Center for
Quantum Networks
NSF Engineering Research Center

https://cqn-erc.org/

The Physics Behind the Quantum Internet: A Gentle Introduction

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2025 CQN Winter School on Quantum Networks

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POLL QUESTION 1

What is your highest level exposure to quantum theory?

A: Popular science media
B: Self-taught
C: High school
D: College
E: Graduate school

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

Type questions into the Q&A box, we will reply to as many as possible

SHORT COURSE (3.5 HR) OUTLINE

PART 1: Quantum information science

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

PART 2: Encoding and transmitting quantum information

Communication systems
Distributing Entangled states
Ways of encoding qubits
Ways of encoding qubits in photons
Focus on photon polarization
State vector representation and Born's Rule
Bell states
Quantum cryptography

PART 3: Quantum state teleportation

Joint measurement
Quantum state teleportation
Why entenglement distribution?

PART 4: The Quantum Internet

Why the quantum internet?
Bell State Creation and Measurement
Quantum memories
Memory-Assisted Teleportation
Entanglement Swapping with Quantum Memories
Quantum repeater networks
What could a quantum Network do?
Perspectives and misconceptions

The Physics Behind the Quantum Internet

PART 1

QUANTUM INFORMATION SCIENCE

Presenter: Michael Raymer
University of Oregon

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?*

- In the context of computer science:
    - *Technical Information* is the set of *symbols* that are sent.

Information Theory answers questions like:

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

Encoding decimal numbers using binary numbers (bits)

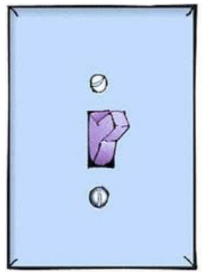
0	0000
1	0001
2	0010
3	0011
4	0100
5	0101
6	0110
7	0111
8	1000
9	1001
10	1010

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

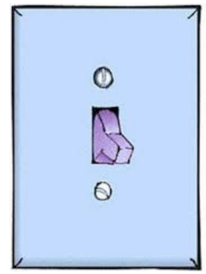
What is a Bit?

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

Ordinary bit:



or



"1" **"0"**

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

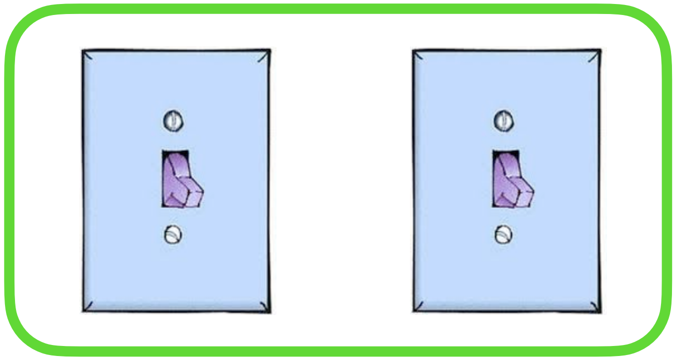
We call the <u>condition</u> of the switch its ***STATE***

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

POLL QUESTION 2

A Memory Cell contains Two classical bits:

memory cell



Green Box = Classical Memory Cell

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

A: 2

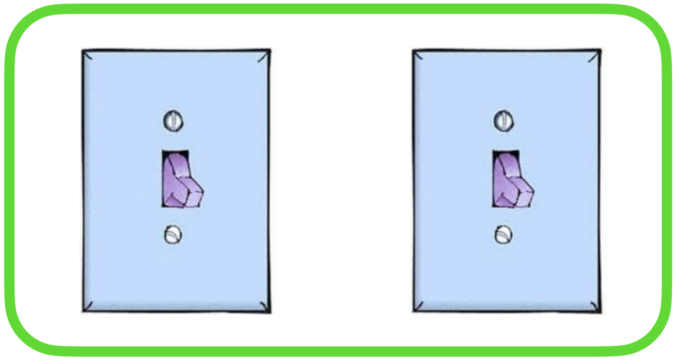
B: 4

C: 8

POLL QUESTION 2

A Memory Cell contains Two classical bits:

memory cell



Green Box = Classical Memory Cell

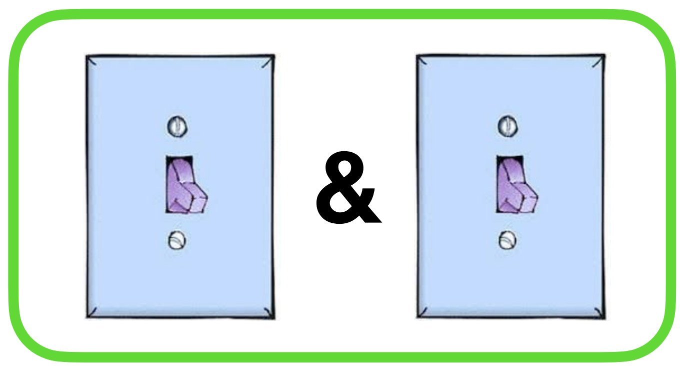
How many possibilities for switch settings (states) are there?

A: 2

B: 4

C: 8

These possibilities are called "Combined States"

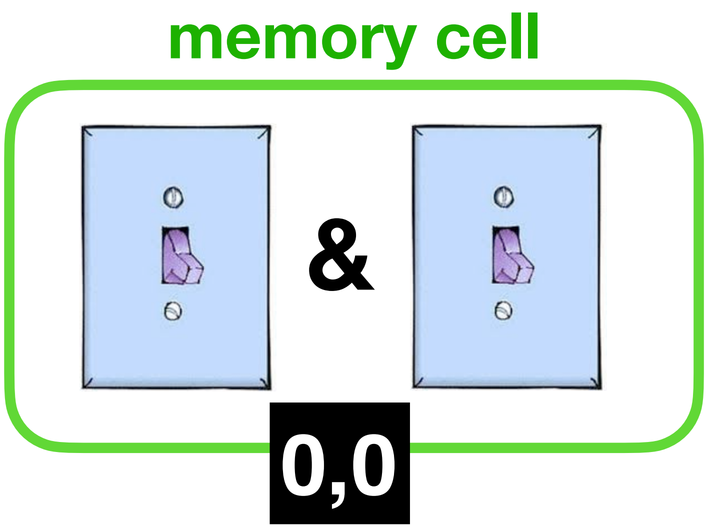


& means "and" (combined with)

(tensor product)

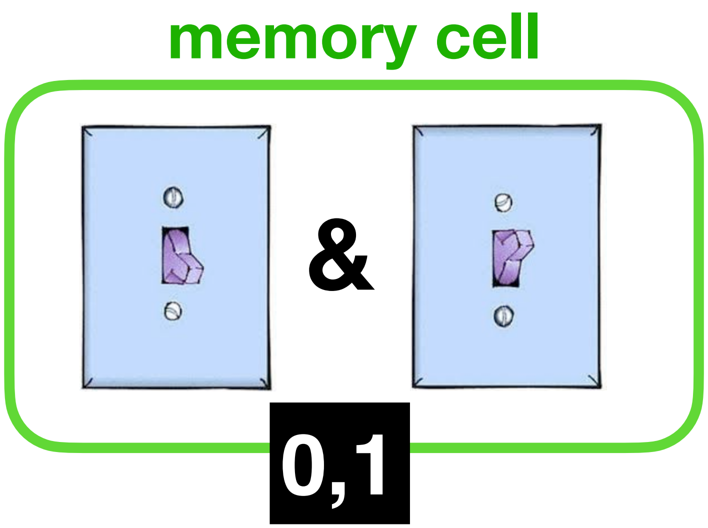
Two Ordinary bits:

4 possibilities



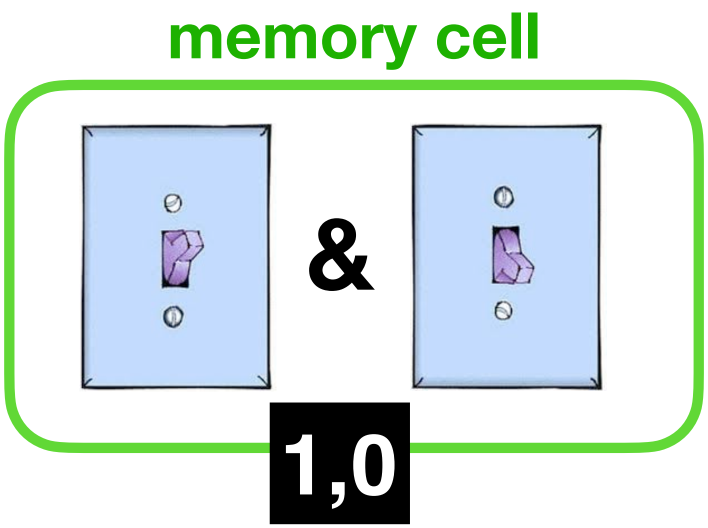
Two Ordinary bits:

4 possibilities



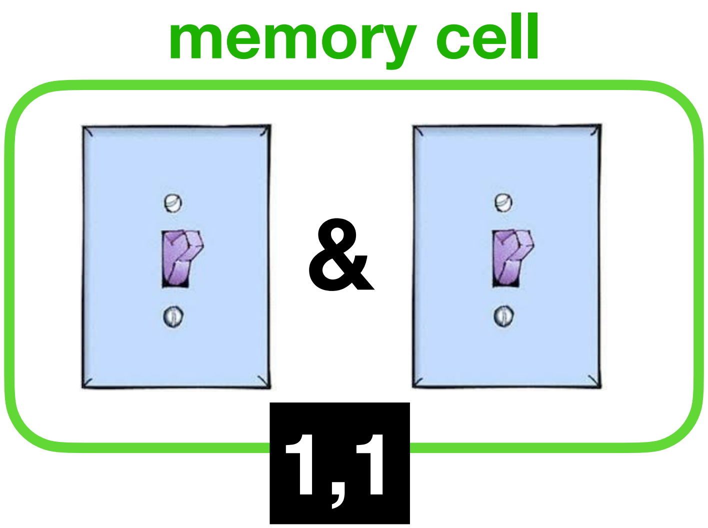
Two Ordinary bits:

4 possibilities



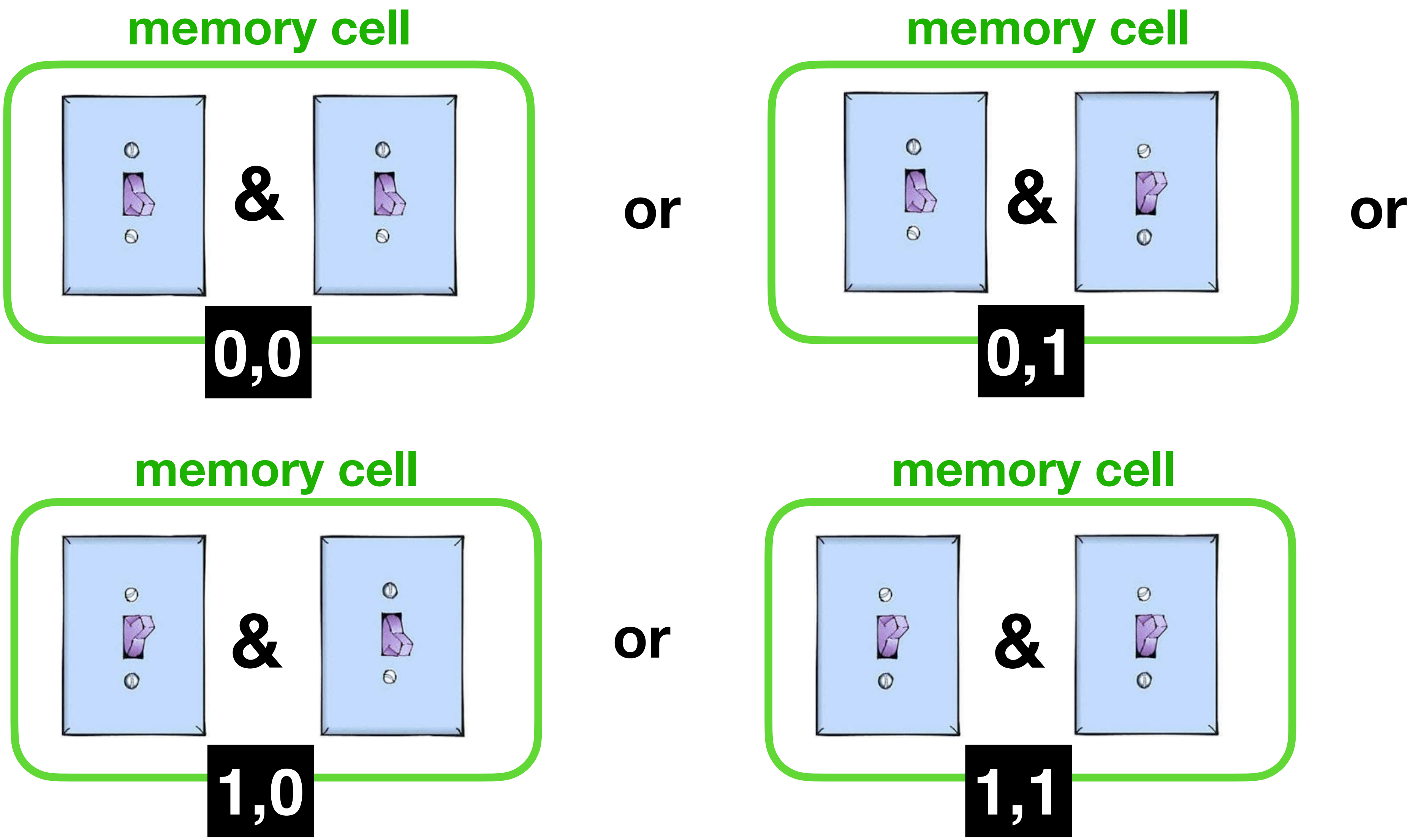
Two Ordinary bits:

4 possibilities



Two Ordinary bits:

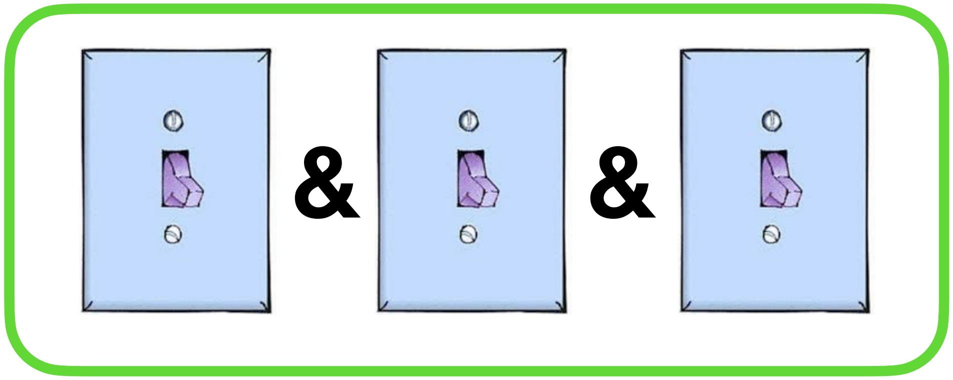
All 4 possibilities



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

reveal

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 ← 8 bits = one byte
9	2x2x2x2x2x2x2x2x2= 512
10	2x2x2x2x2x2x2x2x2x2= 1024

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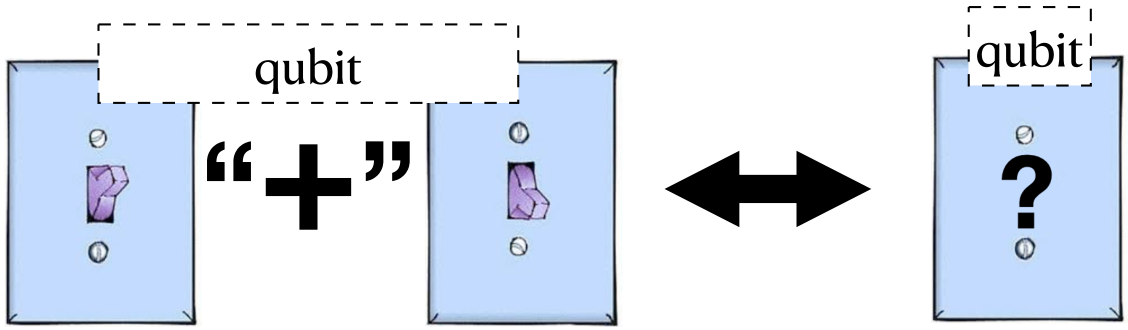
Quantum Information Science is enabled by State Superposition and Entanglement

State Superposition with Quantum bit (qubit):

"+" means "in superposition with"



$|0\rangle$ qubit states $|1\rangle$ $\qquad x|0\rangle + y|1\rangle$

x and y are numbers called *coefficients*

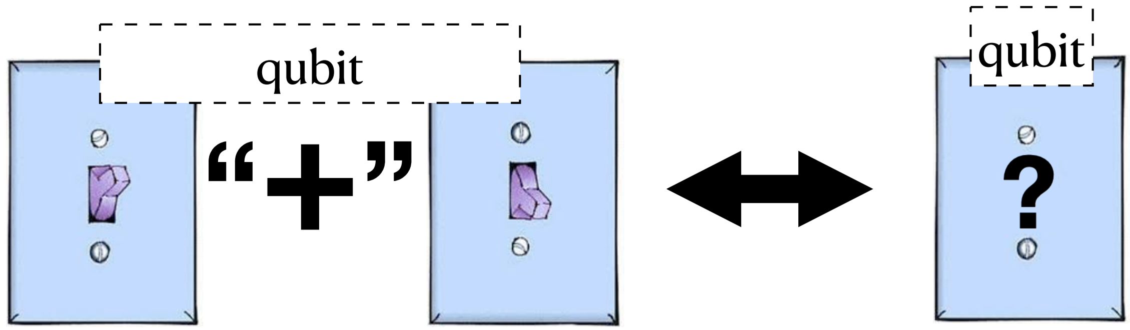
Measuring the qubit gives either 1 or 0 (true randomness, inherent in Nature)

Quantum Information Science is enabled by State Superposition and Entanglement

State Superposition with Quantum bit (qubit):

"+" means "in superposition with"

Two possibilities are in superposition



$|0\rangle$ qubit states $|1\rangle$ $\quad x|0\rangle + y|1\rangle$

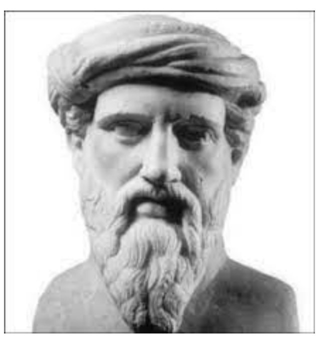
x, y = numbers with values between 0 and 1

Measuring the qubit gives either 1 or 0 (true randomness, inherent in Nature)

Probability to observe "0" upon measurement = x^2

Probability to observe "1" upon measurement = y^2

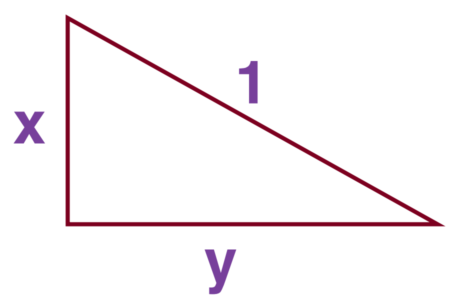
Probability to observe either "0" or "1" = 1



Pythagoras

$x^2 + y^2 = 1^2$

(earlier in Babylonia)



Max Born

POLL QUESTION 4 $qubit\ state = x|0\rangle + y|1\rangle$

A qubit is in a superposition state $\frac{3}{5}|0\rangle + \frac{4}{5}|1\rangle$

What is the probability that, if you measure it, you will observe the qubit in state 0?

A: 0

B: 3/5

C: 9/25

D: I don't know

reveal

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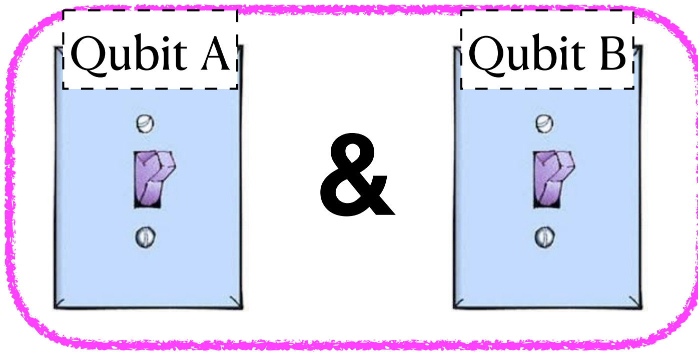
Quantum Information Science is enabled by State Superposition and Entanglement

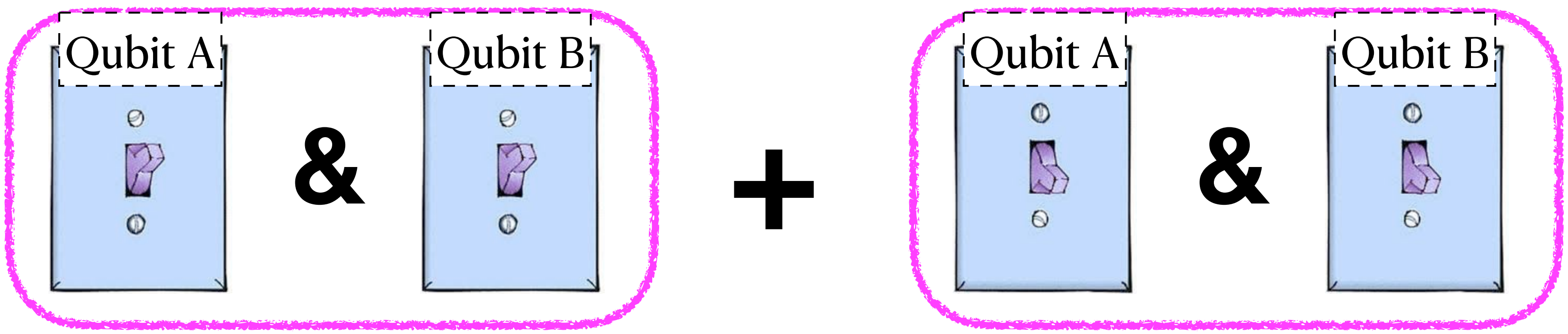
Combined State of two qubits (example):

& means "and"



Purple Box= Two qubits in a **combined** quantum state

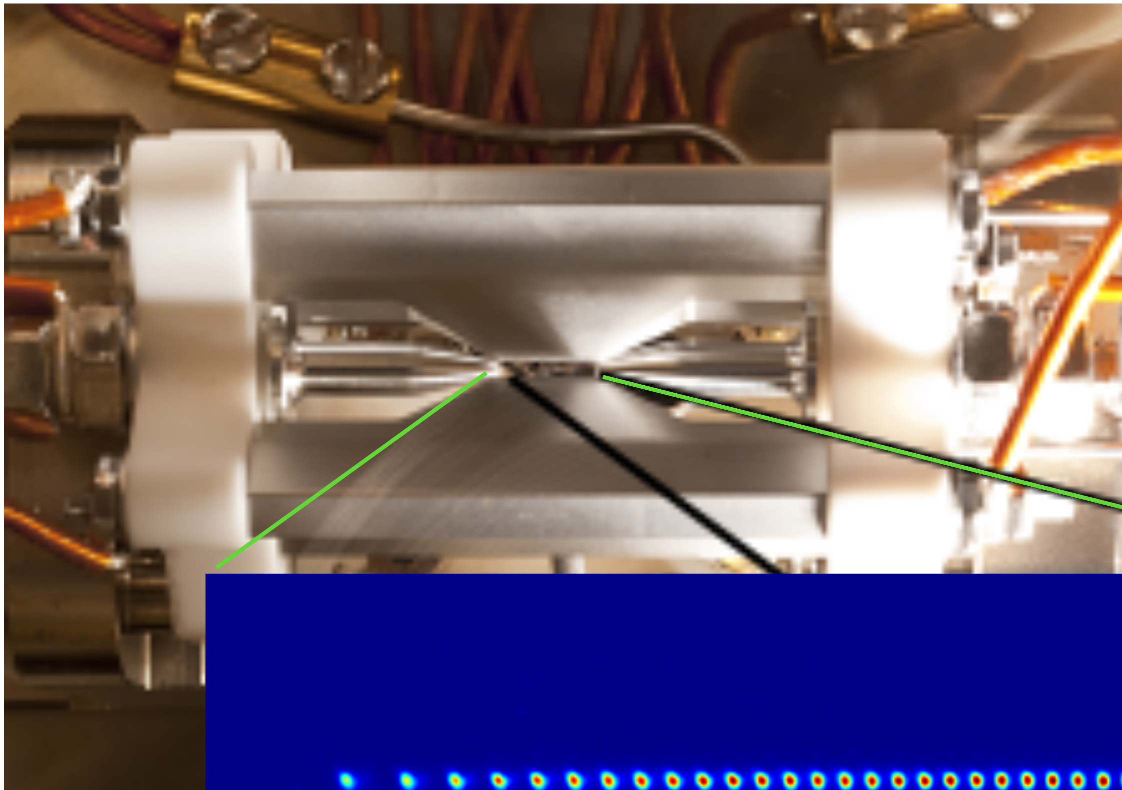
Entangled State of two qubits (example):



$|1\rangle$ $|1\rangle$ $|0\rangle$ $|0\rangle$

"+" means "in superposition with"

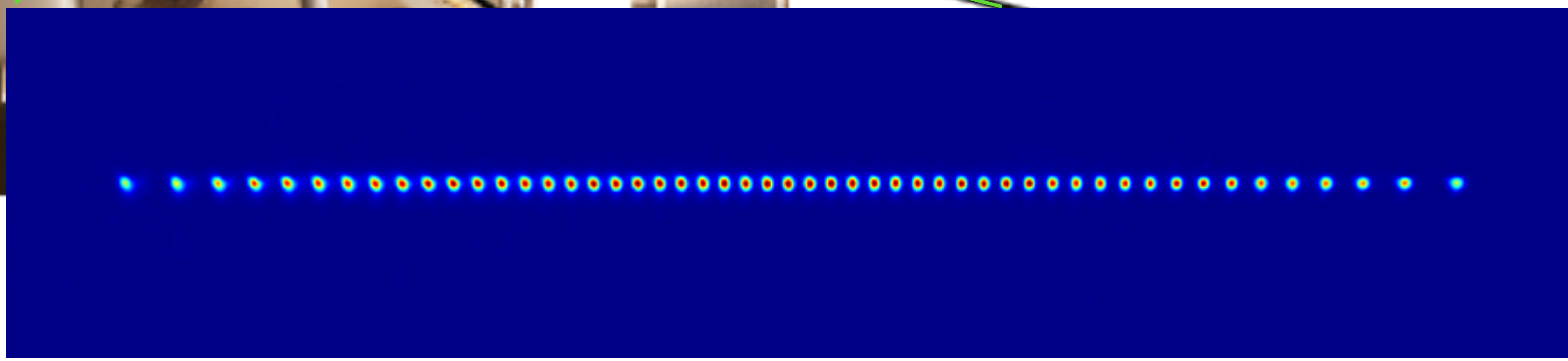
+ is not the same as &



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

"Trapped ion qubits"

How to represent entangled states in elementary objects?

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

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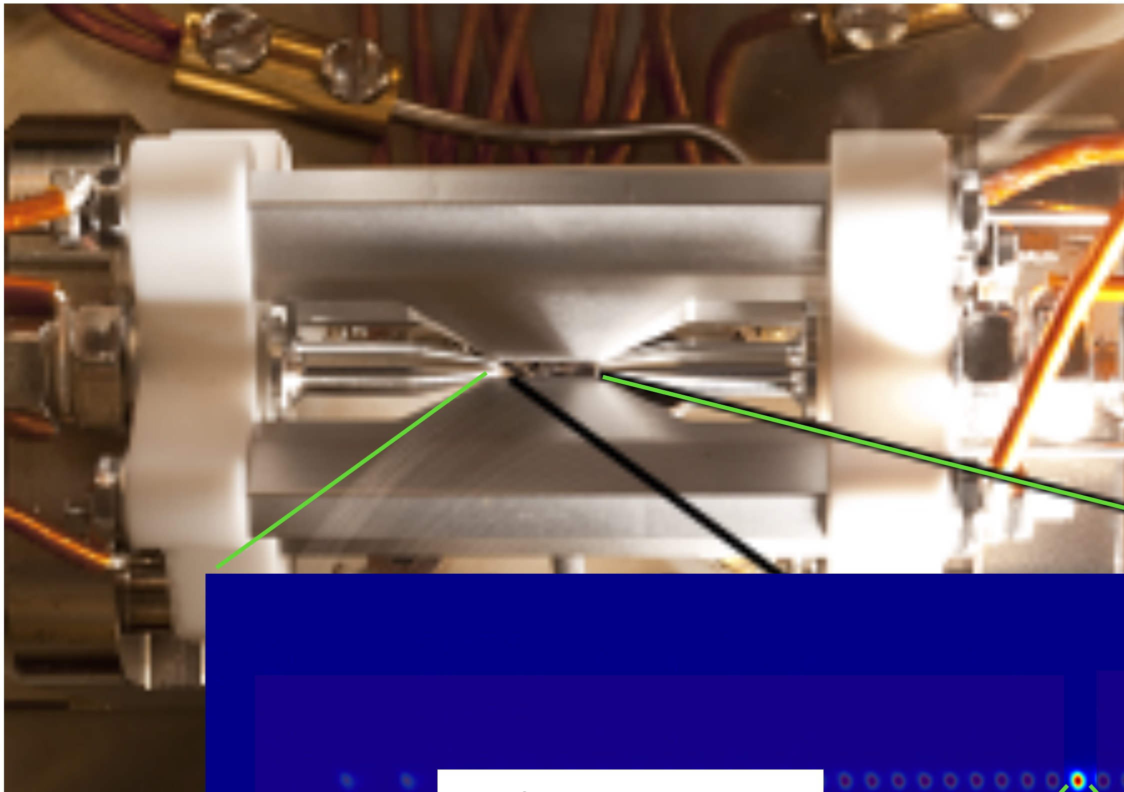
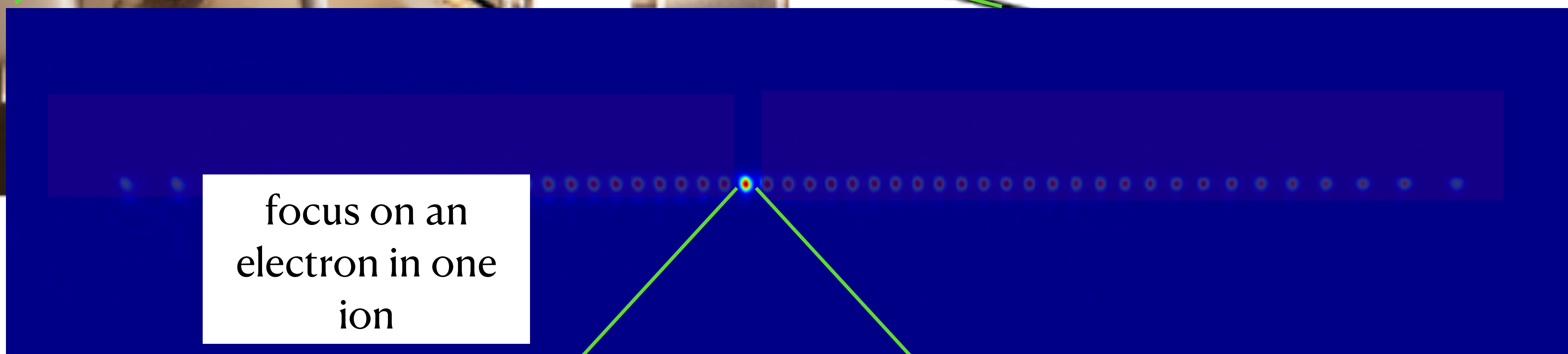
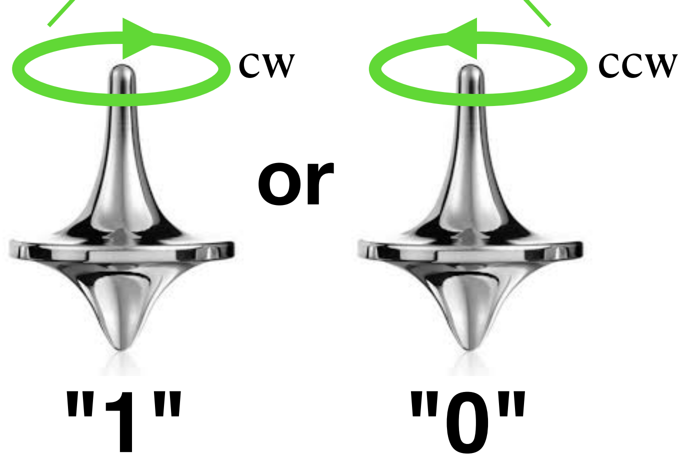




spinning top analogy

spin state can be cw or ccw



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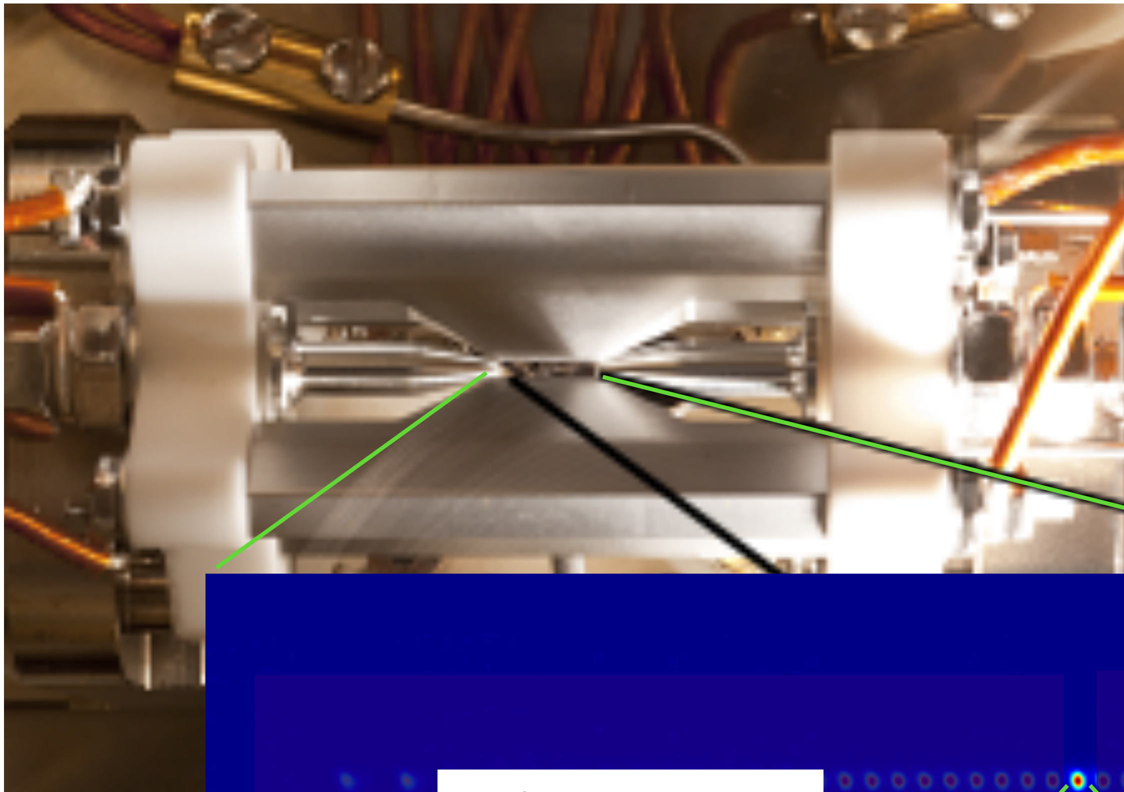
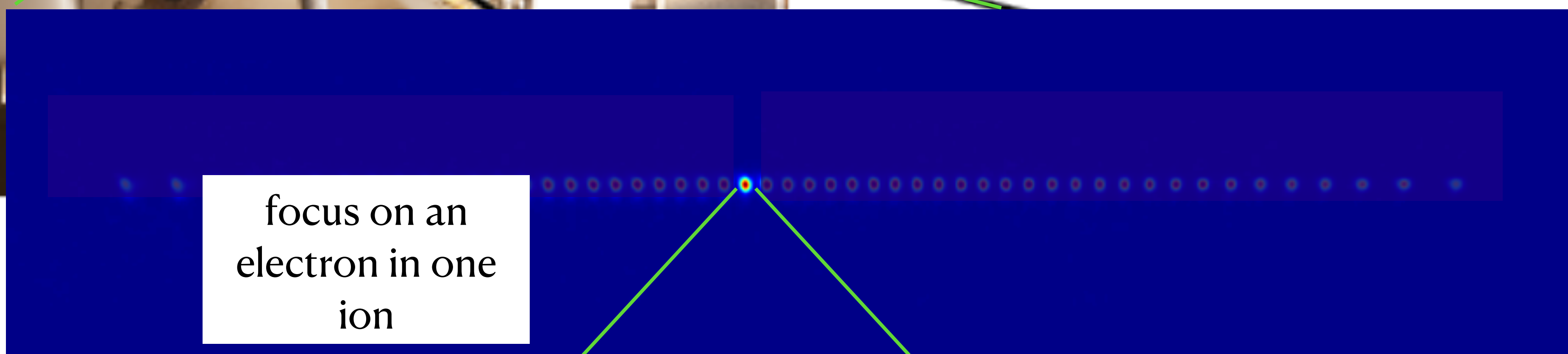
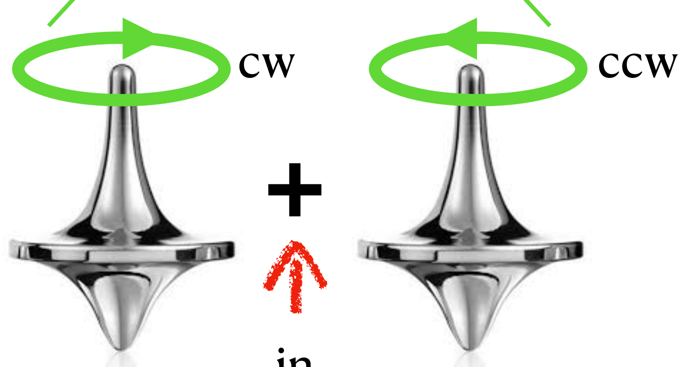




superposition states are possible



in superposition with

same possibilities for every ion

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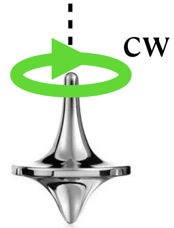
What does superposition mean?
It does not mean 'both at the same time'. It does not mean 'or'.

