Title: The Strange Quantum: What does it mean and how can we use it?

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Abstract: Put two physicists in a room and ask them to talk about the interpretation of quantum mechanics. This is a recipe for disagreement; the mysteries of quantum theory run so deep that itâ€™s hard to find any interpretive claims that are immune to controversy. Therefore, when thinking about quantum theory, it is a useful tactic to first focus on the macroscopic facts it predicts while ignoring the formalism and what it might suggest about the constitution of reality. I will adopt this tactic in my talk to describe the strange features of sequences of Stern-Gerlach measurements. This background will be enough to formulate the principle of â€œno information gain without disturbanceâ€• and the technological possibilities it implies, such as money that canâ€™t be counterfeit and secure ways of distributing secret keys for cryptography. Iâ€™ll then move on to explain one idea about what might be going on at a deeper level â€“ the idea of hidden variables. Finally, Iâ€™ll present Bellâ€™s theorem, a result that reveals an uncomfortable tension between quantum mechanics and the theory of relativity.

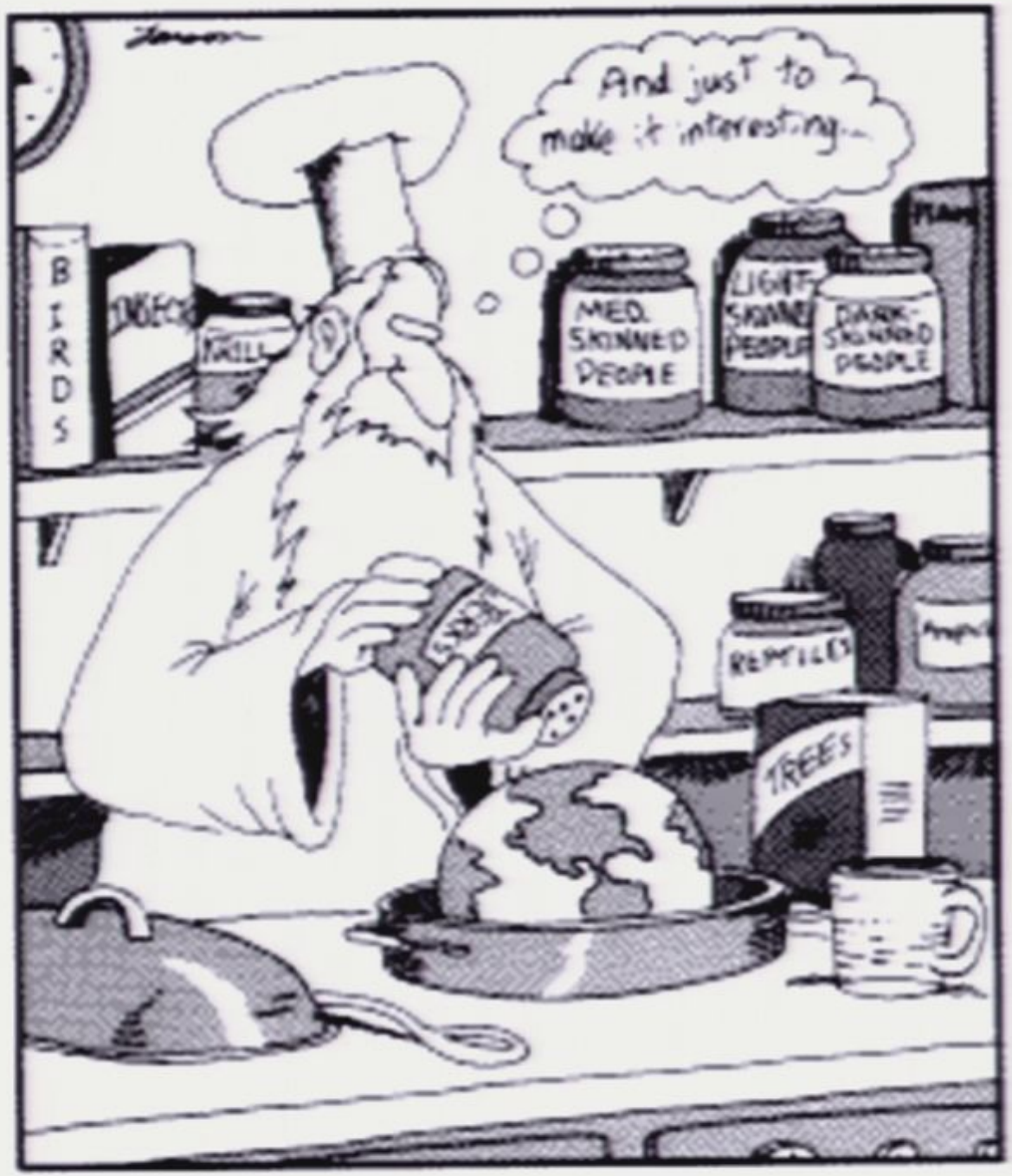
# The Strange Quantum: What does it mean and how can we use it?

Robert Spekkens
University of Cambridge



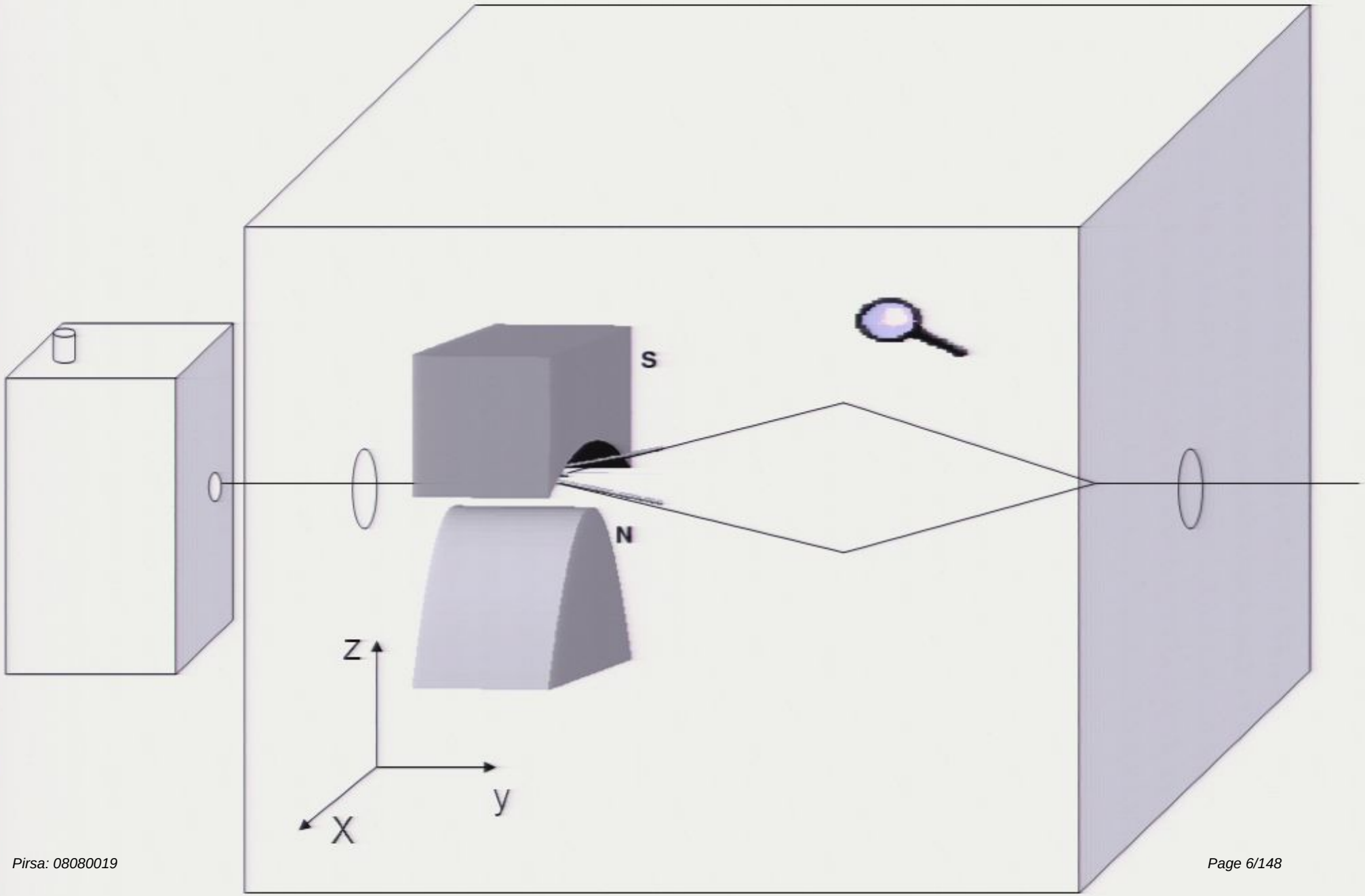


ISSYP, PI, Aug. 15, 2008


And just to make it interesting...
BIRDS
MED. SKINNED PEOPLE
LIGHT SKINNED PEOPLE
DARK-SKINNED PEOPLE
REPTILES
TREES

