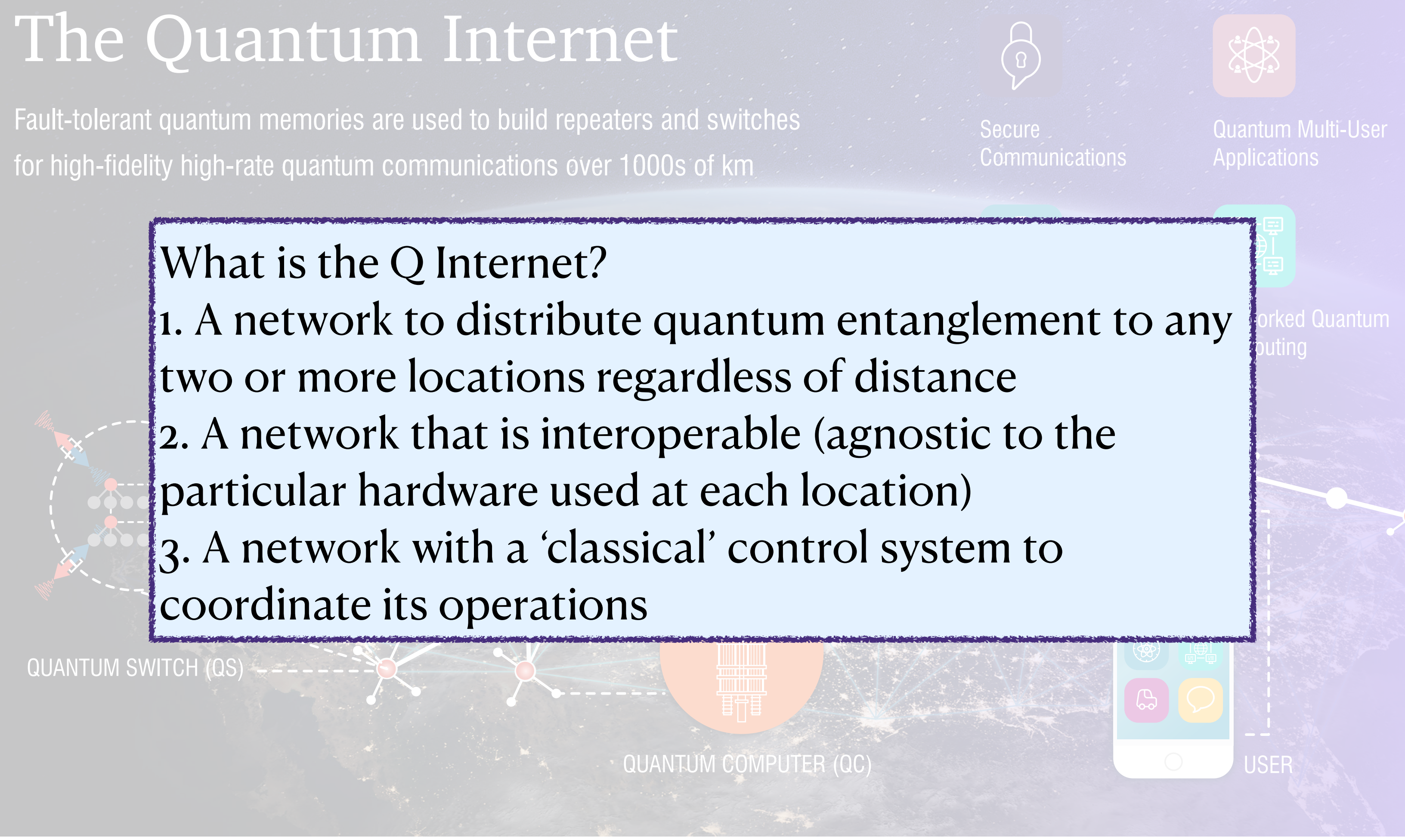
PART 2: Encoding and transmitting quantum information
Communication systems
Distributing Entangled states (e.g.. in Space)
Ways of encoding qubits
Ways of encoding qubits in photons (Flying qubits)
Quantum state teleportation
Space-based quantum networks

PART 3: Bell State measurements
Photon polarization revisited
Quantum measurement - Born's Rule
Correlations and the Bell inequality
Bell-Test experiments

➡ **PART 4: The Quantum Internet**
Application #1: Quantum Cryptography
Bell-State Creating and Measuring
Quantum memories
Application #2: Memory-Assisted Teleportation
Entanglement Swapping with Quantum Memories
Quantum repeater networks
What could a quantum Network do?
Perspectives and misconceptions

The Quantum Internet

Fault-tolerant quantum memories are used to build repeaters and switches for high-fidelity high-rate quantum communications over 1000s of km



What is the Q Internet?

1. A network to distribute quantum entanglement to any two or more locations regardless of distance
2. A network that is interoperable (agnostic to the particular hardware used at each location)
3. A network with a ‘classical’ control system to coordinate its operations