If we prepare and measure:



0 deg rotation axis

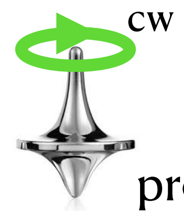
We will get:

with 100% probability (certainty)

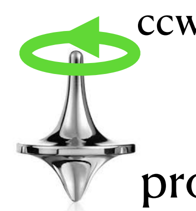
If we prepare and measure:

90 deg rotation axis

We will get:



50% probability



50% probability

If we prepare and measure:

30 deg rotation axis

We will get:

80%

20%

$x^2 + y^2 = 1^2$

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

If we prepare and measure:

0 deg rotation axis

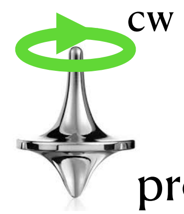
We will get:

with 100% probability (certainty)

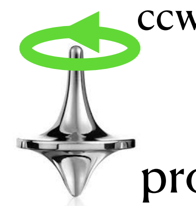
If we prepare and measure:

90 deg rotation axis

We will get:



50% probability



50% probability

If we prepare and measure:

30 deg rotation axis

We will get:

80%

20%

$x^2 + y^2 = 1^2$

If we prepare on 0 deg axis and measure on 30 deg rotation axis:

We will get:

80%

20%

Superposition means that a range of “Measurement Outcomes” are possible, depending on how you measure it.

 means  cw in superposition with  ccw

50% 50%

$$|\mathrm{cw}\rangle_{horizontal} = |\mathrm{cw}\rangle_{vertical} + |\mathrm{ccw}\rangle_{vertical}$$

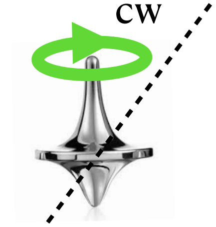
$$= |1\rangle_{vertical} + |0\rangle_{vertical}$$

Each observed result is called a "Measurement Outcome"

Probabilities are predictions that apply to both a single trial and to a series of many trials

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

Prepare
and measure
spin direction around
a 30% rotation axis:



measure around
30 deg rotation
axis:

80%

20%

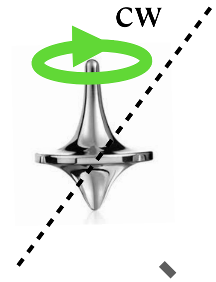
two possible
measurement
outcomes

relative to the new axis

$x^2 + y^2 = 1^2$

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

Prepare
and measure
spin direction around
a 30% rotation axis:



measure around
30 deg rotation
axis:

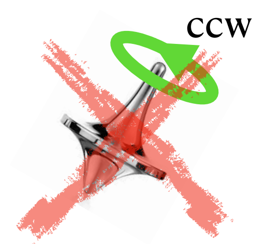
80%

20%

two possible
measurement
outcomes

if this does not happen

relative to the 30 deg
rotation axis



if we observe cw
and
measure the **same** spin
again
around
same axis

100% (with certainty)

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

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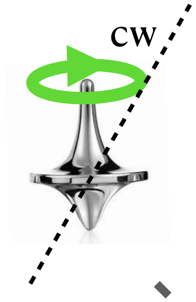
POLL QUESTION 5

Prepare
spin as clockwise
relative to the vertical axis

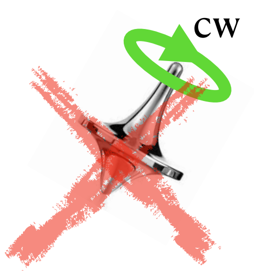


measure around 30
deg rotation axis

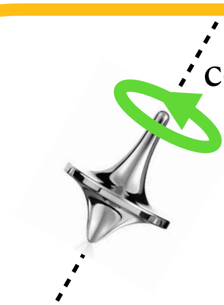
80%

20%

if this does not happen



Say we observe ccw
and then
measure the **same** spin again
around the
same 30 deg axis



relative to the 30 deg
rotation axis

?

What will we observe?

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

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

Alicia Keys

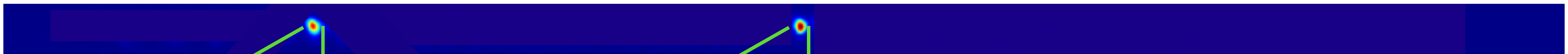
Alice

Bob Dylan

Bob

Alice's ion

Bob's ion



superpostion of electron spin states

"+" means in superposition with

Possible Combined States:

cw & cw

cw & ccw

ccw & cw

ccw & ccw

The most general entangled state:

$$x|ccw\rangle_A \& |ccw\rangle_B \quad + \; y|ccw\rangle_A \& |cw\rangle_B \quad + \; w|cw\rangle_A \& |ccw\rangle_B \quad + \; z|cw\rangle_A \& |cw\rangle_B$$

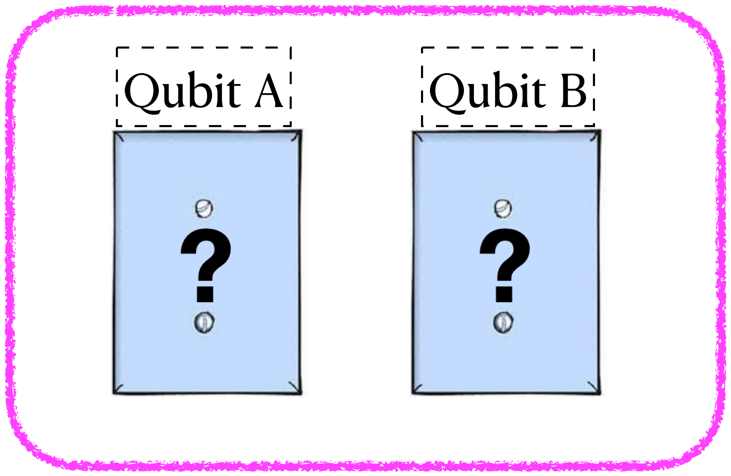
If we measure the spinning direction (cw or cw) of each ion,
we can obtain any one of the four possible combinations.
The probabilities of each are determined by x , y , w , and z

Two Quantum bits: Entanglement

Let's make a measurement!

$$\text{State} = \ x|0\rangle_A \& |0\rangle_B \ + \ y|0\rangle_A \& |1\rangle_B \ + \ w|1\rangle_A \& |0\rangle_B \ + \ z|1\rangle_A \& |1\rangle_B$$

coefficients



Quantum Memory Cell

If we measure (observe) both qubits, what might we get (see)?

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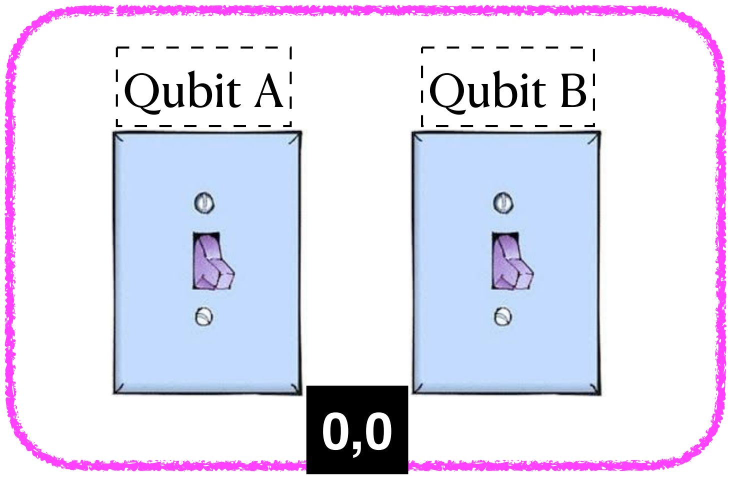
Two Quantum bits: Entanglement

Let's make a measurement!

$$\text{State} = \; x|0\rangle_A \& |0\rangle_B \;+\; y|0\rangle_A \& |1\rangle_B \;+\; w|1\rangle_A \& |0\rangle_B \;+\; z|1\rangle_A \& |1\rangle_B$$



← Quantum Memory Cell

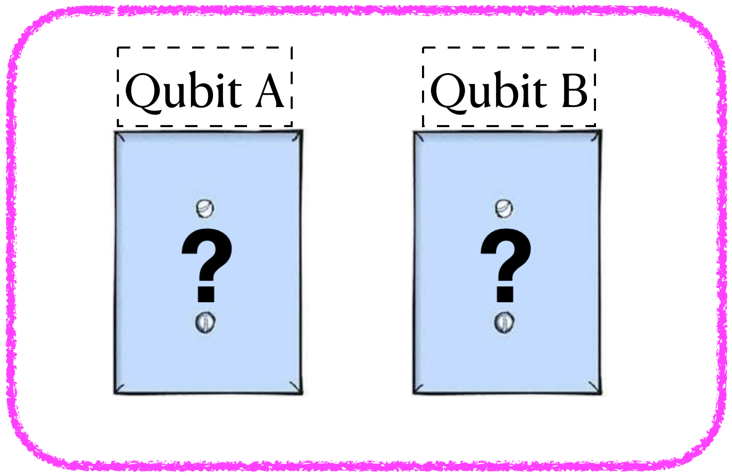
$$\text{State} = \; x\boxed{|0\rangle_A \& |0\rangle_B} \;+\; y|0\rangle_A \& |1\rangle_B \;+\; w|1\rangle_A \& |0\rangle_B \;+\; z|1\rangle_A \& |1\rangle_B$$

now the state is $|0\rangle_A \& |0\rangle_B$

Two Quantum bits: Entanglement

Let's reset the state and make a measurement

$$\text{State} = \; x|0\rangle_A \& |0\rangle_B \; + \; y|0\rangle_A \& |1\rangle_B \; + \; w|1\rangle_A \& |0\rangle_B \; + \; z|1\rangle_A \& |1\rangle_B$$

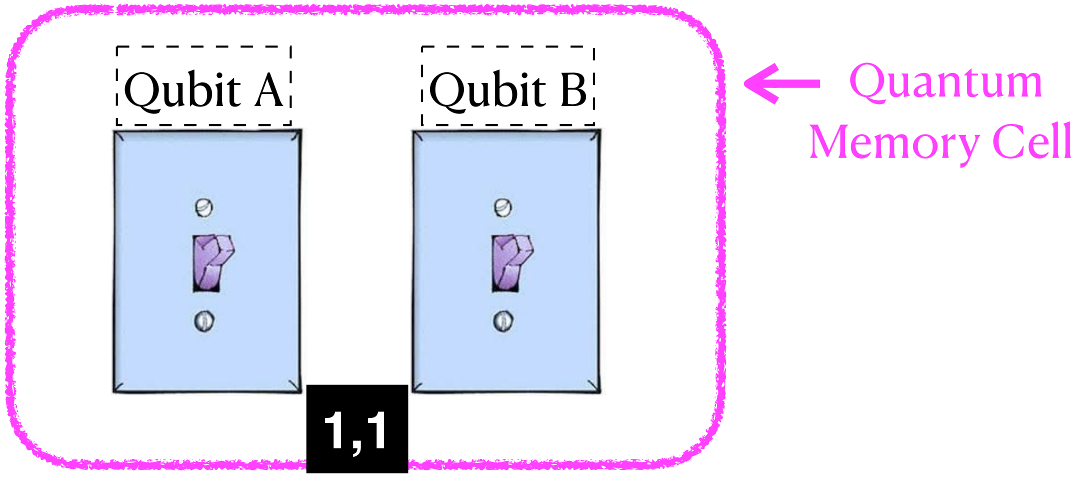


Quantum Memory Cell

Two Quantum bits: Entanglement

Let's reset the state and make a measurement

$$\text{State} = x|0\rangle_A \& |0\rangle_B + y|0\rangle_A \& |1\rangle_B + w|1\rangle_A \& |0\rangle_B + z|1\rangle_A \& |1\rangle_B$$



$$\text{State} = x|0\rangle_A \& |0\rangle_B + y|0\rangle_A \& |1\rangle_B + w|1\rangle_A \& |0\rangle_B + z\boxed{|1\rangle_A \& |1\rangle_B}$$

now the state is $|1\rangle_A \& |1\rangle_B$

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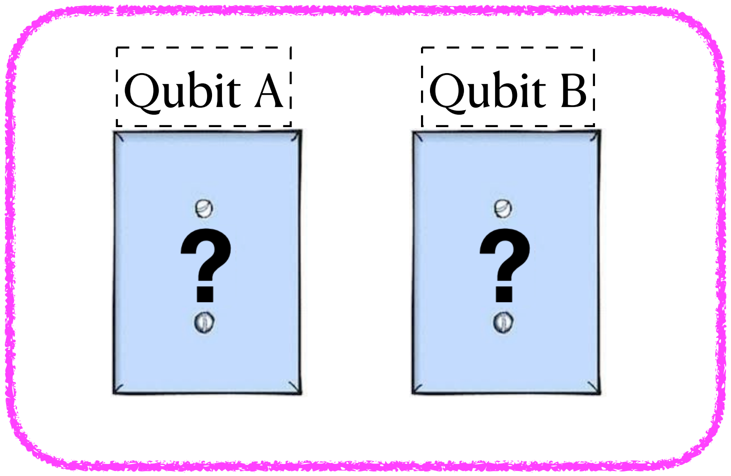
Two Quantum bits: Entanglement

Let's reset the state and make a measurement

$$\text{State} = x|0\rangle_A \& |0\rangle_B + y|0\rangle_A \& |1\rangle_B + w|1\rangle_A \& |0\rangle_B + z|1\rangle_A \& |1\rangle_B$$

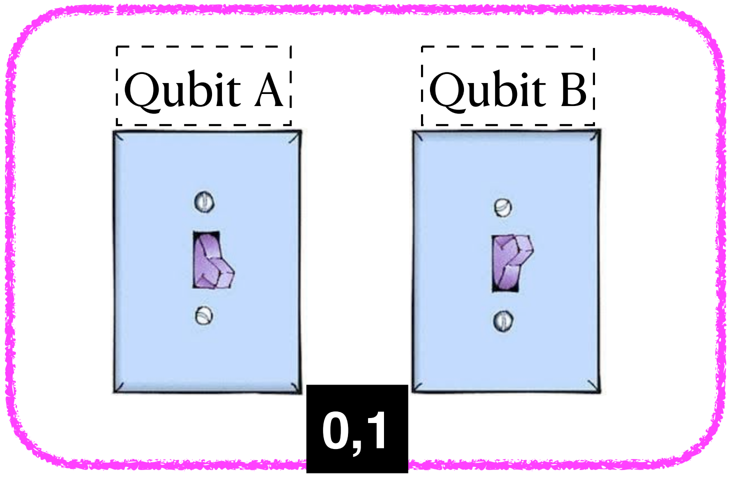


Quantum Memory Cell

Two Quantum bits: Entanglement

Let's reset the state and make a measurement

$$\text{State} = x|0\rangle_A \& |0\rangle_B + y|0\rangle_A \& |1\rangle_B + w|1\rangle_A \& |0\rangle_B + z|1\rangle_A \& |1\rangle_B$$



Quantum Memory Cell

$$\text{State} = x|0\rangle_A \& |0\rangle_B + y\boxed{|0\rangle_A \& |1\rangle_B} + w|1\rangle_A \& |0\rangle_B + z|1\rangle_A \& |1\rangle_B$$

now the state is $|0\rangle_A \& |1\rangle_B$

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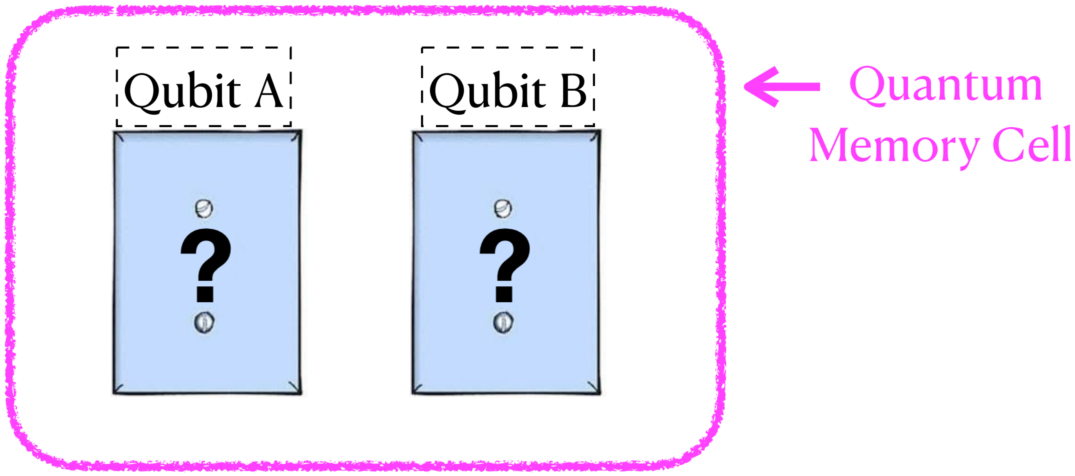
Two Quantum bits: Entanglement



$$\text{State} = x|0\rangle_A \& |0\rangle_B + y|0\rangle_A \& |1\rangle_B + w|1\rangle_A \& |0\rangle_B + z|1\rangle_A \& |1\rangle_B$$

POLL QUESTION 6

If we reset the state again but have not yet measured the qubits, what would be the probability to obtain **0 for qubit A and 1 for qubit B** if you measure them both?

A: 1 (certainty)

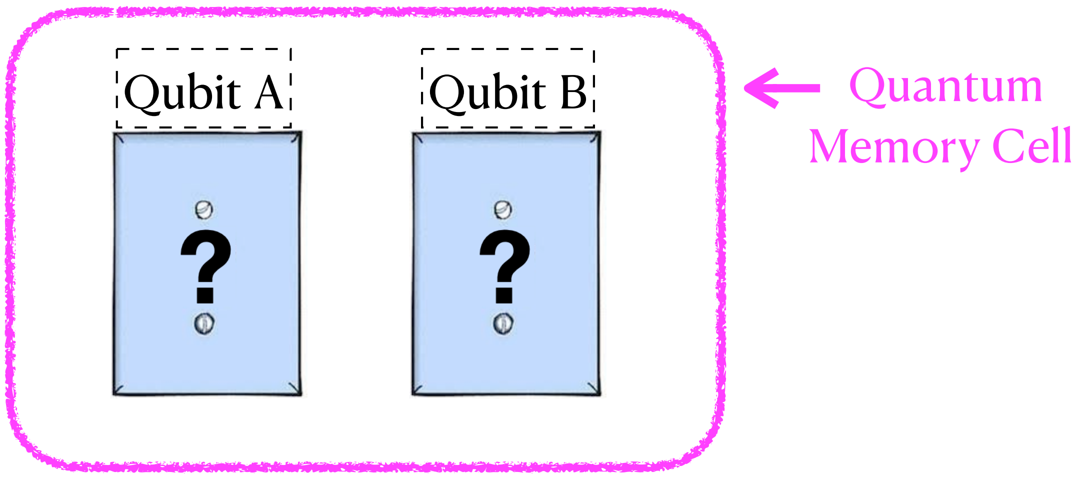
B: 0 (could not happen)

C: y^2

D: I don't know

Two Quantum bits: Entanglement

What are the probabilities for outcomes?



$$\text{State} = x|0\rangle_A \& |0\rangle_B + y|0\rangle_A \& |1\rangle_B + w|1\rangle_A \& |0\rangle_B + z|1\rangle_A \& |1\rangle_B$$

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 w^2

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

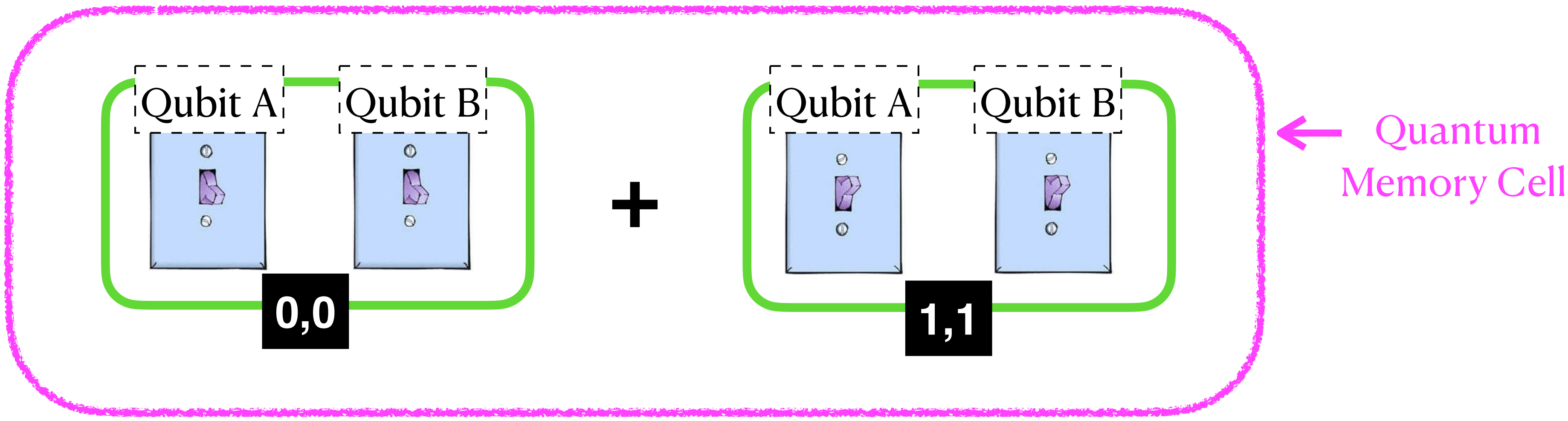
Max Born

Example: Entangled state of two qubits

Measuring one qubit first, then the other

POLL QUESTION 7

$$Example\ State\ =\ x|0\rangle_A \& |0\rangle_B\ +\ y|1\rangle_A \& |1\rangle_B$$

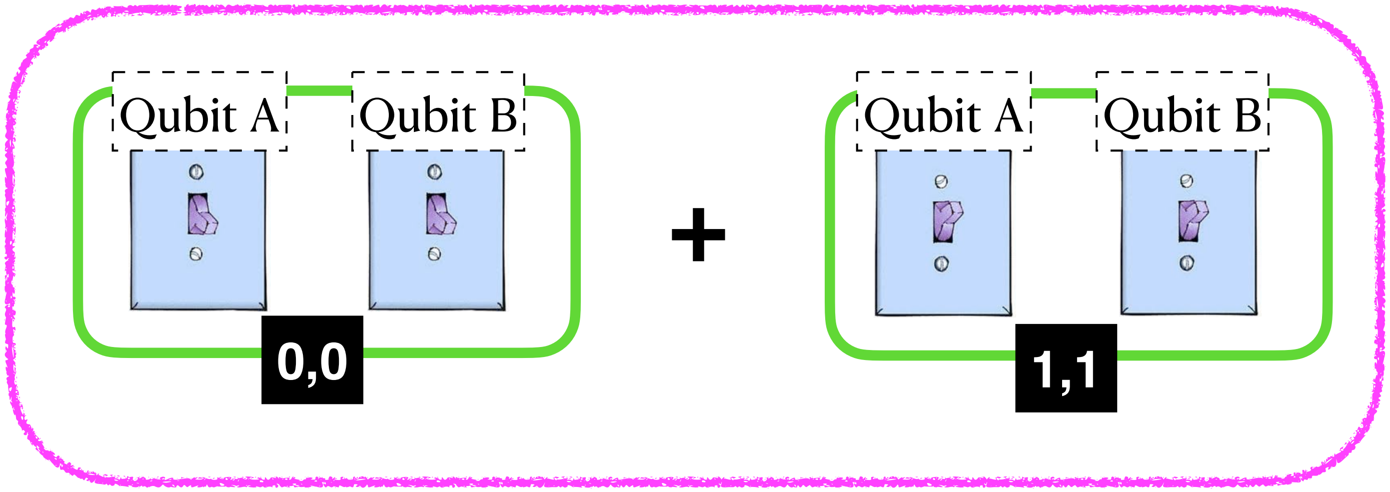


Say you measure the qubit A and obtain 1.
What will a measurement of qubit B then yield?

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

POLL QUESTION 8 $State = x|0\rangle_A \& |0\rangle_B + y|1\rangle_A \& |1\rangle_B$

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?



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

reveal

END PART 1

5 minute break

The Physics Behind the Quantum Internet

PART 2

Encoding and Transmitting Quantum Information

Presenter: Amy Soudachanh
University of Oregon

Center for Quantum Networks NSF-ERC

SHORT COURSE (3.5 HR) OUTLINE

PART 1: Quantum information science

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

PART 2: Encoding and transmitting quantum information

Communication systems
Distributing Entangled states
Ways of encoding qubits
Ways of encoding qubits in photons
Focus on photon polarization
State vector representation and Born's Rule
Bell states
Quantum cryptography

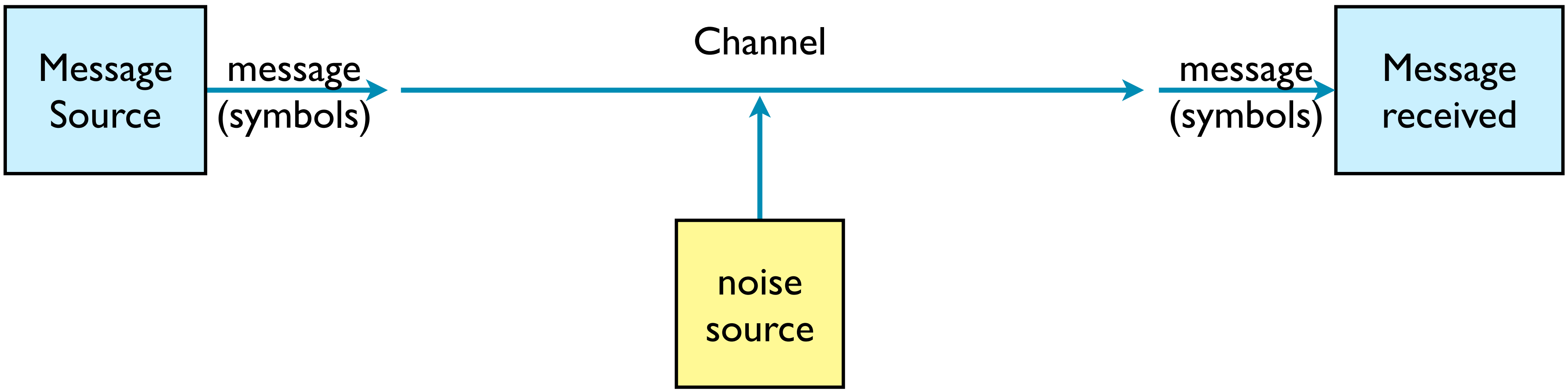
PART 3: Quantum state teleportation

Joint measurement
Quantum state teleportation
Why entenglement distribution?

PART 4: The Quantum Internet

Why the quantum internet?
Bell State Creation and Measurement
Quantum memories
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:

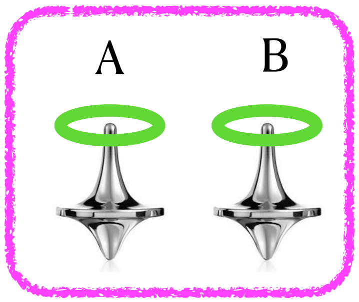
Q1. How much information can be carried by a certain number of symbols?

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 shares quantum information

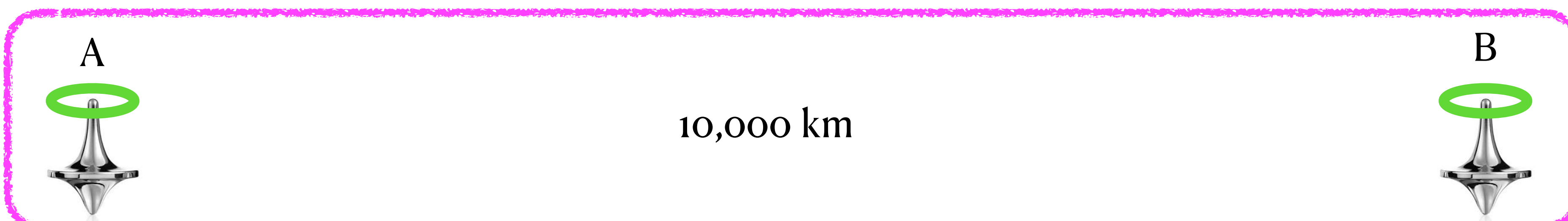
What is quantum information?
information encoded in quantum states of physical objects (e.g. spins)
(cannot be encoded and sent in classical bits through the Internet)
Example of quantum information is Entanglement

How can we create entanglement between far-separated qubits?



$$State \; = \; x|0\rangle_A \& |0\rangle_B \; + \; y|1\rangle_A \& |1\rangle_B$$

Entangled qubits separated by arbitrarily long distance!



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POLL QUESTION 9

Alice and Bob know the combined state is:

$$State = x|0\rangle_A \& |0\rangle_B + y|1\rangle_A \& |1\rangle_B$$

Alice

Bob

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

At what time does **Alice** 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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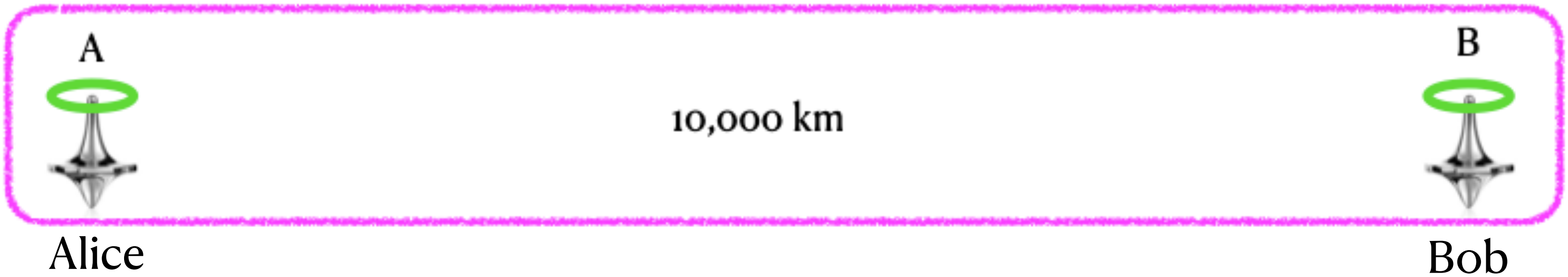
Poll QUESTION 10

Alice and Bob know the combined state is:

$$State \; = \; x|0\rangle_A \& |0\rangle_B \; + \; y|1\rangle_A \& |1\rangle_B$$



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

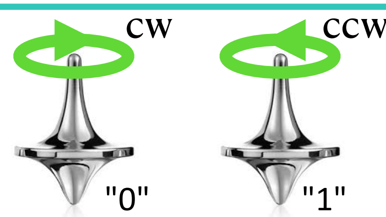
At what time does **Bob** know the state of qubit B, **without** observing it?

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

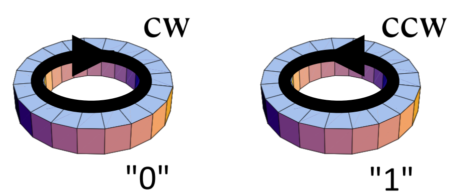
reveal

Qubits can be encoded in various ways

Electron spin states



The states of superconductor current

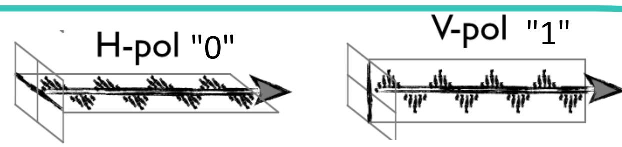


Stationary qubits

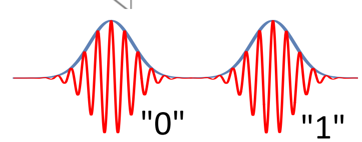
Most useful for storing quantum information

define: a **photon** is a quantum of light (the smallest quantity of light)

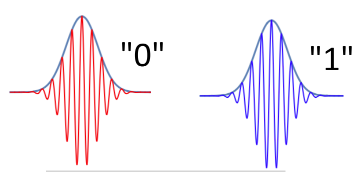
Photon polarization states



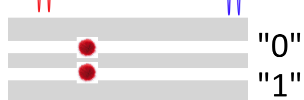
Photon times of arrival (time-bin states)



Photon frequency



Photon beam path



Flying qubits

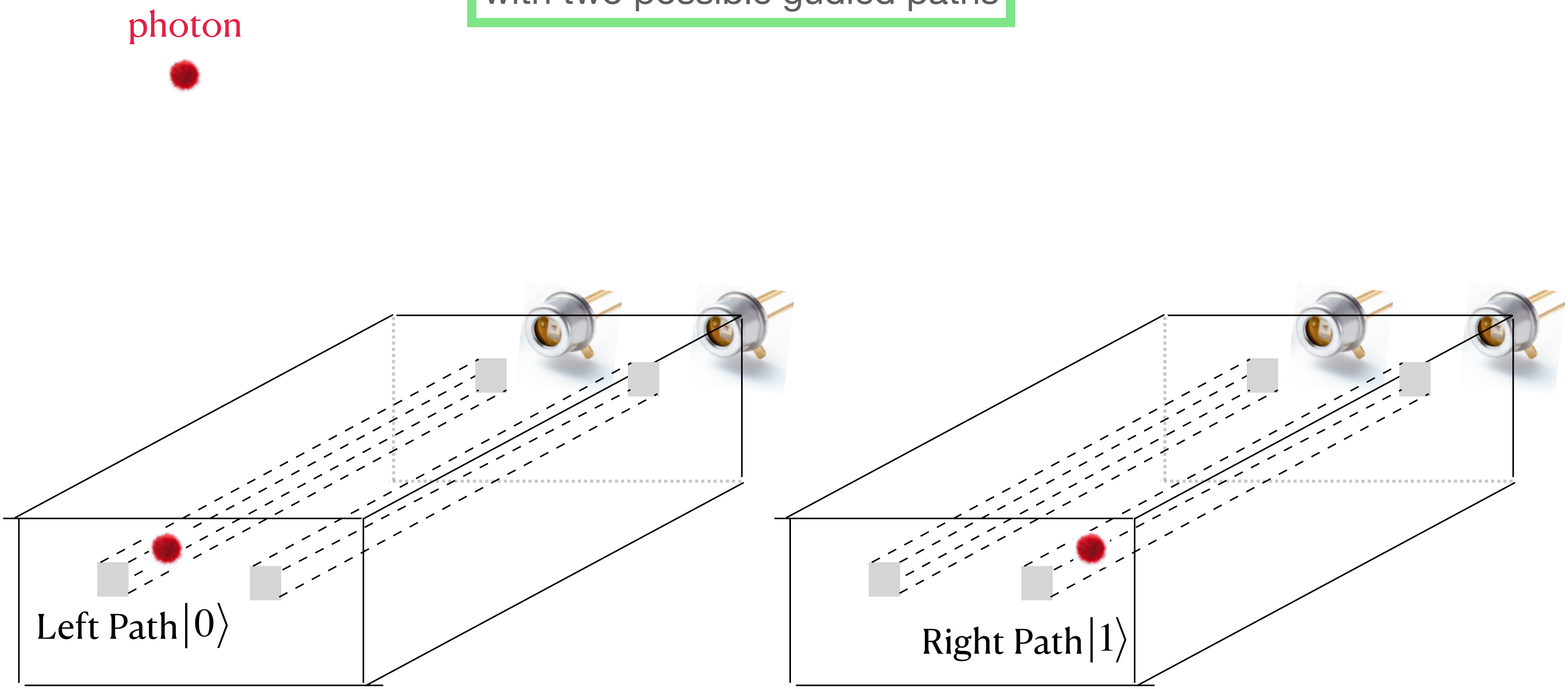
Most useful for transmitting quantum information

Let's talk more about these...