# The Solvay Congress of 1927

# Some simple quantum phenomena


S
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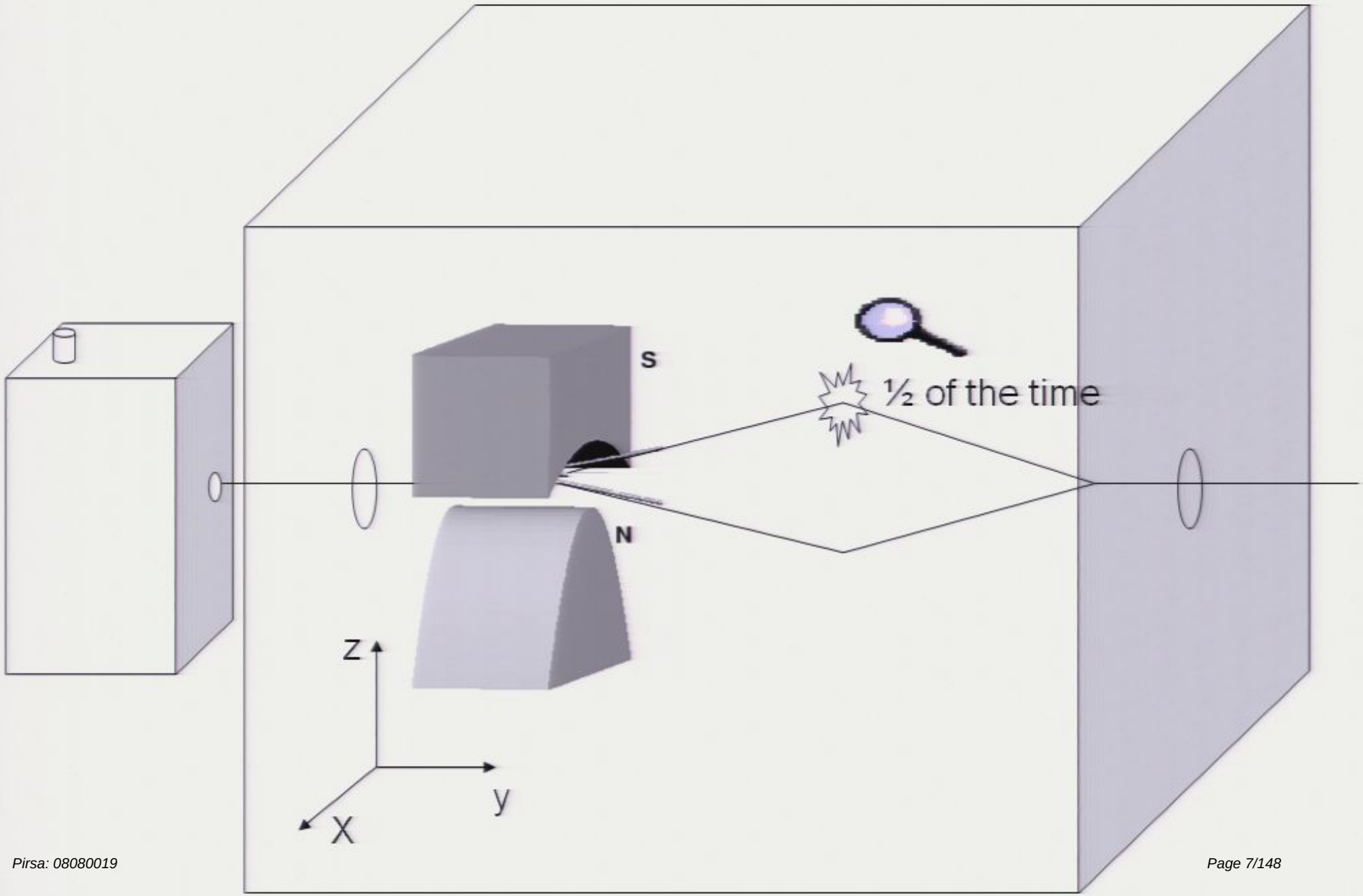
S
½ of the time
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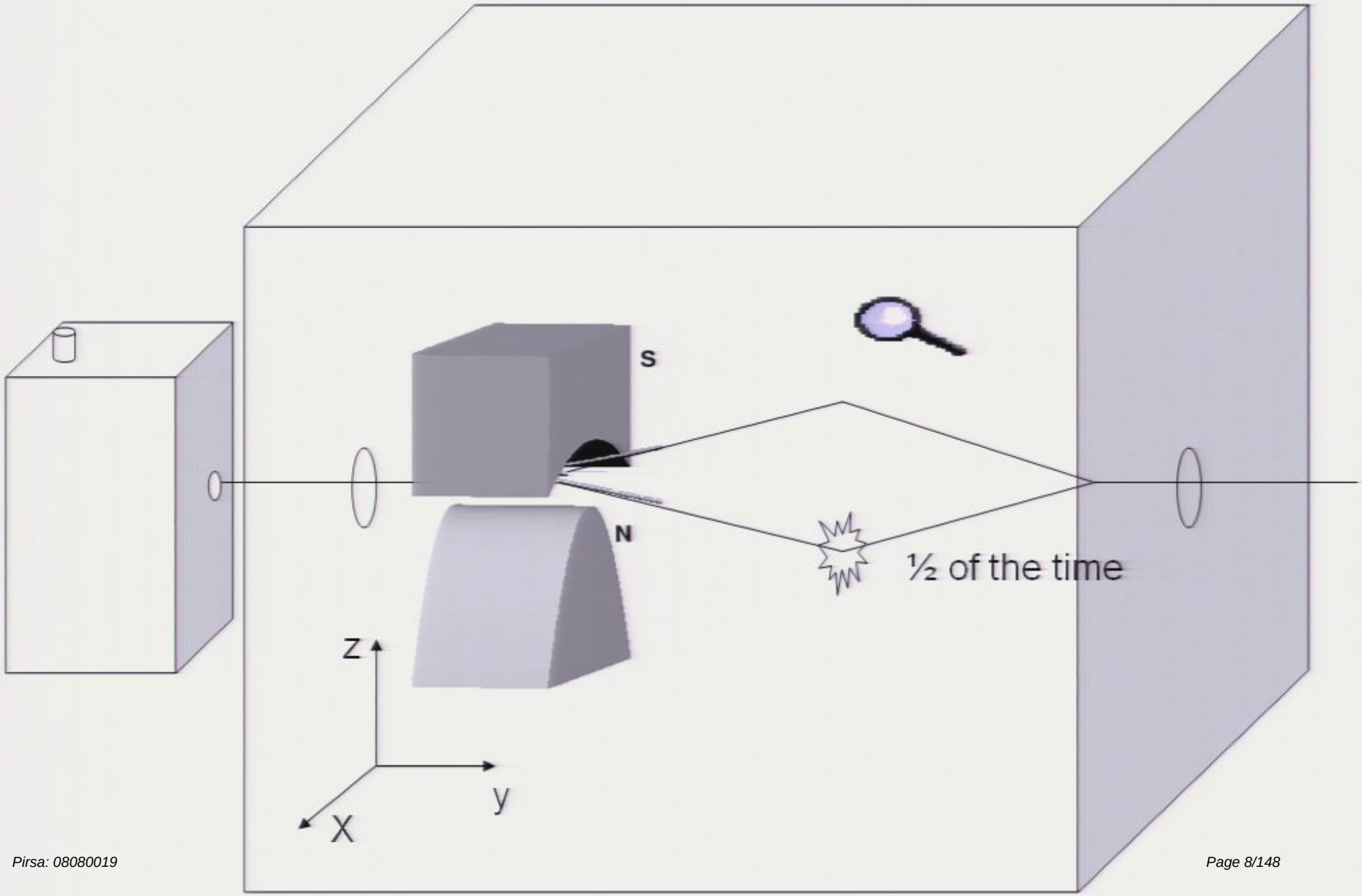
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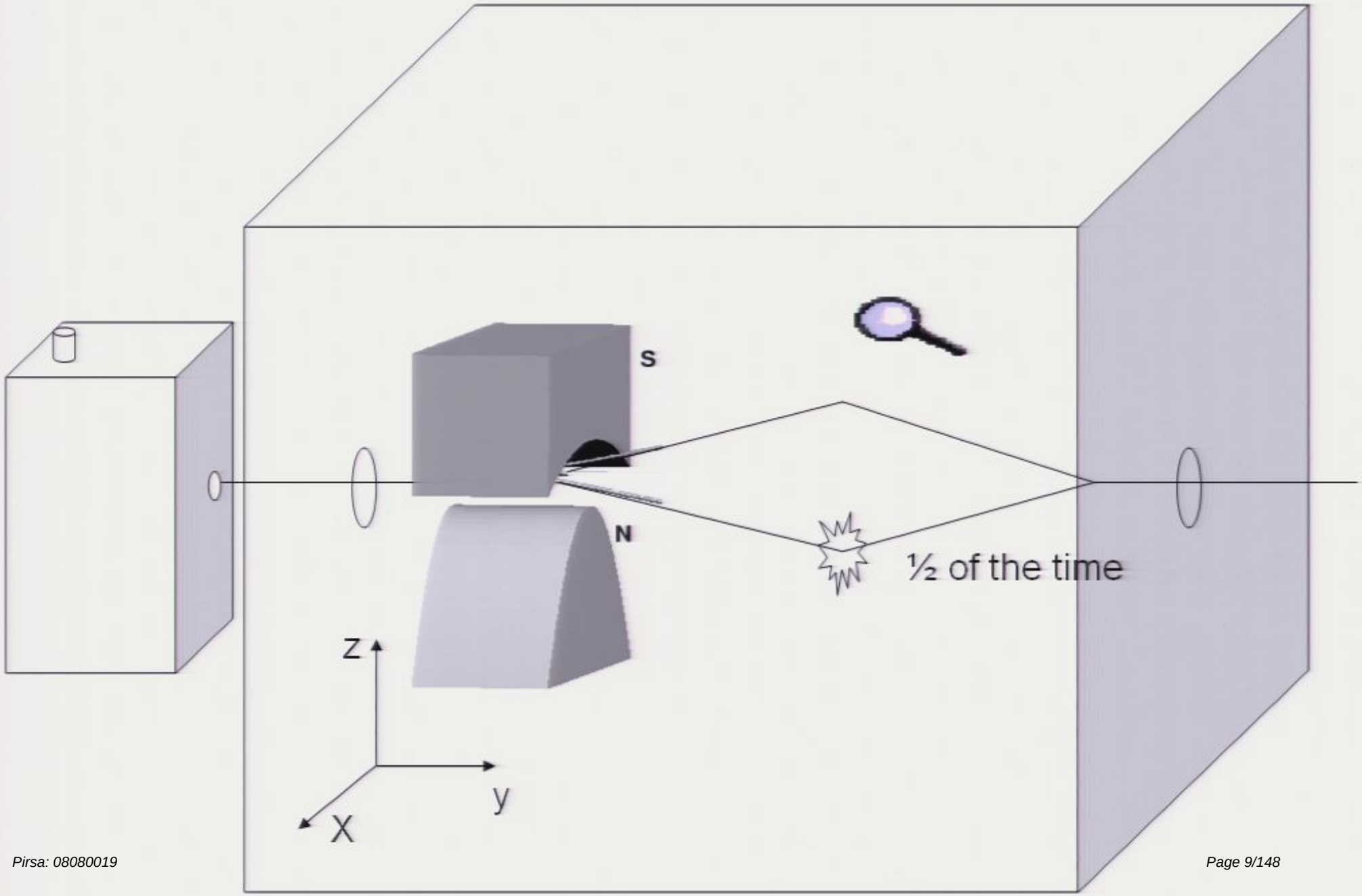
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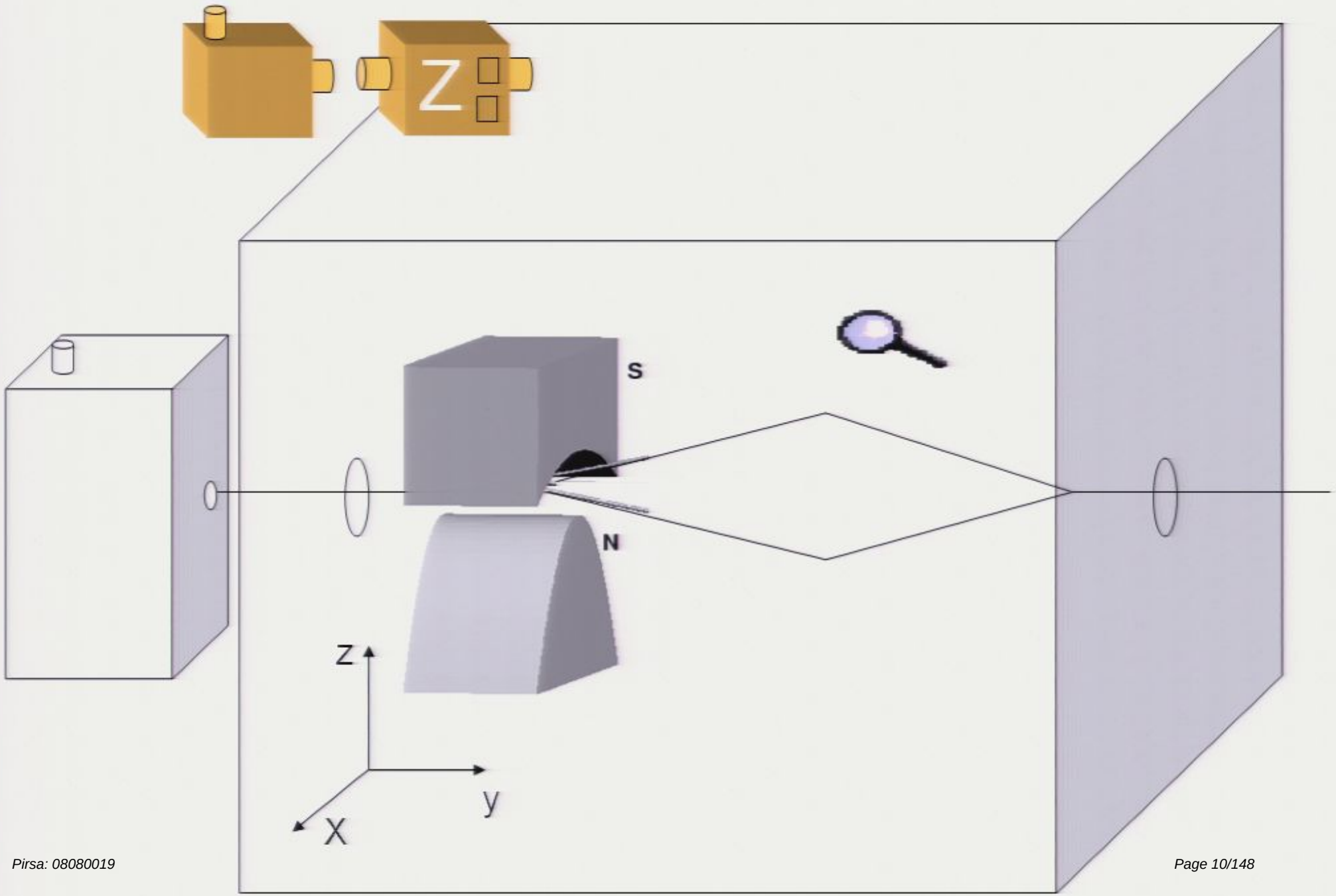
Z
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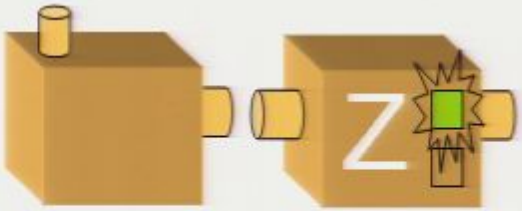
Z

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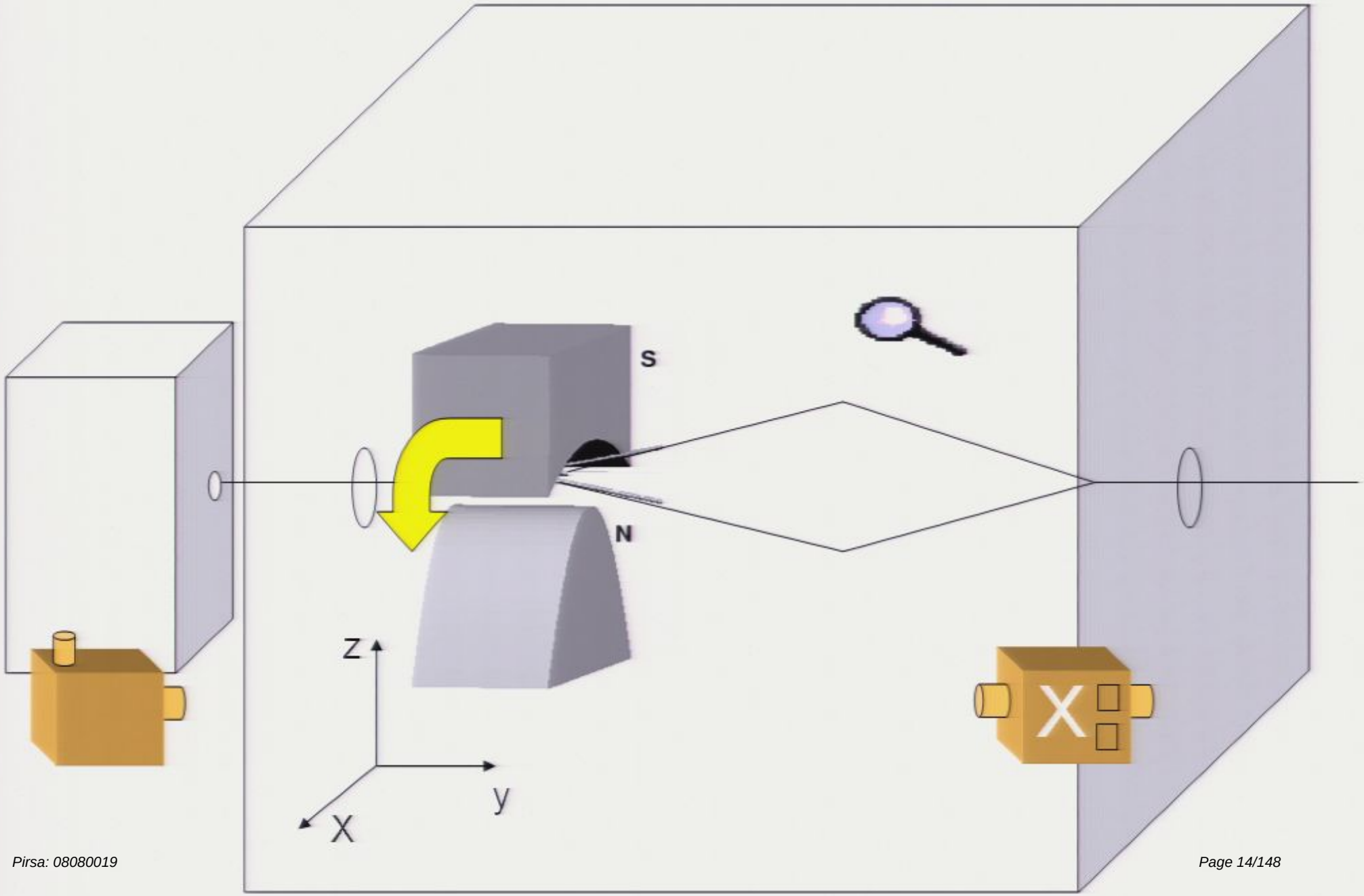
S
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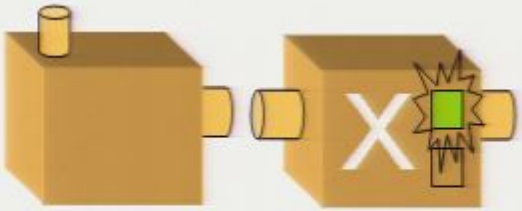