Center for Quantum Networks

SKIP IF NEEDED

Quantum Cryptography

The Information Privacy Problem

Message sender → Message recipient

Eavesdropper

Alice

Eve

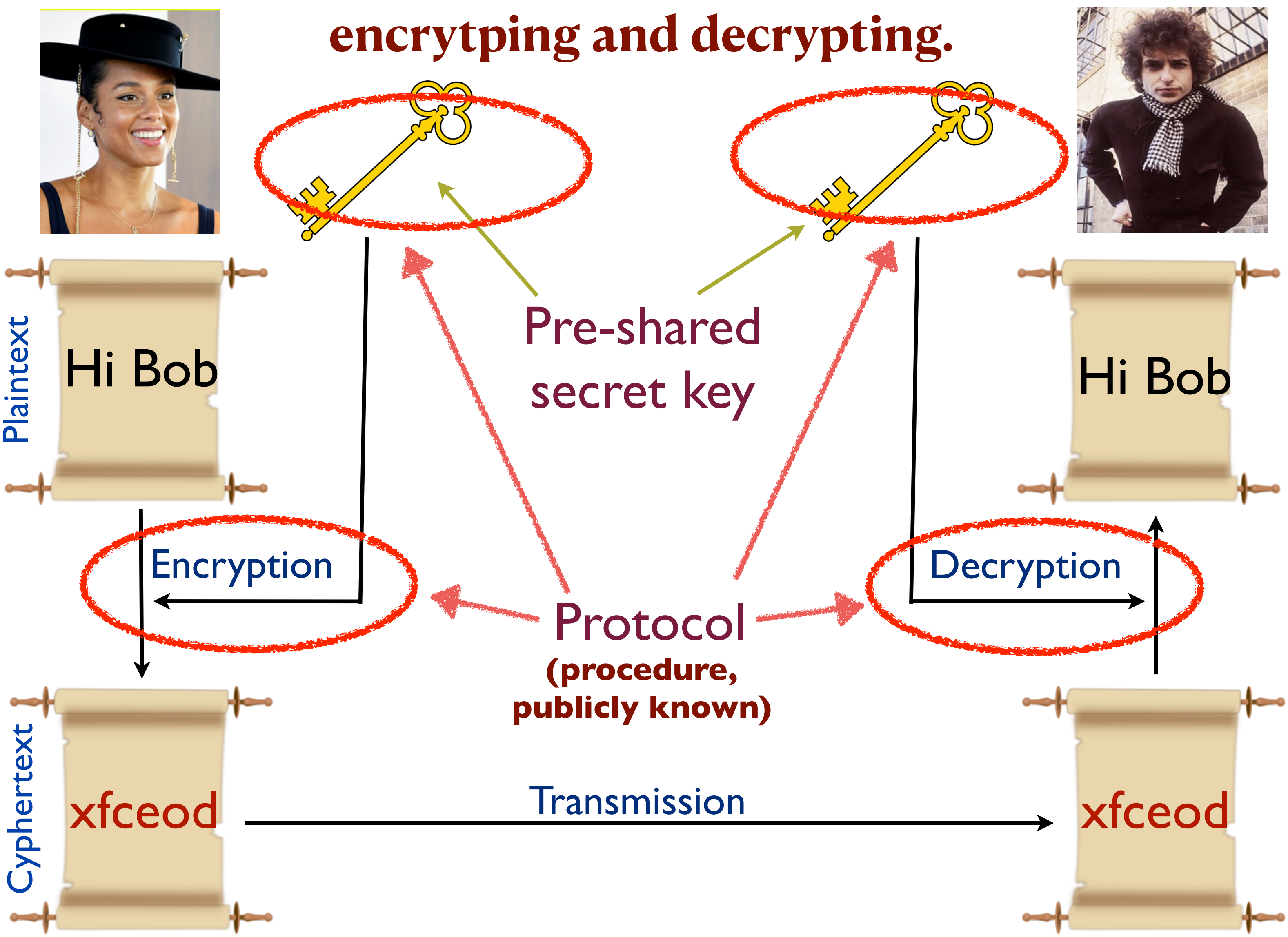
Bob

Alice and Bob want to share a secret message.

But the message can be intercepted!

Alice and Bob need to SHARE a "KEY" for encrypting and decrypting.

Alice and Bob need to SHARE a method of encrytping and decrypting.



optional

1 Alice: Encode message into binary (bits) using ASCII
2 Alice: Encrypt coded message using a Shared Key
3 Alice: Transmit
4 Bob: Receive
5 Bob: Decrypt using same key
6 Bob: Convert received ASCII back to message

To ensure total secrecy: Use a different key number for each bit in the message

message: "240" convert to ASCII -> 11110000

Key Rules:
1 (flip 0→1, 1→0)
0 (leave unchanged)

key:	1 0 1 0 1 0 1 0
original message:	1 1 1 1 0 0 0 0
encrypted message:	_ _ _ _ _ _ _ _

QUESTION What is the encrypted message?

30 seconds

optional

1 Alice: Encode message into binary (bits) using ASCII
2 Alice: Encrypt coded message using a Shared Key
3 Alice: Transmit
4 Bob: Receive
5 Bob: Decrypt using same key
6 Bob: Convert received ASCII back to message

Key Rules:
1 (flip 0→1, 1→0)
0 (leave unchanged)

encrypted message: 0 1 0 1 1 0 1 0

key: 1 0 1 0 1 0 1 0

↓ ↓ ↓ ↓ ↓ ↓ ↓ ↓

_ _ _ _ _ _ _ _

QUESTION What is the original message?

30 seconds

11110000 convert from ASCII -> message: “240”

Quantum Cryptography

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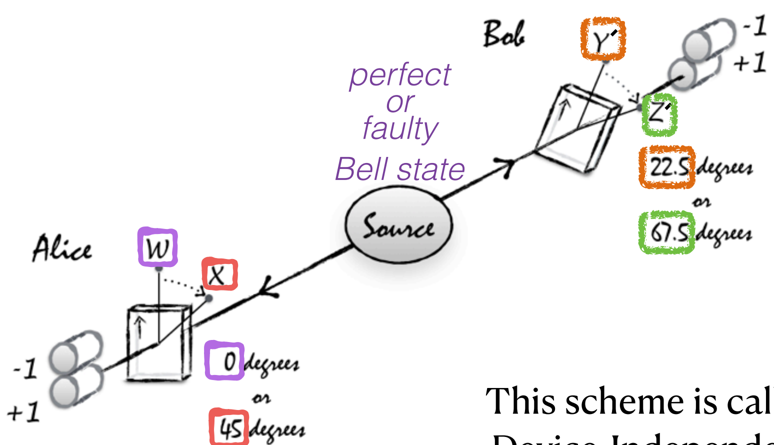
Alice and Bob can generate a secret shared encyption key
by making Bell State Measurements on entangled pairs

The source generates Bell States, whose measurement outcomes are quantum correlated in a manner not possible in classical physics

The source and measurement devices can even be somewhat faulty. If Alice and Bob are able to verify that the measurement outcome statistics violate the Bell inequality, then they can use the outcome data to generate a shared key.



Alice and Bob can be at distant locations

This scheme is called
Device-Independent
Quantum Key Distribution
(QKD)

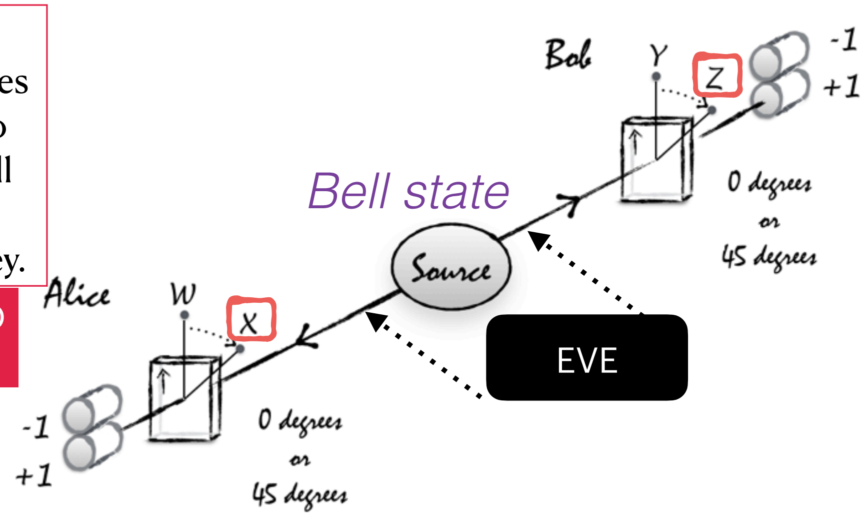
OPTIONAL

Quantum Cryptography

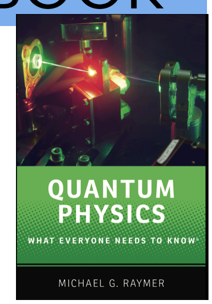
Quantum Key Distribution (QKD)

Or they can use measurement choices that do not lead to violation of the Bell inequality but still generate a secret key.

CORRECTION TO SLIDE



for a simpler scheme see DETAILS IN THE BOOK

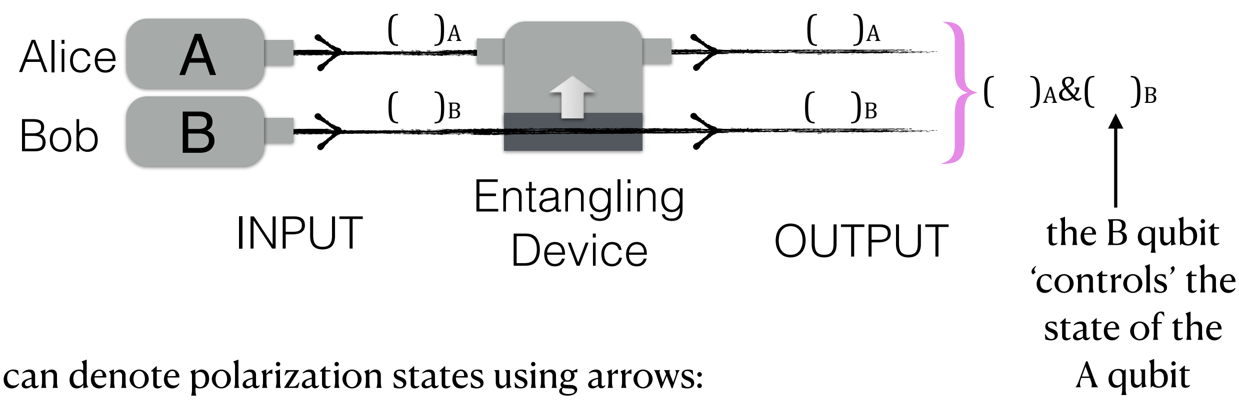


Alice Setting (deg)	Alice Outcome		Bob Setting (deg)	Bob Outcome	Key
45	+1	match	45	+1	+1
0	+1		0	+1	+1
0	-1	mismatch	45	-1	
45	+1	eve	45	-1	
0	-1		0	-1	-1
45	-1		0	-1	
45	-1		45	-1	-1
45	+1		0	+1	
0	+1		0	+1	+1