How to encode information into single photons?

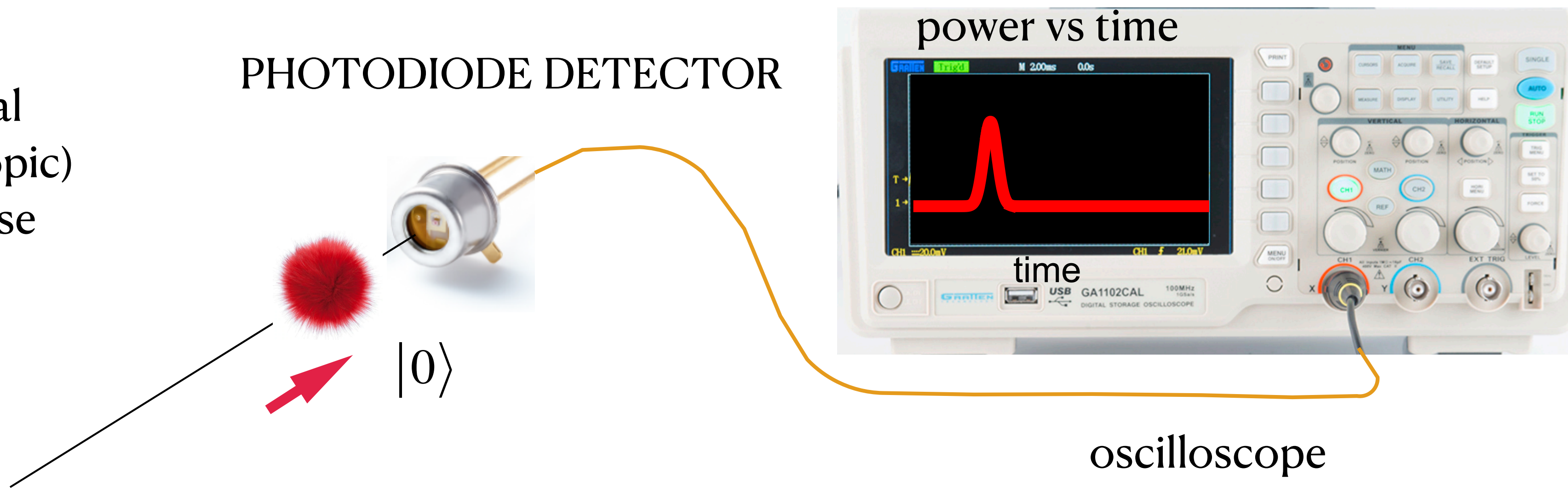
Encoding in Location

Transparent Glass Waveguide
with two possible gudied paths



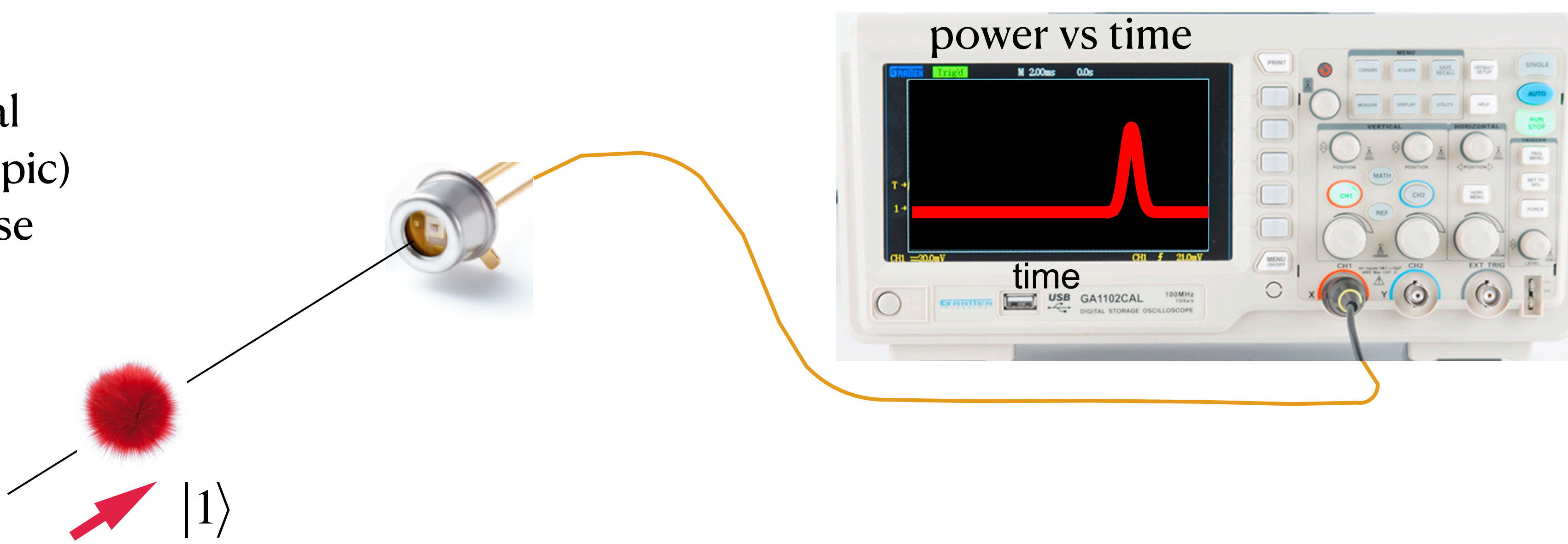
Encoding in Time of Arrival

Classical
(macroscopic)
light pulse

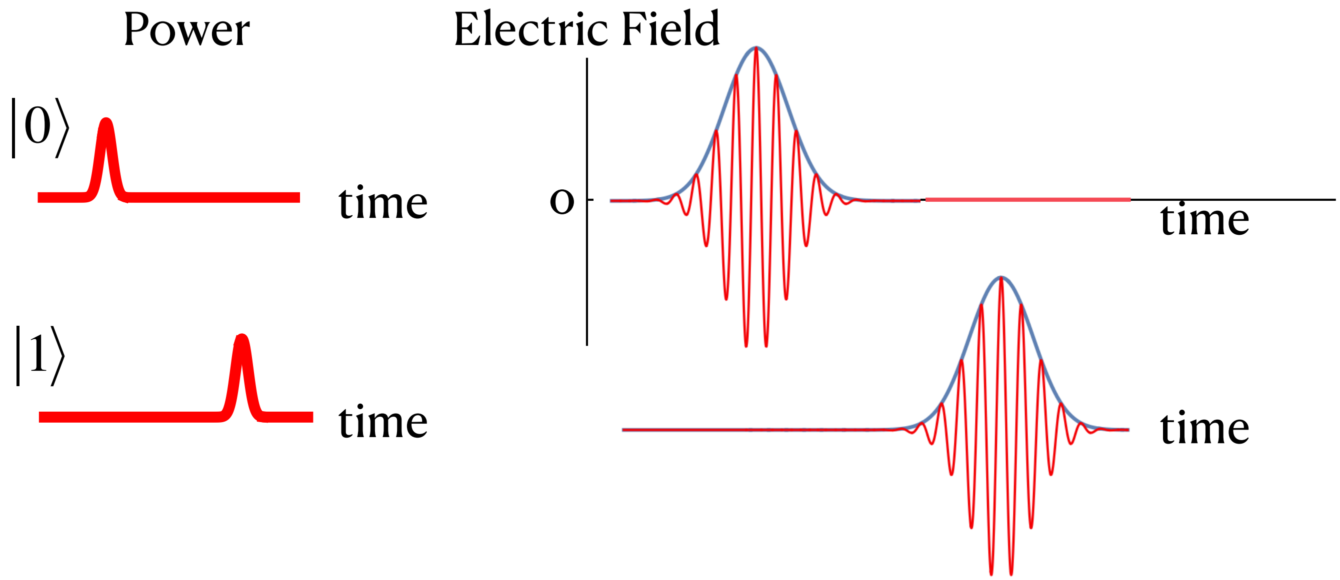


sparkfun.com

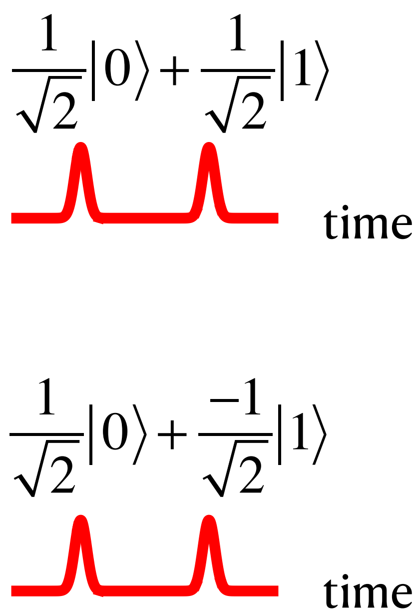
Classical
(macroscopic)
light pulse

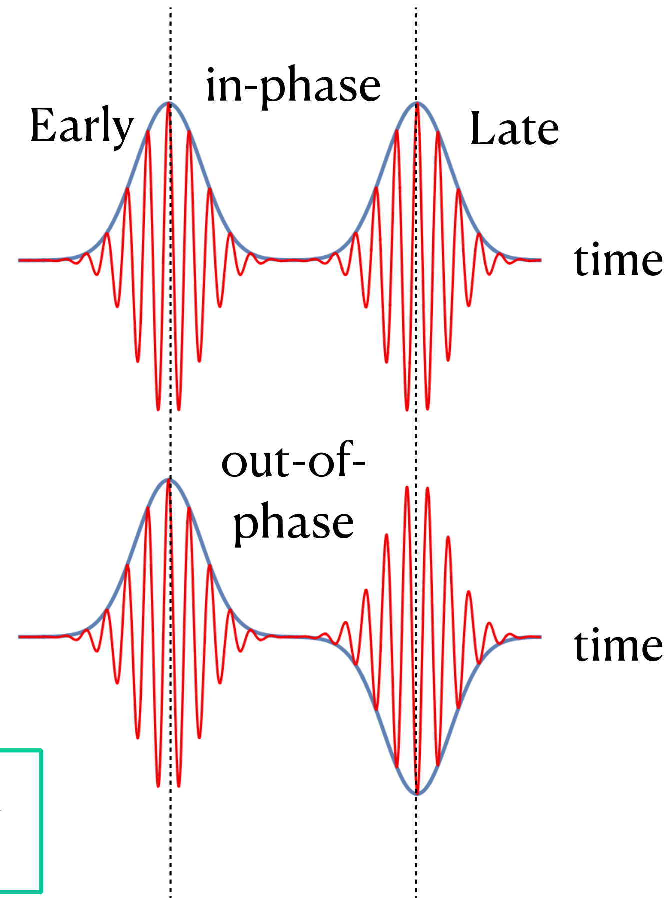


Encoding in Time of Arrival



Superposition





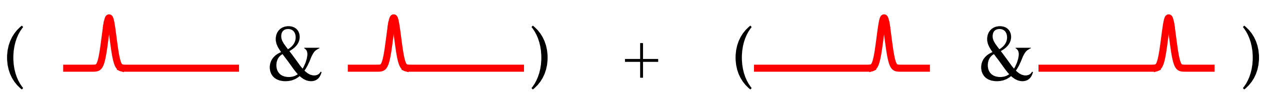
Fragility: A simple phase change can change the state drastically

Recall

One photon:

Entangled State of Two photons:

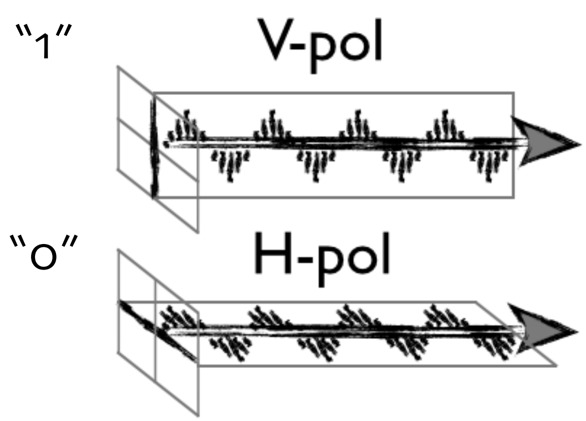
$$\mathit{Example\ State} \;=\; x|0\rangle_A \& |0\rangle_B \;+\; y|1\rangle_A \& |1\rangle_B$$



(Early & Early) + (Late & Late)

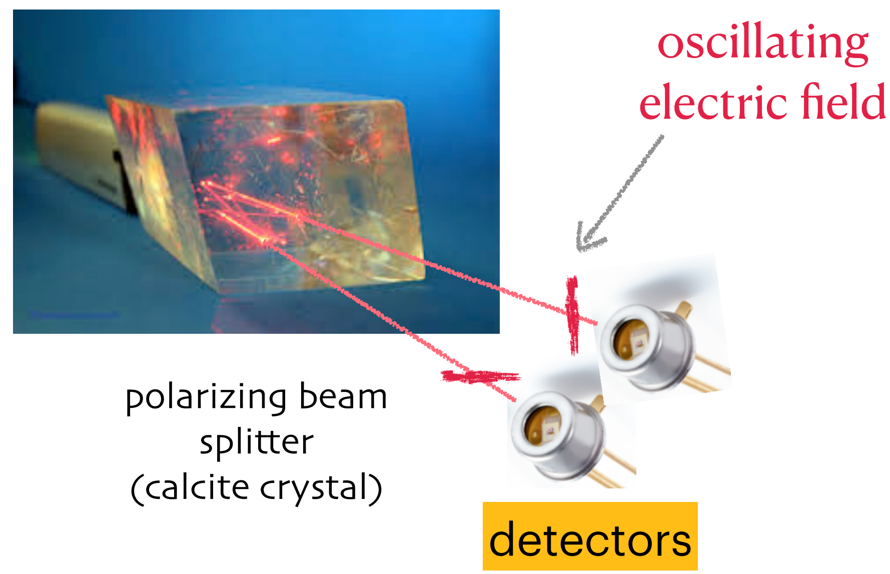
Encoding in Photon Polarization

Polarization can be oriented in **Vertical** or **Horizontal** directions perpendicular to the direction of light's travel:



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

Qubit Measurement



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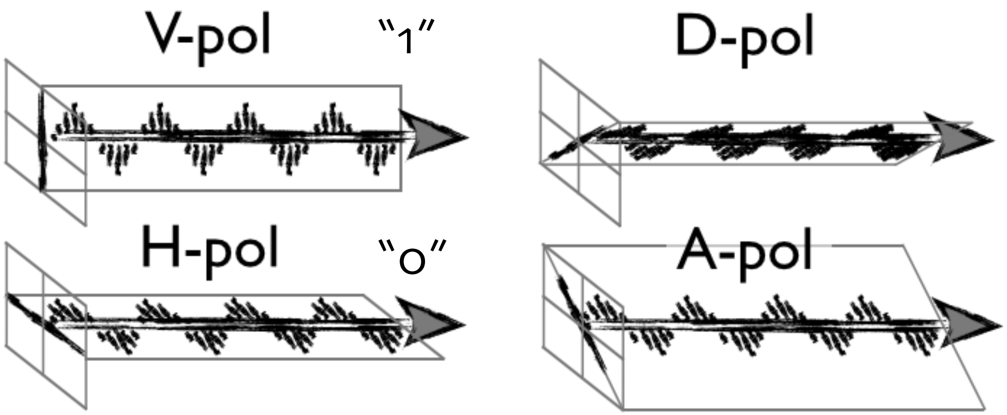
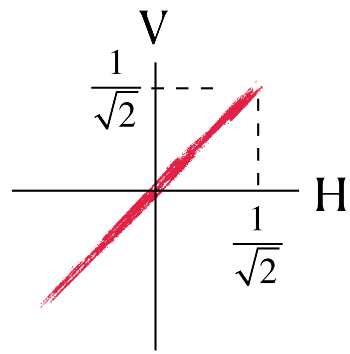
Polarization can also be oriented in **Diagonal** or **Anti-diagonal** directions perpendicular to the direction of light's travel:

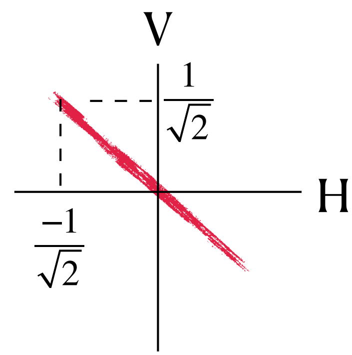




Superposition

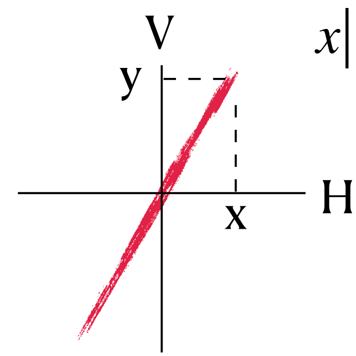
$$|D\rangle = \frac{1}{\sqrt{2}}|H\rangle + \frac{1}{\sqrt{2}}|V\rangle$$

"in superposition with"



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

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



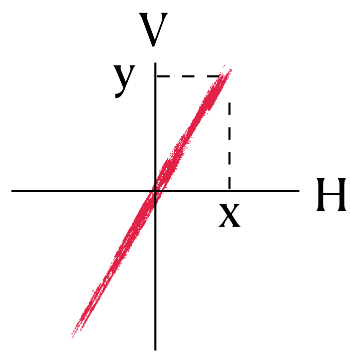
$$x|H\rangle + y|V\rangle$$

(Born Rule) $x^2 + y^2 = 1^2$

Poll QUESTION 11

How many different states could be encoded in:

$$x|H\rangle + y|V\rangle$$



A: 2
B: 4
C: An infinite number
D: I don't know

reveal

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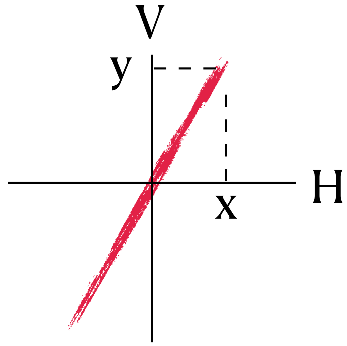
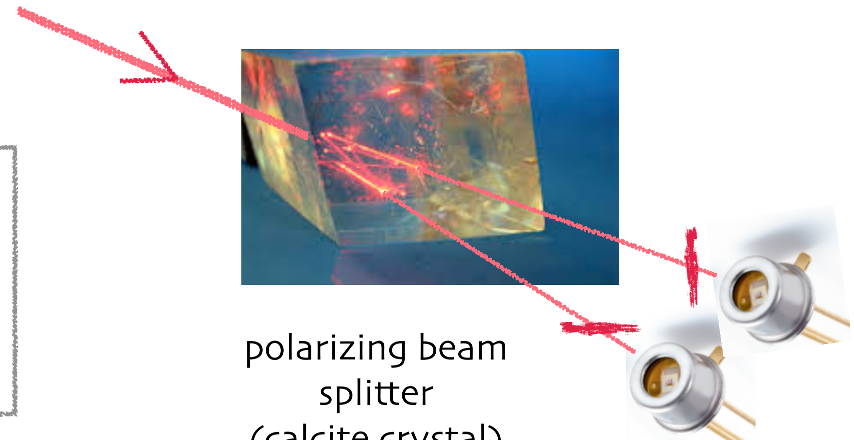
Poll QUESTION 12

$$x|H\rangle + y|V\rangle$$

$$x^2 + y^2 = 1$$



Given particular values of x and y, how many 'bits' of information can you get (obtain) by measuring the photon's polarization using a H/V analyzer (and detectors)?



polarizing beam splitter (calcite crystal)

detectors

A: 1 bit
B: 2 bits
C: An infinite number
D: I don't know

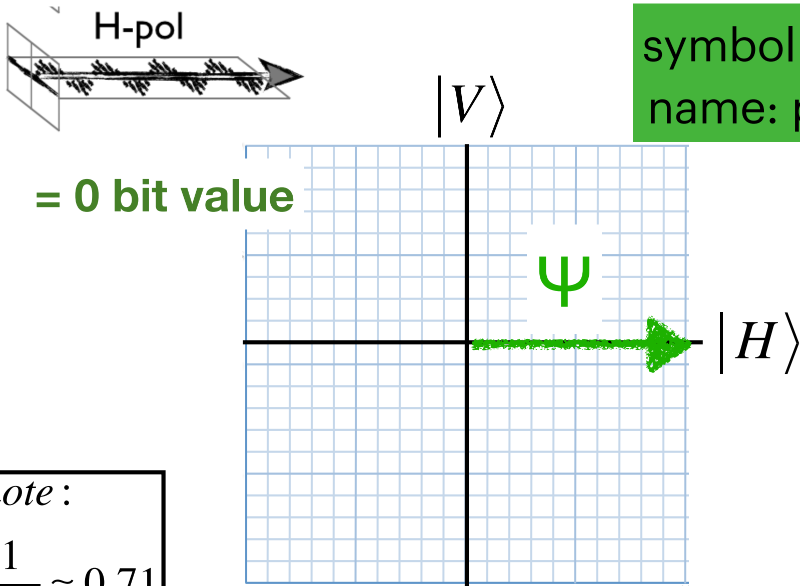
reveal

reveal

State Arrow (vector) representation of Polarization State of single photon

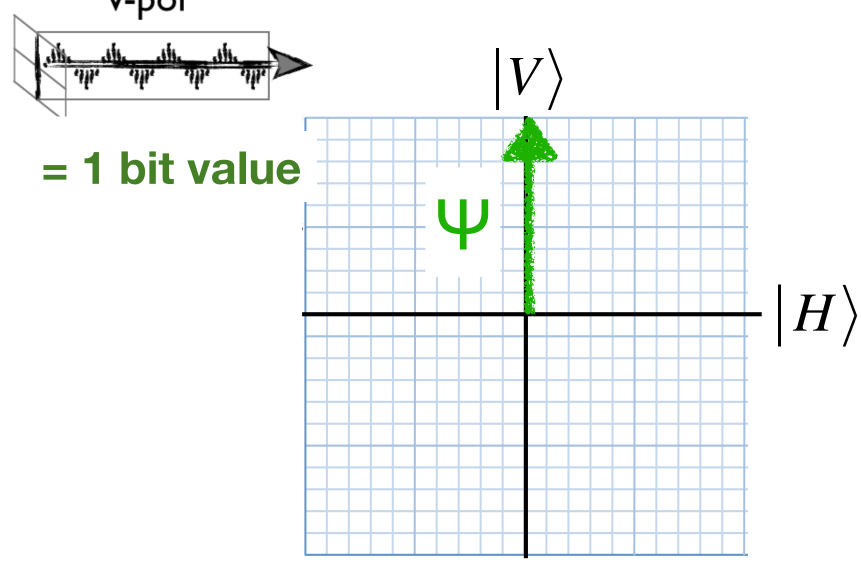
symbol: Ψ
name: psi

H-pol



= 0 bit value

V-pol

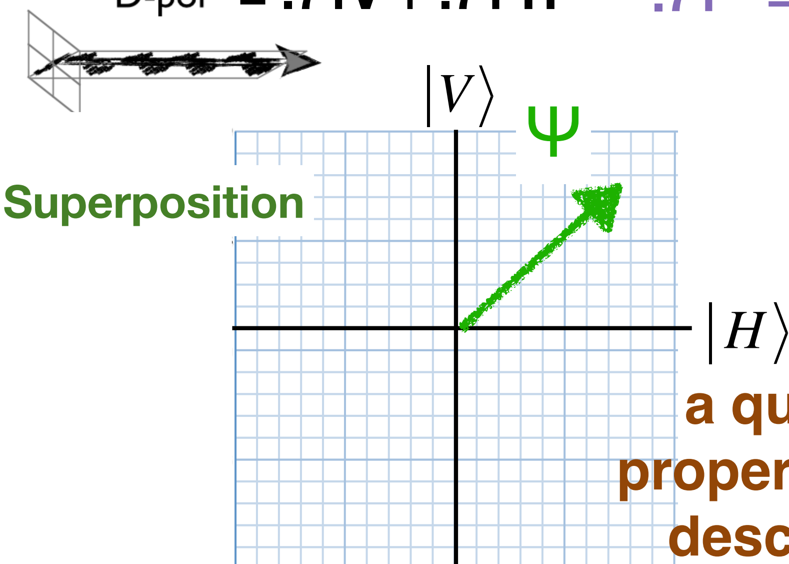


= 1 bit value

note :
$$\frac{1}{\sqrt{2}} \simeq 0.71$$

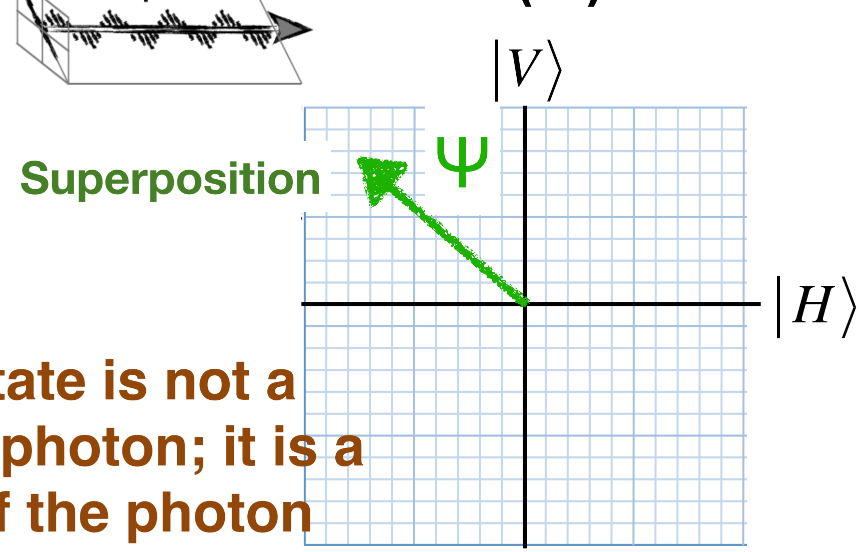
D-pol **= .71V + .71 H**

$.71^2 = 0.5$



Superposition

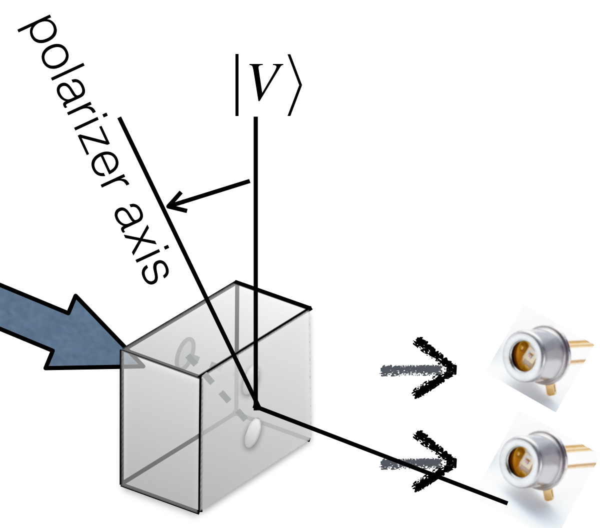
A-pol **= .71V +.71 (-H)**

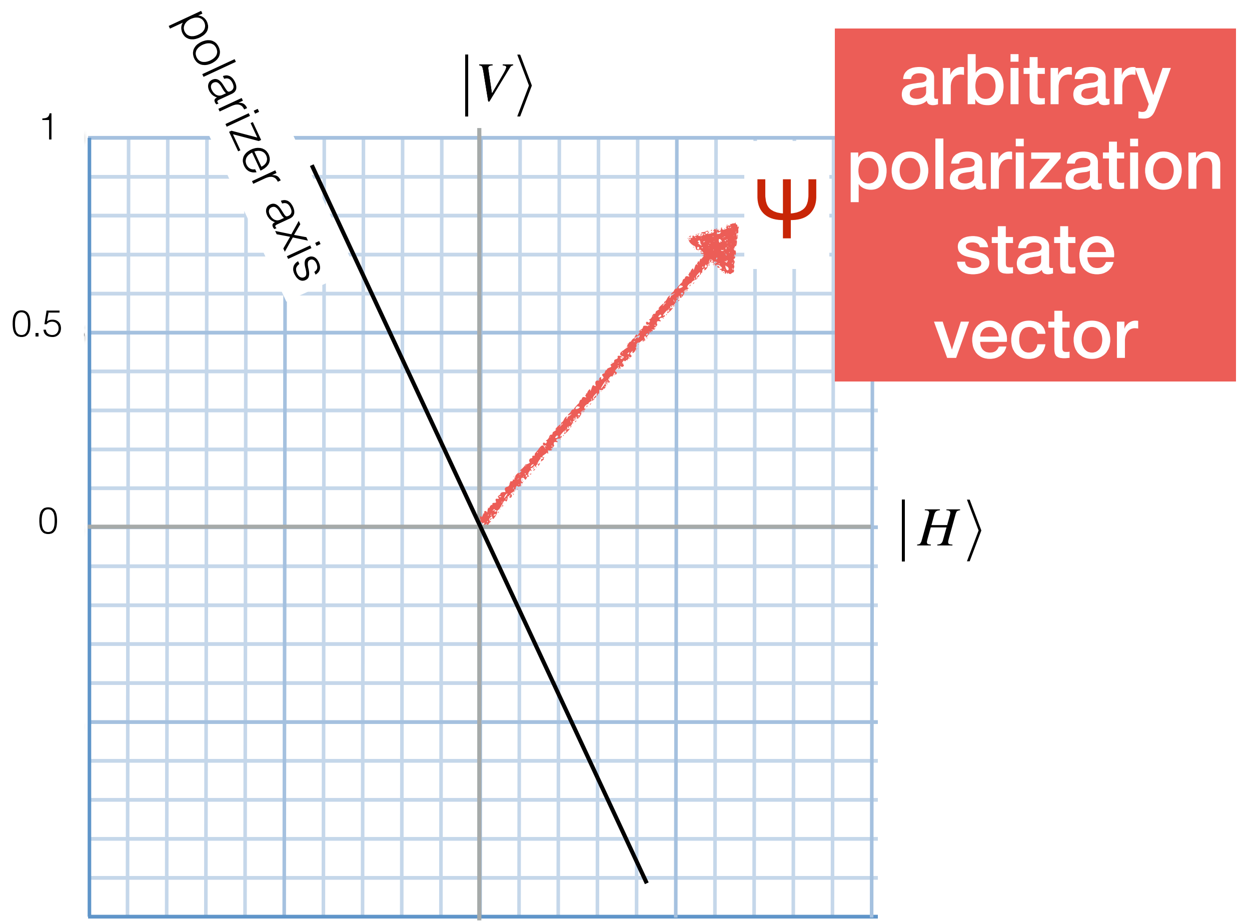


Superposition

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

If we rotate the axis of a polarization analyzer





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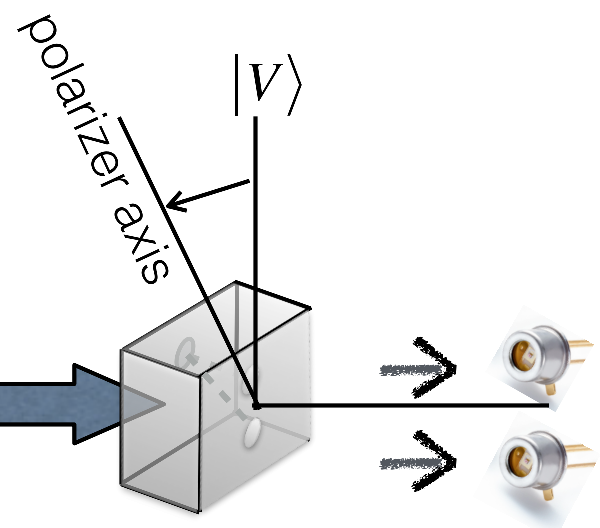
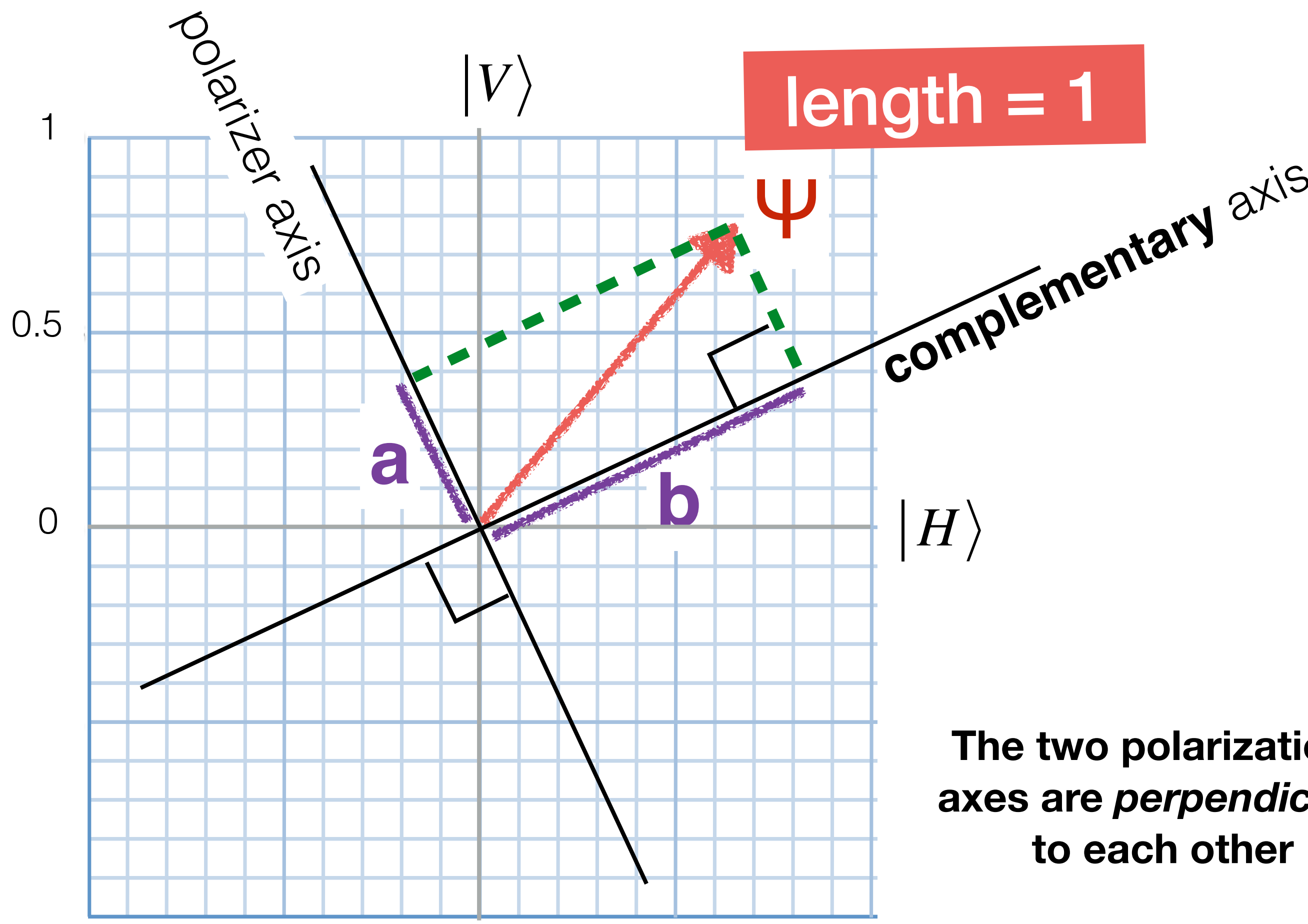
Born's Rule

Which detector will the photon arrive at?