½ of the time

½ of the time

Z
Z

Z
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Z
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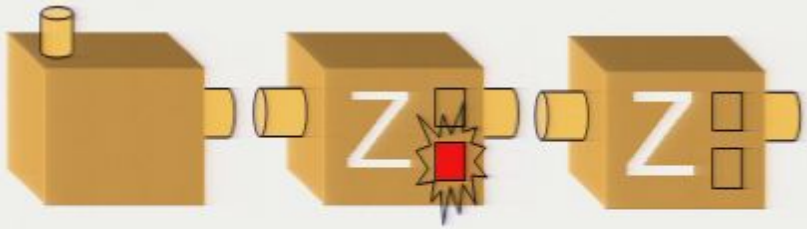
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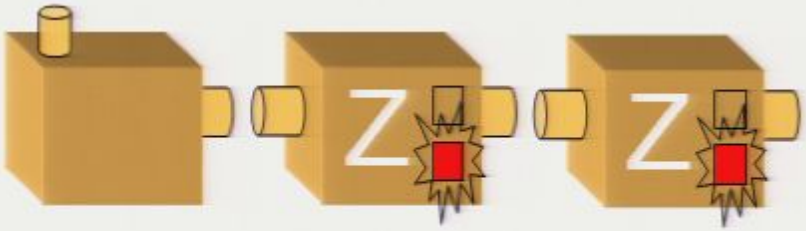
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Z
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X
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X
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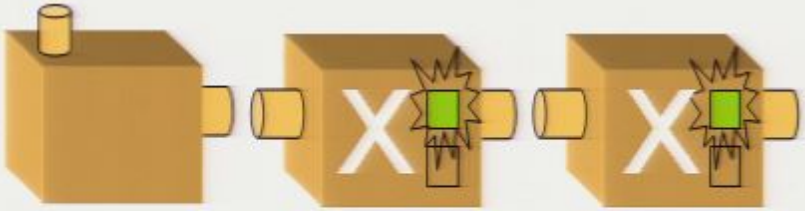
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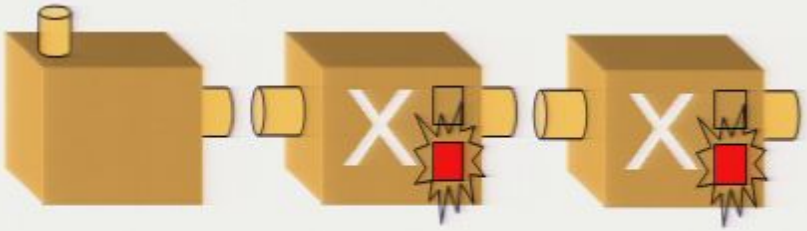
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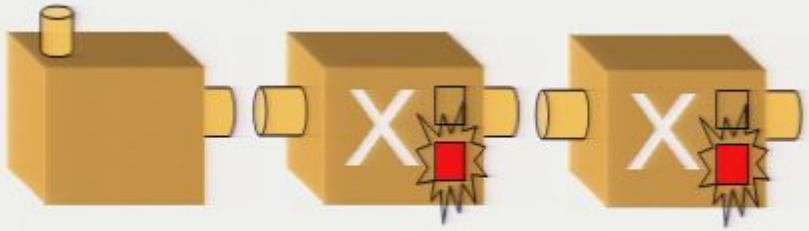
X
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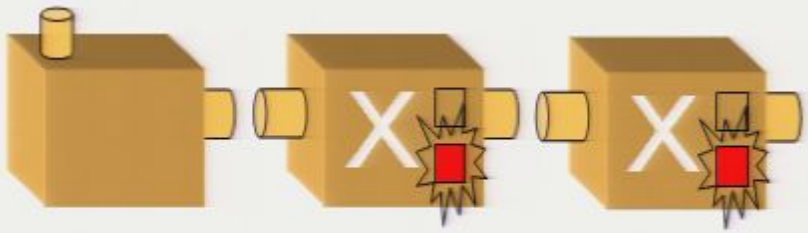
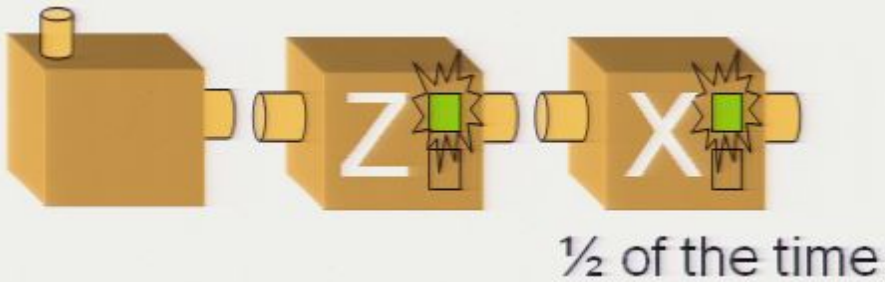
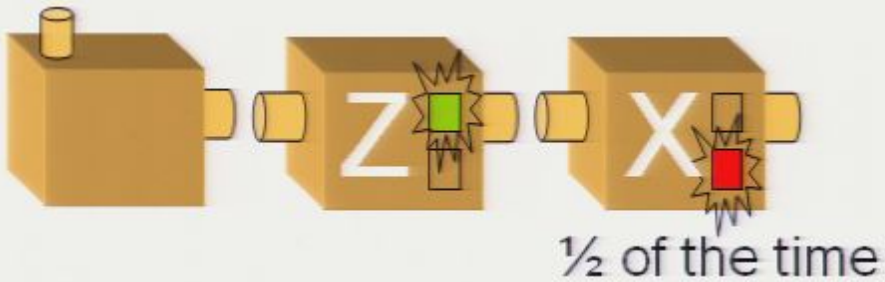


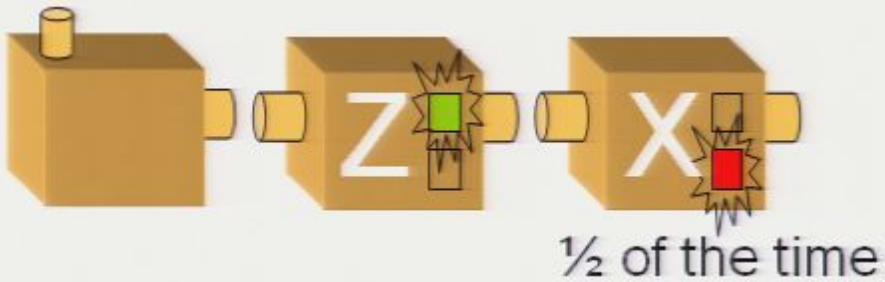

Consecutive identical measurements always yield the same outcome

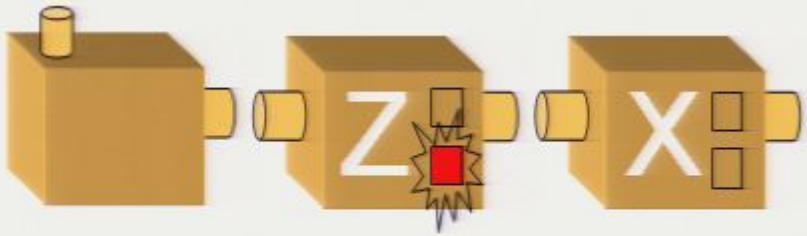
Z
X

Z
X

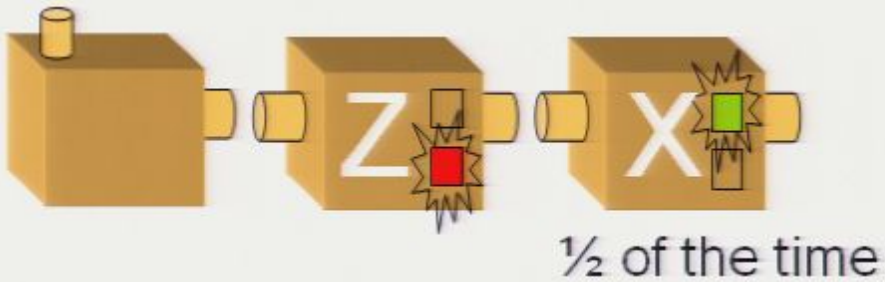

Z
X
½ of the time

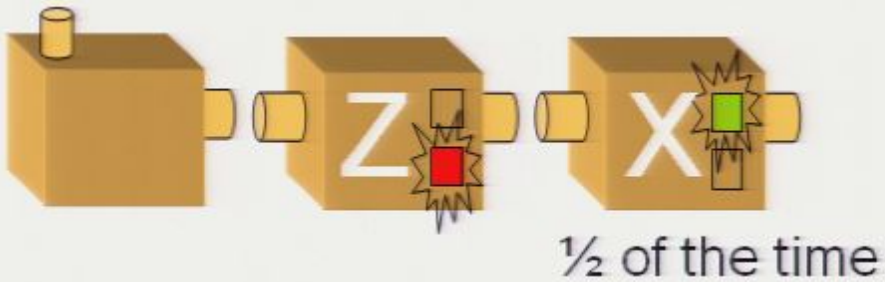

Z
X
½ of the time

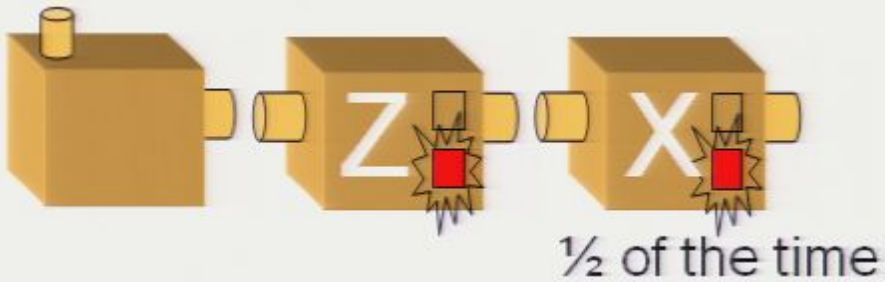

Z
X
½ of the time

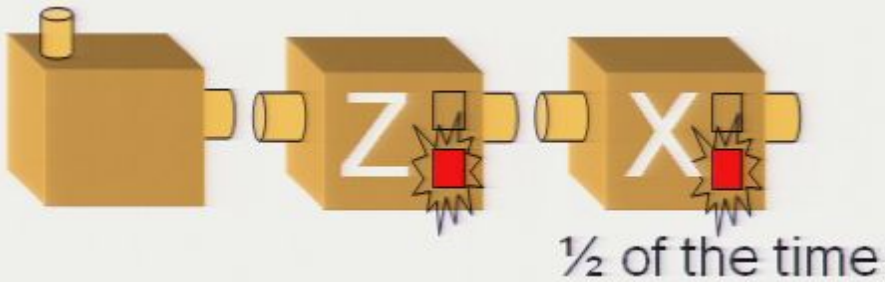

Z
X

Z
X


Z
X
½ of the time


Z
X
½ of the time


Z
X
½ of the time

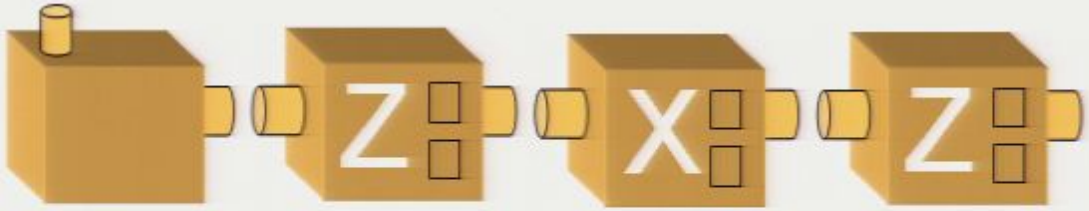


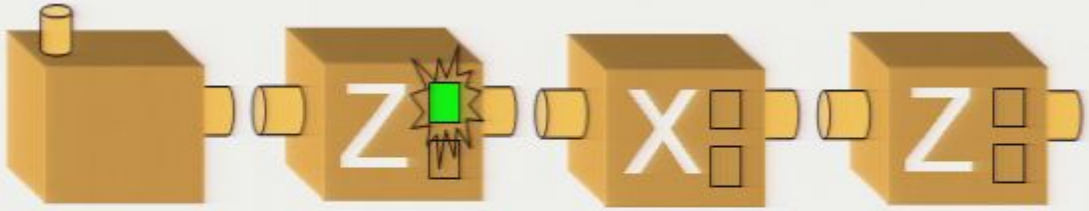

The outcome of an X measurement is uncorrelated with the outcome of an immediately preceding Z measurement