Creating Bell States

Consider an Entangling Device that operates according to the Rules:

1. If the B photon is H-pol, the A photon's polarization is unchanged.
2. If the B photon is V-pol, the A photon's polarization is "rotated" by minus 90 degrees.
3. The B photon's polarization is unchanged in either case.



We can denote polarization states using arrows:

(H) = (→)

(V) = (↑)

(D) = (↗)

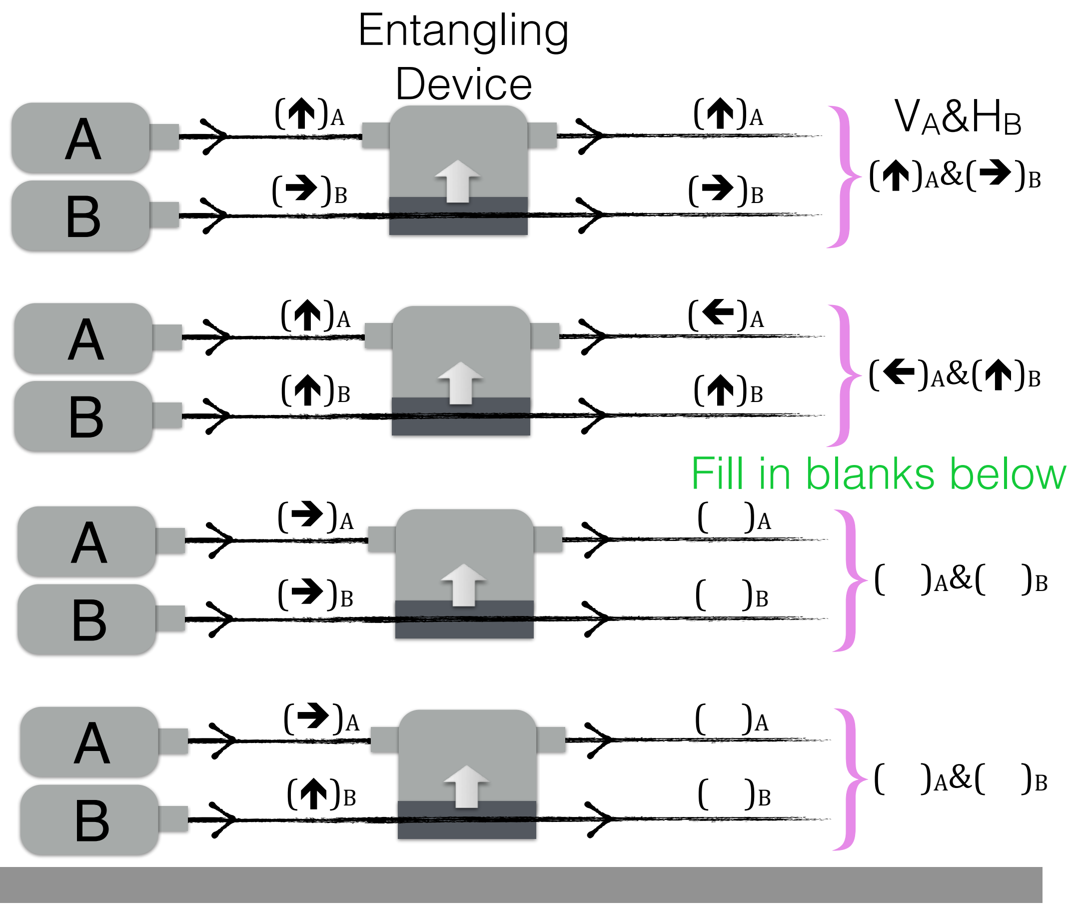
(A) = (↖)

Then:

(↗) = (→) + (↑)

(↗) = (→) + (↑)

1. If the B photon is H-pol, the A photon's polarization is unchanged.
2. If the B photon is V-pol, the A photon's polarization is "rotated" by minus 90 degrees.
3. The B photon's polarization is unchanged in either case.



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1. If the B photon is H-pol, the A photon's polarization is unchanged.
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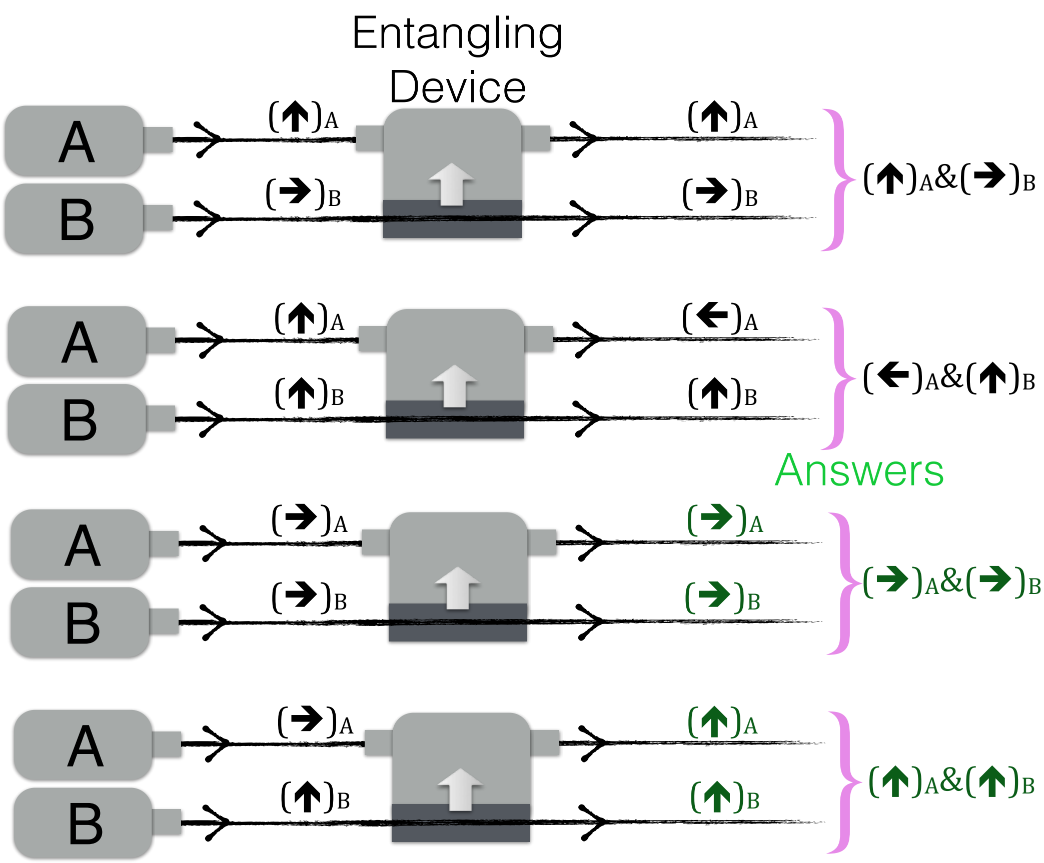