Probability = **a^2**

Complementary Probability = **b^2**

The two polarizations axes are *perpendicular* to each other

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

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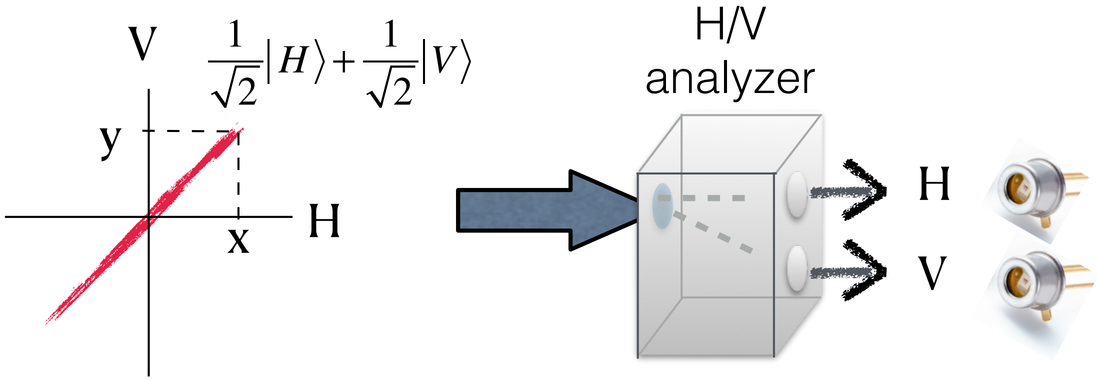
POLL QUESTION 13

single
D-polarized
photon



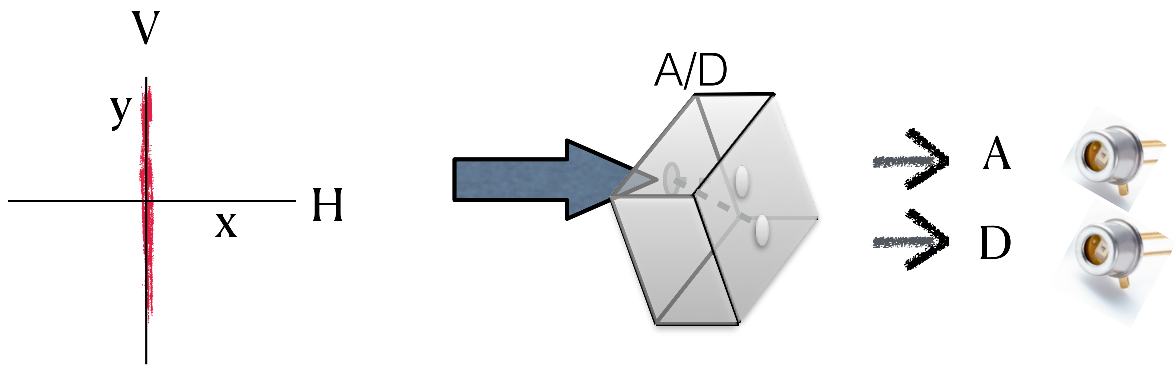
What is the probability the photon will be detected in the <u>vertical</u> polarized output?

A: 0.0
B: 1.0
C: 0.5
D: 0.25
E: I don't know

reveal

POLL QUESTION 14

single
V-polarized
photon



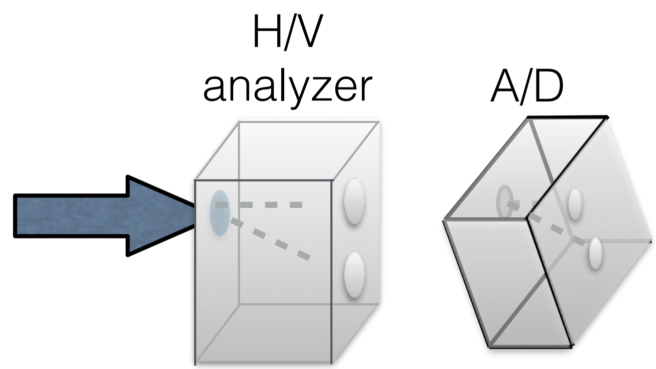
What is the probability the photon will be detected in the diagonal (D) polarized output?

A: 0.0
B: 1.0
C: 0.5
D: 0.25
E: I don't know

POLL QUESTION 15

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

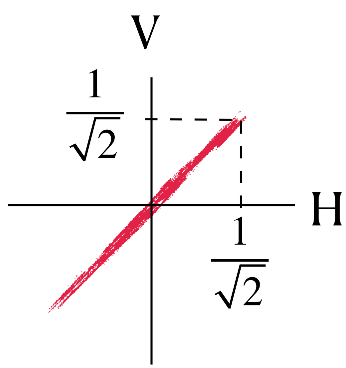
A: Yes, send it through a series of two polarizers
B: No, the first polarizer would change its state
C: Yes for classical light, no for quantum light
D: I'm not sure



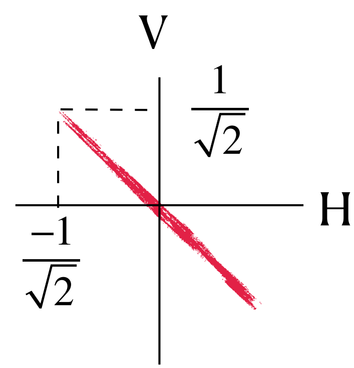
Fragility: A simple phase change can change the state drastically

$$\frac{1}{\sqrt{2}}|H\rangle + \frac{1}{\sqrt{2}}|V\rangle = |D\rangle$$

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



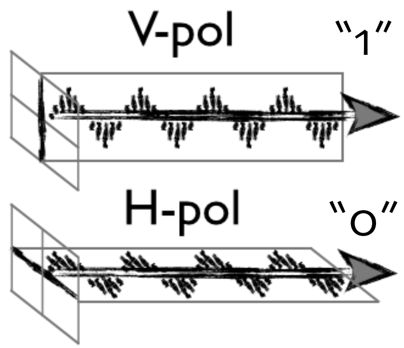
H ➔ - H



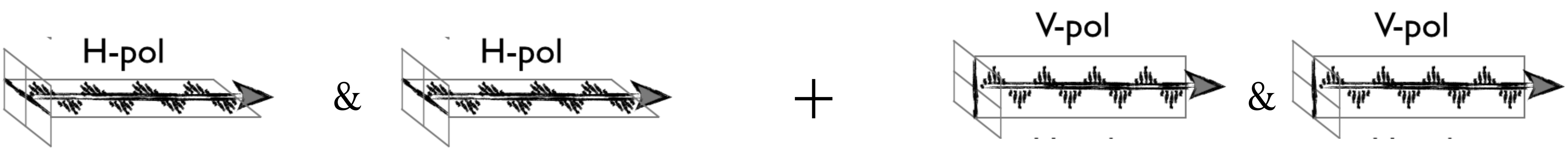
Phase changes (called "**Decoherence**") will lead to errors in a communication system.

Entangled Polarization state of two photons

A single photon can be V or H



A pair of photons A, B could be entangled:



$$State = x|H\rangle_A \& |H\rangle_B + y|V\rangle_A \& |V\rangle_B$$

$$= x|0\rangle_A \& |0\rangle_B + y|1\rangle_A \& |1\rangle_B$$

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Bell States

There are four unique entangled states that are especially useful

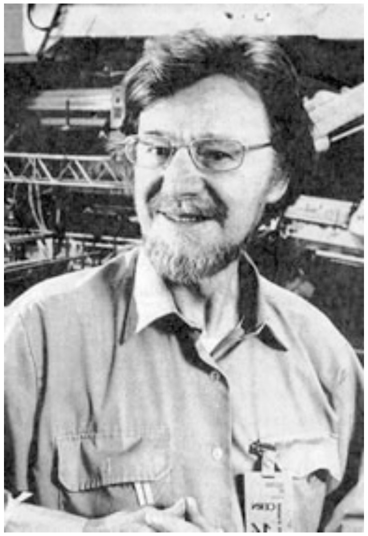
Bells states of photons A and B

$$\frac{1}{\sqrt{2}}|H\rangle_A \& |V\rangle_B + \frac{1}{\sqrt{2}}|V\rangle_A \& |H\rangle_B$$

$$\frac{1}{\sqrt{2}}|H\rangle_A \& |V\rangle_B + \frac{-1}{\sqrt{2}}|V\rangle_A \& |H\rangle_B$$

$$\frac{1}{\sqrt{2}}|H\rangle_A \& |H\rangle_B + \frac{1}{\sqrt{2}}|V\rangle_A \& |V\rangle_B$$

$$\frac{1}{\sqrt{2}}|H\rangle_A \& |H\rangle_B + \frac{-1}{\sqrt{2}}|V\rangle_A \& |V\rangle_B$$



John Bell (1960s)

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Entangled Polarization State of two photons

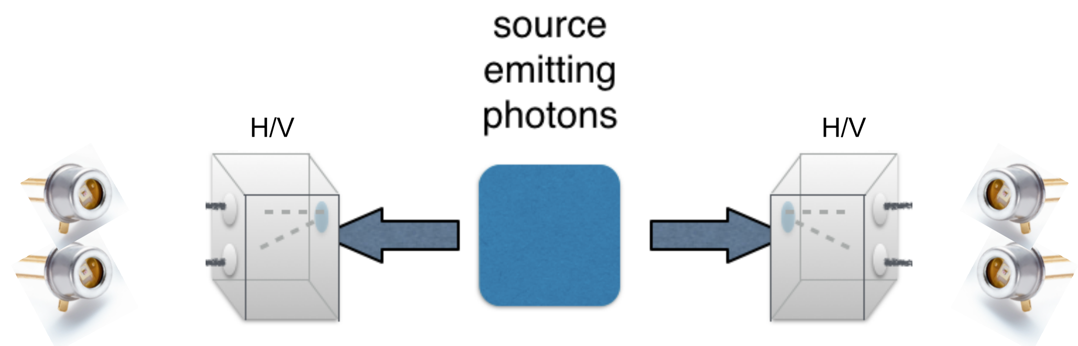
Two photons are in the entangled polarization Bell state:

POLL QUESTION 16

$$x|H\rangle_A \,\&\, |V\rangle_B \;+\; y|V\rangle_A \,\&\, |H\rangle_B$$

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

Alice



Bob

Bob measures his photon and obtains H. What will Alice observe if she measures her photon using a calcite analyzer 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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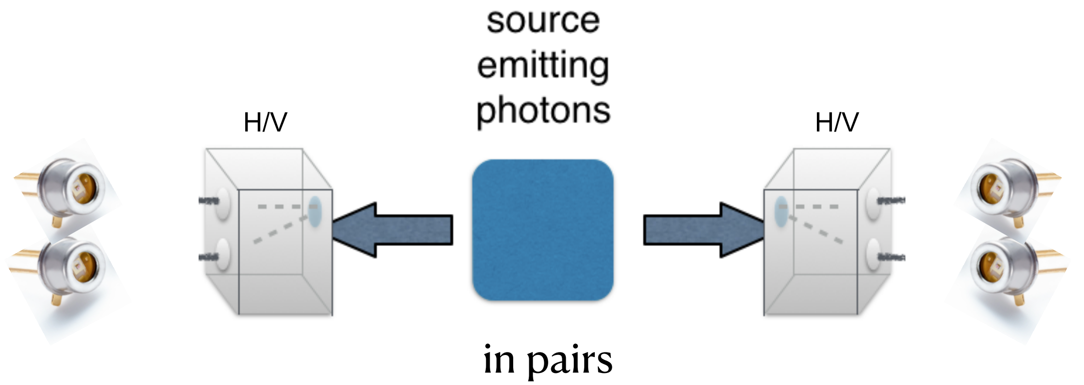
CONDITIONED QUANTUM STATES

Recall:

Alice



Bob

a type of Bell state

$$\left(\frac{1}{\sqrt{2}} |H\rangle_A \,\&\, |V\rangle_B + \frac{-1}{\sqrt{2}} |V\rangle_A \,\&\, |H\rangle_B \right)$$

For this state:
If Alice observes H, then Bob's state will be V.
but
If Alice observes V, then Bob's state will be H.

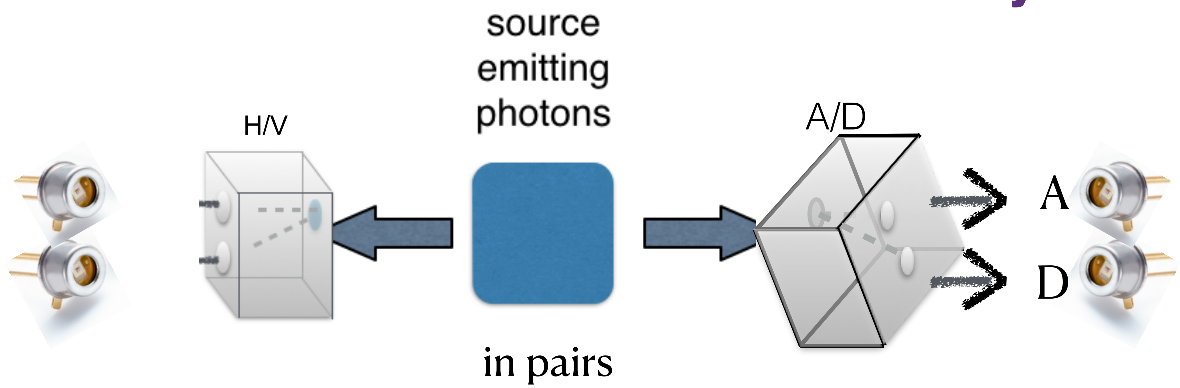
We say that "Alice observing H conditions Bob's state to be V," etc.

CONDITIONED QUANTUM STATES

POLL QUESTION 17

What if Bob instead uses a A/D analyzer?:

Alice



Bob

$$\left(\frac{1}{\sqrt{2}}|H\rangle_A \,\&\, |V\rangle_B + \frac{-1}{\sqrt{2}}|V\rangle_A \,\&\, |H\rangle_B\right)$$

For this state, recall:
If Alice observes V, then Bob's state will be H.

Recall:

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

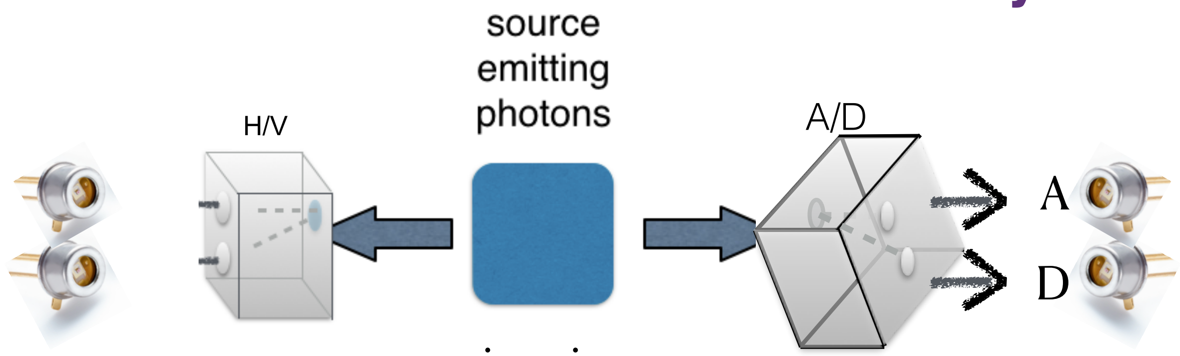
If Alice observes V and Bob uses a A/D analyzer, then:

A: Bob will have 50% probability to observe D or A.
B: Bob will observe D.
C: Bob will observe A.
D: I'm not sure

CONDITIONED QUANTUM STATES

What if Bob instead uses a A/D analyzer?:

Alice



Bob

$$\left(\frac{1}{\sqrt{2}} |H\rangle_A \,\&\, |V\rangle_B + \frac{-1}{\sqrt{2}} |V\rangle_A \,\&\, |H\rangle_B \right)$$

For this state, recall:
If Alice observes V, then Bob's state will be H.

Recall:
$$|H\rangle = \frac{1}{\sqrt{2}}|D\rangle + \frac{-1}{\sqrt{2}}|A\rangle$$

If Alice observes V and Bob uses a A/D analyzer, then:

A:
B:
C:
D:

We now show how such conditioned quantum states can be used to provide security of messaging on the Internet.

Cryptography

The Information Privacy Problem

Message sender

Message recipient

Eavesdropper

Alice

Eve

Bob

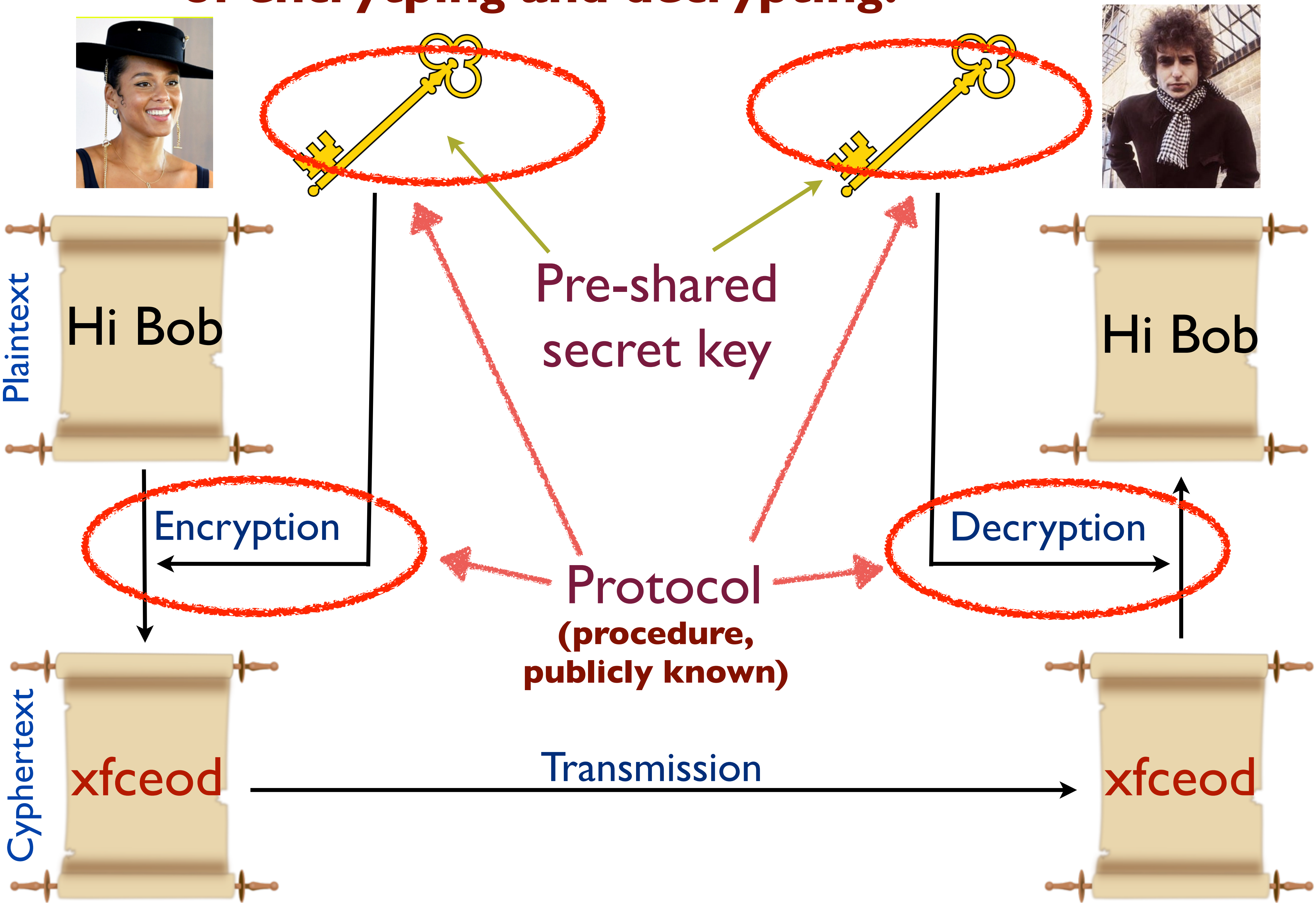
Alice and Bob want to share a secret message.

But the message might be intercepted by Eve.

Alice and Bob need to <u>SHARE</u> a method of encrytping and decrypting.

http://www.freemumia.com/2012/01/new-poem-for-mumia-by-Alice-walker/

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



To transmit digitally, represent alphabet by a Code

Code = an alternative symbolic representation of an "alphabet"

ASCII Code

American Standard Code for Information Interchange

Table 11.1 Part of the Look-Up Table for Binary ASCII Code

A	B	C	D	E	F	G
01000001	01000010	01000011	01000100	01000101	01000110	01000111
H	I	J	K	L	M	N
01001000	01001001	01001010	01001011	01001100	01001101	01001110
O	P	Q	R	S	T	U
01001111	01010000	01010001	01010010	01010011	01010100	01010101
V	W	X	Y	Z		
01010110	01010111	01011000	01011001	01011010		
a	b	c	d	e	f	g
01100001	01100010	01100011	01100100	01100101	01100110	01100111
h	i	j	k	l	m	n
01101000	01101001	01101010	01101011	01101100	01101101	01101110
o	p	q	r	s	t	u
01101111	01110000	01110001	01110010	01110011	01110100	01110101
v	w	x	y	z		
01110110	01110111	01111000	01111001	01111010		

A binary symbol, 0 or 1, is called a **bit**.

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: “p” encoded in ASCII -> 01110000

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

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

QUESTION What is the encrypted message?

30 seconds

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: 1 1 0 1 1 0 1 0

key: 1 0 1 0 1 0 1 0

_ _ _ _ _ _ _ _

QUESTION

What is the <u>original</u> message?

30 seconds

01110000 encoded in ASCII -> message: “p”

Alice and Bob need to share a random key that is at least as long as the message they wish to communicate.

The problem:

Alice and Bob need to share this key over the same network that they suspect is insecure.

The challenge:

Is there a way for Alice and Bob to share a key and be confident that it wasn't intercepted?

The trick for creating a secure shared key:

Quantum Key Distribution (QKD)

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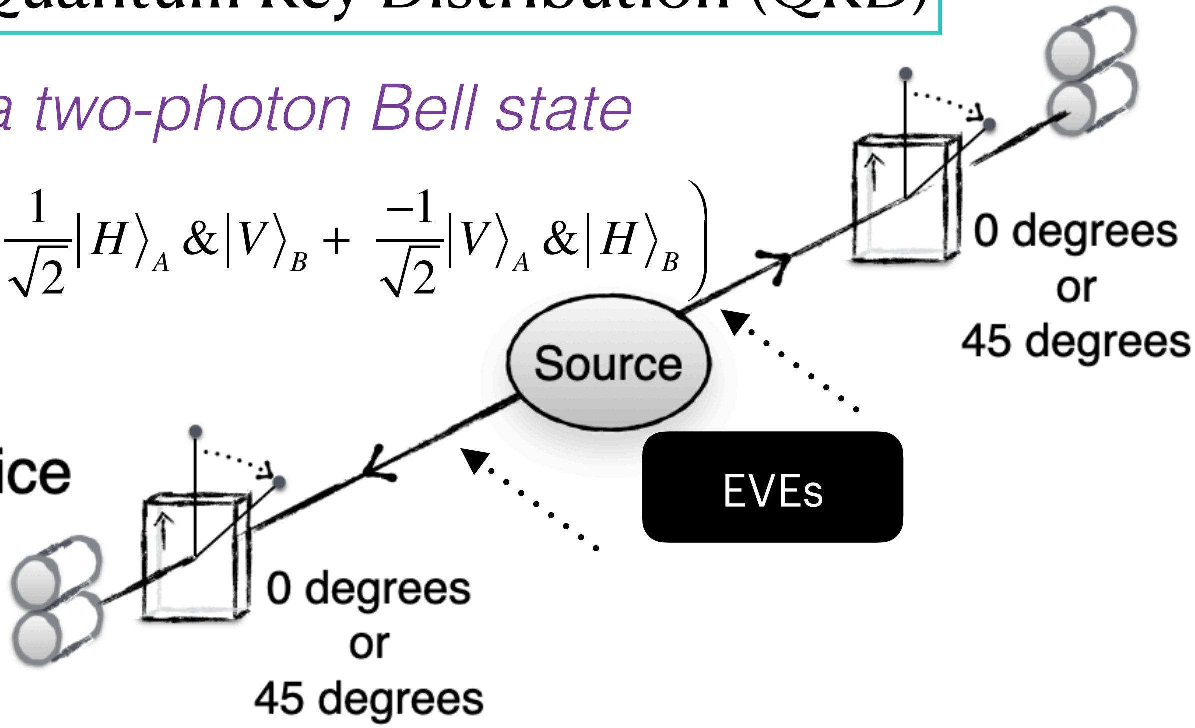
NSF-ERC

a two-photon Bell state

$$\left(\frac{1}{\sqrt{2}}|H\rangle_A \,\&\, |V\rangle_B + \frac{-1}{\sqrt{2}}|V\rangle_A \,\&\, |H\rangle_B\right)$$



A source generates a series of known and identical Bell States, whose measurement by Alice creates conditioned states for Bob.

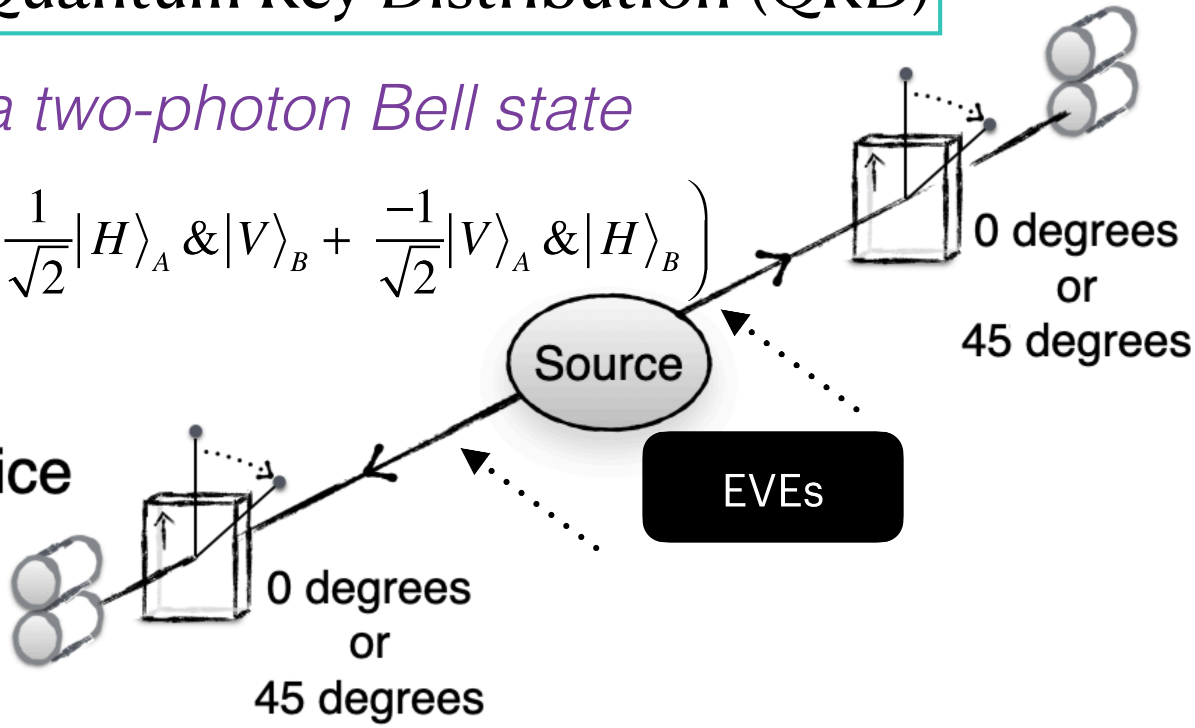
Alice and Bob can generate a secret shared encyption key by making Polarization Measurements on entangled photon pairs

Quantum Key Distribution (QKD)

Center for Quantum Networks NSF-ERC

a two-photon Bell state

$$\left(\frac{1}{\sqrt{2}} |H\rangle_A \& |V\rangle_B + \frac{-1}{\sqrt{2}} |V\rangle_A \& |H\rangle_B \right)$$



Recall for this state:
If Alice observes H, then Bob's state will be V.
whereas If Alice observes V, then Bob's state will be H.

It's not hard to show that this Bell state is equivalent to: $\left(\frac{1}{\sqrt{2}} |D\rangle_A \& |A\rangle_B + \frac{-1}{\sqrt{2}} |A\rangle_A \& |D\rangle_B \right)$

Therefore:
If Alice observes D, then Bob's state will be A.
whereas If Alice observes A, then Bob's state will be D.

The Math (can come back to later if interested)

Recall
$$\left|D\right\rangle = \frac{1}{\sqrt{2}}\left|H\right\rangle + \frac{1}{\sqrt{2}}\left|V\right\rangle$$
$$\left|A\right\rangle = \frac{-1}{\sqrt{2}}\left|H\right\rangle + \frac{1}{\sqrt{2}}\left|V\right\rangle$$
and
$$\frac{1}{\sqrt{2}}\left|D\right\rangle + \frac{1}{\sqrt{2}}\left|A\right\rangle = \left|V\right\rangle$$
$$\frac{1}{\sqrt{2}}\left|D\right\rangle - \frac{1}{\sqrt{2}}\left|A\right\rangle = \left|H\right\rangle$$

So:

$$\left(\frac{1}{\sqrt{2}}\left|H\right\rangle_A \& \left|V\right\rangle_B + \frac{-1}{\sqrt{2}}\left|V\right\rangle_A \& \left|H\right\rangle_B\right) = \frac{1}{\sqrt{2}}\left(\left|H\right\rangle_A \& \left|V\right\rangle_B - \left|V\right\rangle_A \& \left|H\right\rangle_B\right) =$$

$$\frac{1}{\sqrt{2}}\left(\left\{\frac{1}{\sqrt{2}}\left|D\right\rangle_A - \frac{1}{\sqrt{2}}\left|A\right\rangle_A\right\} \& \left\{\frac{1}{\sqrt{2}}\left|D\right\rangle_B + \frac{1}{\sqrt{2}}\left|A\right\rangle_B\right\} - \left\{\frac{1}{\sqrt{2}}\left|D\right\rangle_A + \frac{1}{\sqrt{2}}\left|A\right\rangle_A\right\} \& \left\{\frac{1}{\sqrt{2}}\left|D\right\rangle_B - \frac{1}{\sqrt{2}}\left|A\right\rangle_B\right\}\right) =$$

$$\frac{1}{\sqrt{2}}\frac{1}{2}\left(\left\{\left|D\right\rangle_A - \left|A\right\rangle_A\right\} \& \left\{\left|D\right\rangle_B + \left|A\right\rangle_B\right\} - \left\{\left|D\right\rangle_A + \left|A\right\rangle_A\right\} \& \left\{\left|D\right\rangle_B - \left|A\right\rangle_B\right\}\right) =$$

$$\frac{1}{\sqrt{2}}\frac{1}{2}\left(\left\{\left|D\right\rangle_A\right\} \& \left\{\cancel{\left|D\right\rangle_B} + \left|A\right\rangle_B\right\} - \left\{\cancel{\left|D\right\rangle_A} + \left|A\right\rangle_A\right\} \& \left\{\left|D\right\rangle_B\right\}\right) +$$
$$\frac{1}{\sqrt{2}}\frac{1}{2}\left(\left\{-\left|A\right\rangle_A\right\} \& \left\{\left|D\right\rangle_B + \cancel{\left|A\right\rangle_B}\right\} - \left\{\left|A\right\rangle_A\right\} \& \left\{\left|D\right\rangle_B - \cancel{\left|A\right\rangle_B}\right\}\right) =$$

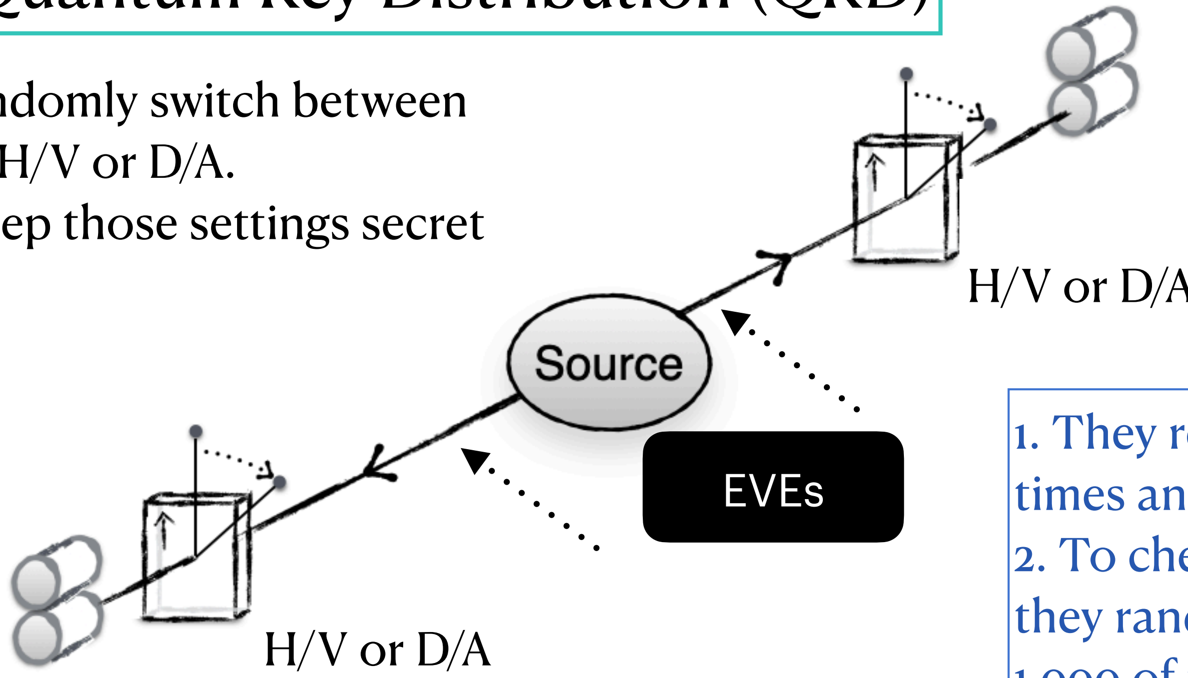
Thus :

$$\left(\frac{1}{\sqrt{2}}\left|H\right\rangle_A \& \left|V\right\rangle_B + \frac{-1}{\sqrt{2}}\left|V\right\rangle_A \& \left|H\right\rangle_B\right) = \frac{1}{\sqrt{2}}\left(\left|D\right\rangle_A \& \left|A\right\rangle_B - \left|A\right\rangle_A \left|D\right\rangle_B\right)$$

Quantum Key Distribution (QKD)

Center for Quantum Networks NSF-ERC

Alice and Bob both randomly switch between their analyzer settings H/V or D/A.
They keep track but keep those settings secret from the world.



1. They repeat 10,000 times and keep records
2. To check for an Eve they randomly select 1,000 of trials and share (publicly) those settings and measurement results.

Alice Result	Alice Setting	settings	Bob Setting	Bob Result	
H	H/V	match	H/V	V	OK
A	D/A		D/A	D	OK
H	H/V	mismatch	D/A	A	irrelevant
D	D/A		D/A	D	Error potentially caused by Eve
V	H/V		H/V	H	
D	D/A		H/V	V	

If too many errors are seen, they discard all the data and don't use it as a key

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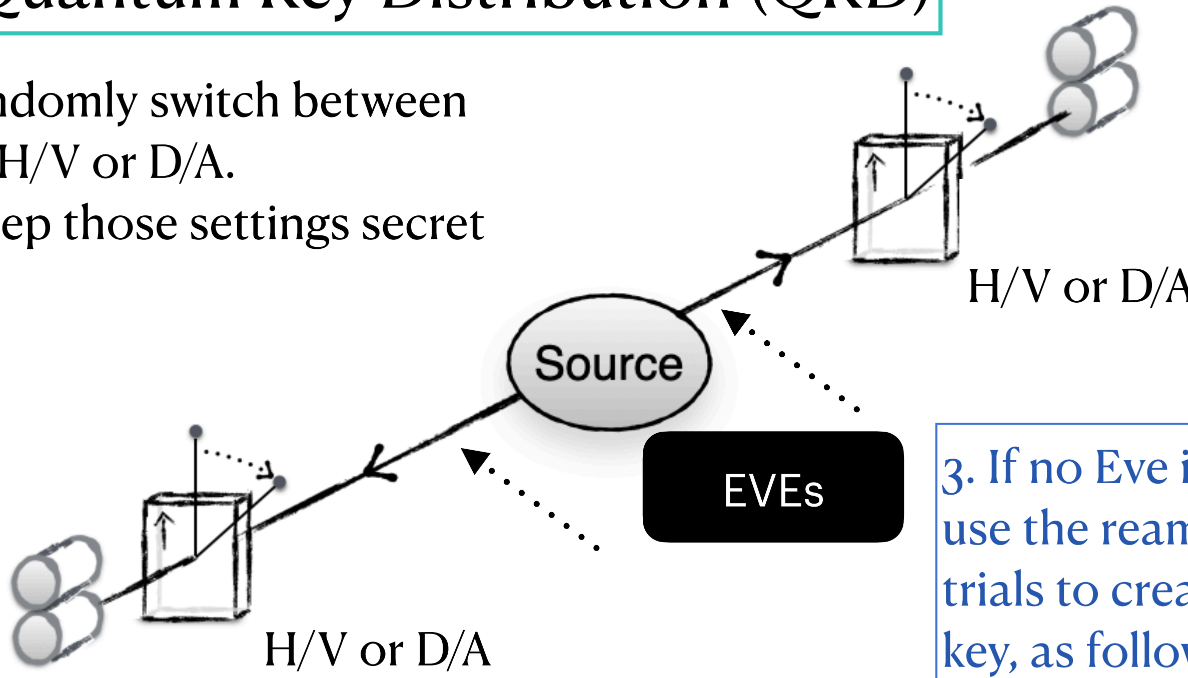
Quantum Key Distribution (QKD)

Alice and Bob both randomly switch between their analyzer settings H/V or D/A.
They keep track but keep those settings secret from the world.