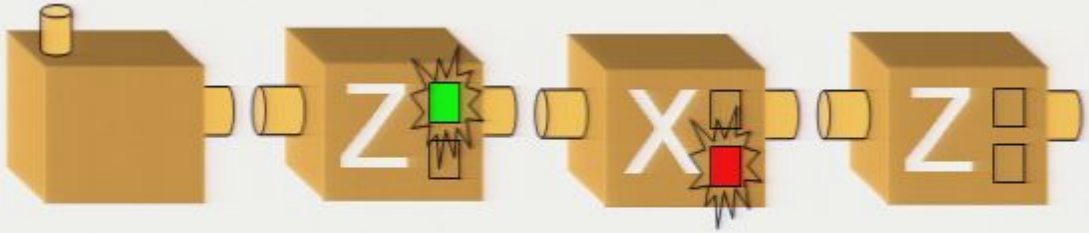


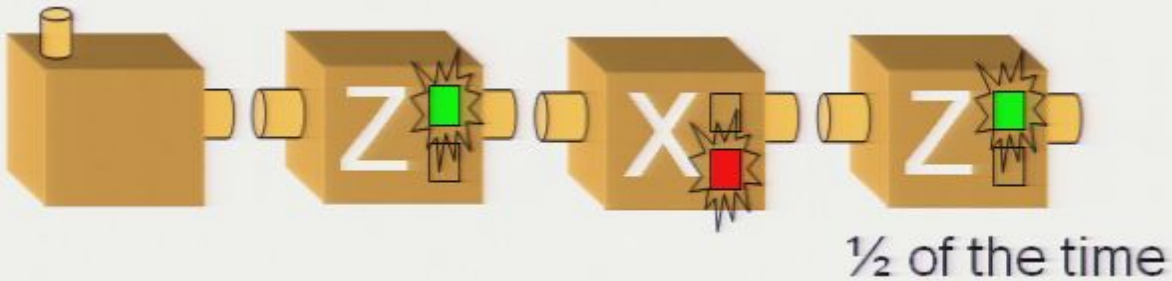


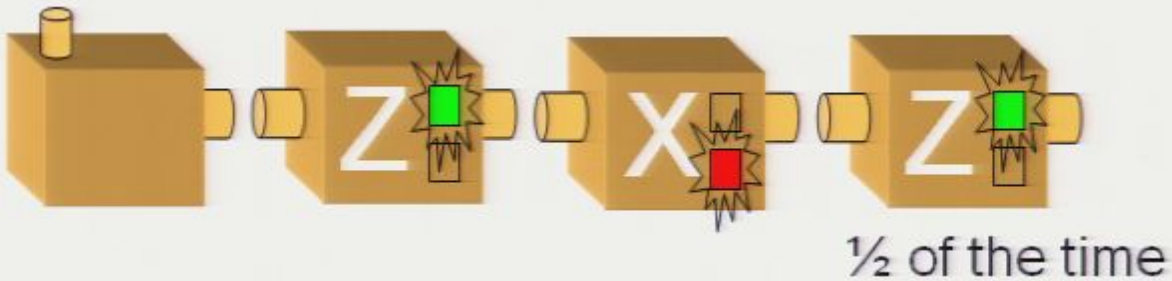
Same thing for X then Z

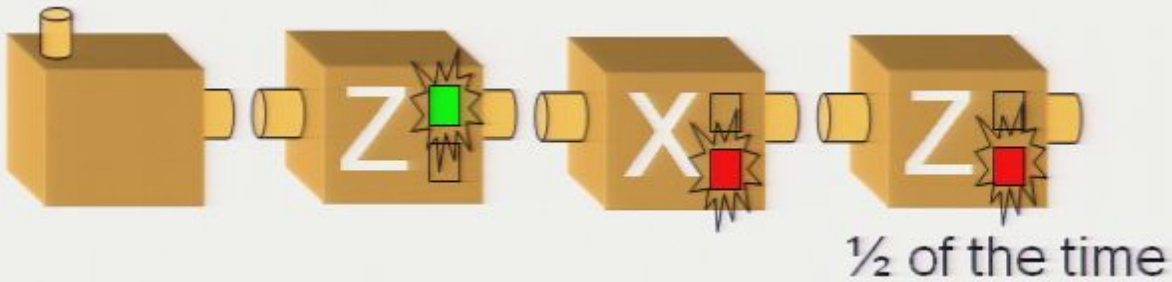

Z
X
Z


Z
X
Z


Z
X
Z

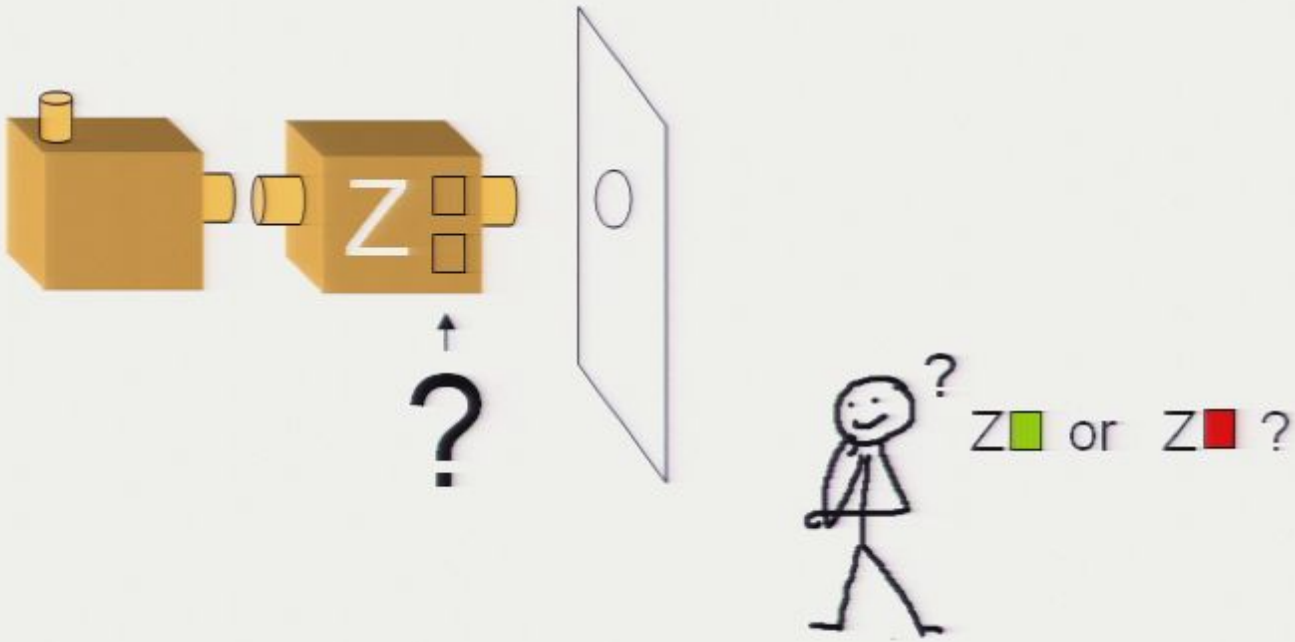

Z
X
Z
½ of the time

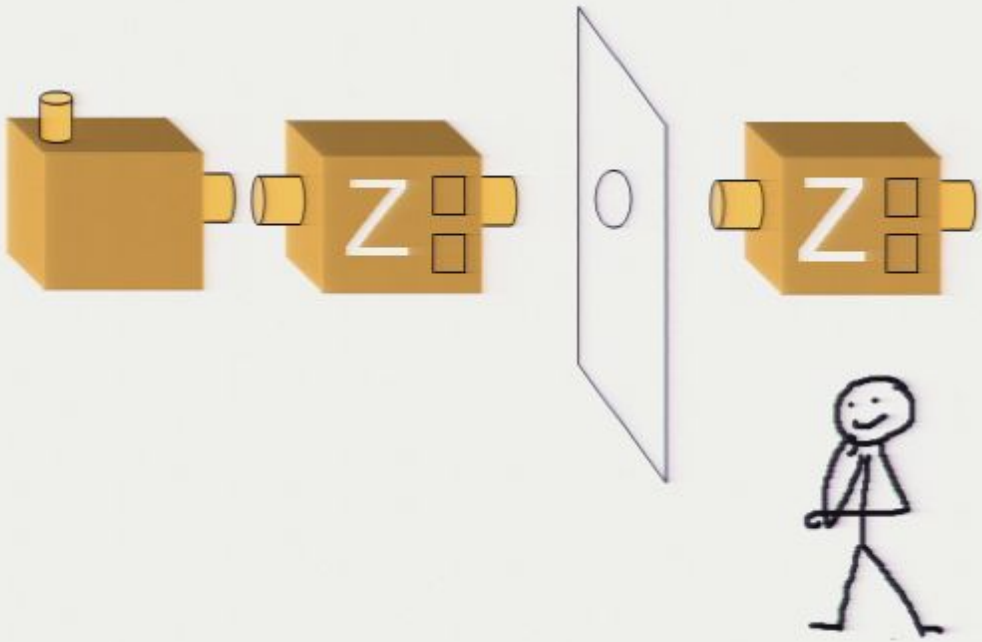

Z
X
Z
½ of the time




An intervening X measurement randomizes the outcome of a Z measurement

Same thing for X Z X


Z
?
Z or Z ?


Z
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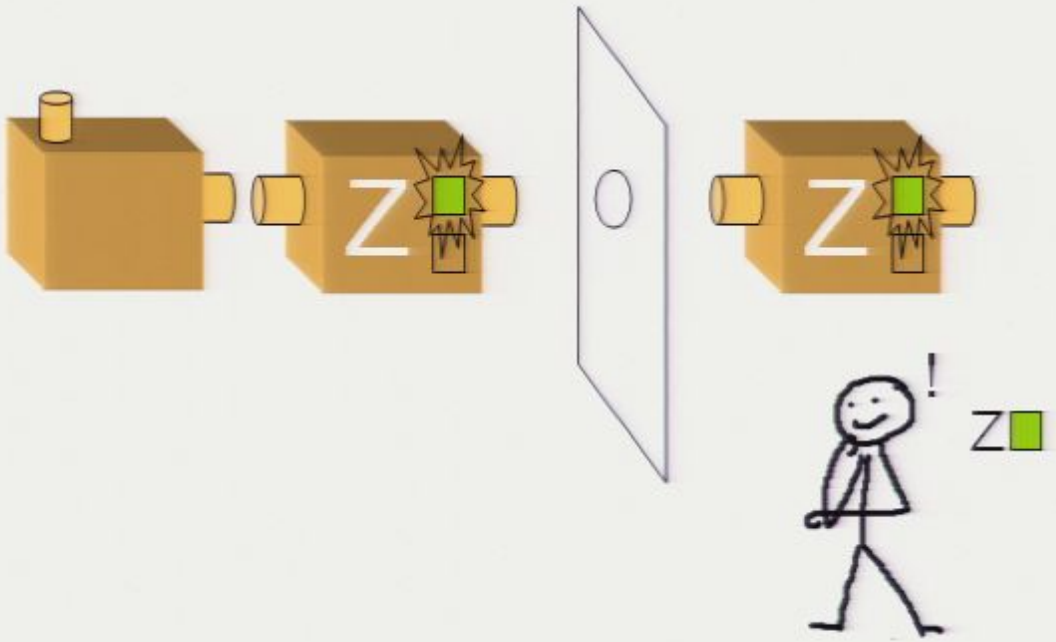
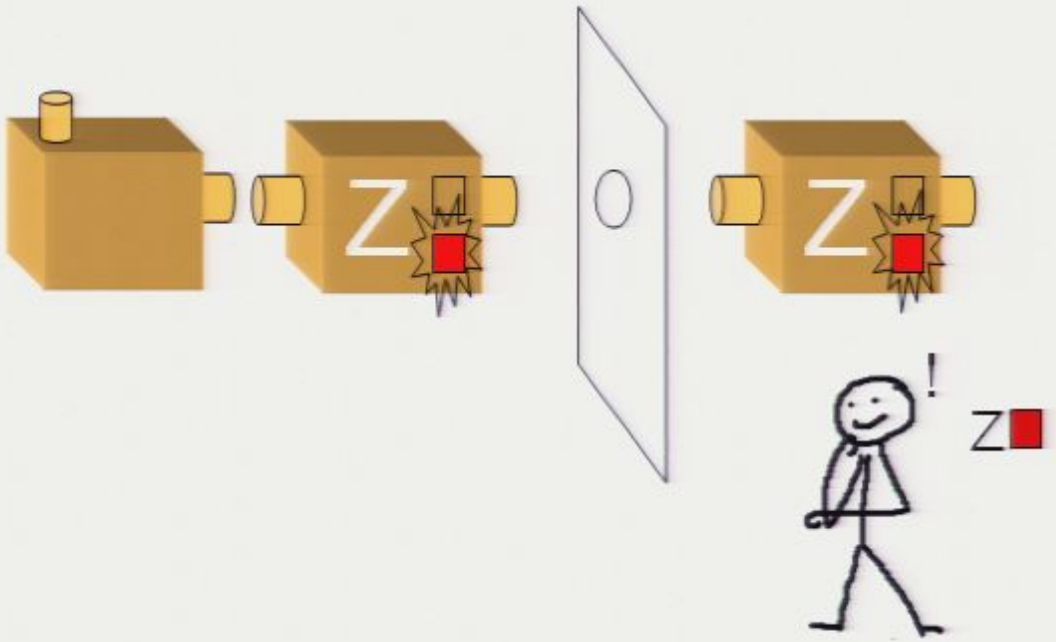