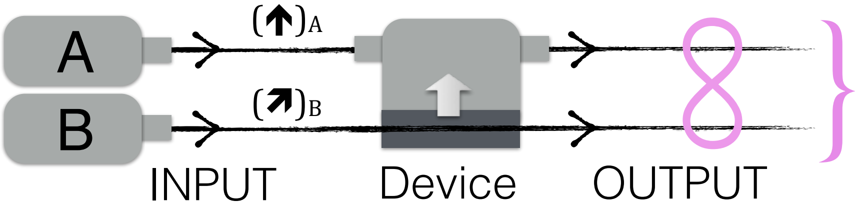
POLL QUESTION 13

D = H + V

Input at B the superposition state (↗)$_B$= (→)$_B$ + (↑)$_B$

Recall the Rules:

1. If the B photon is H-pol, the A photon's polarization is unchanged.
2. If the B photon is V-pol, the A photon's polarization is "rotated" by minus 90 degrees.
3. The B photon's polarization is unchanged in either case.



What is the Composite Output State?

The device is a CNOT Gate

A: (↑)$_A$&(→)$_B$

B: (←)$_A$&(↑)$_B$

C: (↑)$_A$&(→)$_B$ + (←)$_A$&(↑)$_B$

D: I don't know

PROOF: INPUT STATE IS:

(↑)$_A$& (↗)$_B$ which is same as:

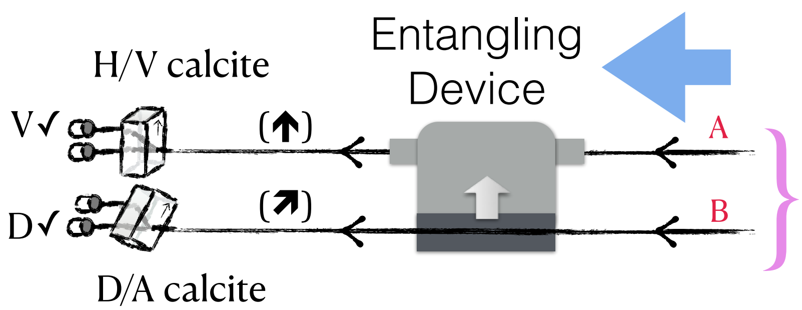
(↑)$_A$&(→)$_B$ + (↑)$_A$&(↑)$_B$

which becomes:

(↑)$_A$&(→)$_B$ + (←)$_A$&(↑)$_B$

Bell State Disentangler

To verify you have a particular Bell State prepared, use a **Bell State Disentangler**:
Send the photon pair **from right to left** to undo the entangling operation.



Example:
Want to verify you have this particular Bell State

$(\uparrow)_A \& (\rightarrow)_B + (\leftarrow)_A \& (\uparrow)_B$

If the B photon is V-pol, the A photon's polarization is "rotated" by plus 90 degrees.

$(\uparrow)_A \& (\rightarrow)_B + (\uparrow)_A \& (\uparrow)_B$

same as $(\uparrow)_A \ \& \ [(\rightarrow) + (\uparrow)]_B$

same as $(\uparrow)_A \ \& \ (\nearrow)_B$

$(V)_A \ \& \ (D)_B$

Measure photon polarization using calcite crystals and detectors

(note: the book has an error in the drwaing at the far left)

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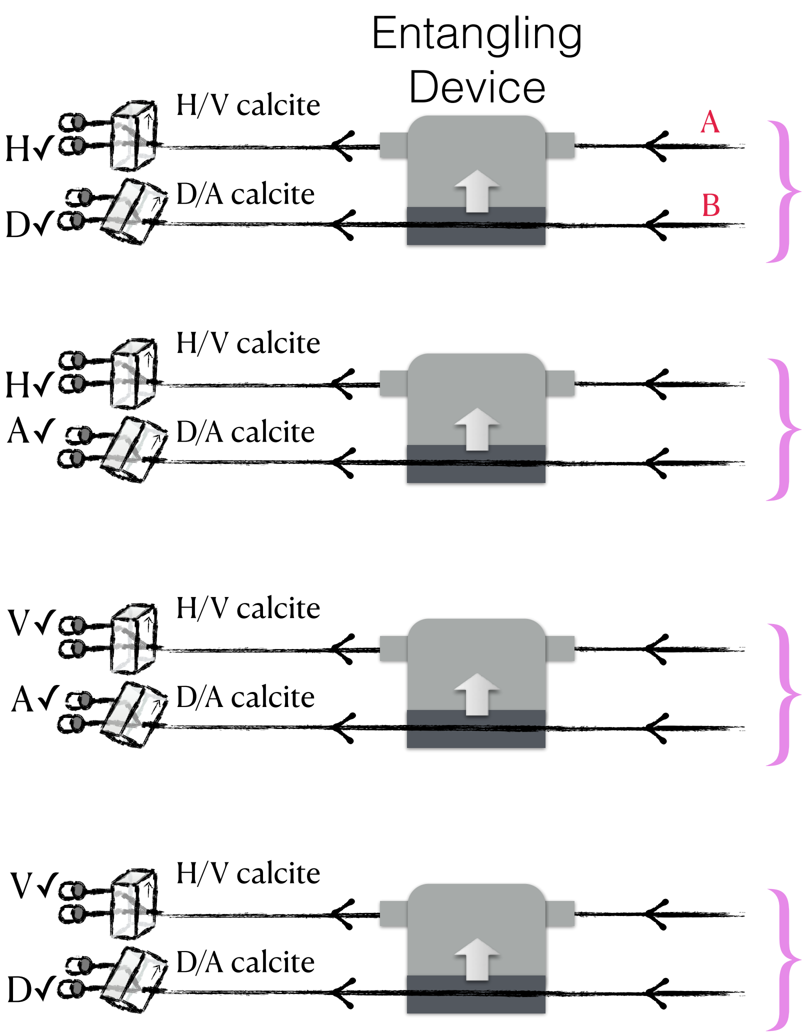
Bell State Measurement (BSM)



If you know you have our of the four Bell States:

BS_1 = (H & H) + (V & V)

A B A B

If the B photon is V-pol, the A photon's polarization is "rotated" by plus 90 degrees.

BS_2 = (H & H) - (V & V)

BS_3 = (H & V) + (V & H)

BS_4 = (H & V) - (V & H)

Measuring Bell States

A **Bell State Measurement** is a joint measurement of two qubits that determines which of the four Bell states the two qubits were prepared in.