3. If no Eve is detected they use the reamaining 9,000 trials to create their shared key, as follows:
Alice: V = 1, H = 0, D = 1, A = 0
Bob: V = 0, H = 1, D = 0, A = 1

Alice Result (secret)	Alice Setting (public)	settings	Bob Setting (public)	Bob Result (secret)		Key
H	H/V	match	H/V	V	OK	0
D	D/A		D/A	A	OK	1
H	H/V	mismatch	D/A	A		
D	D/A		D/A	D	OK	0
V	H/V		H/V	H	OK	1
D	D/A		H/V	V		
					OK	.
					OK	.
						.

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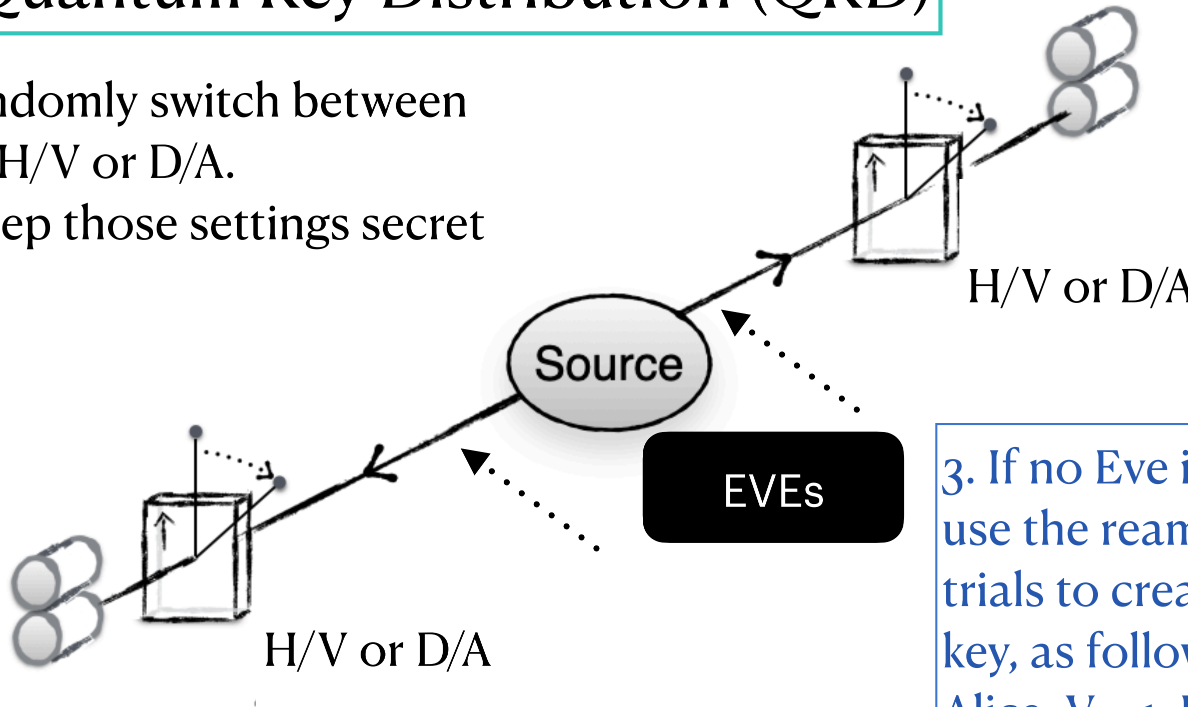
Quantum Key Distribution (QKD)

Alice and Bob both randomly switch between their analyzer settings H/V or D/A.
They keep track but keep those settings secret from the world.



3. If no Eve is detected they use the reamaining 9,000 trials to create their shared key, as follows:
Alice: V = 1, H = 0, D = 1, A = 0
Bob: V = 0, H = 1, D = 0, A = 1

Alice Result (secret)	Alice Setting (public)	settings	Bob Setting (public)	Bob Result (secret)		Key
H	H/V	match	H/V	V	OK	0
D	D/A		D/A	A	OK	1
H	H/V	mismatch	D/A	A		
D	D/A		D/A	D	OK	0
V	H/V					1
D	D/A					
						.
						.
						.

they use the key
to encrypt and decrypt a message
sent over the classical
internet

END PART 2

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10 minute break

The Physics Behind the Quantum Internet

PART 3

QUANTUM STATE TELEPORTATION

Presenter: Amy Soudachanh
University of Oregon

UNIVERSITY OF OREGON

Center for Quantum Networks NSF-ERC

SHORT COURSE (3.5 HR) OUTLINE

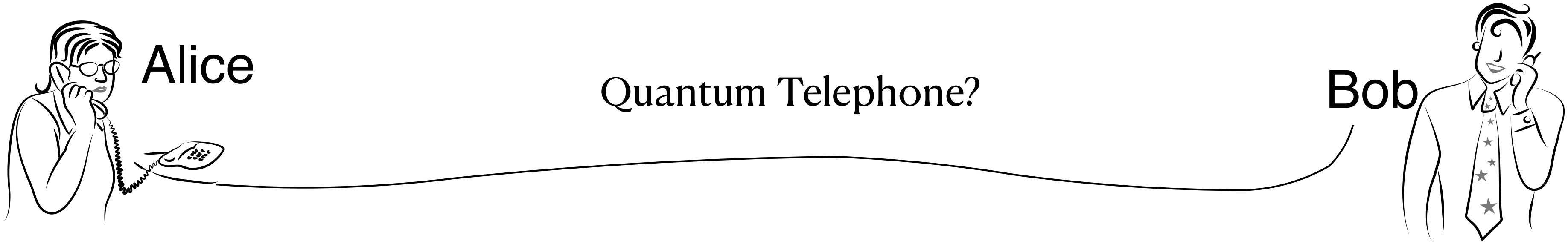
PART 1: Quantum information science
The Center for Quantum Networks
The National Quantum Initiative
What is *information*?
Bits and qubits
Superposition and entanglement

PART 2: Encoding and transmitting quantum information
Communication systems
Distributing Entangled states
Ways of encoding qubits
Ways of encoding qubits in photons
Focus on photon polarization
State vector representation and Born's Rule
Bell states
Quantum cryptography

PART 3: Quantum state teleportation
Joint measurement
Quantum state teleportation
Why entenglement distribution?

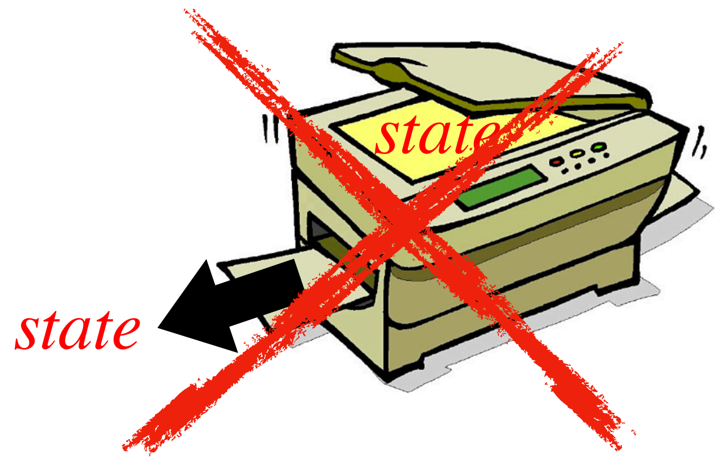
PART 4: The Quantum Internet
Why the quantum internet?
Bell State Creation and Measurement
Quantum memories
Memory-Assisted Teleportation
Entanglement Swapping with Quantum Memories
Quantum repeater networks
What could a quantum Network do?
Perspectives and misconceptions

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 a physical object.
It could do so by moving the object.
Alternatively it may do so by state teleportation.

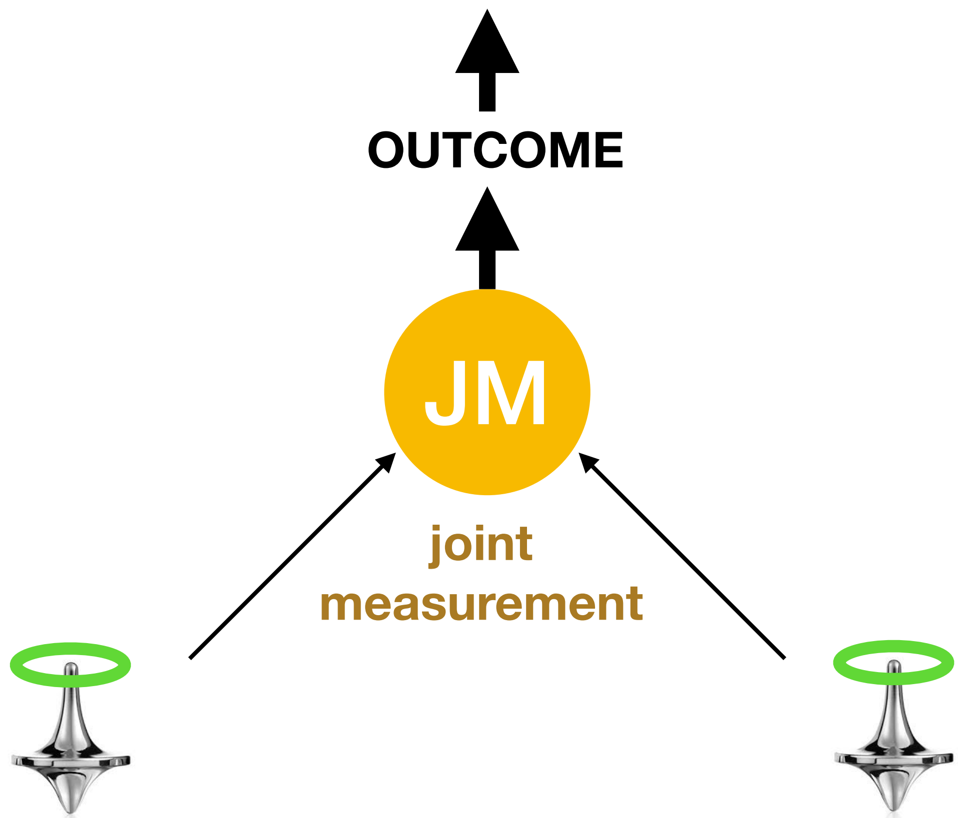
https://clipartstation.com/wp-content/uploads/2017/11/xerox-machine-clipart-8.jpg

A Useful Tool: Joint Measurement

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

Possible outcomes:

They are the same
or
They are different



example with unknown spins

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Joint Qubit Measurement

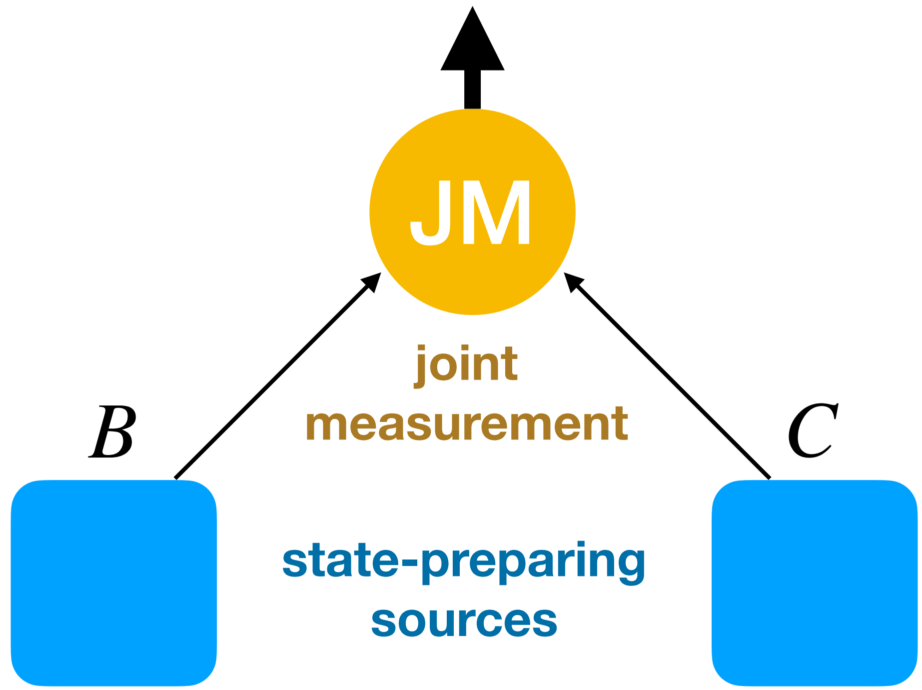
Joint Measurement gives information about the pair, but not full information about each member

example outcome #1

They are the same
(0, 0) or (1,1)
Don't know which

$$x|0\rangle_B \;\&\; w|0\rangle_C + y|1\rangle_B \;\&\; z|1\rangle_C$$

OUTCOME



$$State_B = x|0\rangle_B + y|1\rangle_B \qquad State_C = w|0\rangle_C + z|1\rangle_C$$

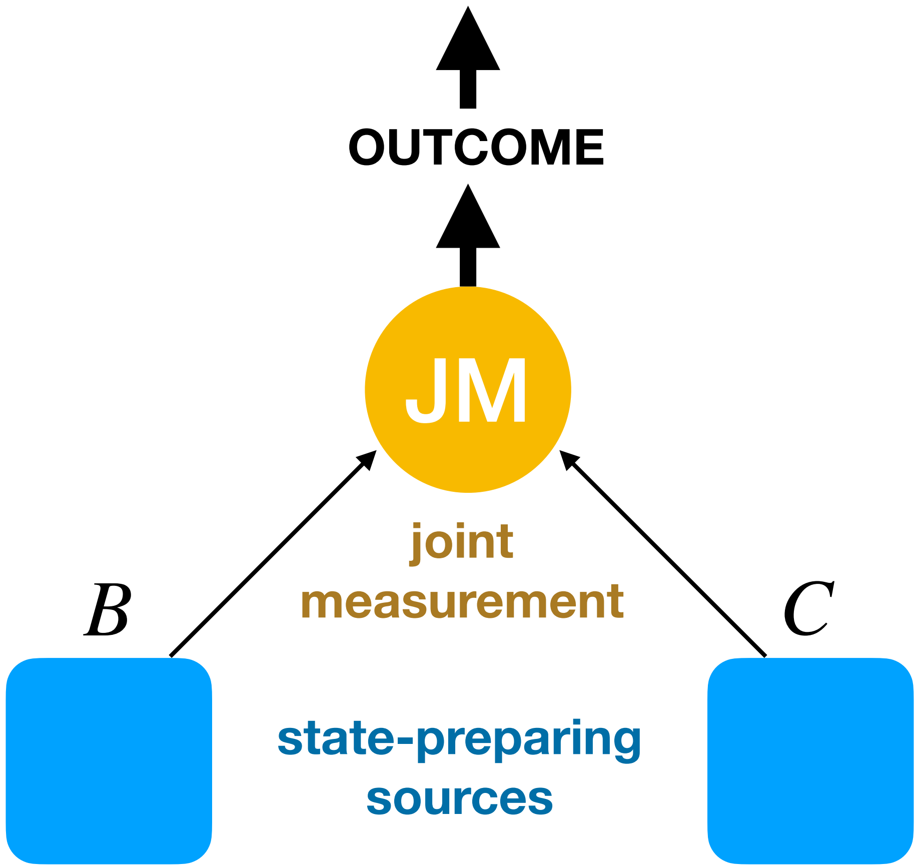
Joint Qubit Measurement

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)
Don't know which

$$x|0\rangle_B \,\&\, z|1\rangle_C + y|1\rangle_B \,\&\, w|0\rangle_C$$



$$State_B = x|0\rangle_B + y|1\rangle_B \qquad State_C = w|0\rangle_C + z|1\rangle_C$$

Entanglement Swapping

start with two separate Bell states

entangled state of A and B

A,B

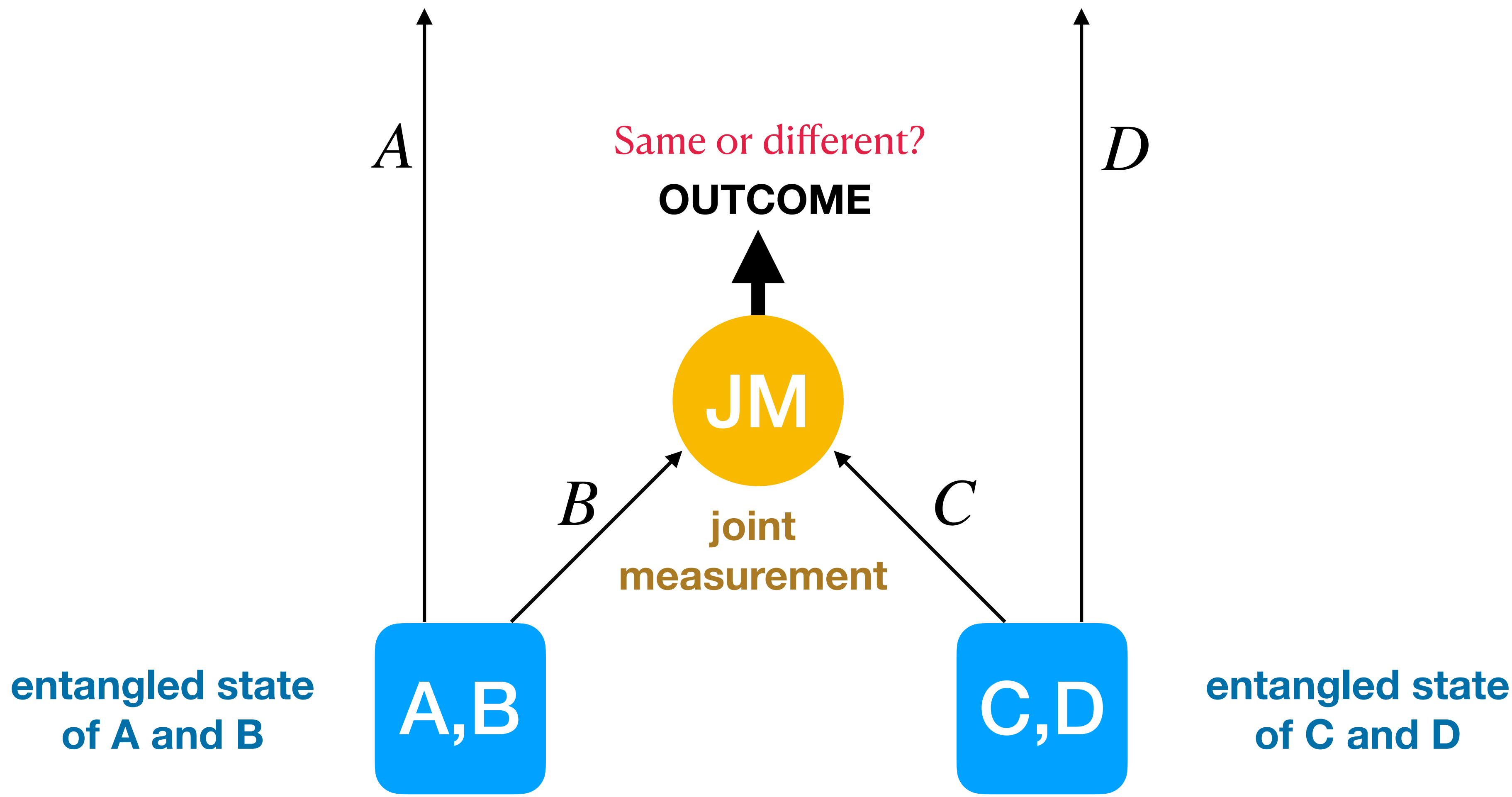
C,D

entangled state of C and D

$$\left(\frac{1}{\sqrt{2}}|0\rangle_A \,\&\, |1\rangle_B + \frac{1}{\sqrt{2}}|1\rangle_A \,\&\, |0\rangle_B\right) \quad \& \quad \left(\frac{1}{\sqrt{2}}|0\rangle_C \,\&\, |1\rangle_D + \frac{1}{\sqrt{2}}|1\rangle_C \,\&\, |0\rangle_D\right)$$

Entanglement Swapping

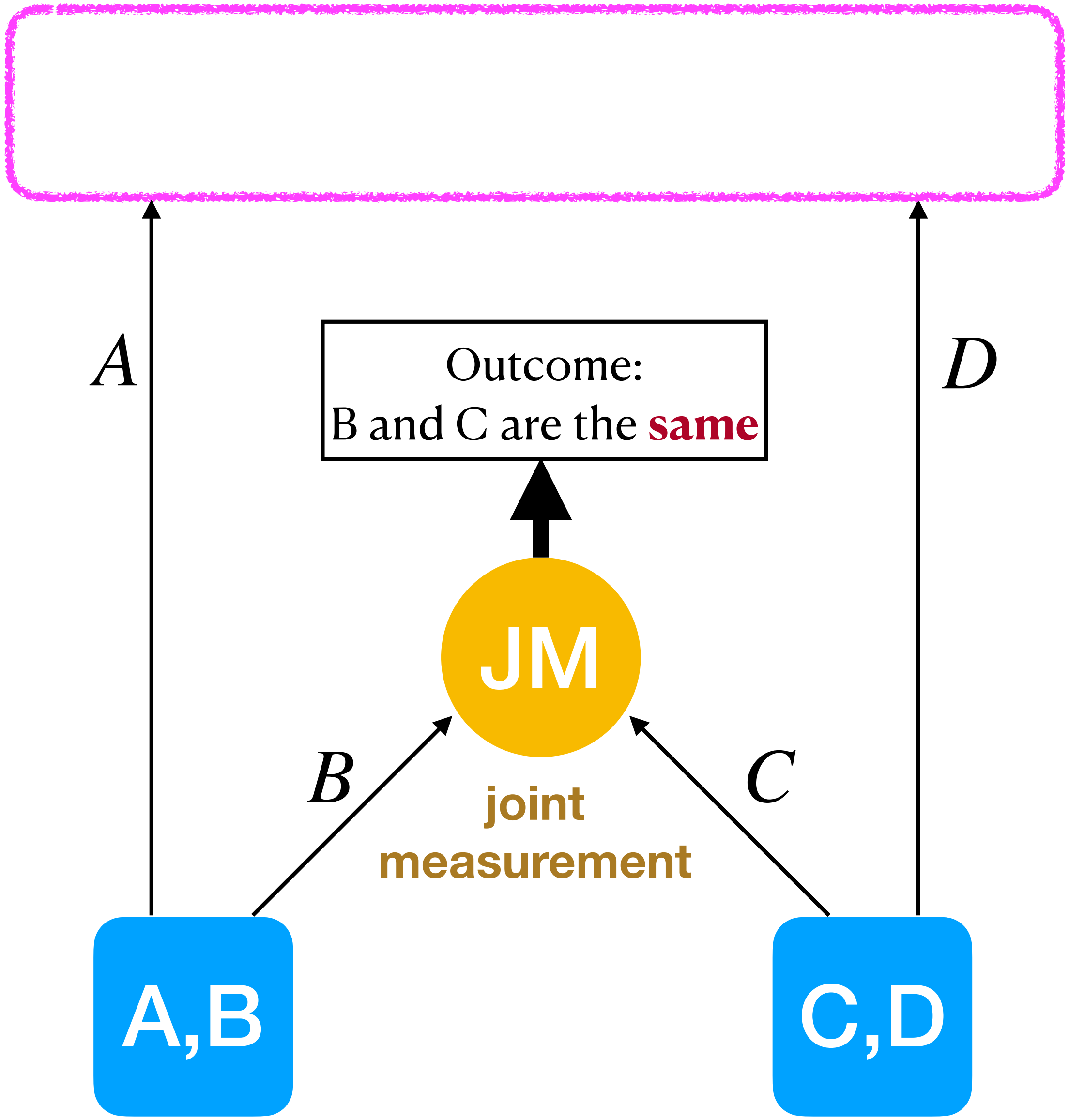
Send B and C into a Joint Measurement.



$$\left(\frac{1}{\sqrt{2}}|0\rangle_A \,\&\, |1\rangle_B + \frac{1}{\sqrt{2}}|1\rangle_A \,\&\, |0\rangle_B\right) \quad \& \quad \left(\frac{1}{\sqrt{2}}|0\rangle_C \,\&\, |1\rangle_D + \frac{1}{\sqrt{2}}|1\rangle_C \,\&\, |0\rangle_D\right)$$

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?



$$\left(\frac{1}{\sqrt{2}}|0\rangle_A \& |1\rangle_B + \frac{1}{\sqrt{2}}|1\rangle_A \& |0\rangle_B\right) \ \& \ \left(\frac{1}{\sqrt{2}}|0\rangle_C \& |1\rangle_D + \frac{1}{\sqrt{2}}|1\rangle_C \& |0\rangle_D\right)$$

Two possible cases:

$|\ \rangle_B = |1\rangle_B$ *and* $|\ \rangle_C = |1\rangle_C$

Then

$$|0\rangle_A \& |1\rangle_B + \cancel{|1\rangle_A \& |0\rangle_B}$$

$$\&$$

$$\cancel{|0\rangle_C \& |1\rangle_D} + |1\rangle_C \& |0\rangle_D$$

In superposition with

$|\ \rangle_B = |0\rangle_B$ *and* $|\ \rangle_C = |0\rangle_C$

$$\cancel{|0\rangle_A \& |1\rangle_B} + |1\rangle_A \& |0\rangle_B$$

$$\&$$

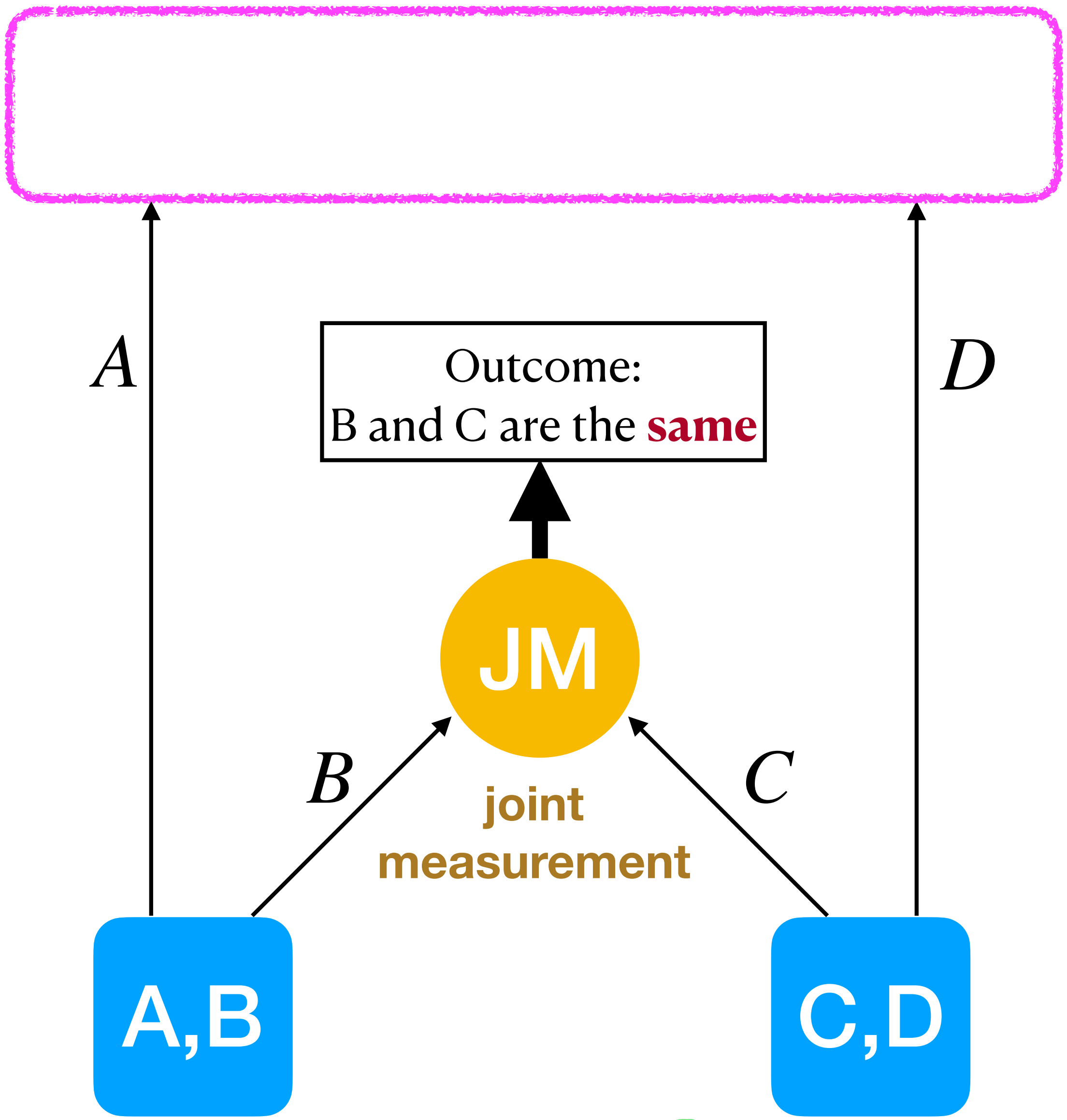
$$|0\rangle_C \& |1\rangle_D + \cancel{|1\rangle_C \& |0\rangle_D}$$

Final State:

$$\frac{1}{\sqrt{2}}|0\rangle_A \& |0\rangle_D + \frac{1}{\sqrt{2}}|1\rangle_A \& |1\rangle_D$$

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?



$$\left(\frac{1}{\sqrt{2}}|0\rangle_A \,\&\, |1\rangle_B + \frac{1}{\sqrt{2}}|1\rangle_A \,\&\, |0\rangle_B\right) \;\&\; \left(\frac{1}{\sqrt{2}}|0\rangle_C \,\&\, |1\rangle_D + \frac{1}{\sqrt{2}}|1\rangle_C \,\&\, |0\rangle_D\right)$$

TWO POSSIBLE CASES:

$|\ \rangle_B = |1\rangle_B$ *and* $|\ \rangle_C = |1\rangle_C$

THEN

$$|0\rangle_A \,\&\, |1\rangle_B + \cancel{|1\rangle_A \,\&\, |0\rangle_B}$$

$$\&$$

$$\cancel{|0\rangle_C \,\&\, |1\rangle_D} + |1\rangle_C \,\&\, |0\rangle_D$$

IN SUPERPOSITION WITH

$|\ \rangle_B = |0\rangle_B$ *and* $|\ \rangle_C = |0\rangle_C$

$$\cancel{|0\rangle_A \,\&\, |1\rangle_B} + |1\rangle_A \,\&\, |0\rangle_B$$

$$\&$$

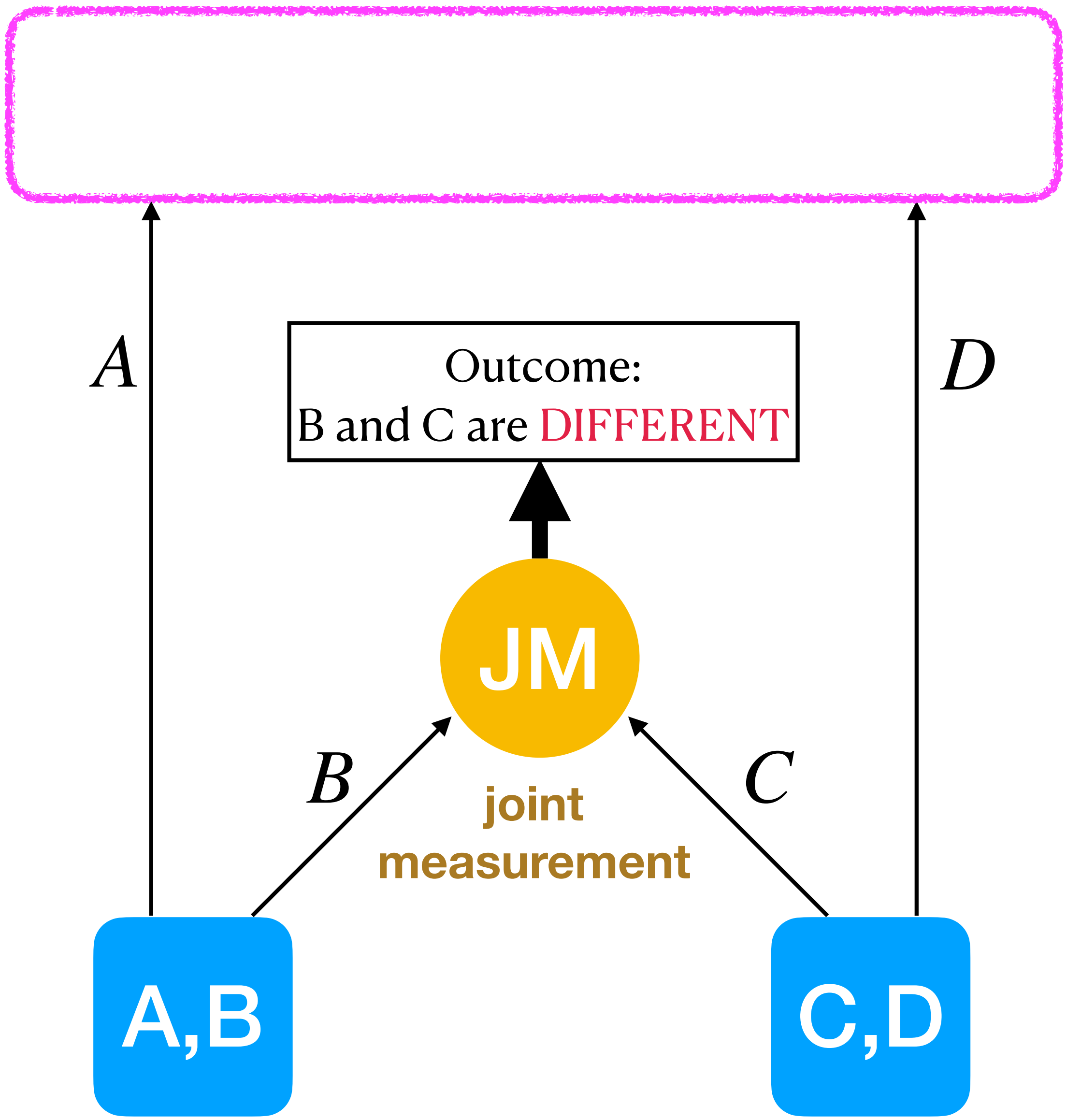
$$|0\rangle_C \,\&\, |1\rangle_D + \cancel{|1\rangle_C \,\&\, |0\rangle_D}$$

Final State:

$$\frac{1}{\sqrt{2}}|0\rangle_A \,\&\, |0\rangle_D + \frac{1}{\sqrt{2}}|1\rangle_A \,\&\, |1\rangle_D$$

POLL QUESTION 18 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?



$$\left(\frac{1}{\sqrt{2}}|0\rangle_A \,\&\, |1\rangle_B + \frac{1}{\sqrt{2}}|1\rangle_A \,\&\, |0\rangle_B\right) \;\&\; \left(\frac{1}{\sqrt{2}}|0\rangle_C \,\&\, |1\rangle_D + \frac{1}{\sqrt{2}}|1\rangle_C \,\&\, |0\rangle_D\right)$$

A. $|1\rangle_A \& |0\rangle_D + |0\rangle_A \& |1\rangle_D$

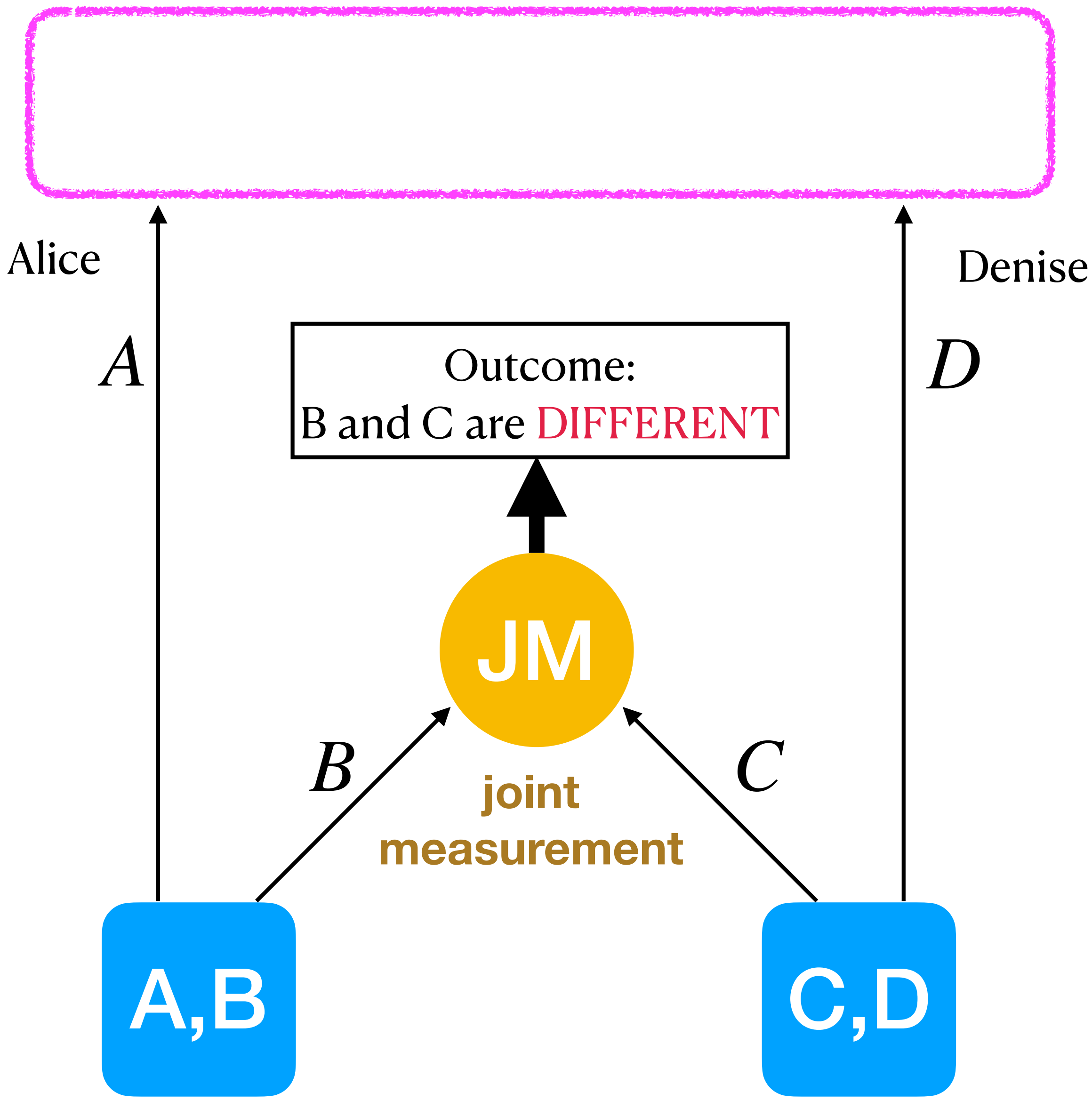
B. $|1\rangle_A \& |0\rangle_B + |0\rangle_C \& |1\rangle_D$

C. $|1\rangle_A \& |1\rangle_D + |0\rangle_A \& |0\rangle_D$

D. I don't know

Let's work it out 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?



$$\left(\frac{1}{\sqrt{2}}|0\rangle_A \& |1\rangle_B + \frac{1}{\sqrt{2}}|1\rangle_A \& |0\rangle_B\right) \; \& \; \left(\frac{1}{\sqrt{2}}|0\rangle_C \& |1\rangle_D + \frac{1}{\sqrt{2}}|1\rangle_C \& |0\rangle_D\right)$$

Two possible cases:

$|\ \rangle_B = |0\rangle_B$ *and* $|\ \rangle_C = |1\rangle_C$

Then

$$\cancel{|0\rangle_A \& |1\rangle_B} + |1\rangle_A \& |0\rangle_B$$

&

$$\cancel{|0\rangle_C \& |1\rangle_D} + |1\rangle_C \& |0\rangle_D$$

In superposition with

$|\ \rangle_B = |1\rangle_B$ *and* $|\ \rangle_C = |0\rangle_C$

$$|0\rangle_A \& |1\rangle_B + \cancel{|1\rangle_A \& |0\rangle_B}$$

&

$$|0\rangle_C \& |1\rangle_D + \cancel{|1\rangle_C \& |0\rangle_D}$$

Final State:

$$\frac{1}{\sqrt{2}}|1\rangle_A \& |0\rangle_D + \frac{1}{\sqrt{2}}|0\rangle_A \& |1\rangle_D$$

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Quantum State Teleportation

Say Professor Xavier has a photon X.
He wants to transfer the state of X over to Bob, who is a long distance away.