Z
Z
!
Z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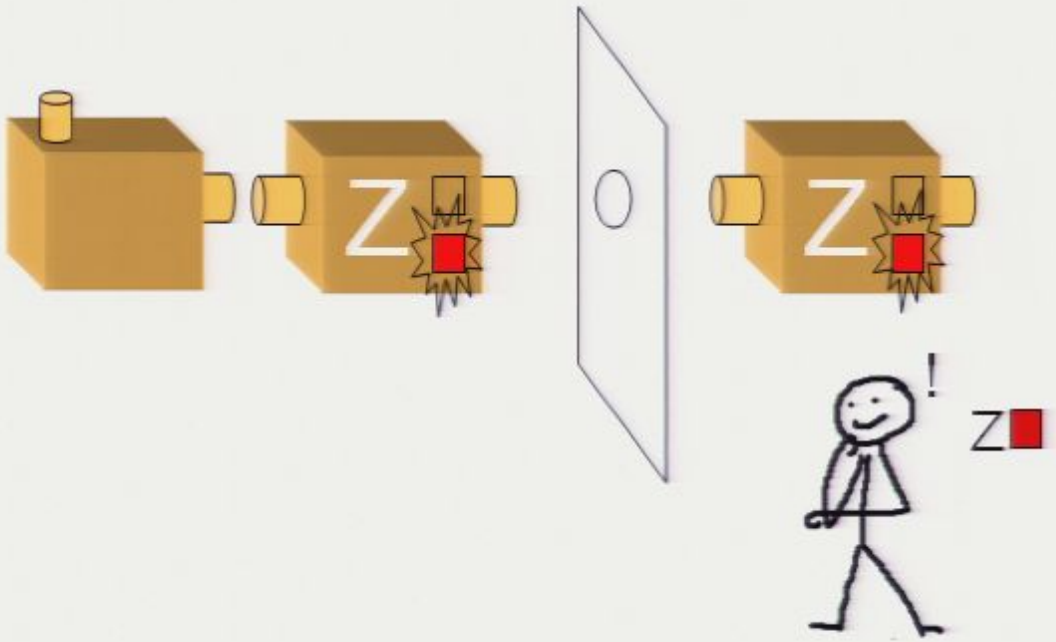
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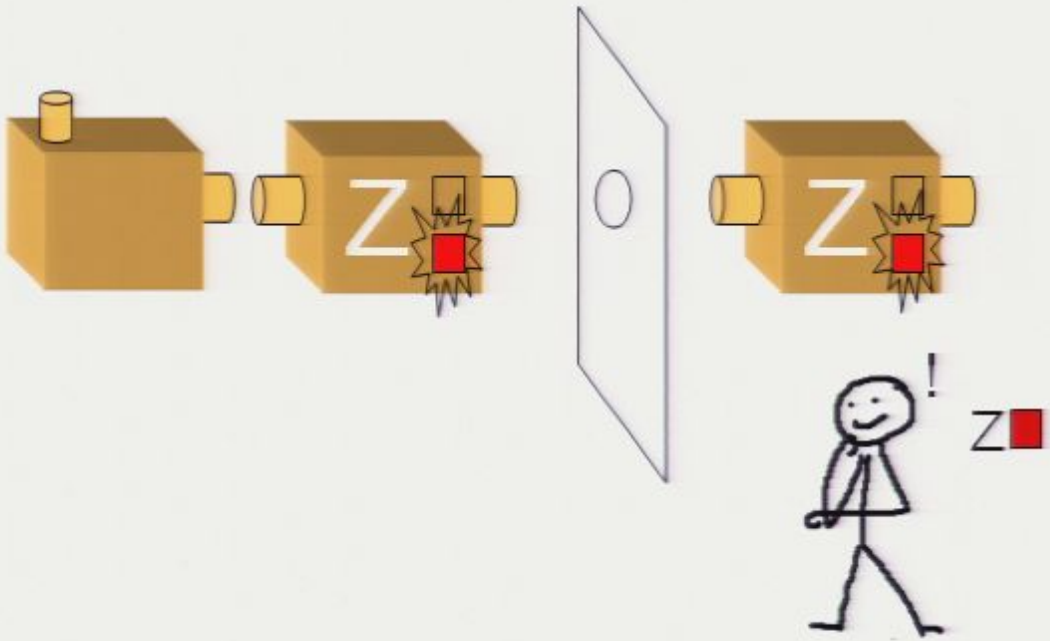
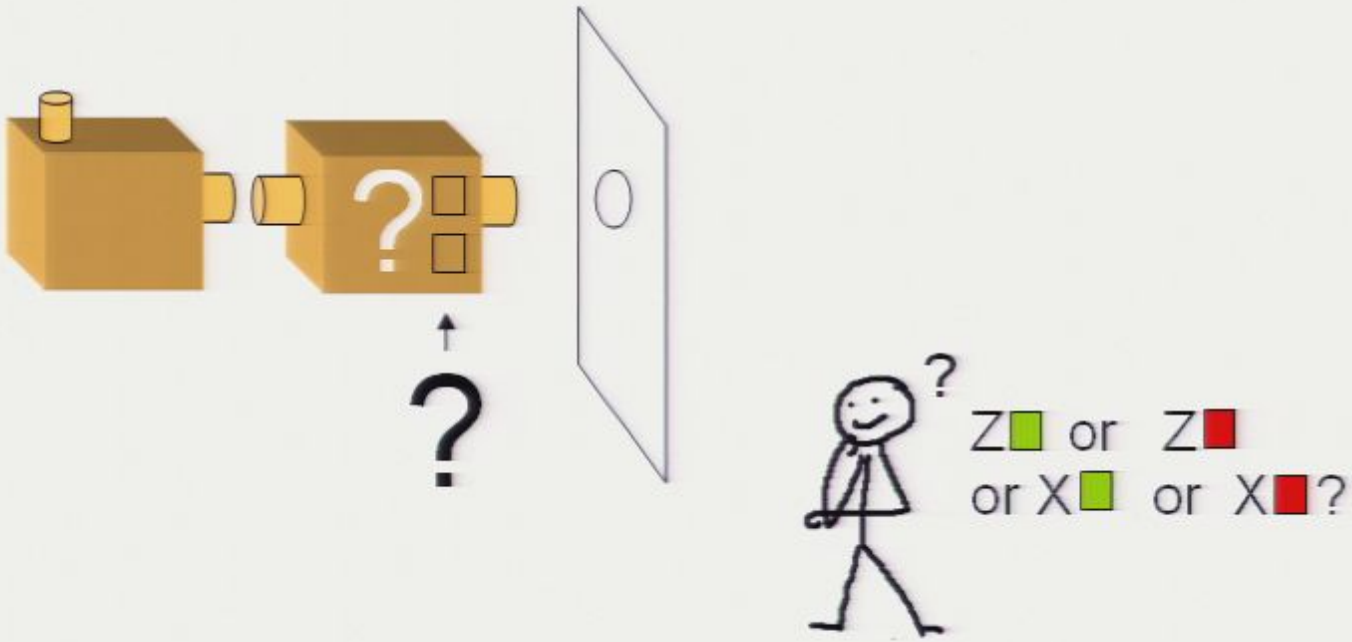
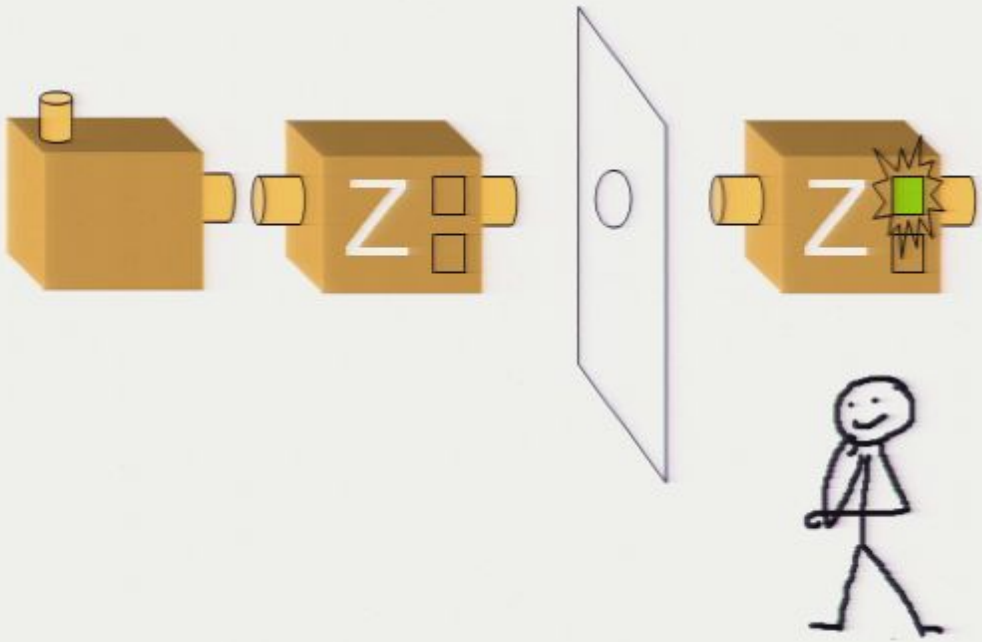
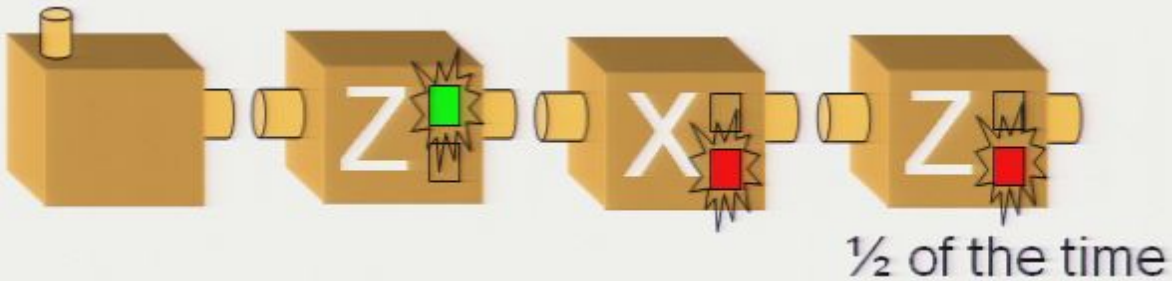


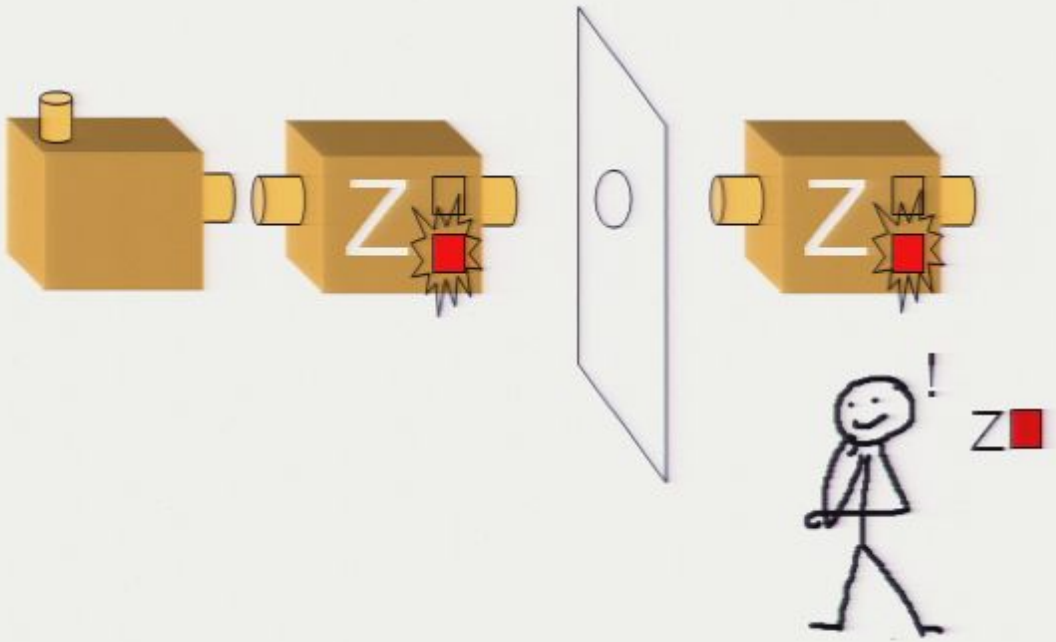

It is possible to distinguish between
Z Green and Z Red

(The same is true for X Green and X Red)


?
?
Z or Z
or X or X?


Z
Z


Z
X
Z
½ of the time


Z
Z
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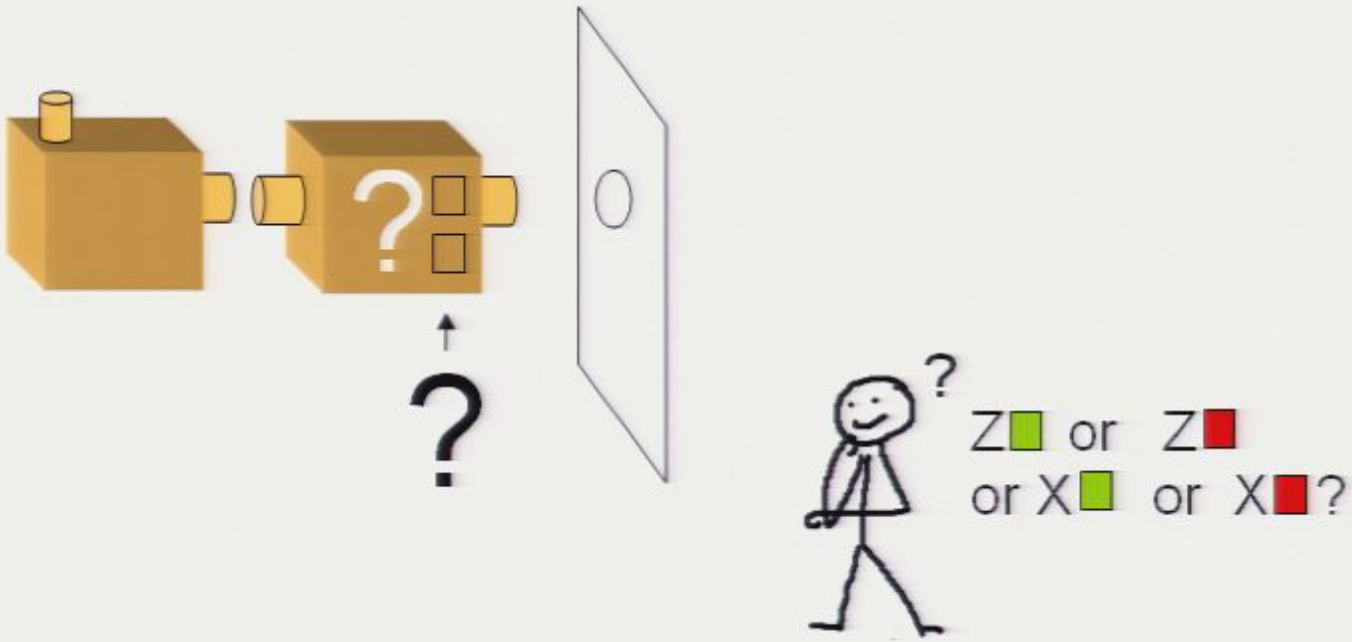
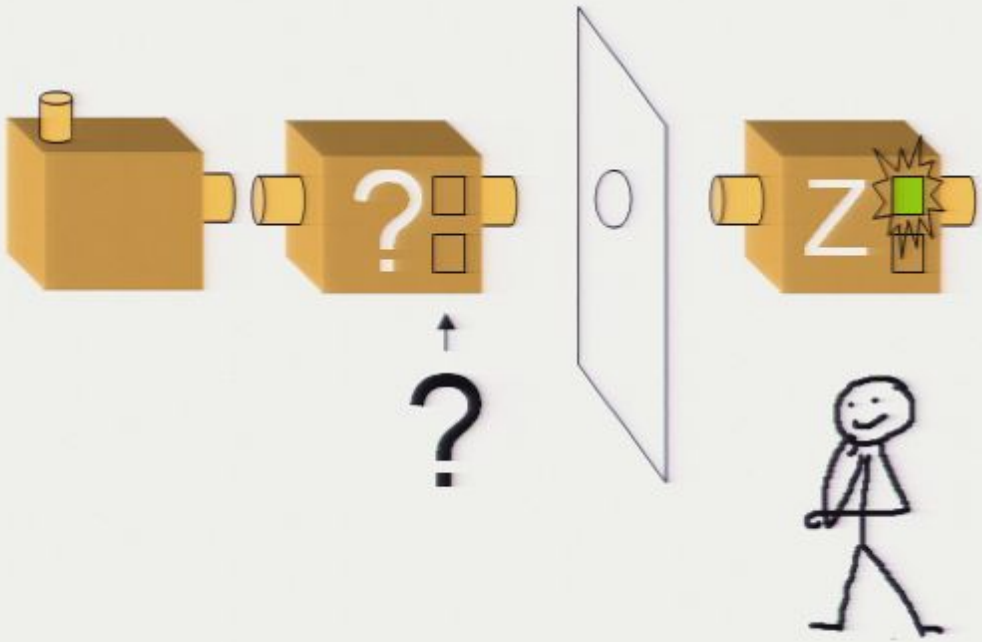
Z