(An example of the Joint Measurement we discussed for State Teleportation)

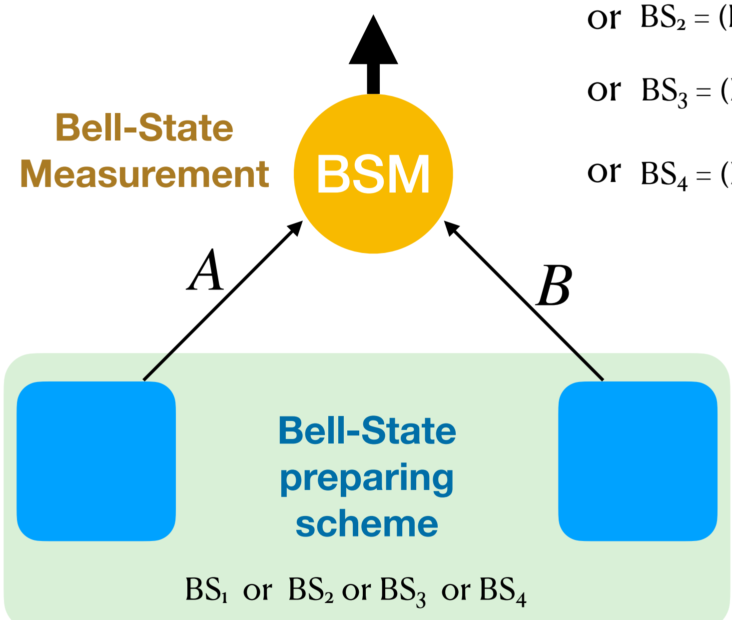
OUTCOME:
The pair was prepared in: $BS_1 = (H \,\&\, H) + (V \,\&\, V)$

or $BS_2 = (H \,\&\, H) - (V \,\&\, V)$

or $BS_3 = (H \,\&\, V) + (V \,\&\, H)$

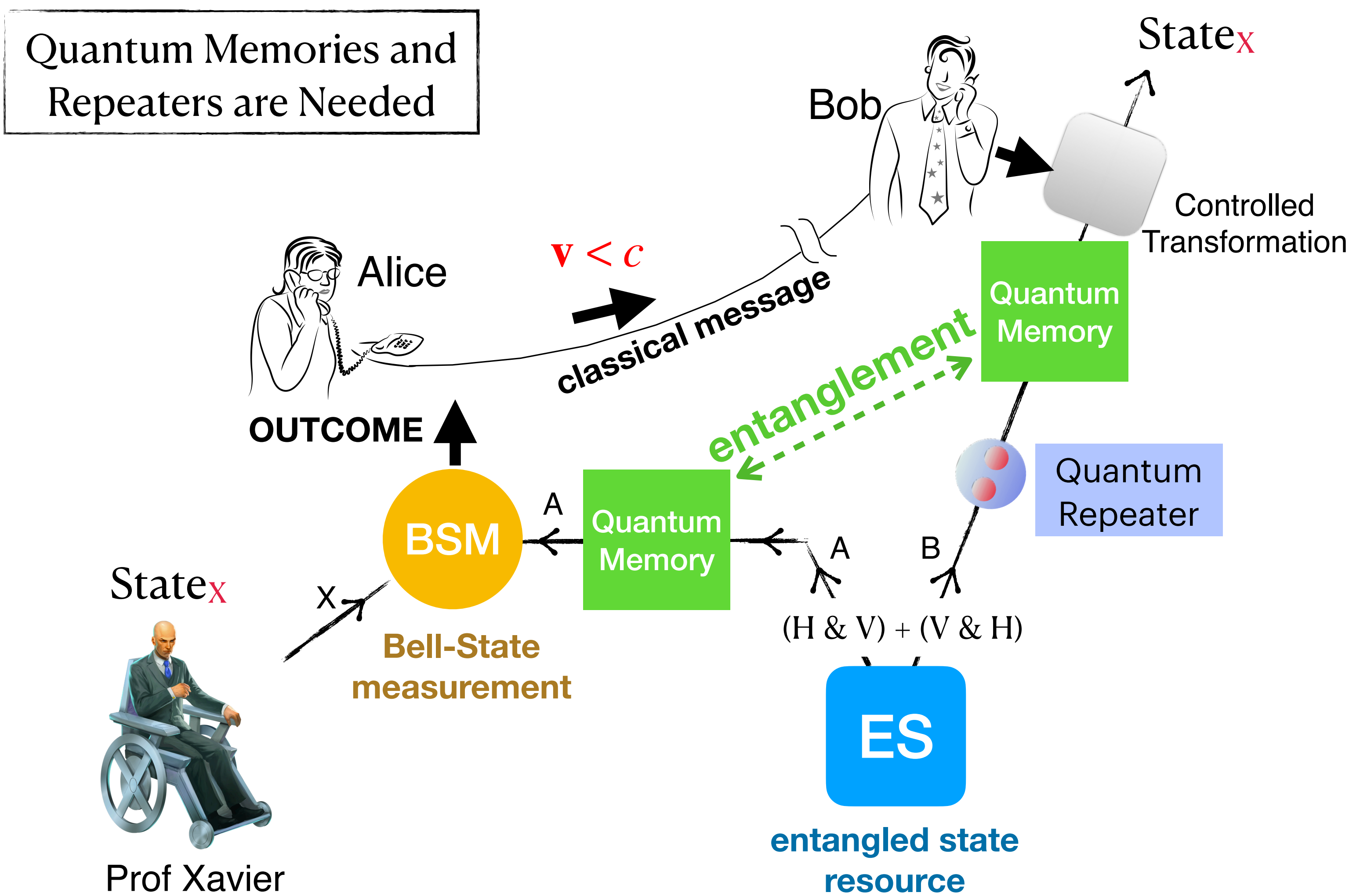
or $BS_4 = (H \,\&\, V) - (V \,\&\, H)$

Joint Measurement = **Bell-State Measurement**



I won't attempt to explain here how the BSM is carried out.

Memory and Repeater-Assisted State Teleportation



Why are Quantum Memories and Repeaters Needed?

Light is lost as it travels in a fiber by absorption and scattering.

For telecom (Near-IR) wavelength = 1550 nm, typical loss rate = 0.5 dB/km

The decrease is exponential with length:

after 20 km the power is decreased by a factor = 10 dB, which is a factor of 10

after 40 km the power is decreased by a factor = 20 dB, which is a factor of 100

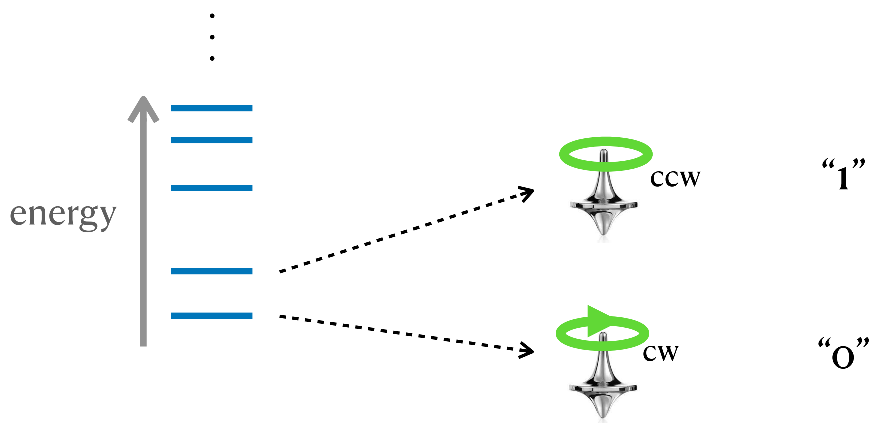
after 60 km the power is decreased by a factor = 30 dB, which is a factor of 1,000

after 80 km the power is decreased by a factor = 40 dB, which is a factor of 10,000