Can be done by Quantum State Teleportation

with the help of Alice and a satellite that provides an entangled photon pair

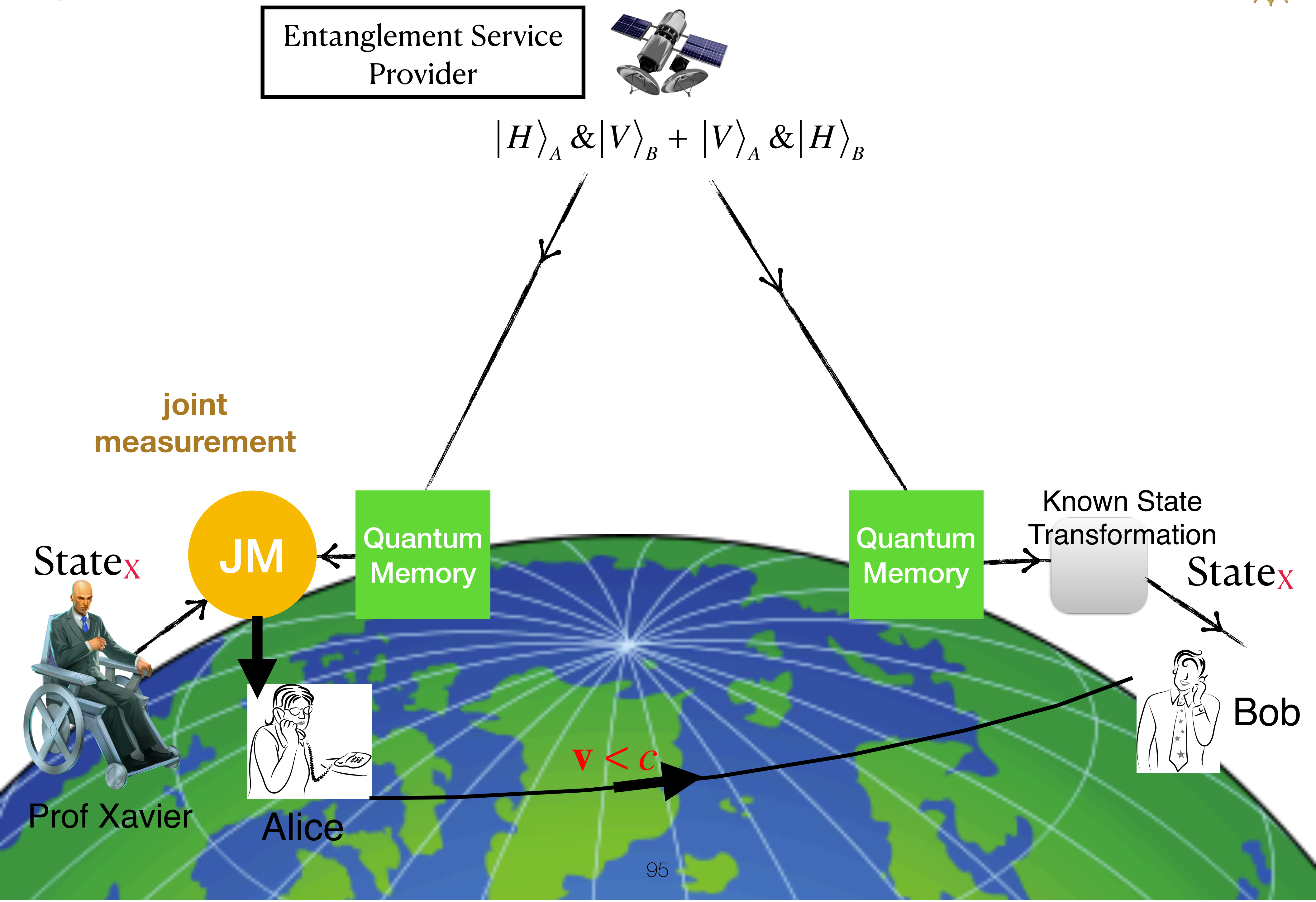
State$_{X}$

Prof Xavier

Bob

Center for Quantum Networks NSF-ERC

Satellite-Assisted Quantum State Teleportation



Quantum State Teleportation

Bob

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

$$State_X = x\left|H\right\rangle_X + y\left|V\right\rangle_X$$

X

Prof Xavier

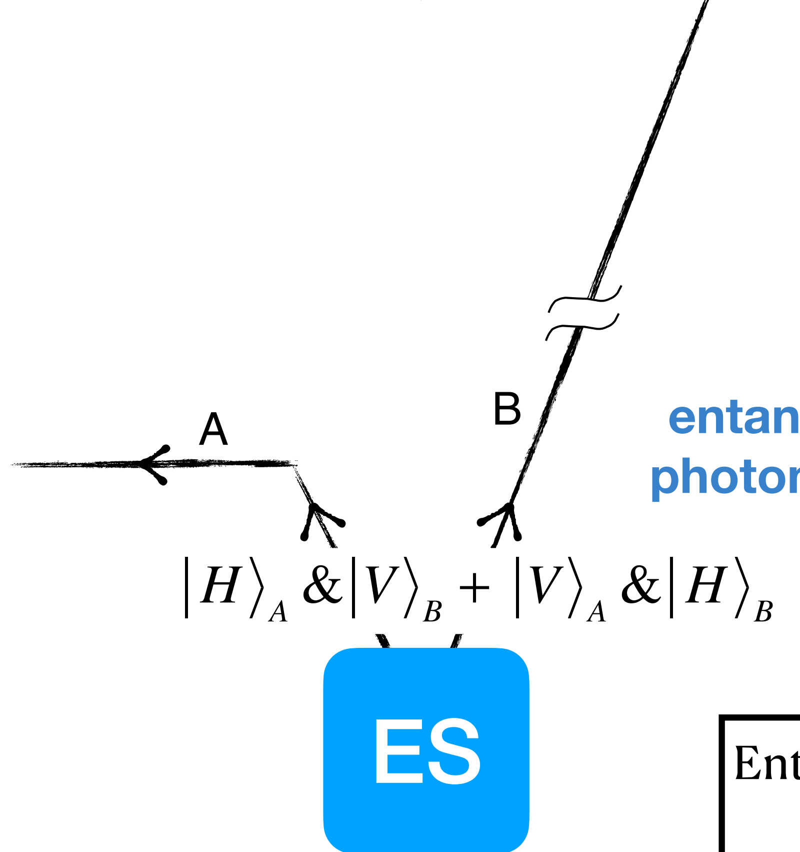
Quantum State Teleportation

Center for Quantum Networks NSF-ERC

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

Bob

Alice



entangled photon pair

$$|H\rangle_A \& |V\rangle_B + |V\rangle_A \& |H\rangle_B$$

entangled state

$$State_X = x|H\rangle_X + y|V\rangle_X$$

X

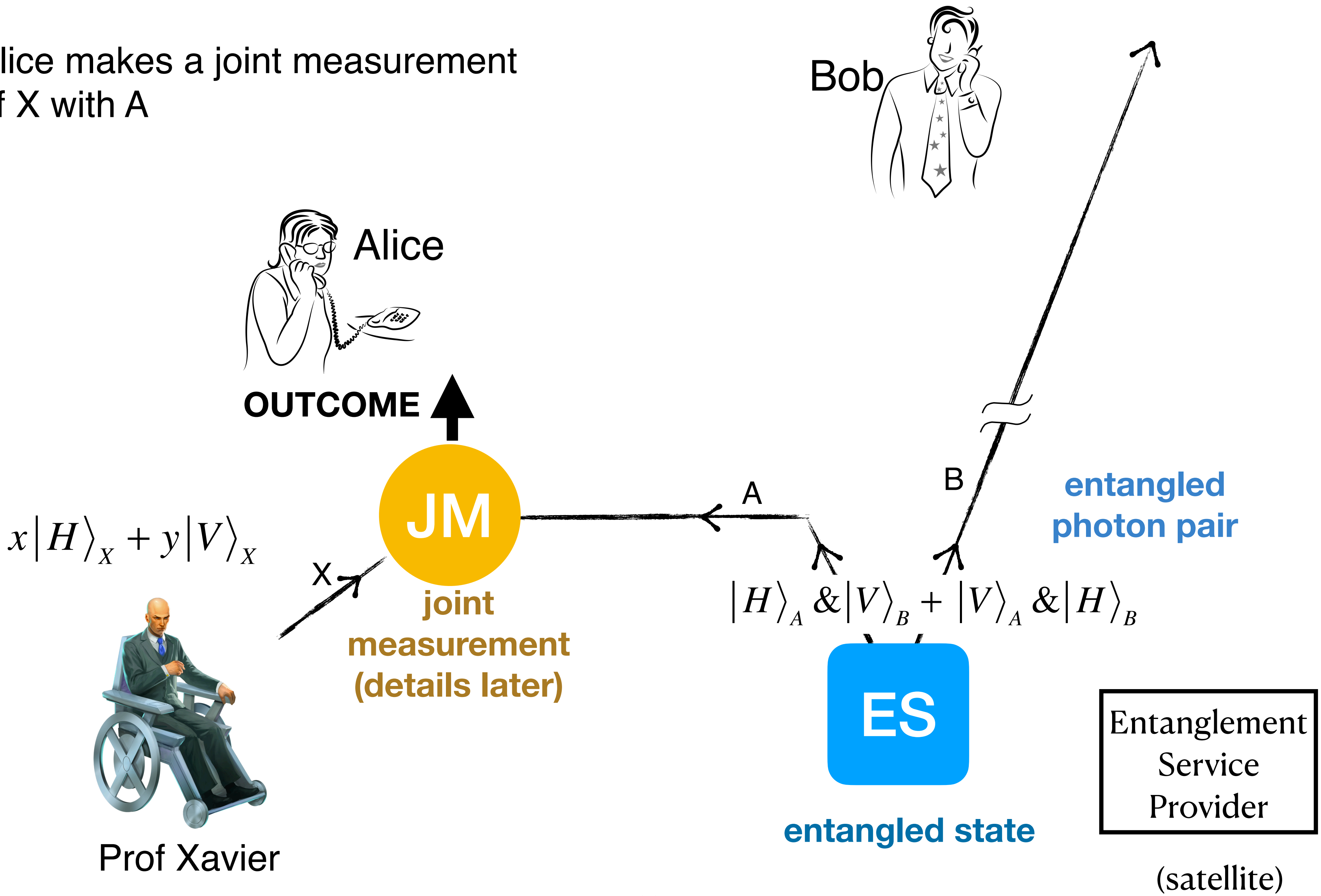
Prof Xavier

Entangelement Service Provider

(satellite)

Quantum State Teleportation

Alice makes a joint measurement of X with A



Quantum State Teleportation

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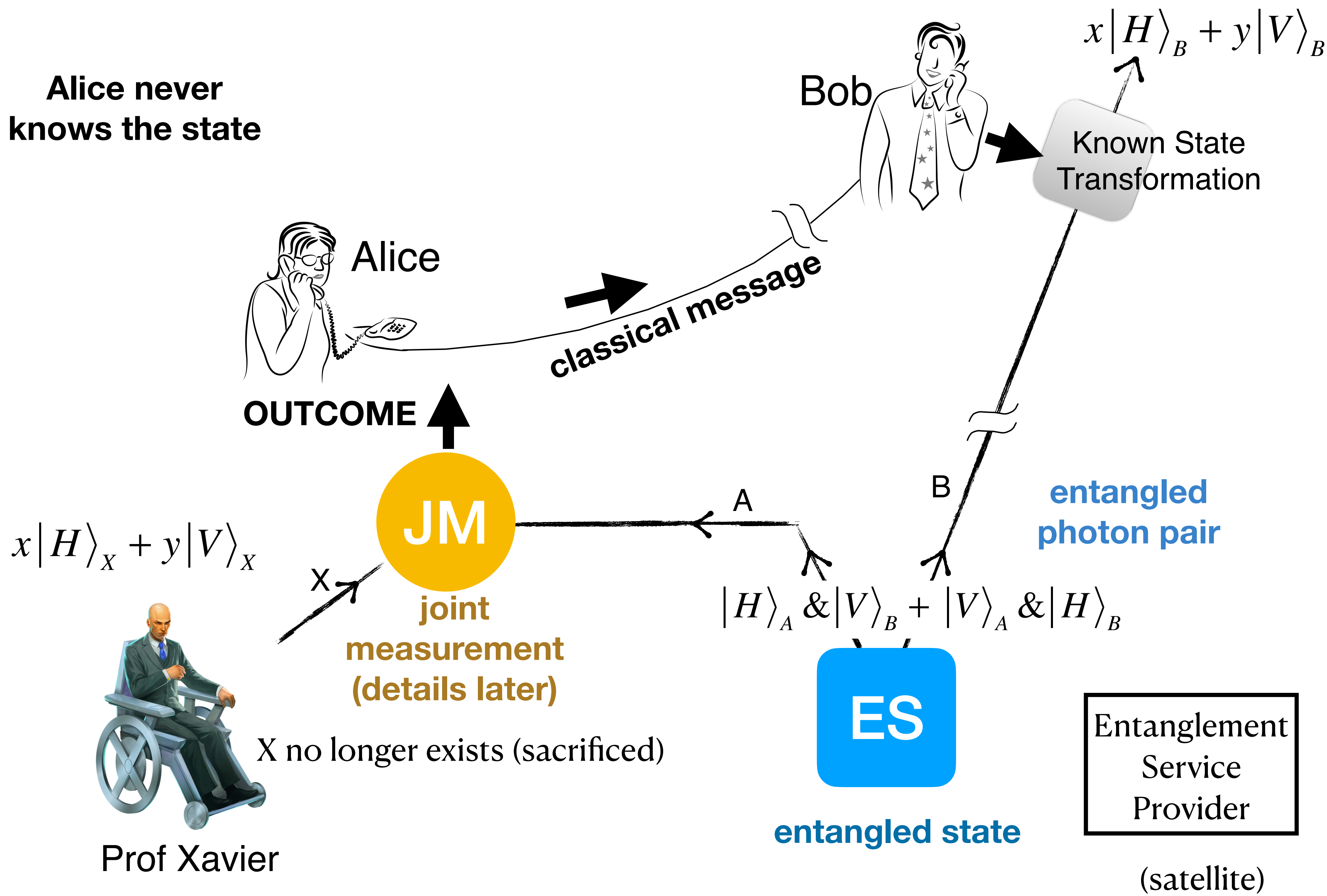
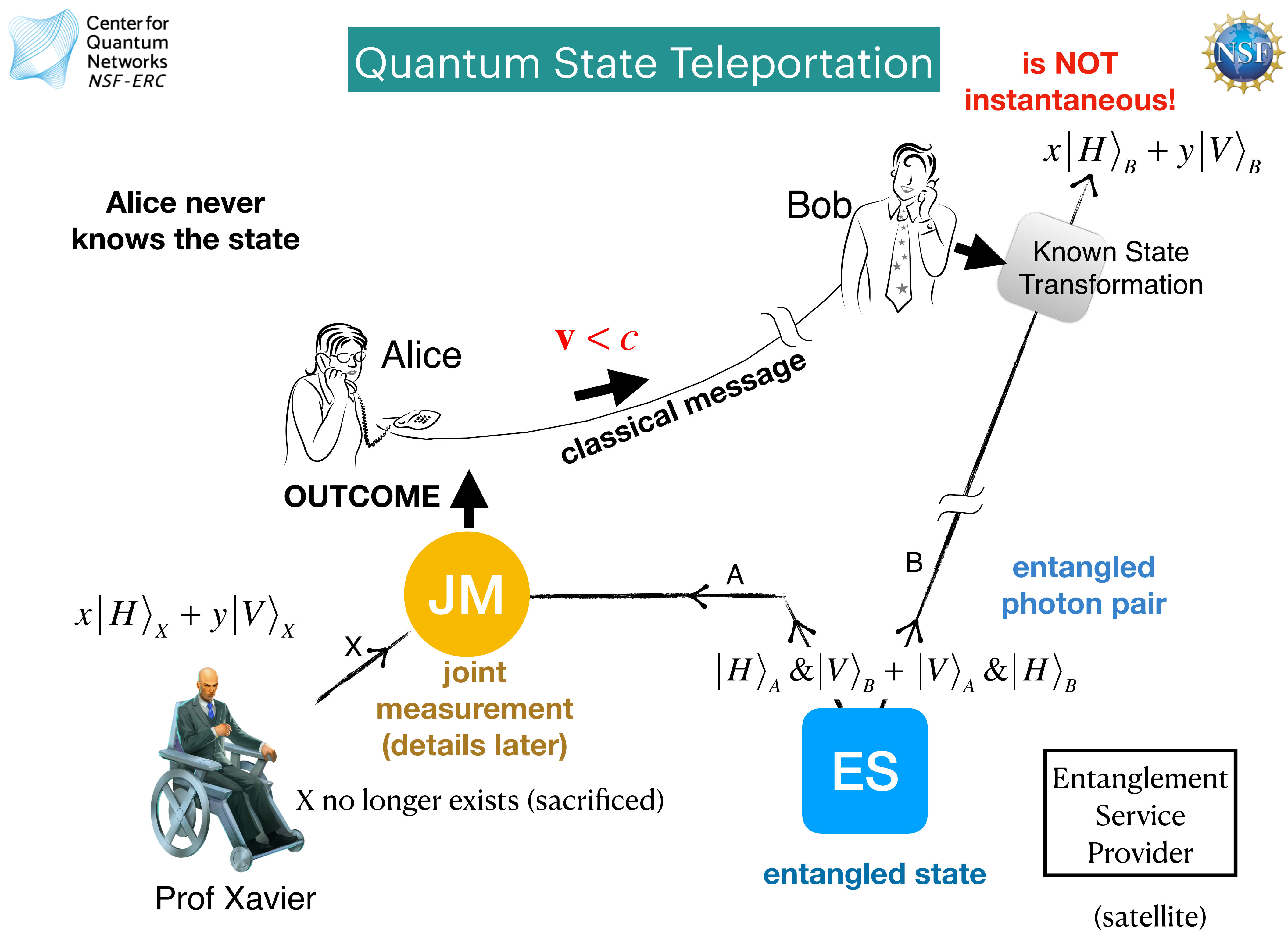
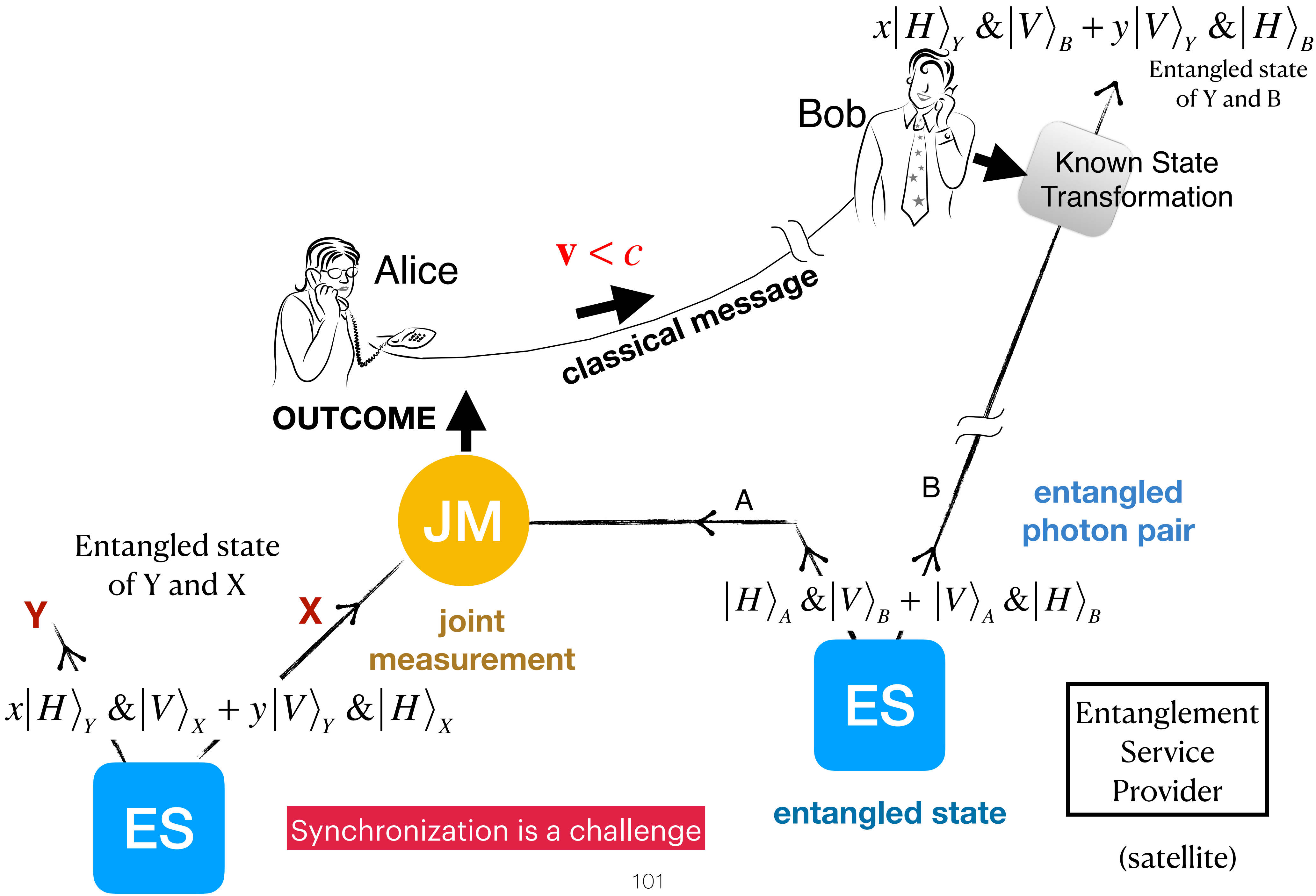
Bob gets the state!



Quantum State Teleportation



Teleport One-Half of an Entangled State

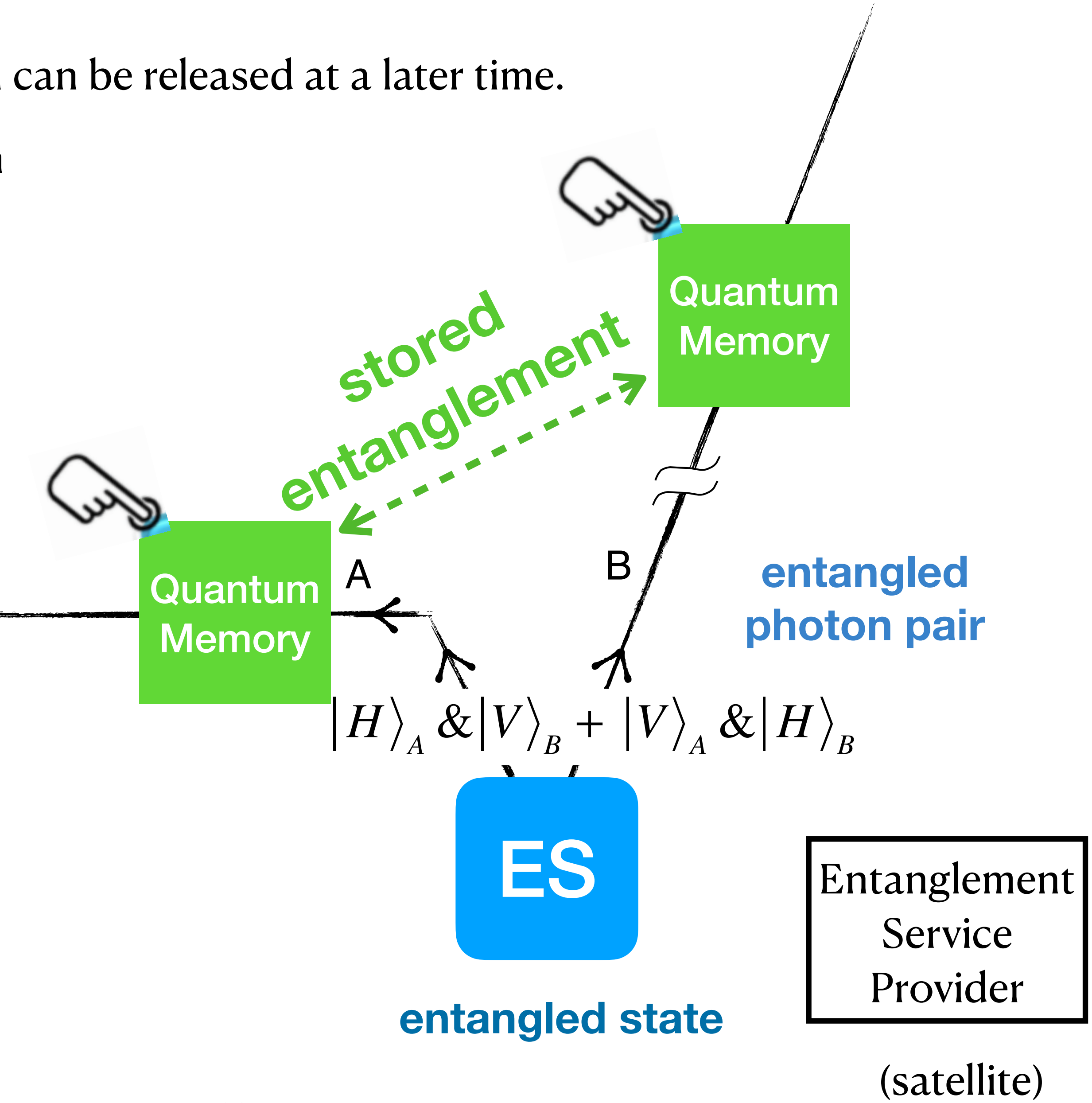


Optical Quantum Memories

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



Optical Quantum Memories

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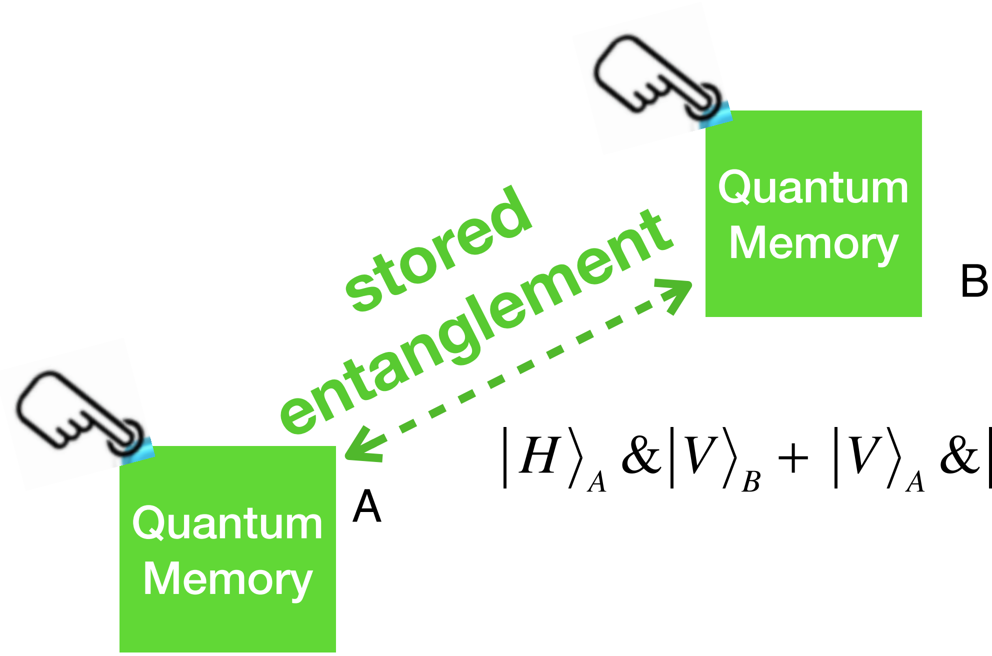
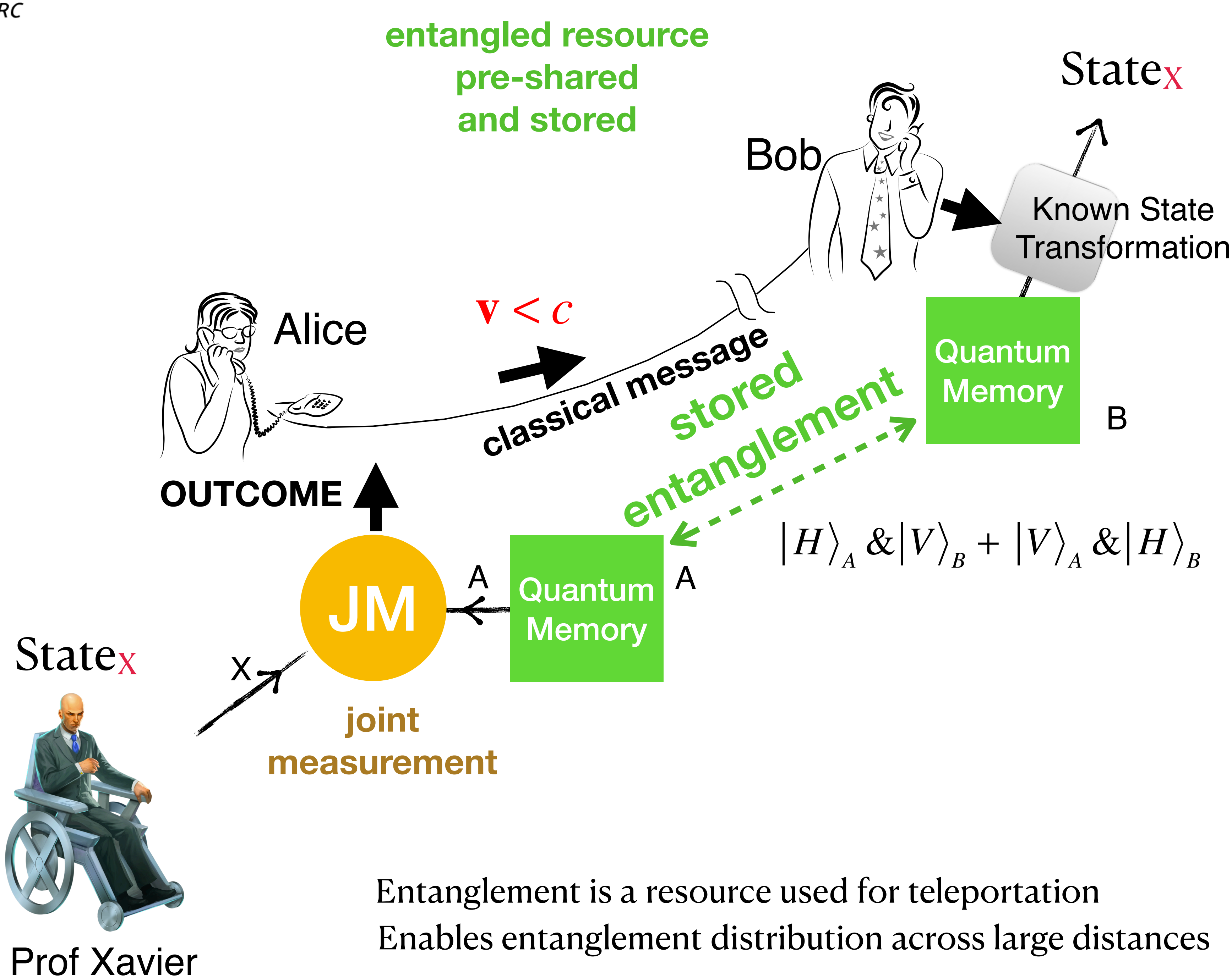
Solves the synchronization problem



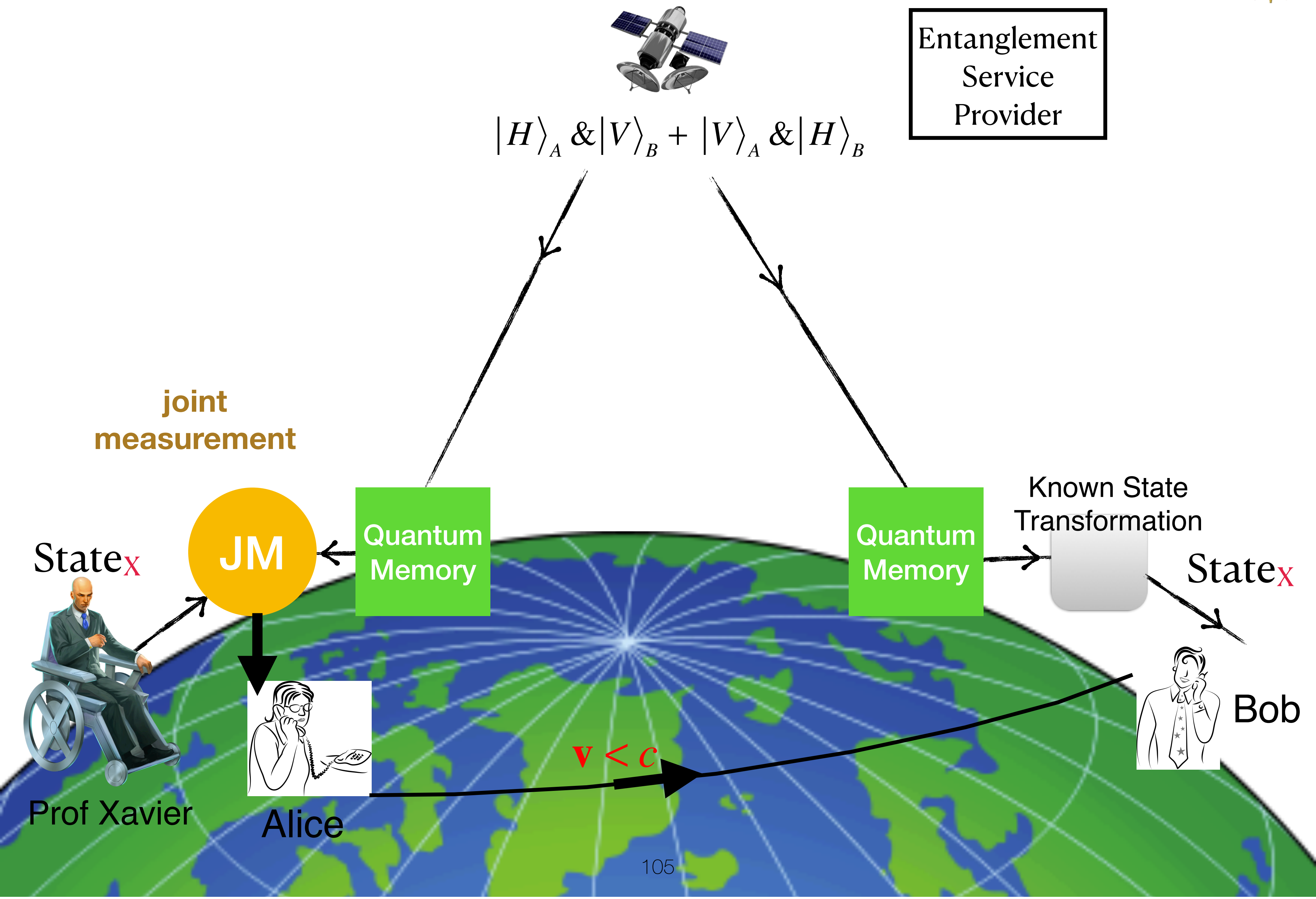
$$|H\rangle_A \,\&\, |V\rangle_B + |V\rangle_A \,\&\, |H\rangle_B$$

Memory-Assisted Quantum State Teleportation



Entanglement is a resource used for teleportation
Enables entanglement distribution across large distances

Satellite-Assisted Quantum State Teleportation



Why Quantum Entanglement Distribution?