?
?
Z or Z
or X or X?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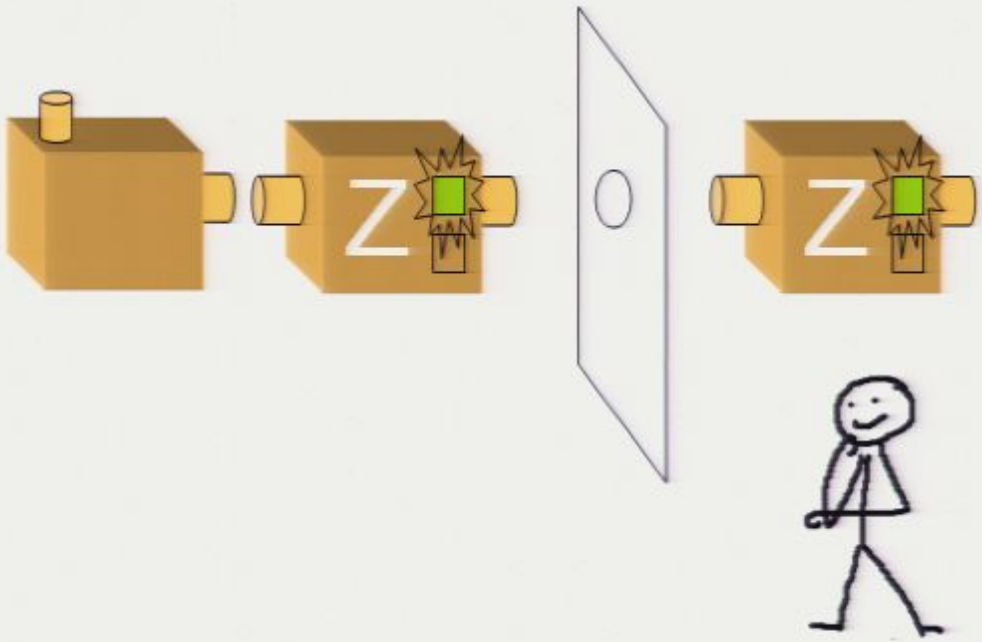
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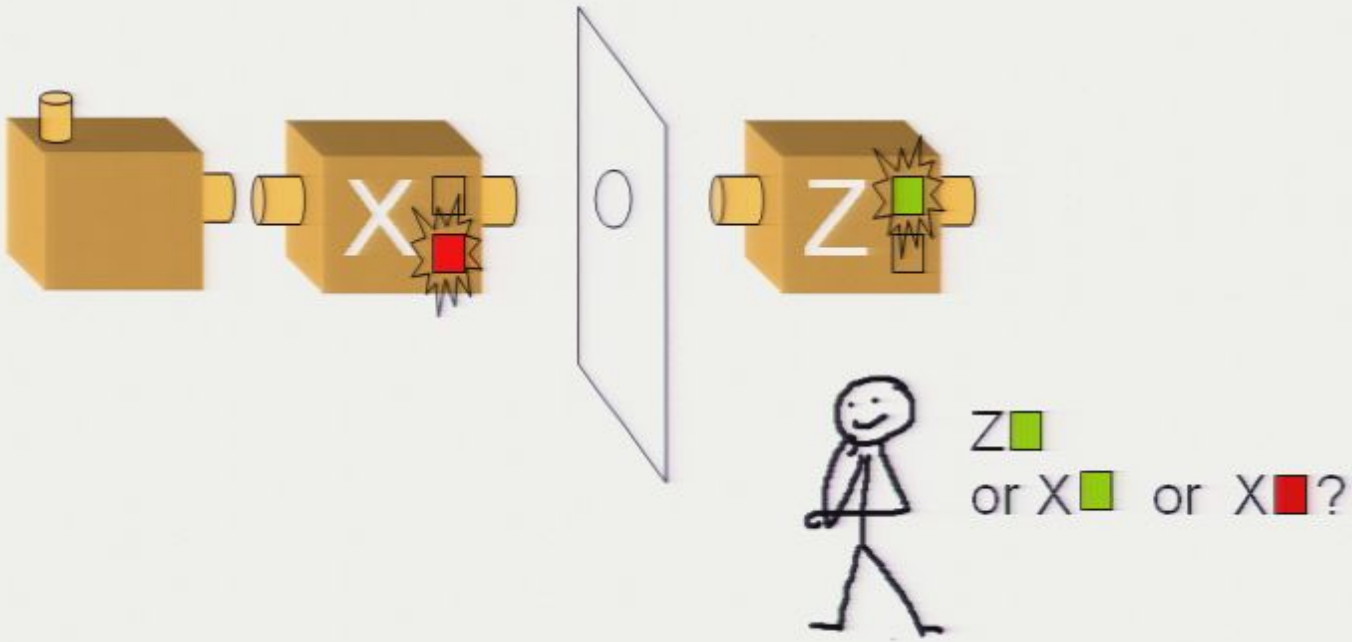
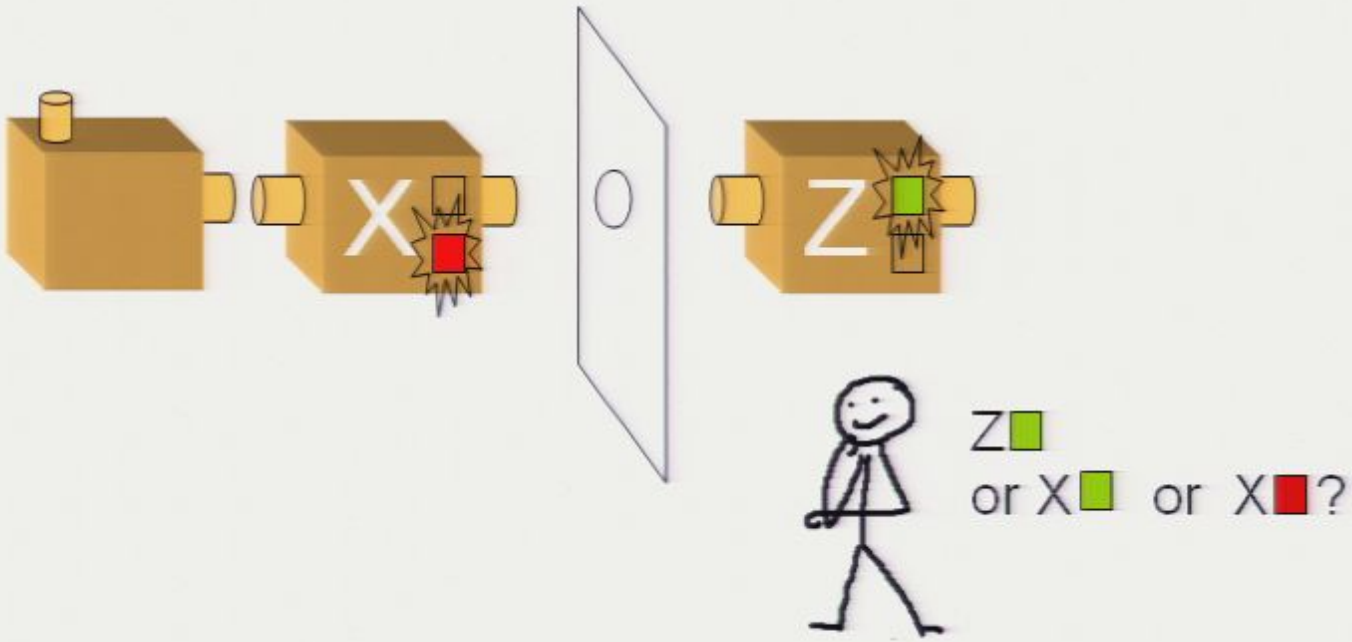
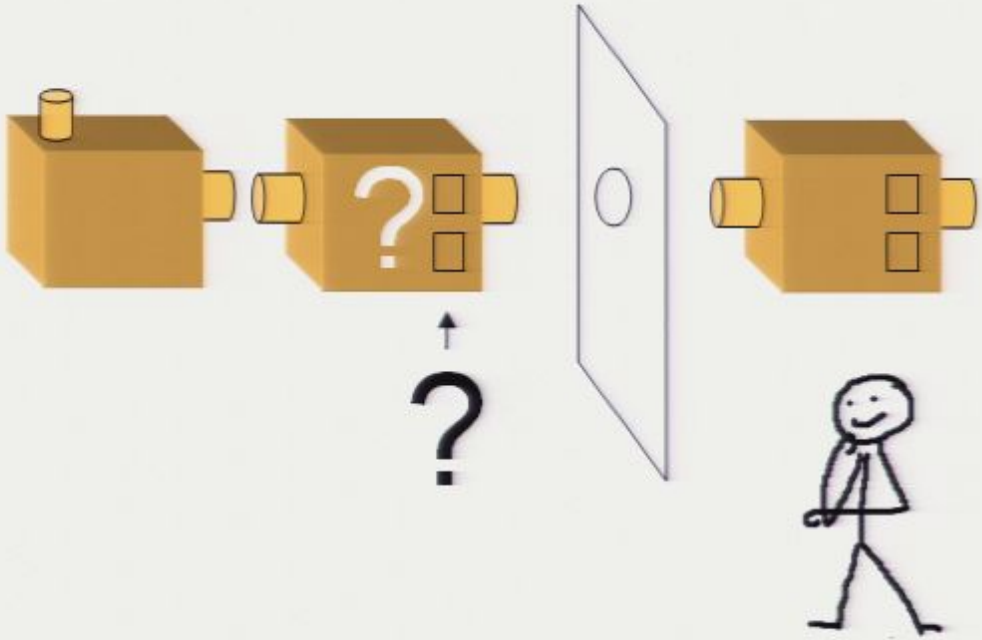

X
Z
Z
or X or X?




It is impossible to distinguish between
Z Green, Z Red, X Green and X Red



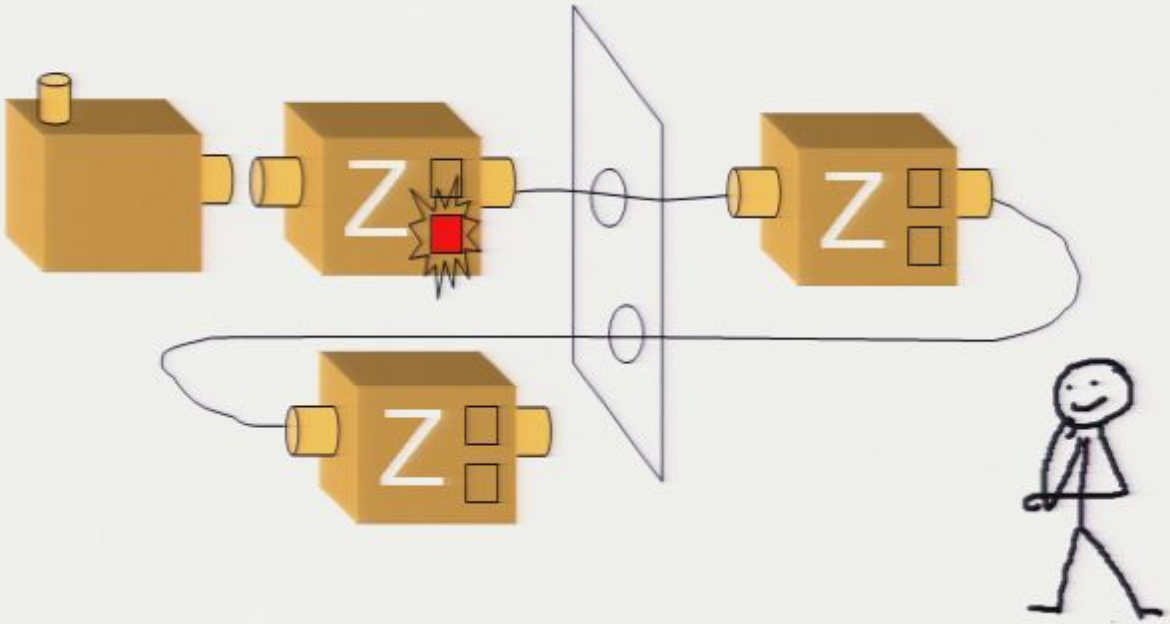

## Probability of estimating correctly

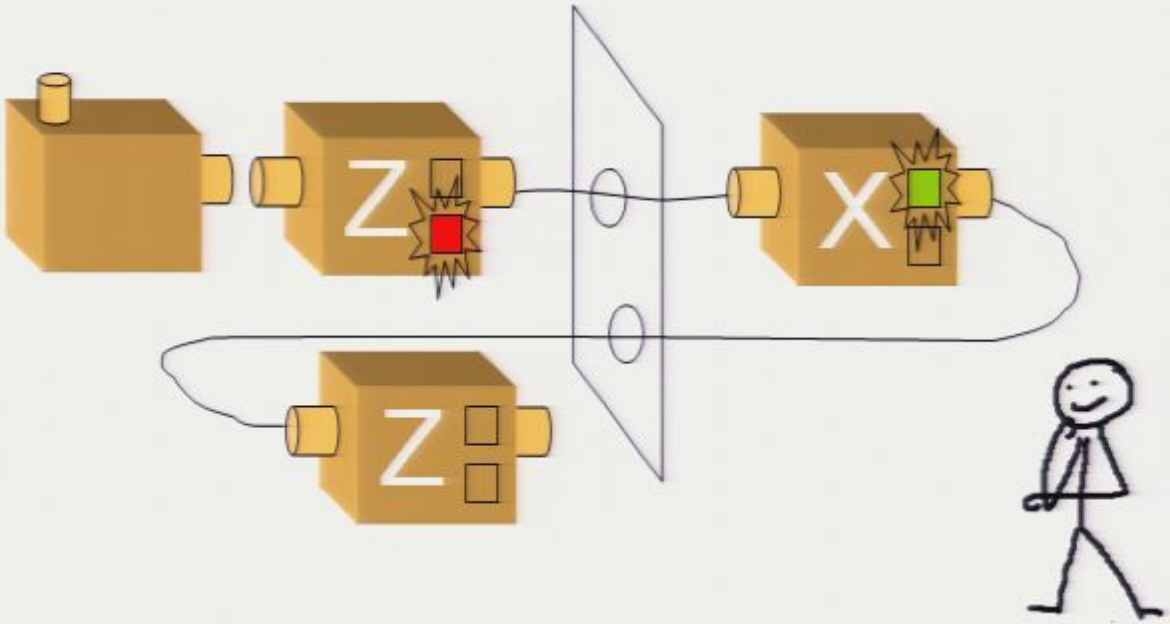
= P(get Z vs. X right) X P(get Red vs. Green right | you got Z vs. X right)