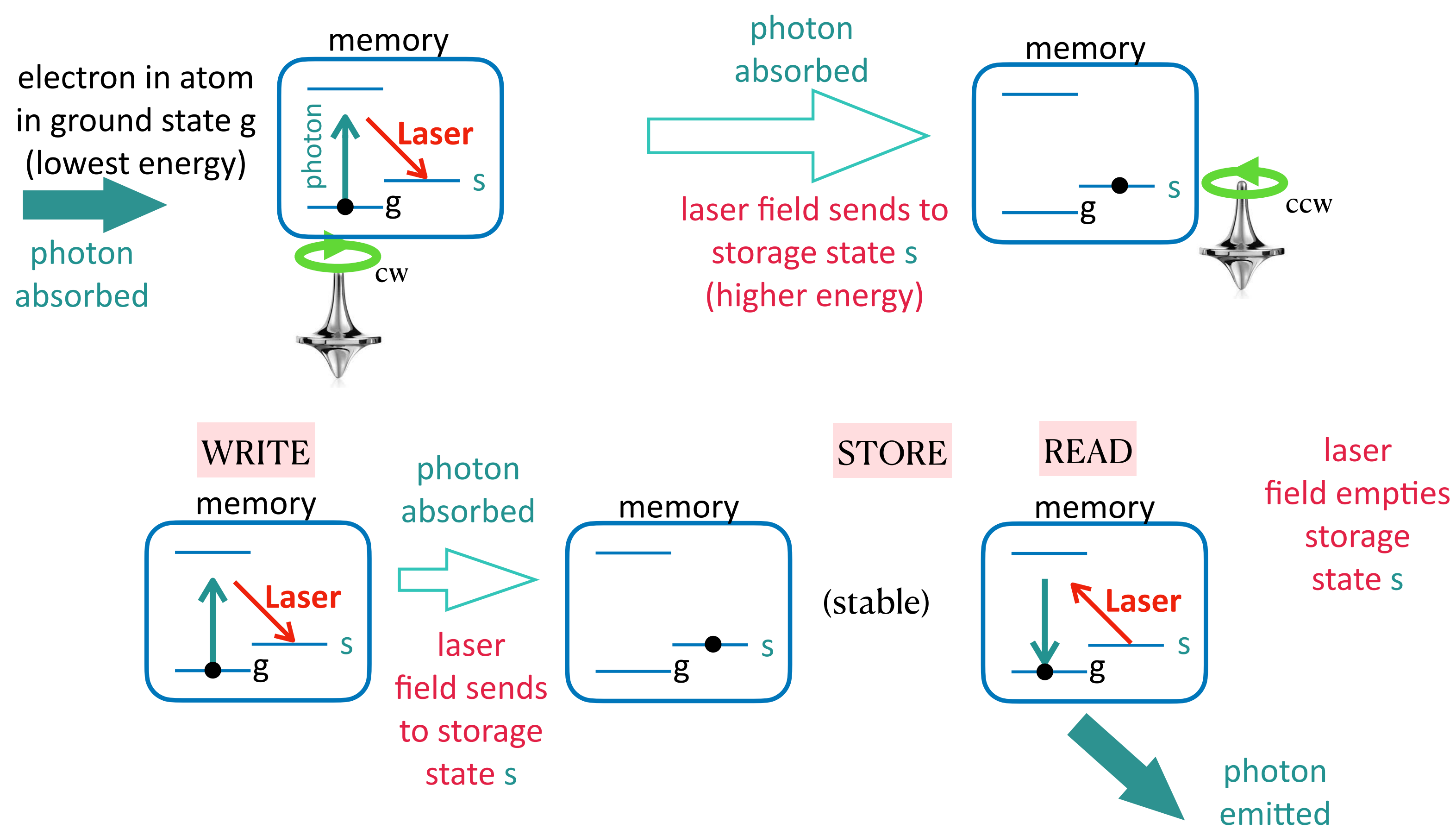
Quantum Memories

An electron in an atom can store
a qubit value in its spin state

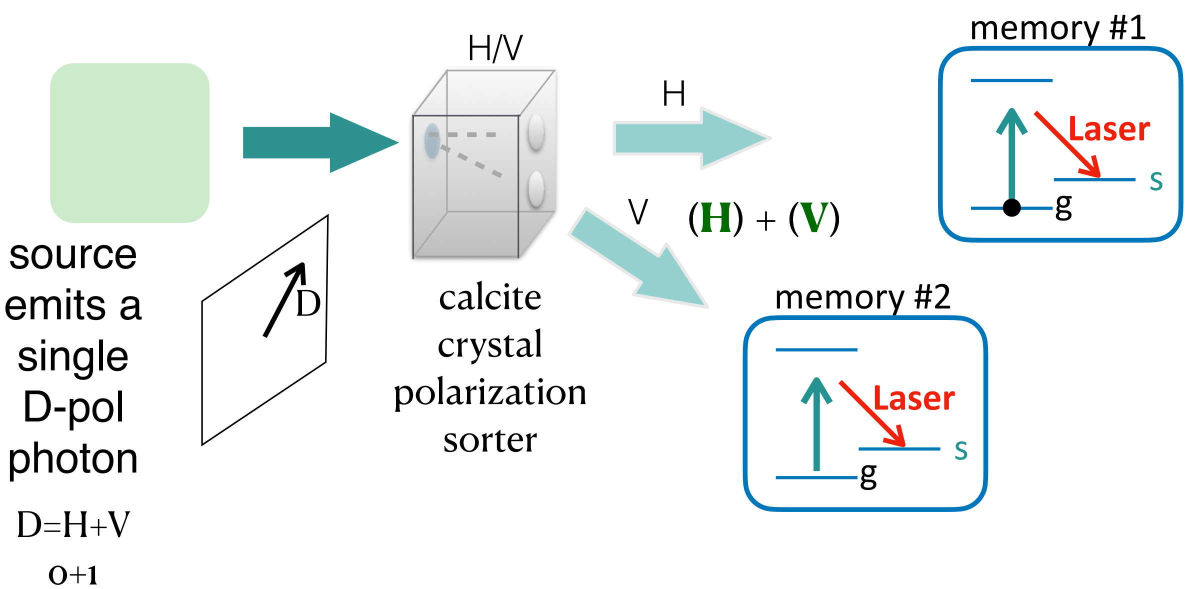
energy
is
quantized



Quantum Memories



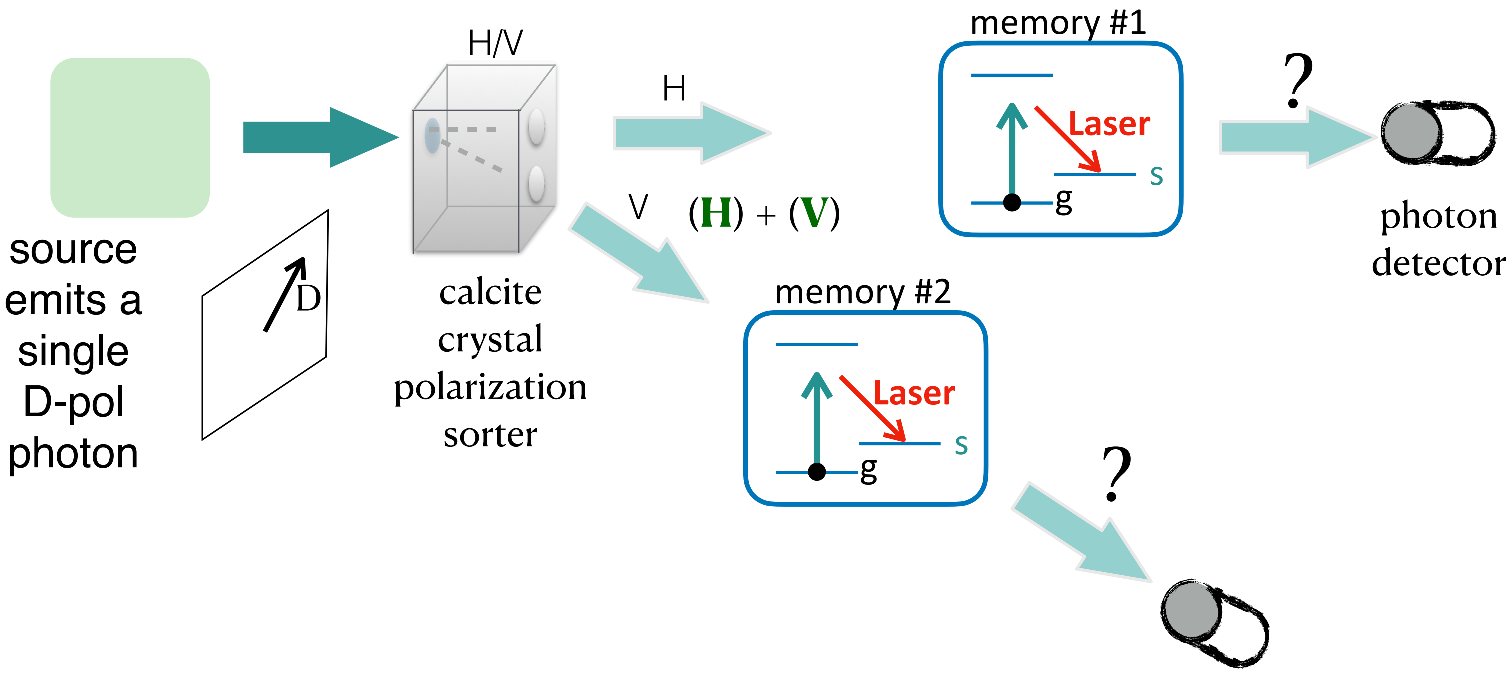
Quantum Memory Storage of Photon Polarization