Connecting quantum computers across vast distances enables:

- Remote quantum computing

- Distributed quantum computing

- Secure Communications

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

Quantum enhanced fundamental physics, Quantum gravity / new physics

END PART 3

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5 minute break

The Physics Behind the Quantum Internet

PART 4

THE QUANTUM INTERNET

Presenter: Michael Raymer
University of Oregon

Center for Quantum Networks NSF-ERC

SHORT COURSE (3.5 HR) OUTLINE

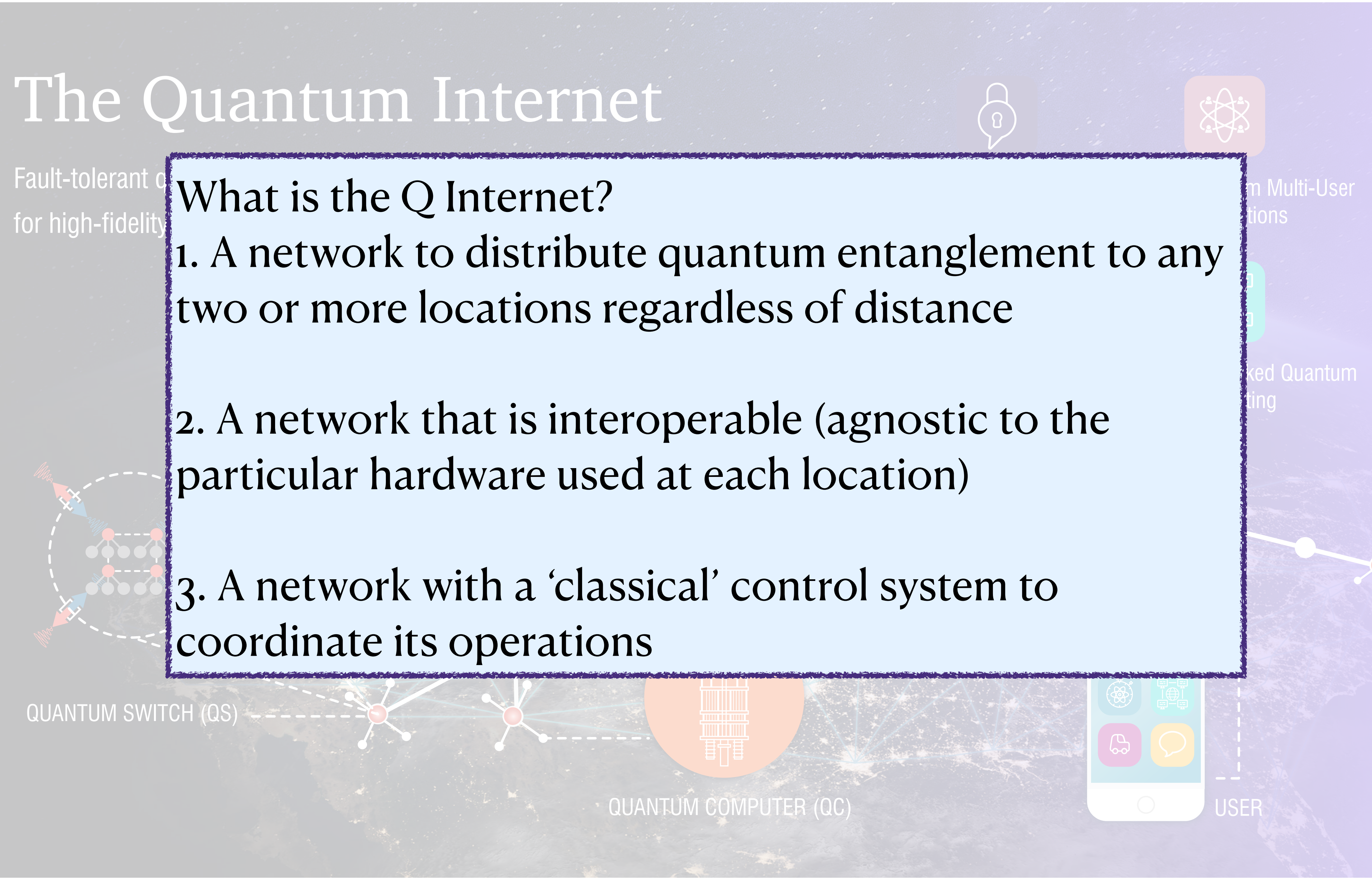
PART 1: Quantum information science
The Center for Quantum Networks
The National Quantum Initiative
What is *information*?
Bits and qubits
Superposition and entanglement

PART 2: Encoding and transmitting quantum information
Communication systems
Distributing Entangled states
Ways of encoding qubits
Ways of encoding qubits in photons
Focus on photon polarization
State vector representation and Born's Rule
Bell states
Quantum cryptography

PART 3: Quantum state teleportation
Joint measurement
Quantum state teleportation
Why entenglement distribution?

PART 4: The Quantum Internet
Why the quantum internet?
Bell State Creation and Measurement
Quantum memories
Memory-Assisted Teleportation
Entanglement Swapping with Quantum Memories
Quantum repeater networks
What could a quantum Network do?
Perspectives and misconceptions

The Quantum Internet



What is the Q Internet?

1. A network to distribute quantum entanglement to any two or more locations regardless of distance

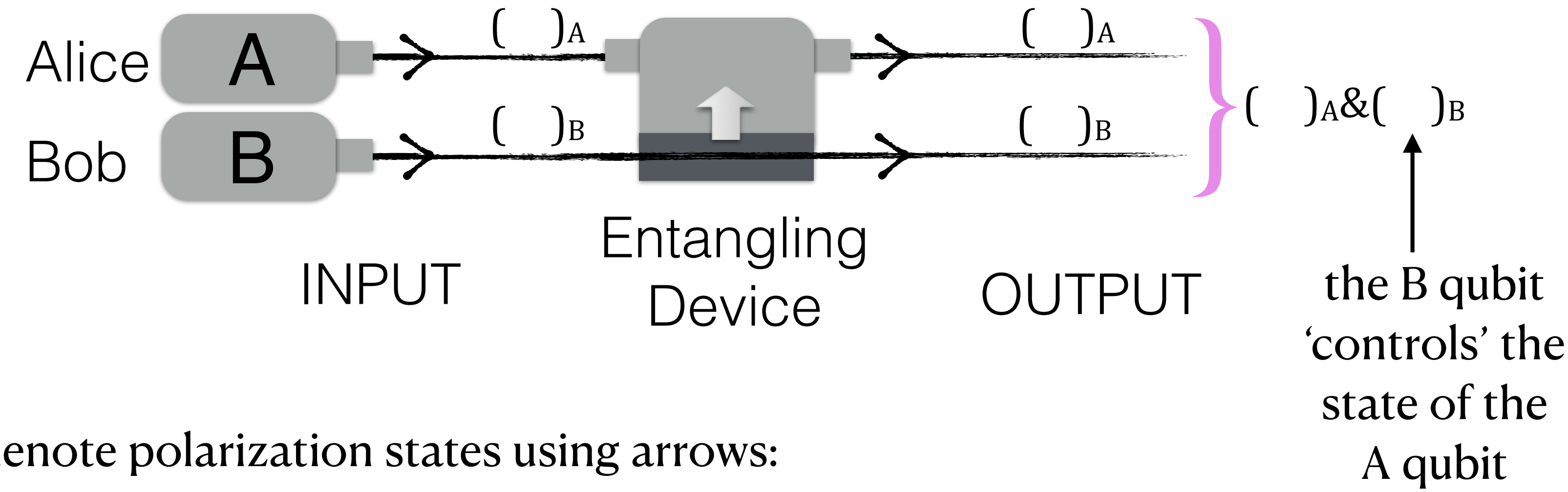
2. A network that is interoperable (agnostic to the particular hardware used at each location)

3. A network with a ‘classical’ control system to coordinate its operations

Bell States and their measurement: important tools for the Quantum Internet

To create Bell States, use 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:

$|H\rangle = (\rightarrow)$ $\quad -|H\rangle = (\leftarrow)$

$|V\rangle = (\uparrow)$ $\quad -|V\rangle = (\downarrow)$

$|D\rangle = (\nearrow)$ $\quad -|D\rangle = (\swarrow)$

$|A\rangle = (\nwarrow)$ $\quad -|A\rangle = (\searrow)$

Then:

$(\nearrow) = (\rightarrow) + (\uparrow)$

$(\nearrow) = (\rightarrow) + (\uparrow)$

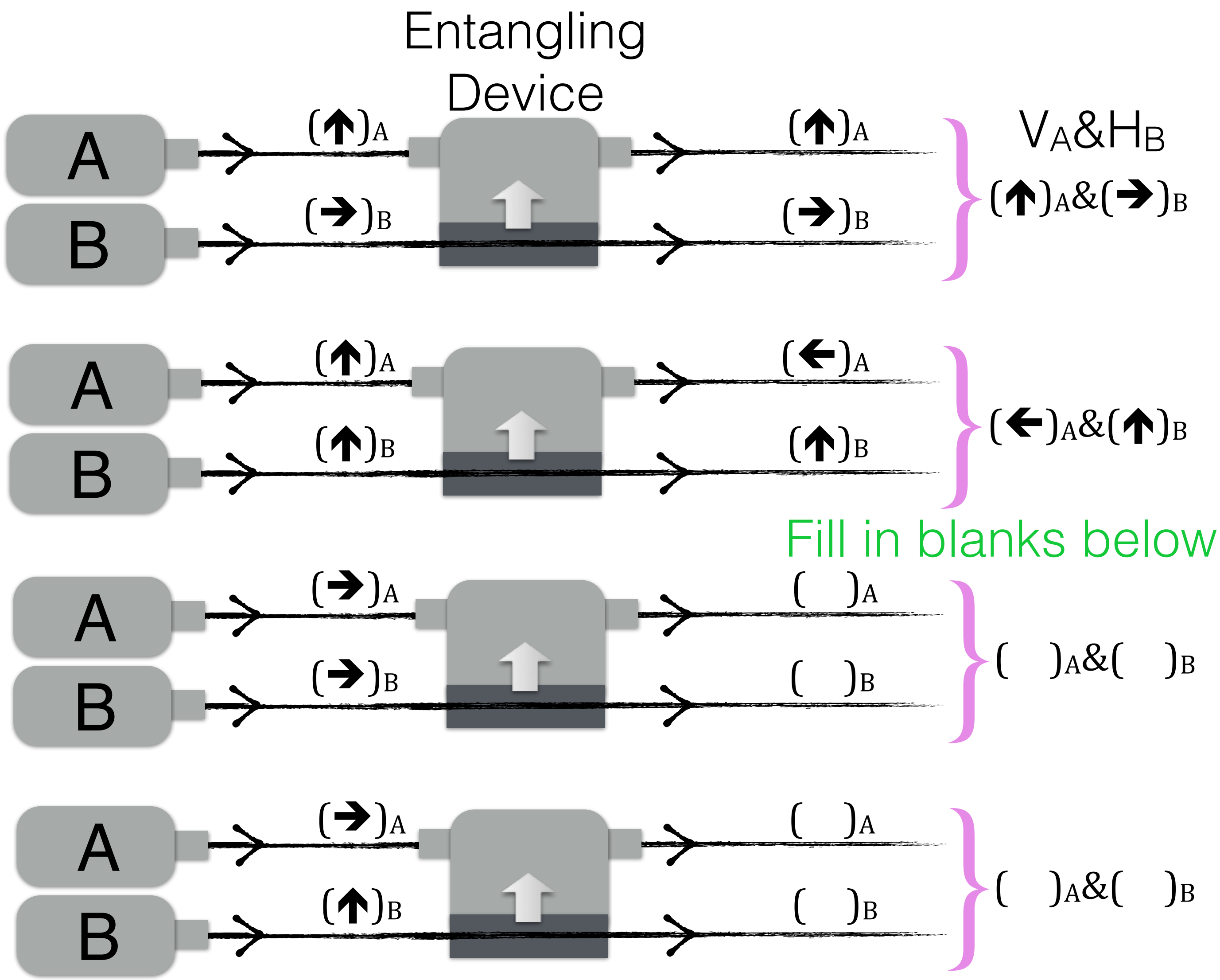
1. If the B photon is H-pol, the A photon's polarization is unchanged.
2. If the B photon is V-pol, the A photon's polarization is "rotated" by minus 90 degrees.
3. The B photon's polarization is unchanged in either case.

$|H\rangle = (\rightarrow)$

$|V\rangle = (\uparrow)$

$|D\rangle = (\nearrow)$

$|A\rangle = (\nwarrow)$



1. If the B photon is H-pol, the A photon's polarization is unchanged.
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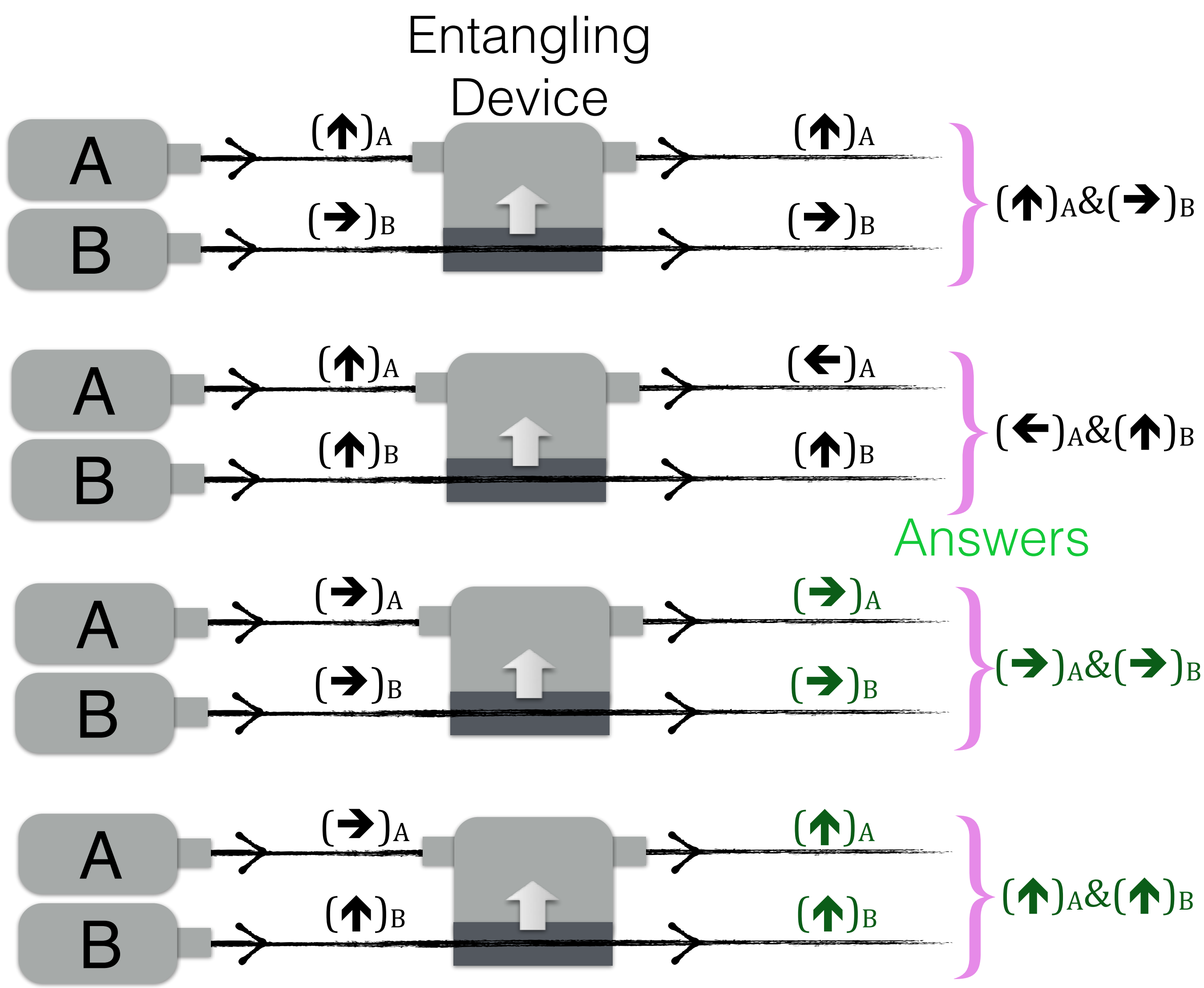
3. The B photon's polarization is unchanged in either case.

$$|H\rangle = (\rightarrow)$$
$$|V\rangle = (\uparrow)$$
$$|D\rangle = (\nearrow)$$
$$|A\rangle = (\nwarrow)$$



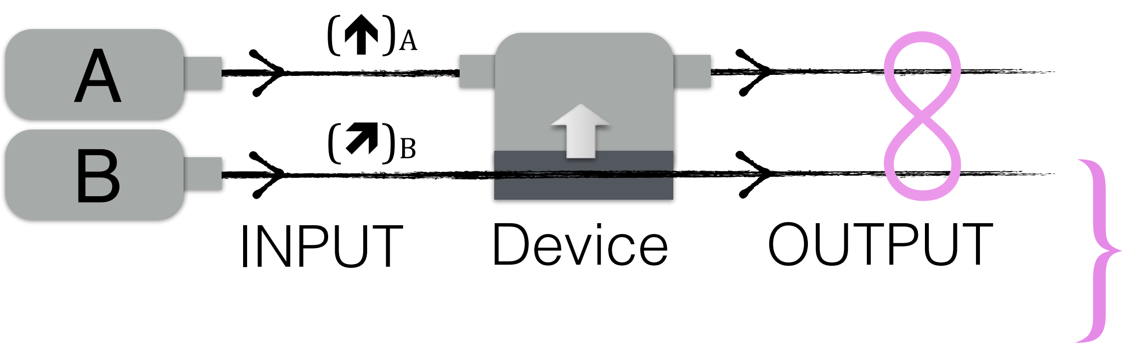
POLL QUESTION 19

$$\frac{1}{\sqrt{2}}|H\rangle_B + \frac{1}{\sqrt{2}}|V\rangle_B = \frac{1}{\sqrt{2}}|\rightarrow\rangle_B + \frac{1}{\sqrt{2}}|\uparrow\rangle_B$$

Recall the Device Rules:

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

The B photon's polarization is unchanged in either case.



The input at B is the superposition state $(\nearrow)_B = (\rightarrow)_B + (\uparrow)_B$

What is the Composite Output State?

A: $(\uparrow)_A\&(\rightarrow)_B$

B: $(\leftarrow)_A\&(\uparrow)_B$

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

D: I don't know

reveal

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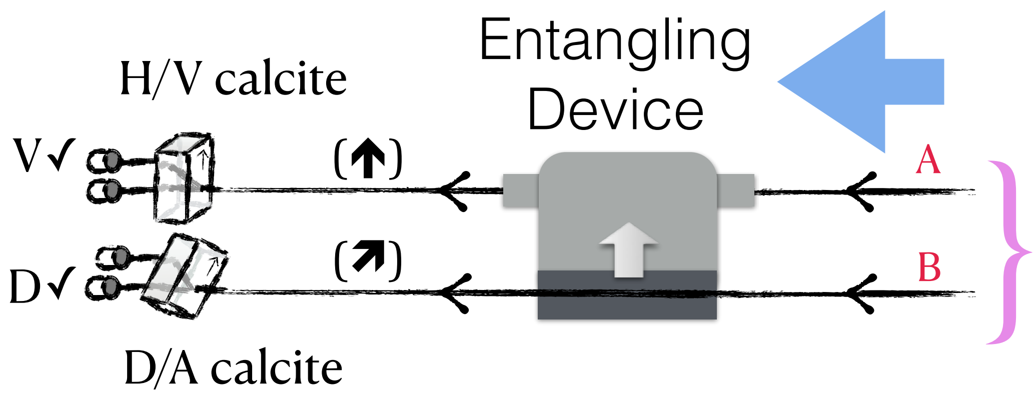
Bell State Disentangler

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 drawing at the far left)

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)

The pair was prepared in:

$$\frac{1}{\sqrt{2}}|H\rangle_A \& |H\rangle_B + \frac{1}{\sqrt{2}}|V\rangle_A \& |V\rangle_B$$

OR

$$\frac{1}{\sqrt{2}}|H\rangle_A \& |H\rangle_B + \frac{-1}{\sqrt{2}}|V\rangle_A \& |V\rangle_B$$

OR

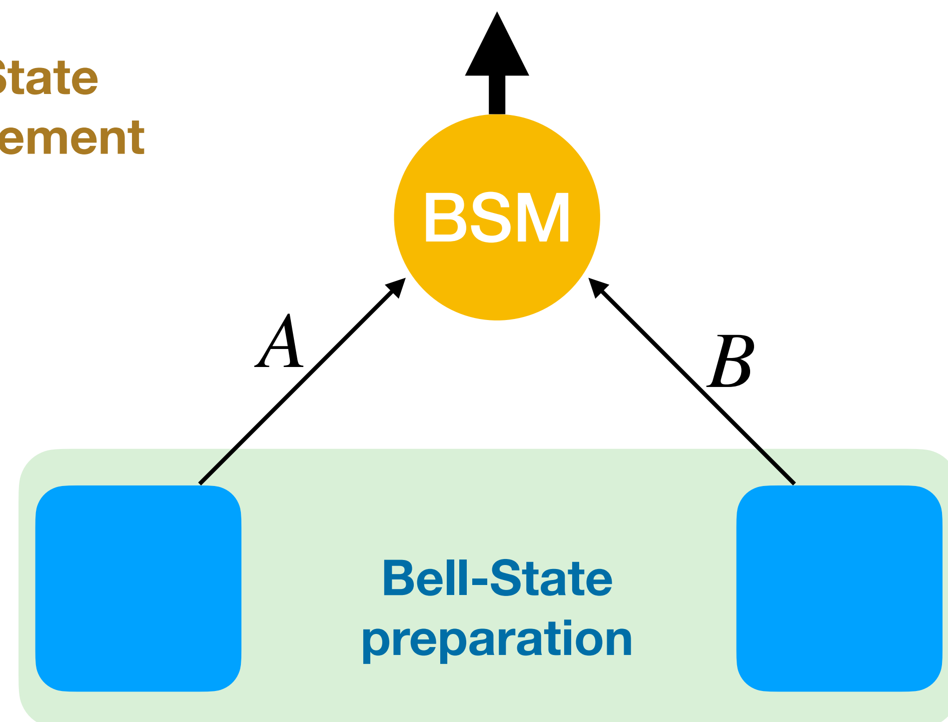
$$\frac{1}{\sqrt{2}}|H\rangle_A \& |V\rangle_B + \frac{1}{\sqrt{2}}|V\rangle_A \& |H\rangle_B$$

OR

$$\frac{1}{\sqrt{2}}|H\rangle_A \& |V\rangle_B + \frac{-1}{\sqrt{2}}|V\rangle_A \& |H\rangle_B$$

Joint Measurement = **Bell-State Measurement**

OUTCOME tells which Bell State



BSM is an important tool for building a quantum Internet

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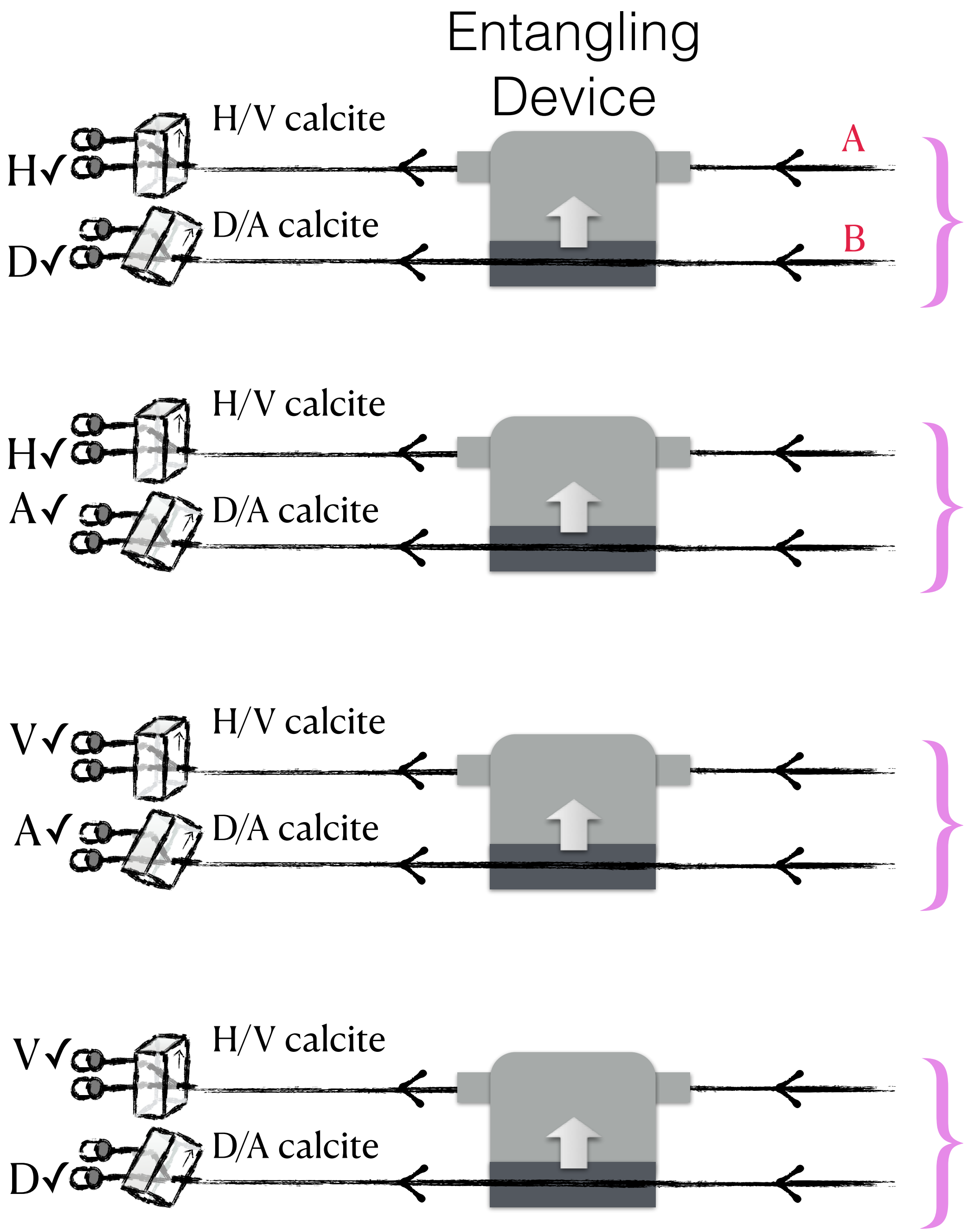
Bell State Measurement



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

$$\frac{1}{\sqrt{2}}|H\rangle_A \& |H\rangle_B + \frac{1}{\sqrt{2}}|V\rangle_A \& |V\rangle_B$$

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

$$\frac{1}{\sqrt{2}}|H\rangle_A \& |H\rangle_B + \frac{-1}{\sqrt{2}}|V\rangle_A \& |V\rangle_B$$

$$\frac{1}{\sqrt{2}}|H\rangle_A \& |V\rangle_B + \frac{1}{\sqrt{2}}|V\rangle_A \& |H\rangle_B$$

$$\frac{1}{\sqrt{2}}|H\rangle_A \& |V\rangle_B + \frac{-1}{\sqrt{2}}|V\rangle_A \& |H\rangle_B$$

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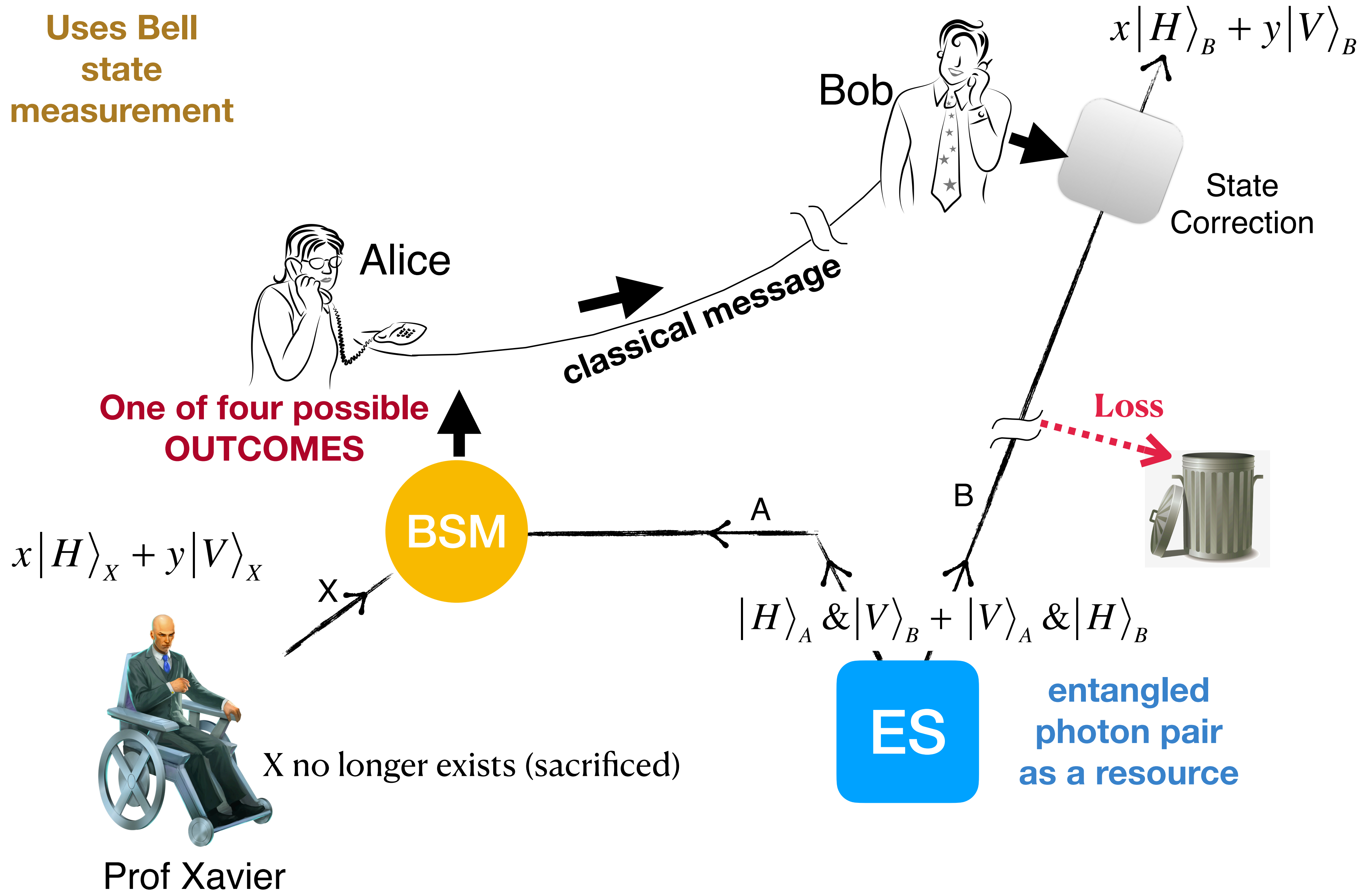
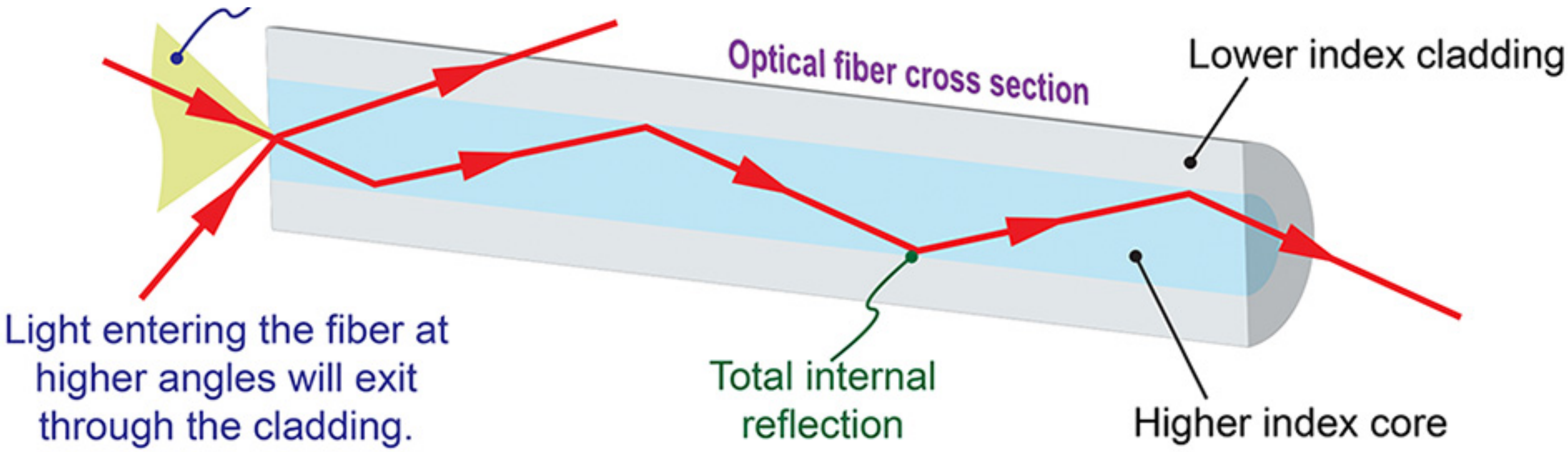
Quantum State Teleportation