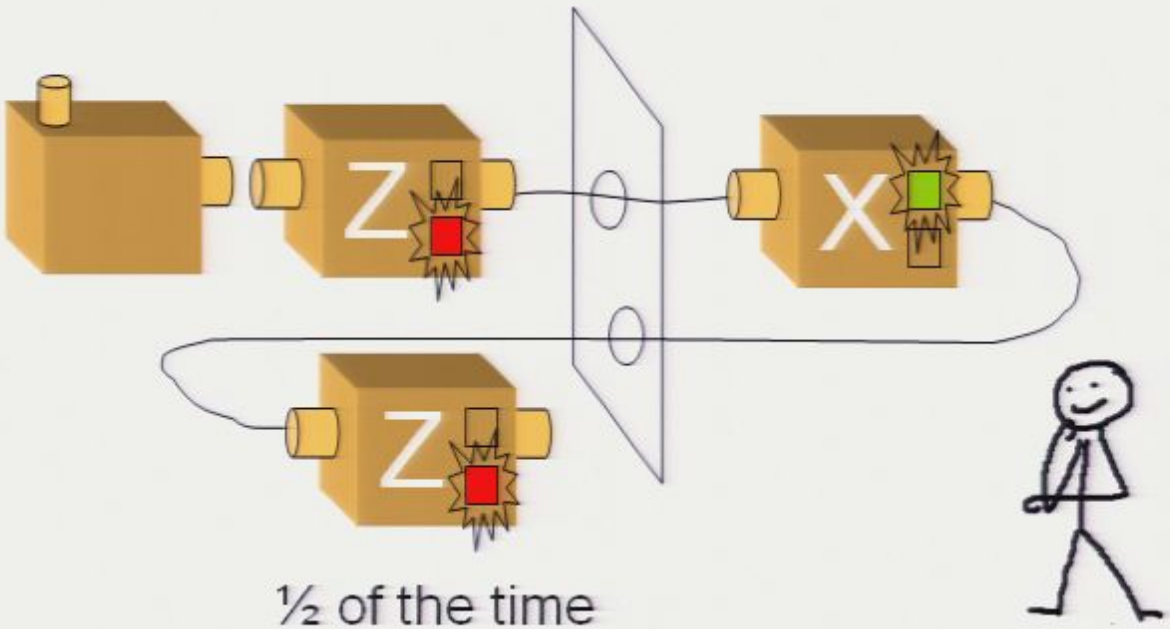
$= \frac{1}{2} \times 1$

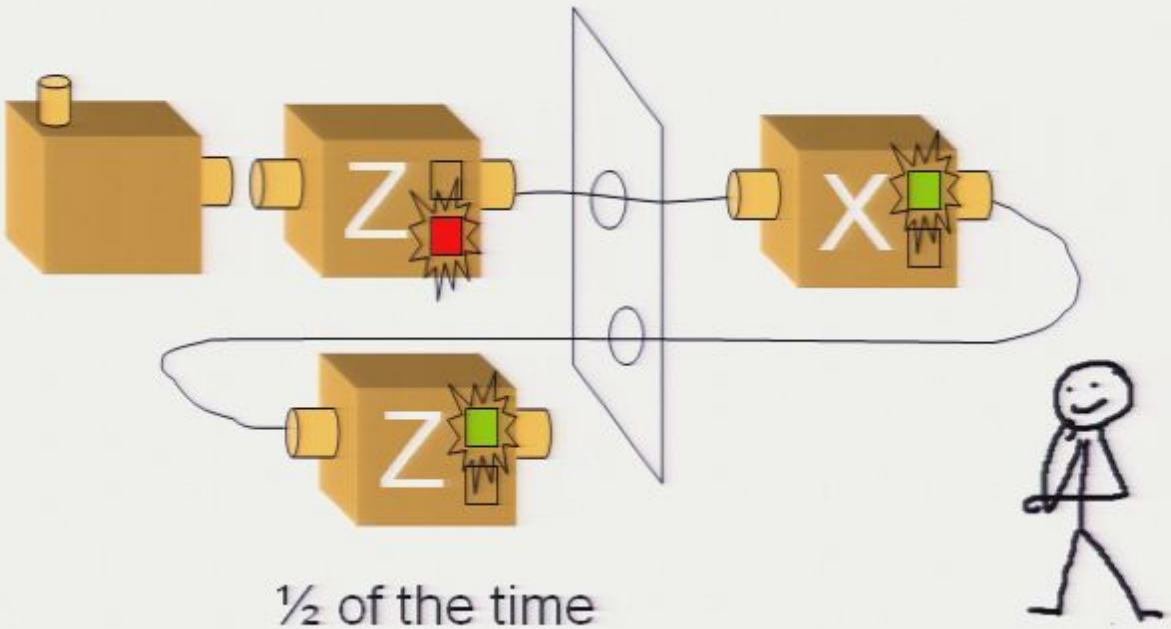
$= \frac{1}{2}$

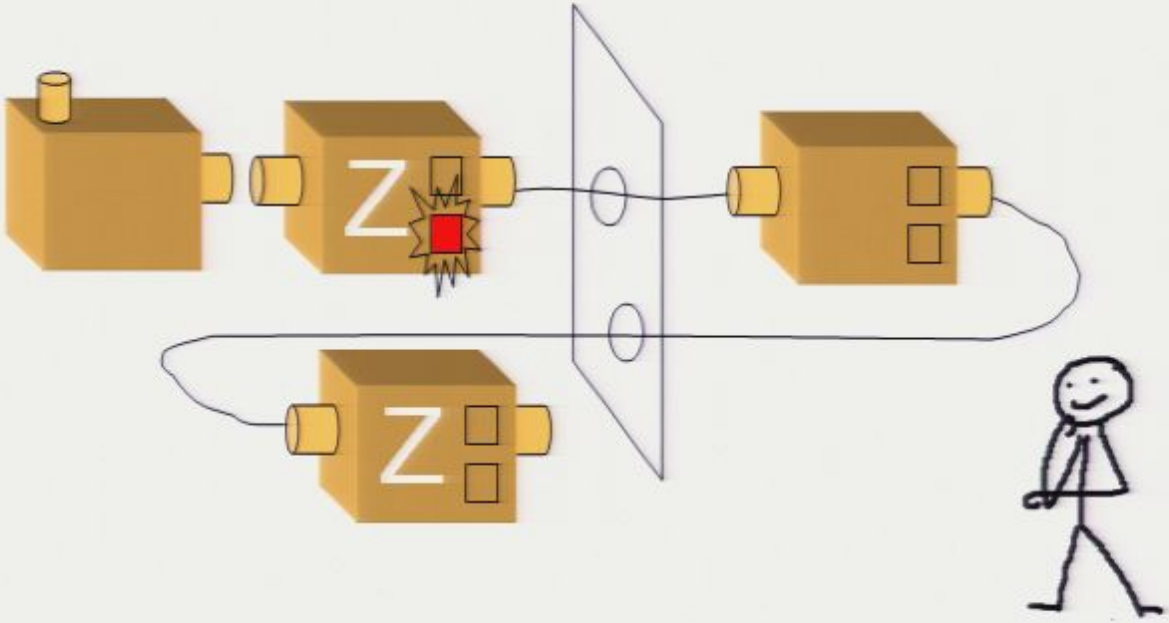
## No perfect information gain


Z
Z
Z


Z
X
Z


Z
X
Z
½ of the time


Z
X
Z
½ of the time




## Probability of passing test

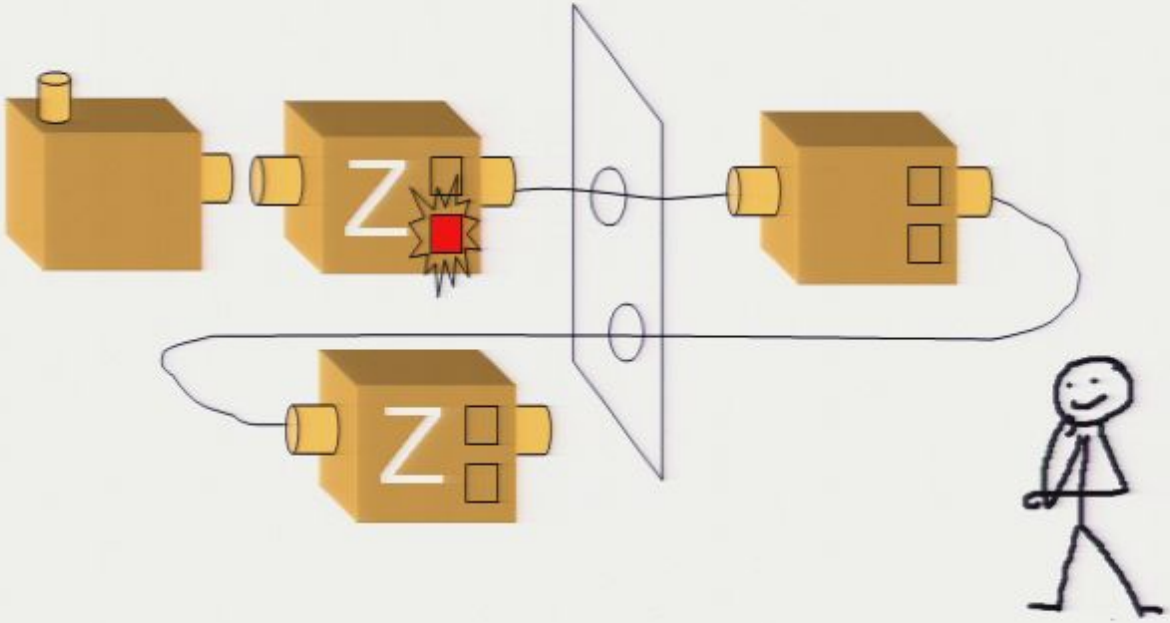
= P(get Z vs. X right) X P(pass the test | you got Z vs. X right)

+ P(get Z vs. X wrong) X P(pass the test | you got Z vs. X wrong)

$= \frac{1}{2} \times 1$

$+ \frac{1}{2} \times \frac{1}{2}$

$= \frac{3}{4}$

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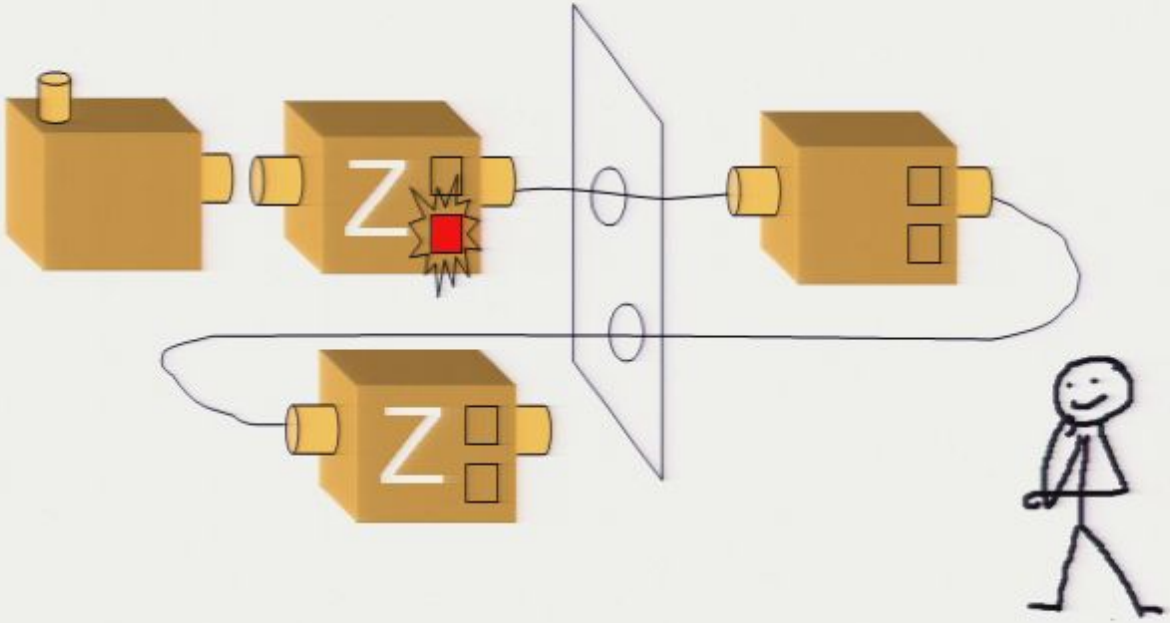
$= \frac{1}{2} \times 1$

$+ \frac{1}{2} \times \frac{1}{2}$

$= \frac{3}{4}$




## Probability of passing test

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+ P(get Z vs. X wrong) X P(pass the test | you got Z vs. X wrong)