Resulting state of the two Memories = (**s** & g) + (g & **s**)

A Photon Polarization State is stored in the entangled state of the Memories

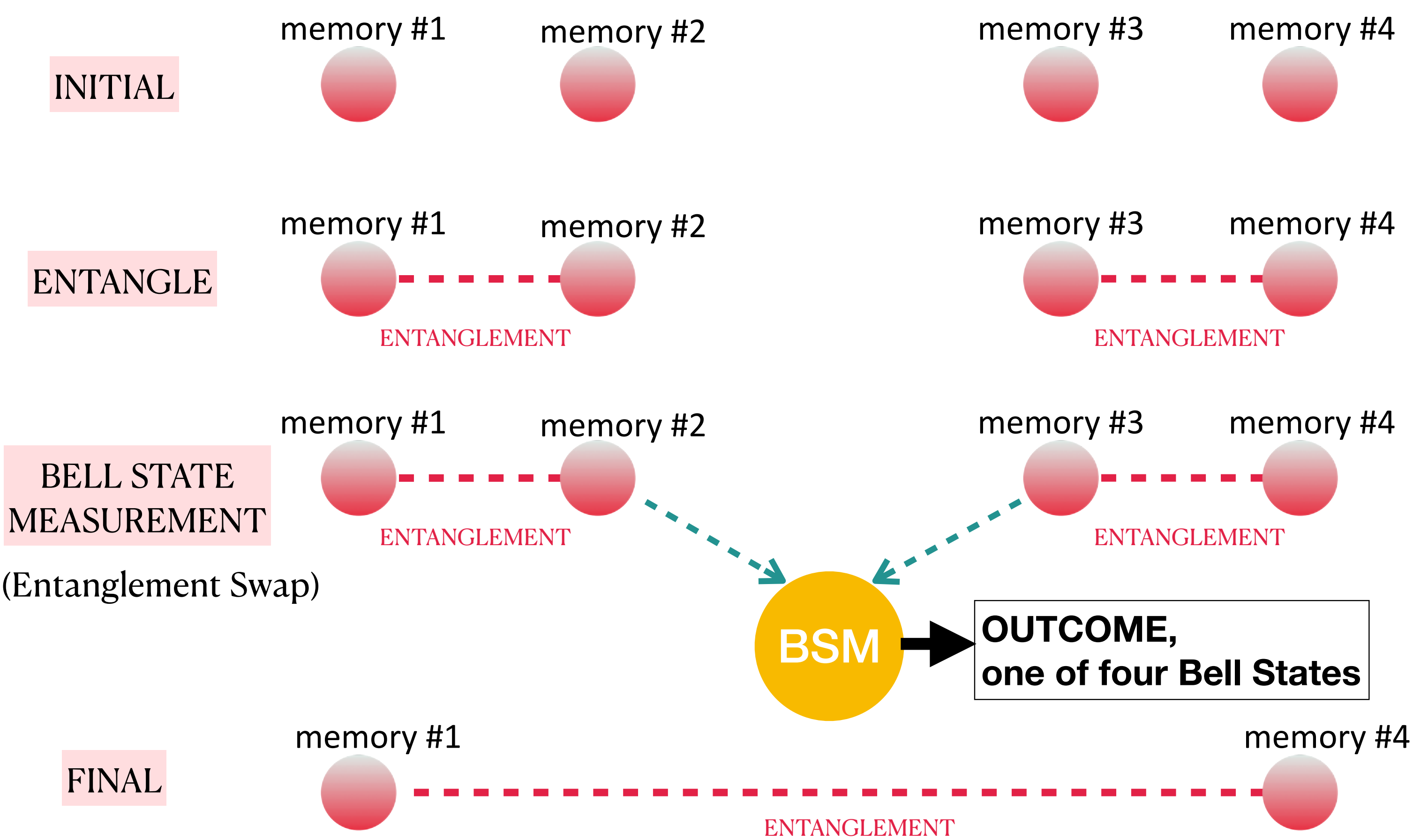
How to verify entanglement has been created between the memories?



If both detectors register no photon, we know entanglement has been created between the memories.

The probability of success is denoted p.

Representation of Entanglement Swapping



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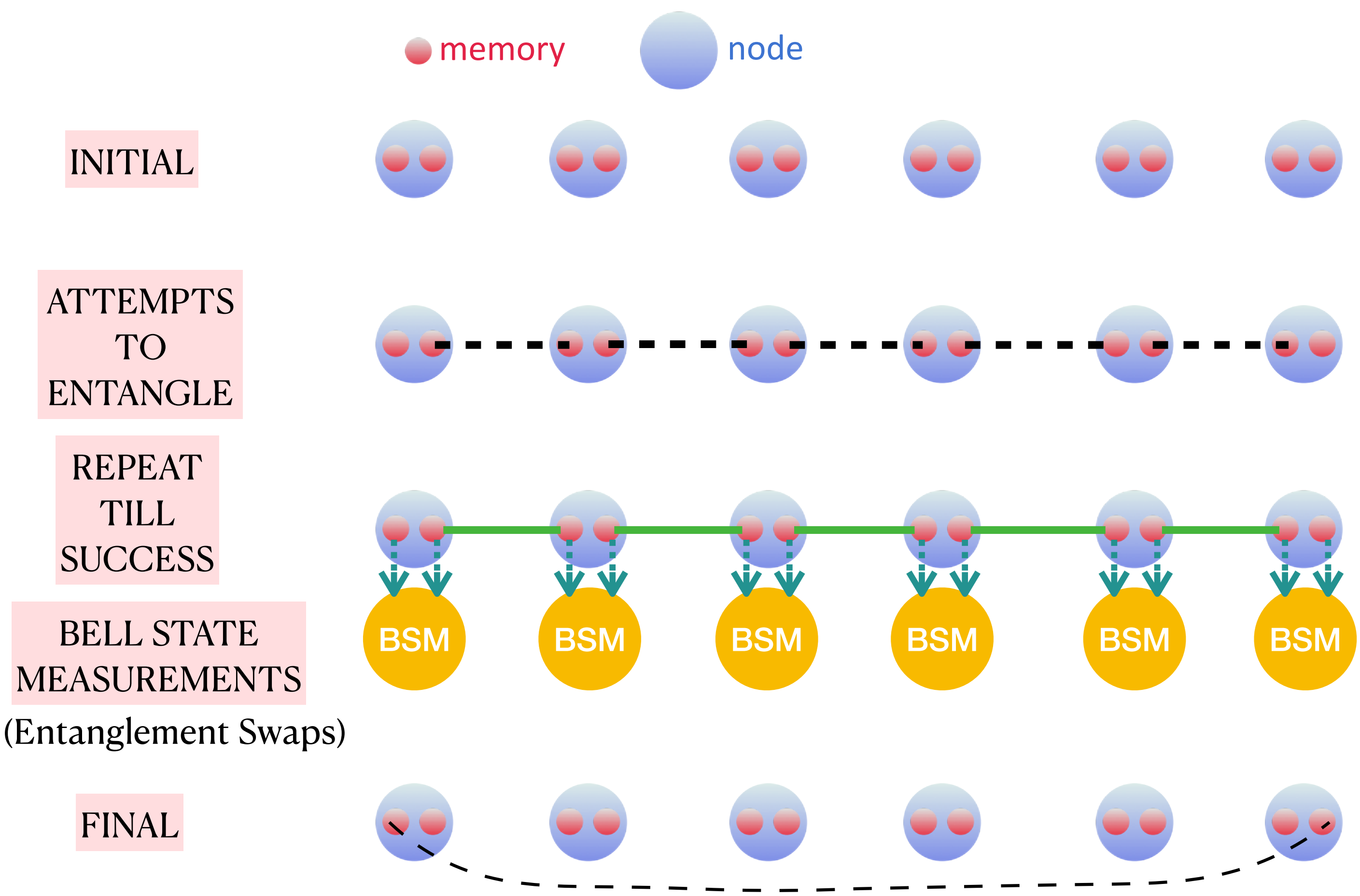
Creating a Chain Network of Entangled Memories