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



https://www.coherent.com/news/glossary/optical-fibers

For telecom (Near-IR) light The decrease is exponential with length:

after 20 km the power is decreased by a factor of 10

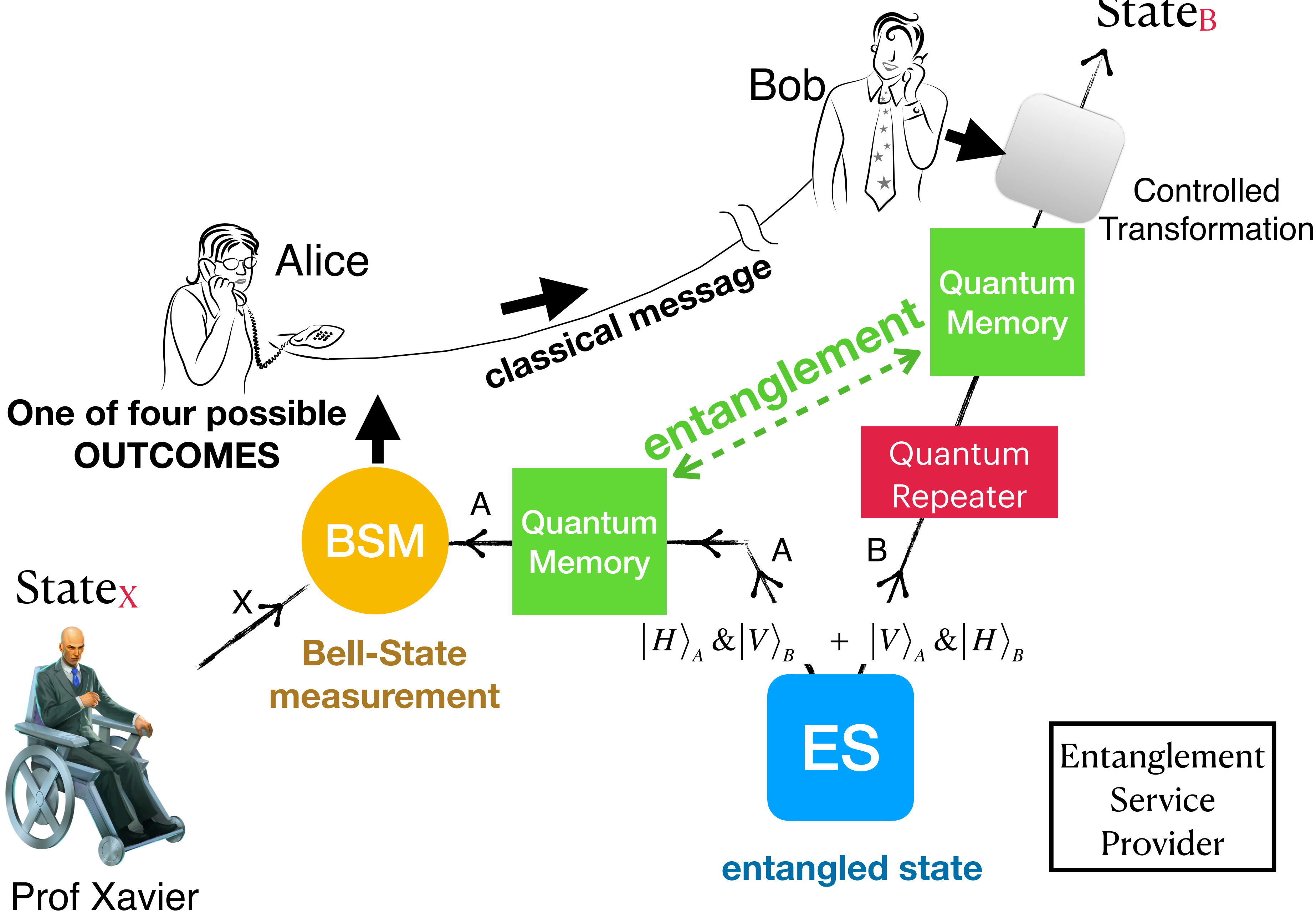
after 40 km the power is decreased by a factor of 100

after 60 km the power is decreased by a factor of 1,000

after 80 km the power is decreased by a factor of 10,000

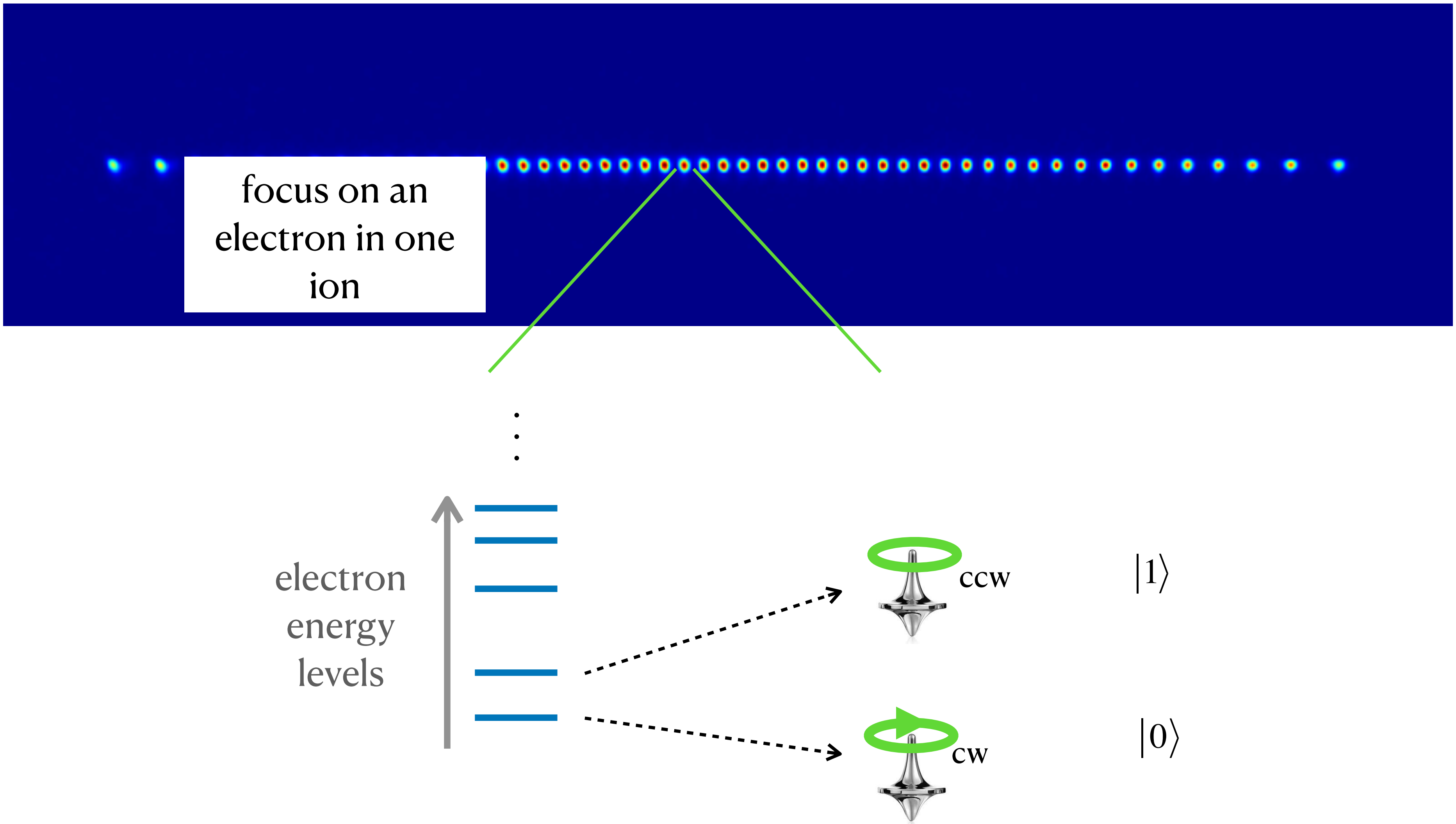
Similar for photons traveling through the atmosphere.

To Extend Teleportation to Longer Distances, Quantum Memories and Repeaters are Needed

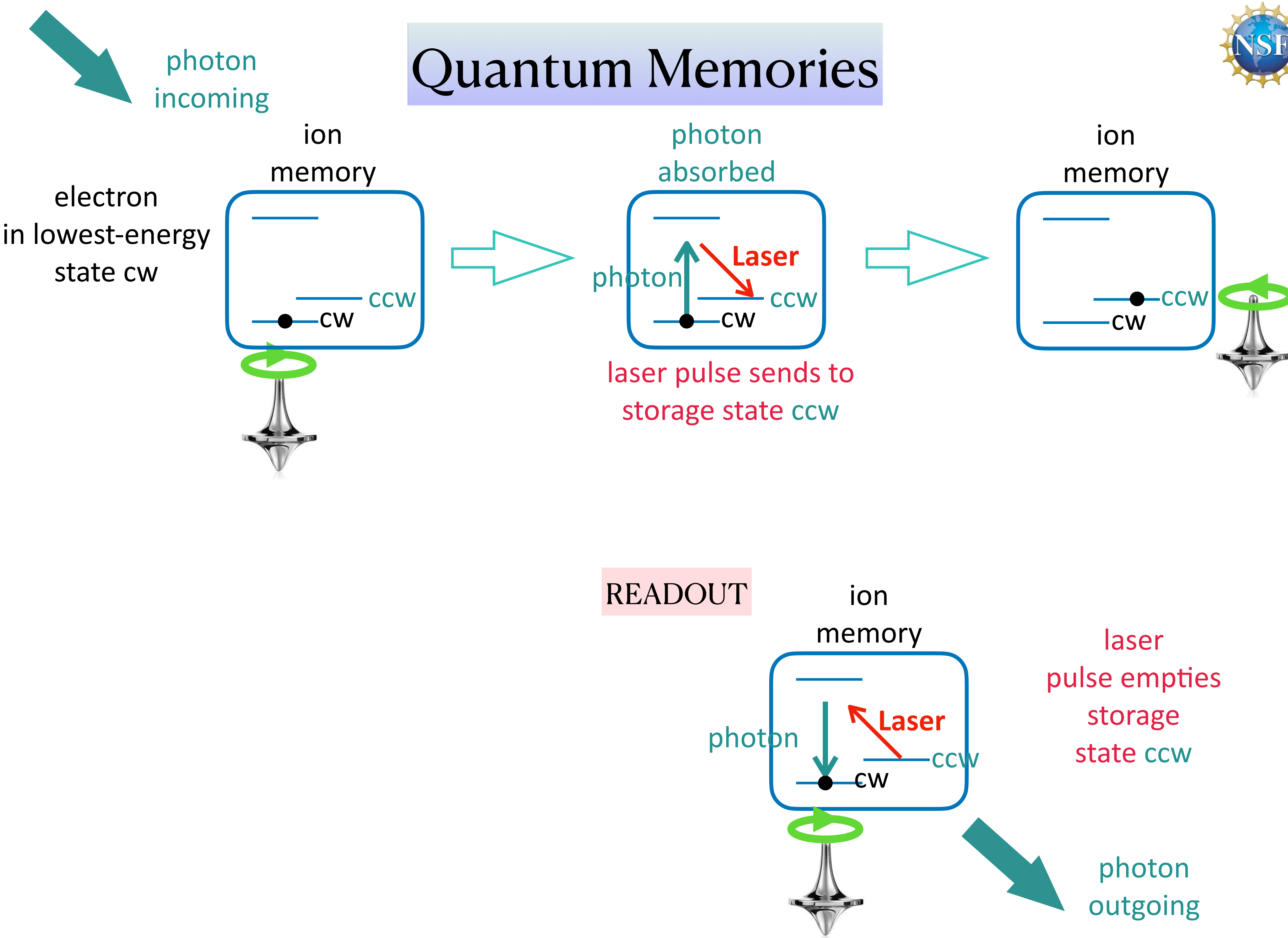


Quantum Memories

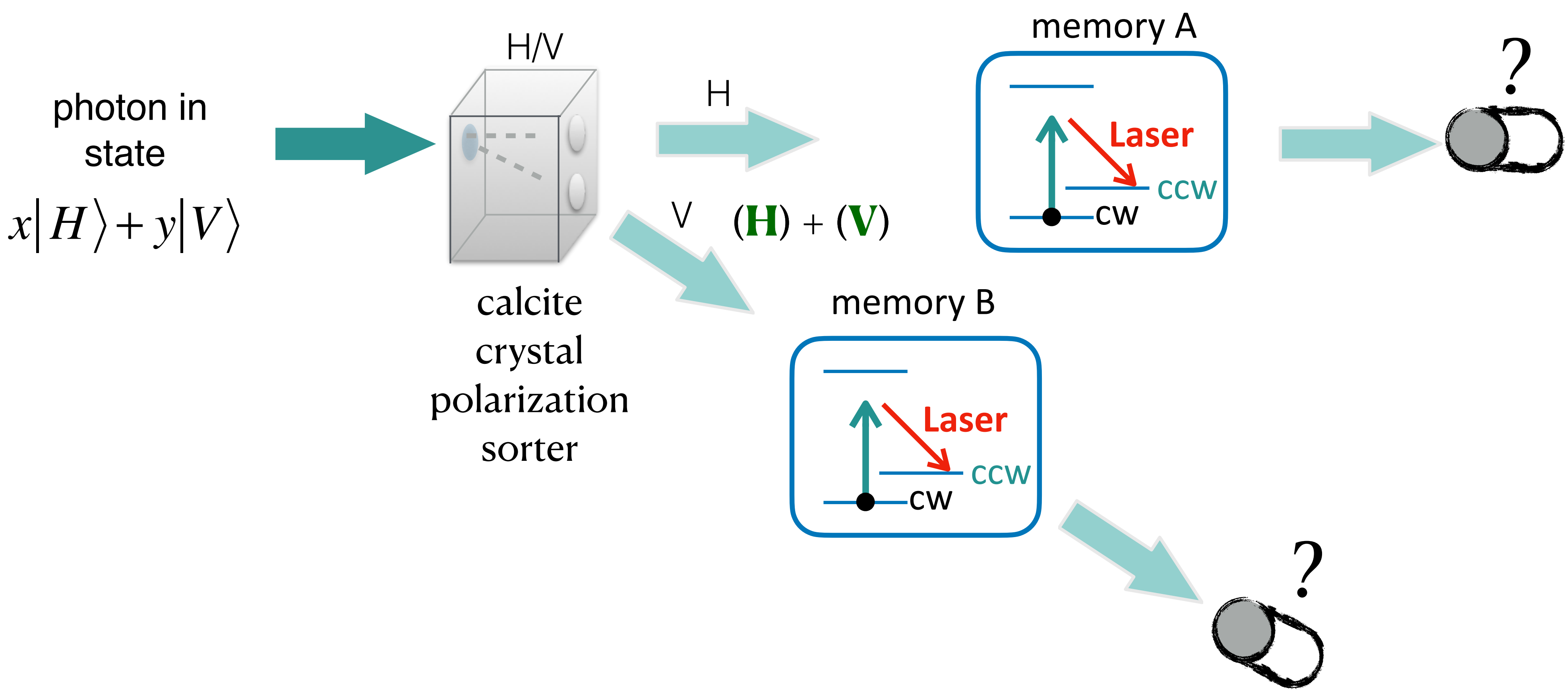
An electron in an atomic **ion** can store
a qubit value in its spin state



Quantum Memories



Quantum Memory Storage of Photon Polarization



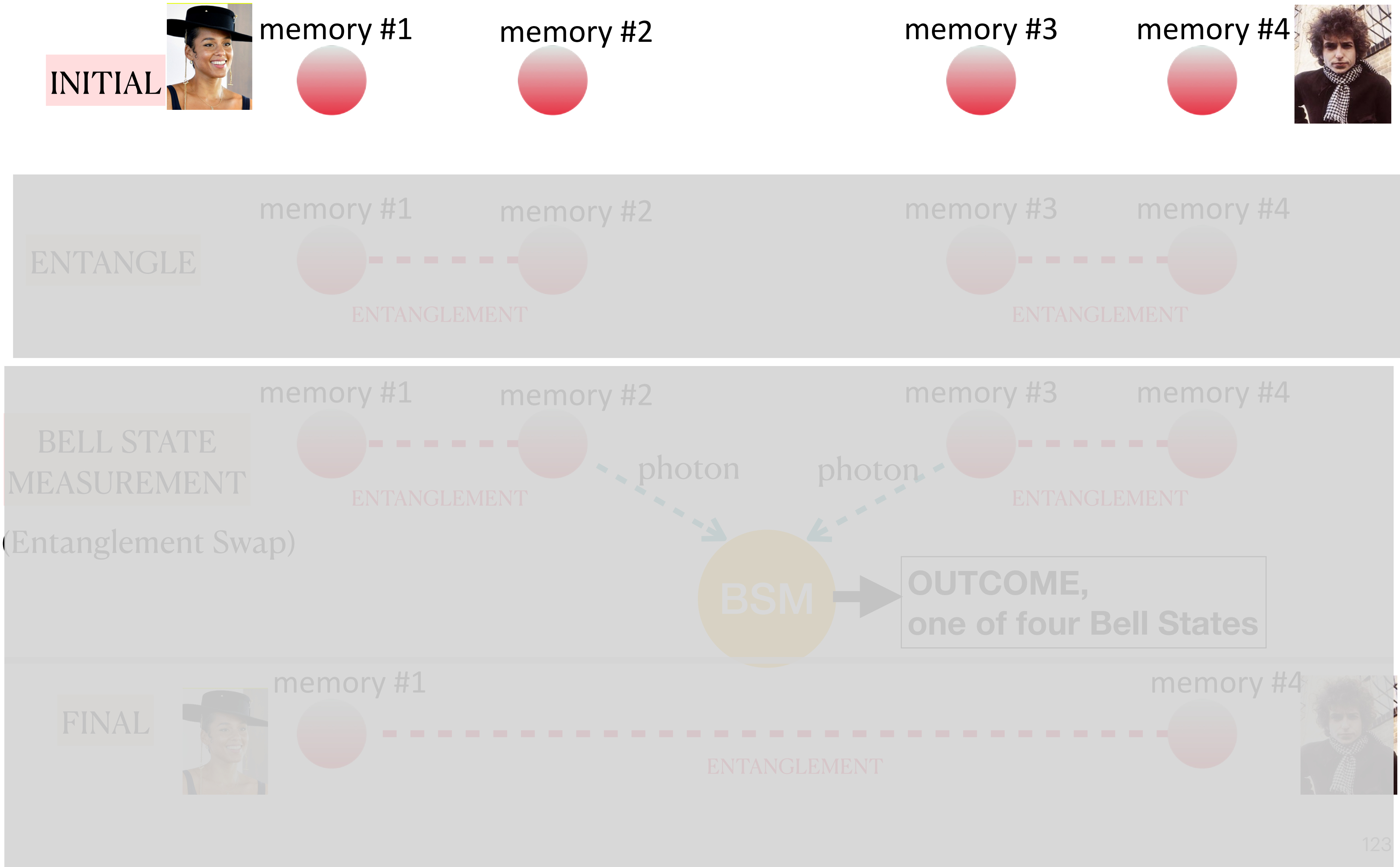
If both detectors register no photon, we know entanglement has been created between the memories.

Resulting state of the two Memories =

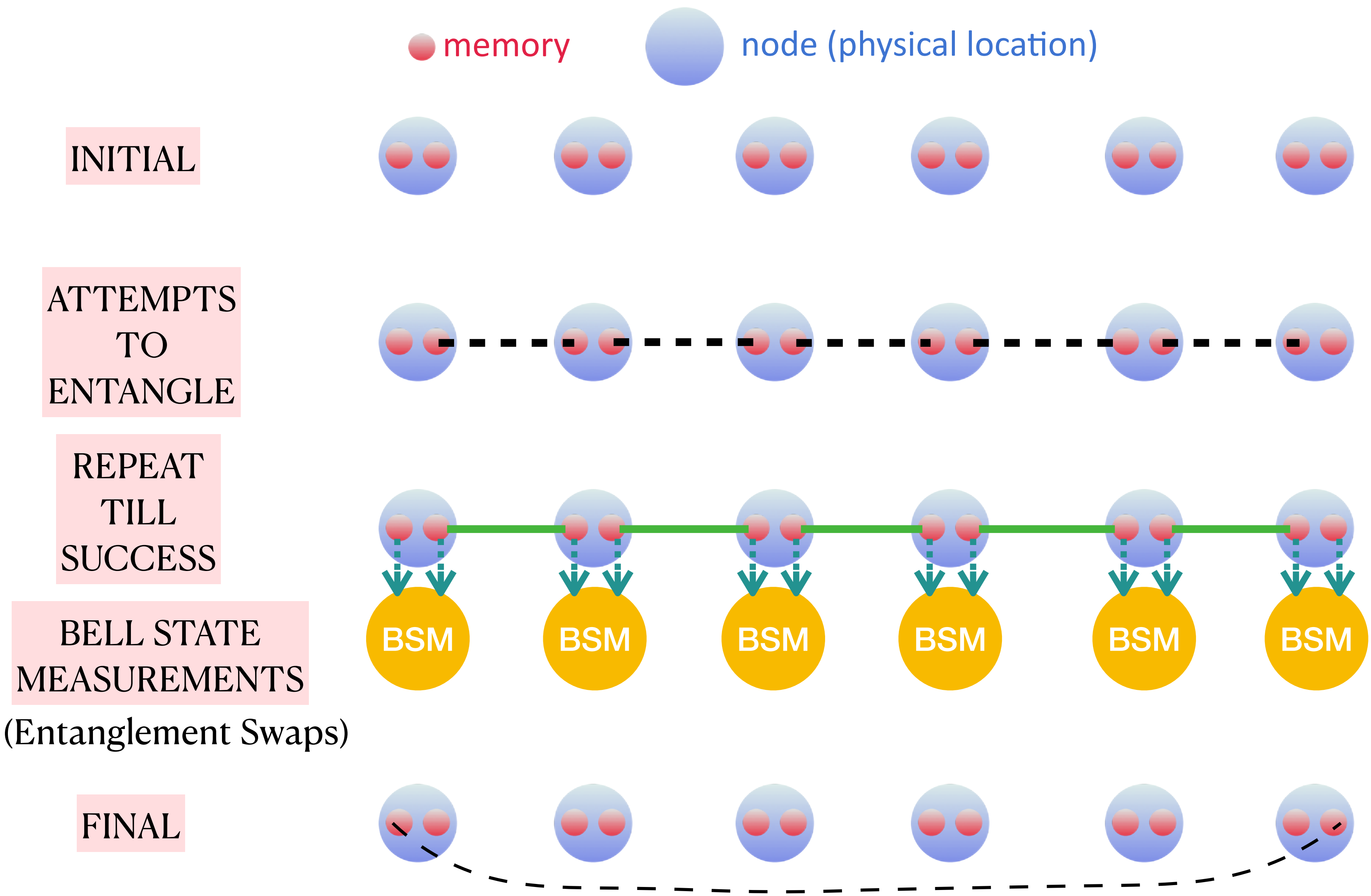
$$x|ccw\rangle_A \& |cw\rangle_B + y|cw\rangle_A \& |ccw\rangle_B$$

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

A quantum Repeater is needed to extend an entangled state separation: Done by Entanglement Swapping



Creating a Chain Network of Entangled Memories



Creating a Grid Network of Entangled Memories

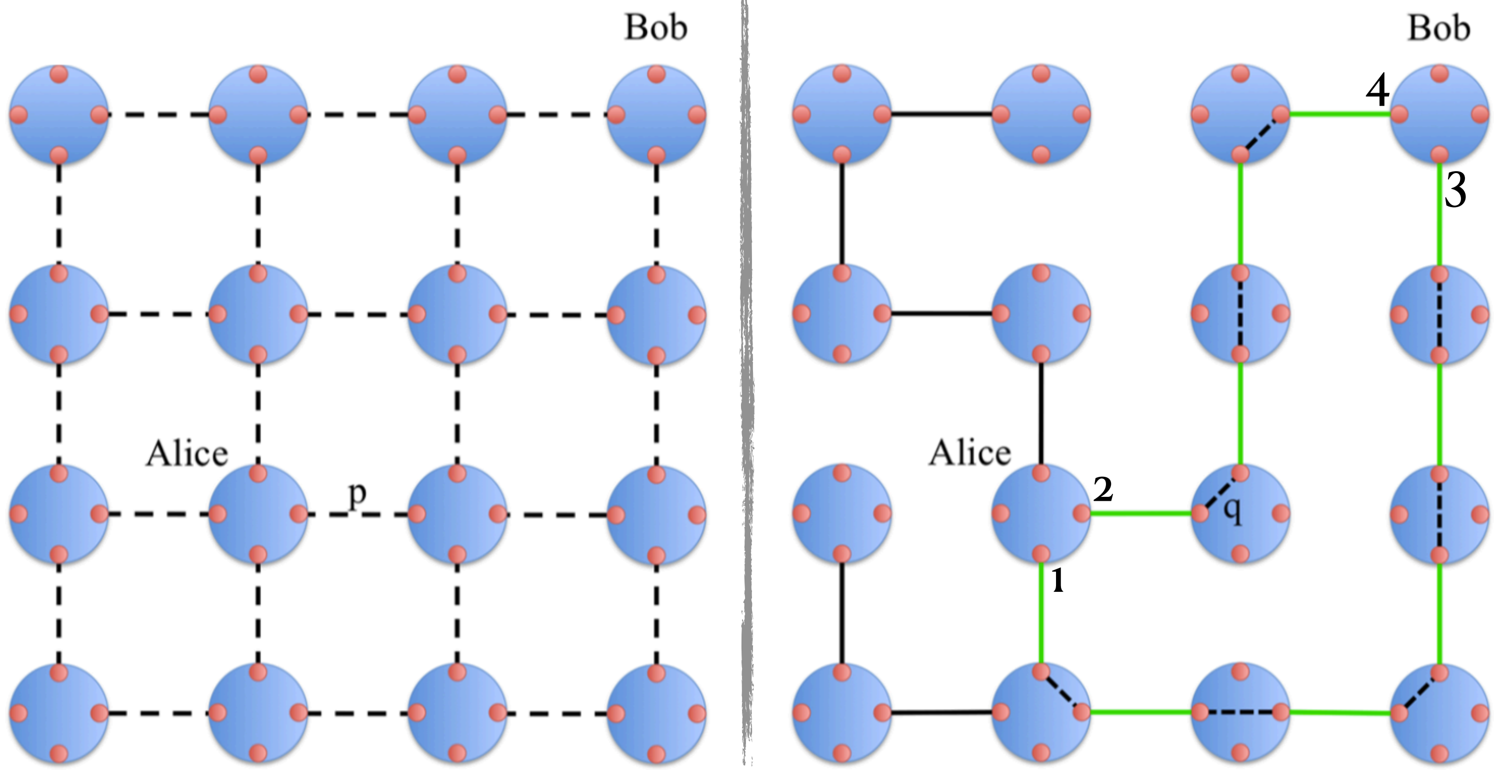
memory node

ATTEMPTS TO ENTANGLE USING BELL STATE MEASUREMENTS

PARTIAL SUCCESS

INITIAL

no entangled paths



FINAL

two entangled paths from Alice to Bob

Modeling by the Center for Quantum Networks:

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

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

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 storing results)

3. private database queries (without the computer storing results)

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

5. global timekeeping and synchronization

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

7. physics tests (e.g. entanglement of macroscopic objects, quantum gravity)

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

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

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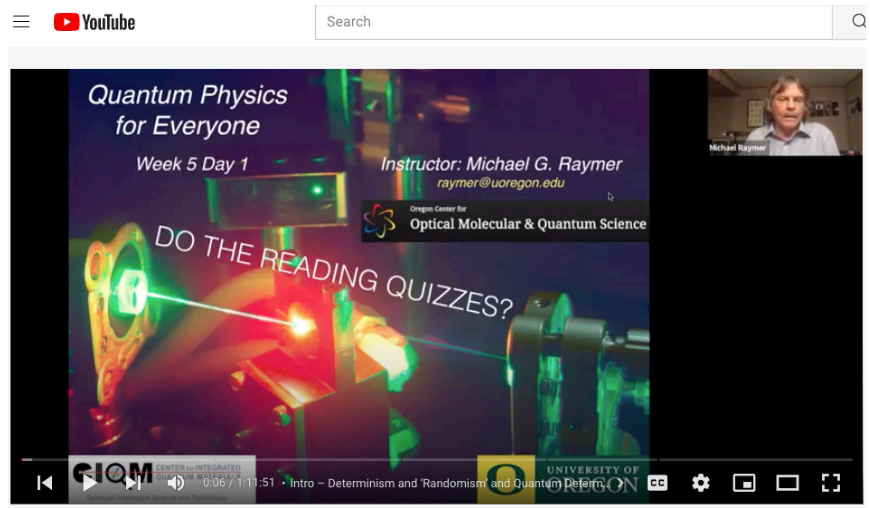
For 20 hour series of related lectures, see
Quantum Physics for Everyone: Lectures 1 through 12
by MG Raymer
Harvard Center for Integrated Quantum Materials



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

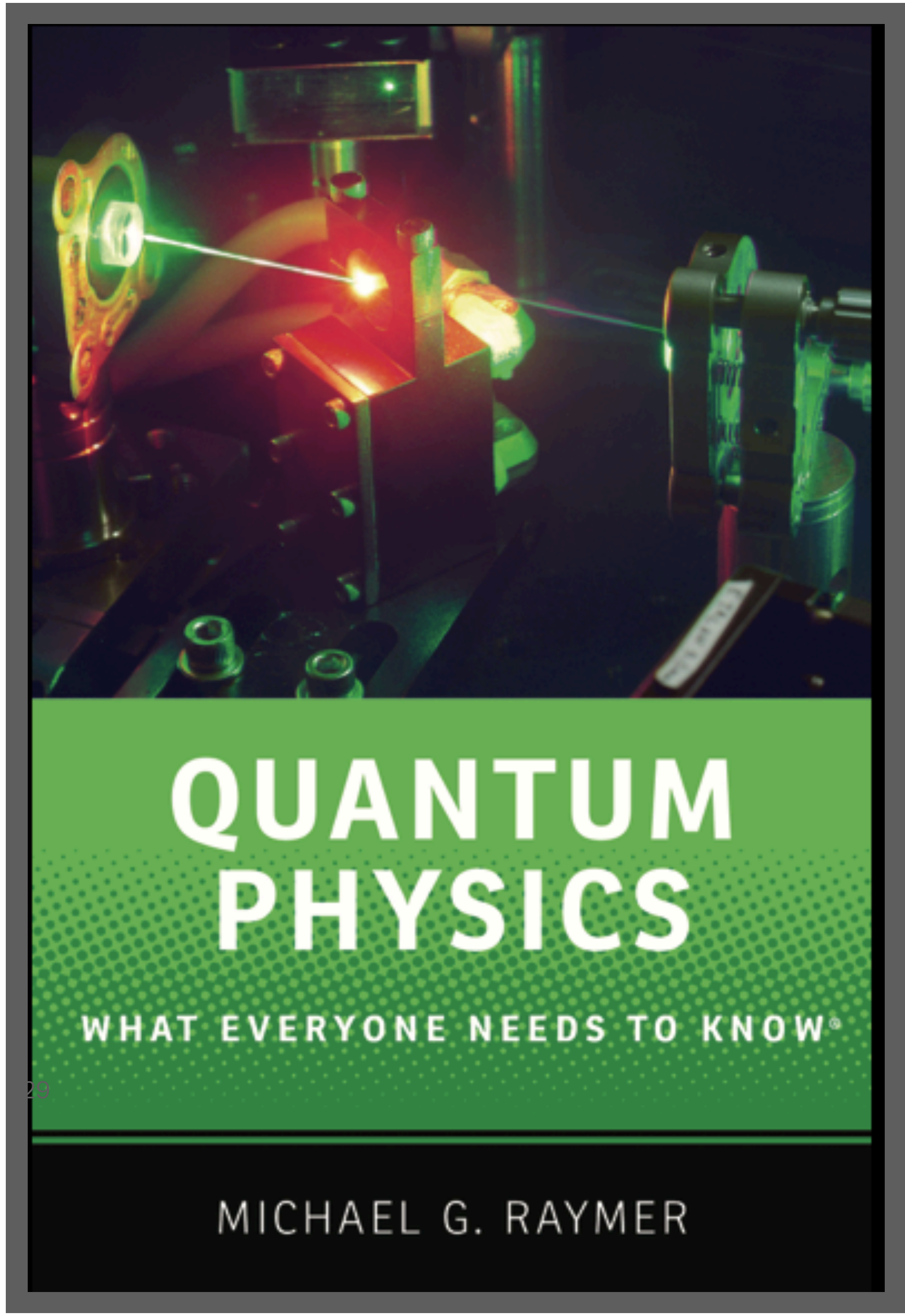
search YouTube for Quantum Physics for Everyone

Book 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

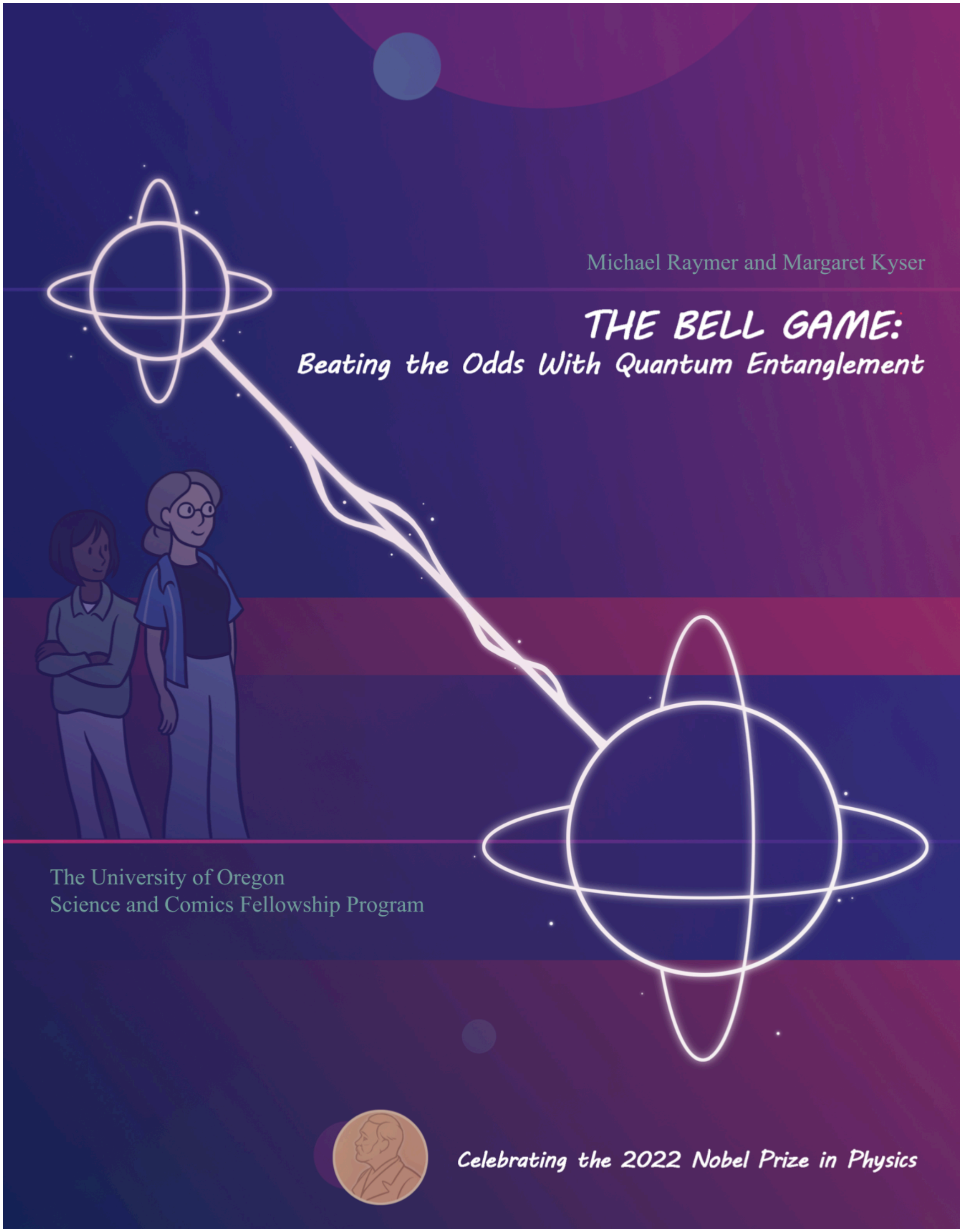
also available in Chinese, Japanese and Polish translations

UNIVERSITY OF OREGON



I co-wrote a comic book!

A pdf copy will be shared with the course materials.



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

Funded by National Science Foundation Grant #1941583