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Creating a Grid Network of Entangled Memories

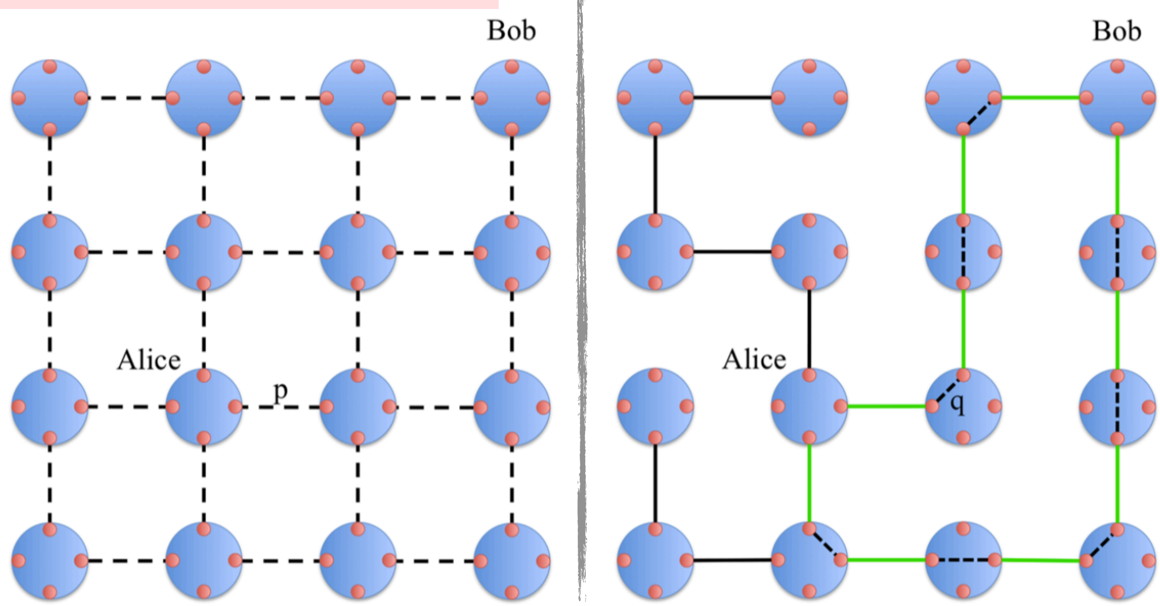
memory node

ATTEMPTS TO ENTANGLE USING BELL STATE MEASUREMENTS

PARTIAL SUCCESS

INITIAL

no entangled paths



FINAL

two entangled paths from Alice to Bob

Fig. 2 Schematic of a square-grid topology. The blue circles represent repeater stations and the red circles represent quantum memories. Every cycle (time slot) of the protocol consists of two phases. **a** In the first (external) phase, entanglement is attempted between neighboring repeaters along all edges, each of which succeed with probability *p* (dashed lines). **b** In the second (internal) phase, entanglement swaps are attempted within each repeater node based on the successes and failures of the neighboring links in the first phase—with the objective of creating an unbroken end-to-end connection between Alice and Bob. Each of these internal connections succeed with probability *q*. Memories can hold qubits for $T \geq 1$ time slots

Modeling by the Center for Quantum Networks:

Pant et al, npj Quantum Information (2019)5:25 ; https://doi.org/10.1038/s41534-019-0139-x

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What could a quantum Network do?

A global quantum network would allow the distribution of *quantum states* and *quantum entanglement*, enabling:

1. quantum key distribution (secure encryption)

2. blind/private quantum computing (without the computer recording)

3. private database queries (without the computer recording)

4. global timekeeping and synchronization

5. improved sensing (magnetic, electric and gravitational fields, medical, bio research, mineral exploration, atomic clocks, telescopes, very long baseline interferometric telescopes)

6. physics tests (e.g. quantum non-locality and quantum gravity)

7. distributed quantum computing (combining power of Q computers)

Christoph Simon, "Towards a global quantum network." Nature Photonics 11, no. 11 (2017): 678-680.

Mihir Pant, et al, Routing entanglement in the quantum internet, npj Quantum Information (2019)5:25 ; https://doi.org/10.1038/s41534-019-0139-x

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COMMON MISCONCEPTIONS

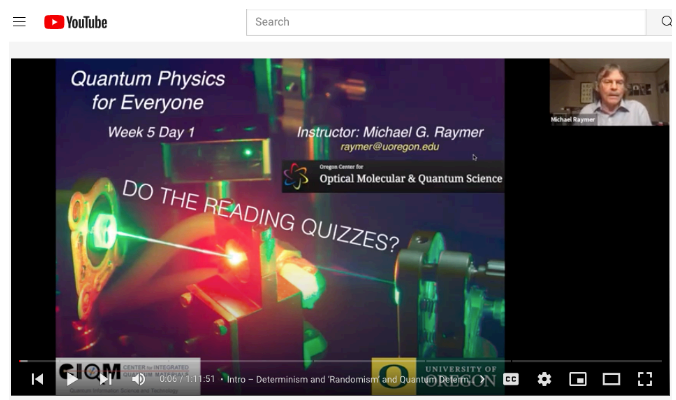
What will the Quantum Internet NOT do?

1. NOT: Faster than light communication

2. NOT: Causation across a distance

3. NOT greatly increase data rate (Mbytes per second) compared to classical networks

For 20 hour series of lectures, see
Quantum Physics for Everyone: Lectures 1 through 12
by MG Raymer
Harvard Center for Integrated Quantum Materials



Link to the course videos on youtube:
https://youtube.com/playlist?list=PLoCLfRiRFyPCTRxyINPShN-Z8RFpTKRRo

search YouTube for Quantum Physics for Everyone

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Course Evaluation Survey

We value your feedback on all aspects of this short course. Please go to the link provided in the Zoom Chat or in the email you will soon receive to give your opinions of what worked and what could be improved.

CQN Winter School on Quantum Networks

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