$= \frac{1}{2} \times 1$

$+ \frac{1}{2} \times \frac{1}{2}$

$= \frac{3}{4}$



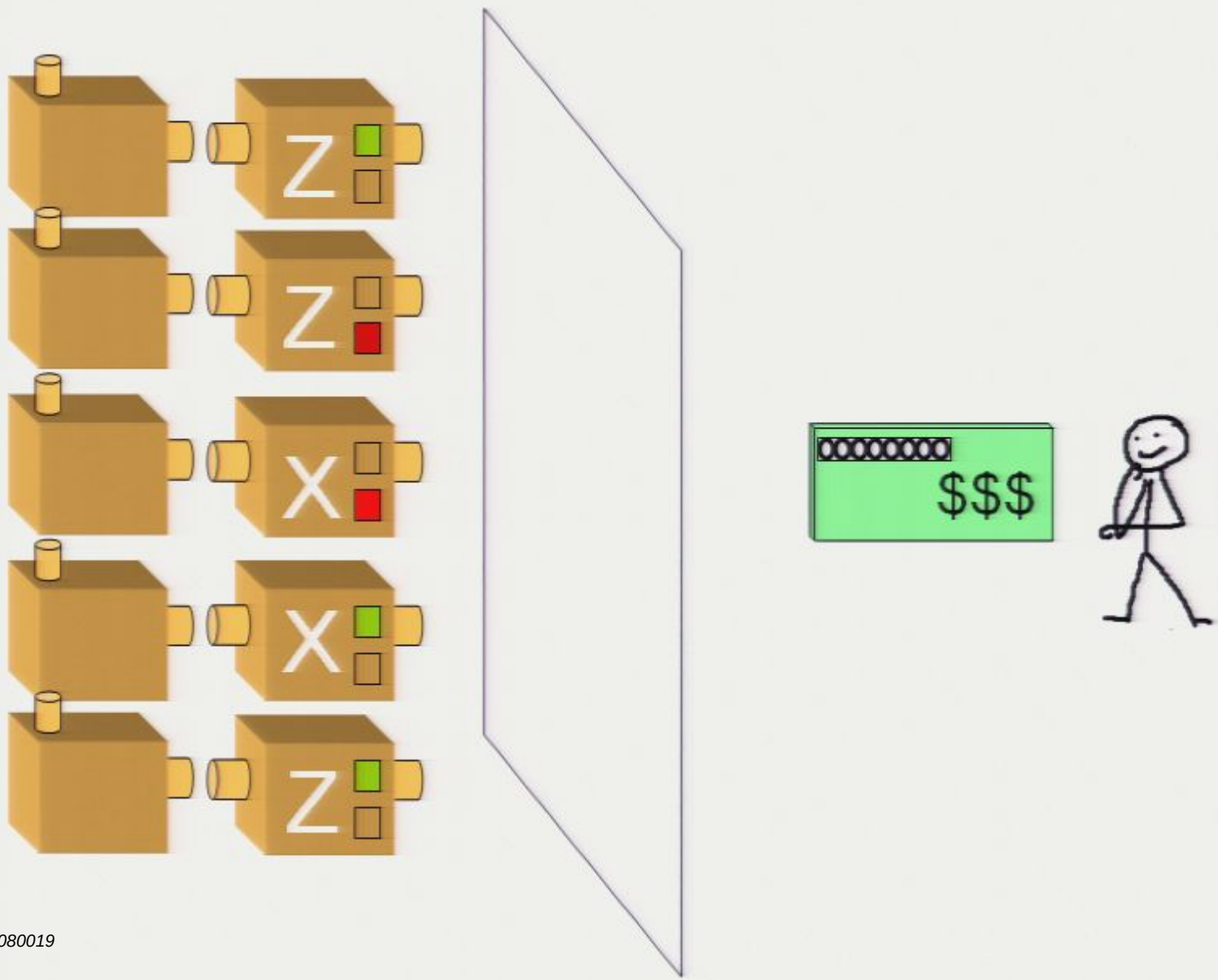
# Information gain causes a disturbance

Some applications of these phenomena to cryptography

Quantum
counterfeit-proof
money

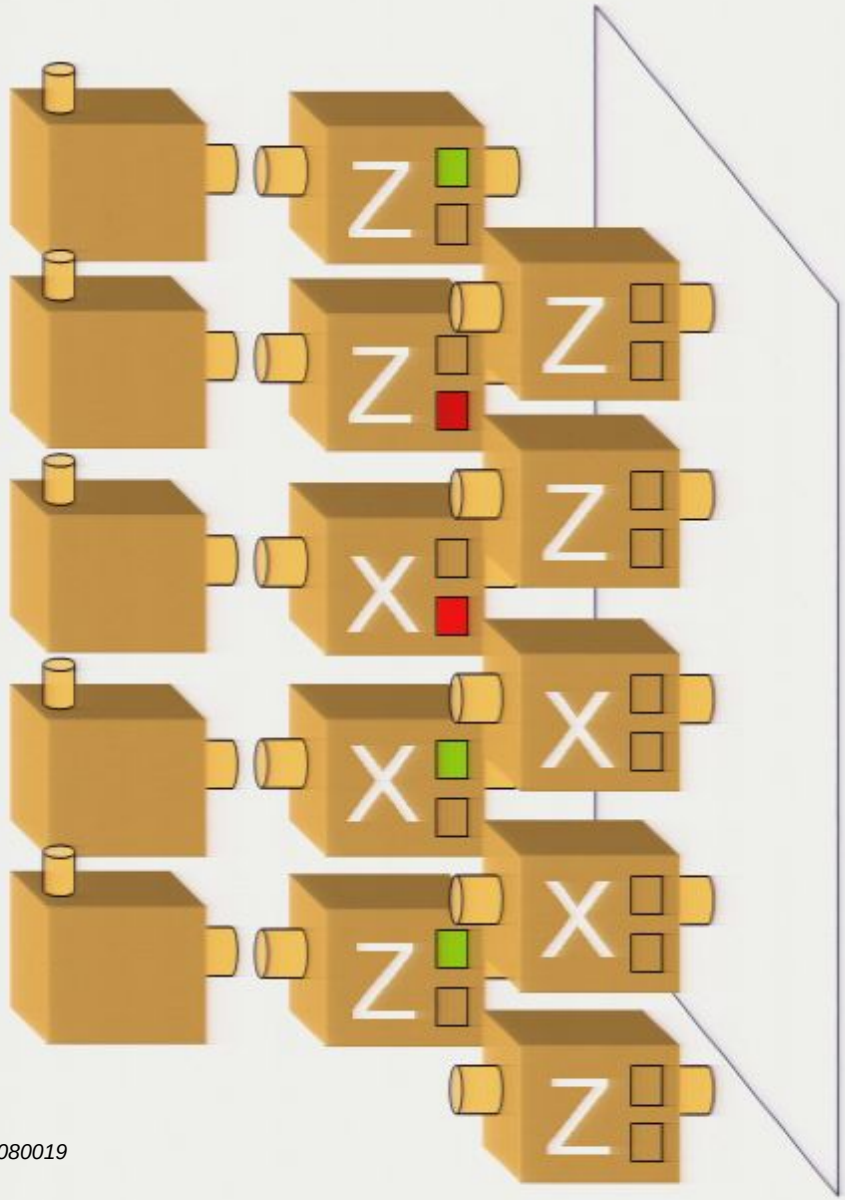
# Quantum Counterfeit-Proof Money

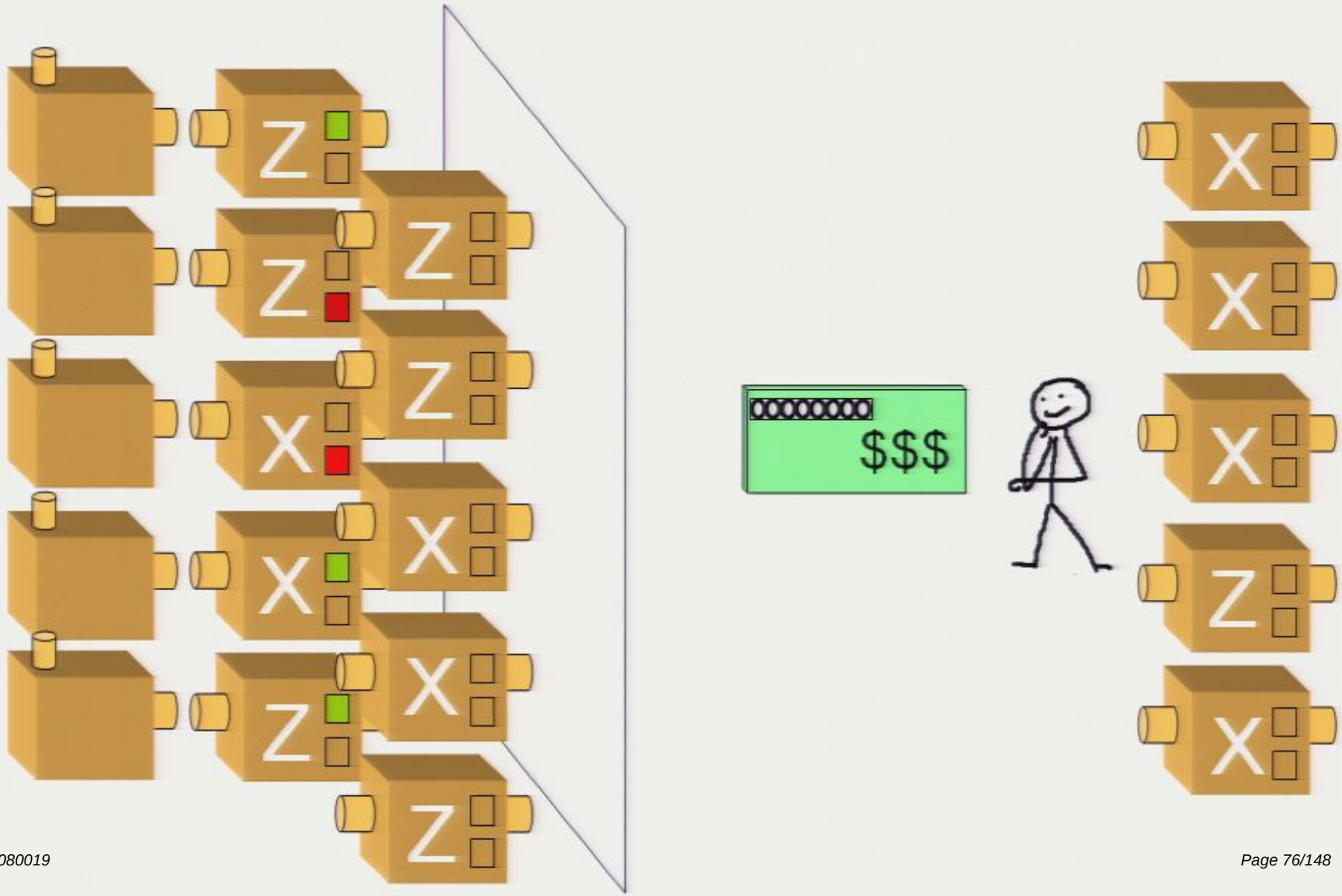
# QUANTUM COUNTERFEIT-PROOF MONEY


The Mint
The rest of the world
Z
Z
X
X
Z
$$$

The Mint

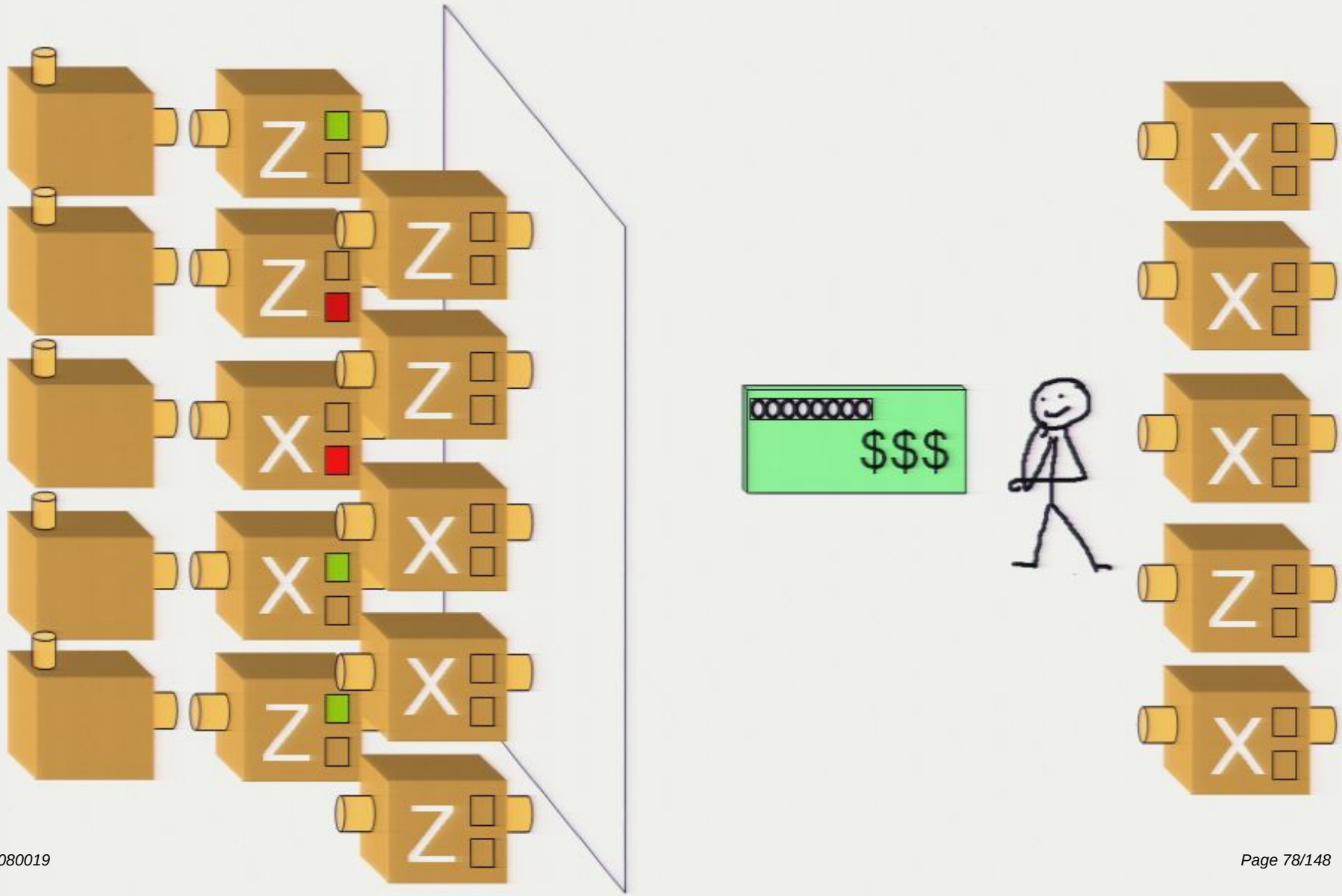
The rest of the world




The Mint
The rest of the world
Z
Z
Z
Z
X
X
X
X
Z
Z
X
X
X
X
Z
X
$$$

Probability every hidden measurement is estimated correctly:

$$\frac{1}{2} \times \frac{1}{2} \times \frac{1}{2} \times \frac{1}{2} \times \frac{1}{2} \times \frac{1}{2} \times \frac{1}{2} \times \frac{1}{2} = \left(\frac{1}{2}\right)^8 \simeq 0.0039$$


The Mint
The rest of the world
Z
Z
Z
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X
X
X
X
Z
Z
X
X
X
X
Z
X
$$$

Probability every hidden measurement is estimated correctly:

$$\frac{1}{2} \times \frac{1}{2} \times \frac{1}{2} \times \frac{1}{2} \times \frac{1}{2} \times \frac{1}{2} \times \frac{1}{2} \times \frac{1}{2} = \left(\frac{1}{2}\right)^8 \simeq 0.0039$$

Probability every hidden measurement is estimated correctly:

$$\frac{1}{2} \times \frac{1}{2} \times \frac{1}{2} \times \frac{1}{2} \times \frac{1}{2} \times \frac{1}{2} \times \frac{1}{2} \times \frac{1}{2} = \left(\frac{1}{2}\right)^8 \simeq 0.0039$$

Probability original passes the test:

$$\frac{3}{4} \times \frac{3}{4} \times \frac{3}{4} \times \frac{3}{4} \times \frac{3}{4} \times \frac{3}{4} \times \frac{3}{4} \times \frac{3}{4} = \left(\frac{3}{4}\right)^8 \simeq 0.10$$

# Quantum detection of eavesdroppers

# Private Channel

# Private Channel

# Caesar cipher

plain-text: "MEETMEATTHERIVER"

shift each letter by $x \in \{0,\ldots, 26\}$
key: 2

cipher-text: "OGGVOGCVVJGTKXGT"

# Caesar cipher

plain-text: "MEETMEATTHERIVER"

shift each letter by $x \in \{0,\ldots, 26\}$
key: 2

cipher-text: "OGGVOGCVVJGTKXGT"

# Vernam cipher

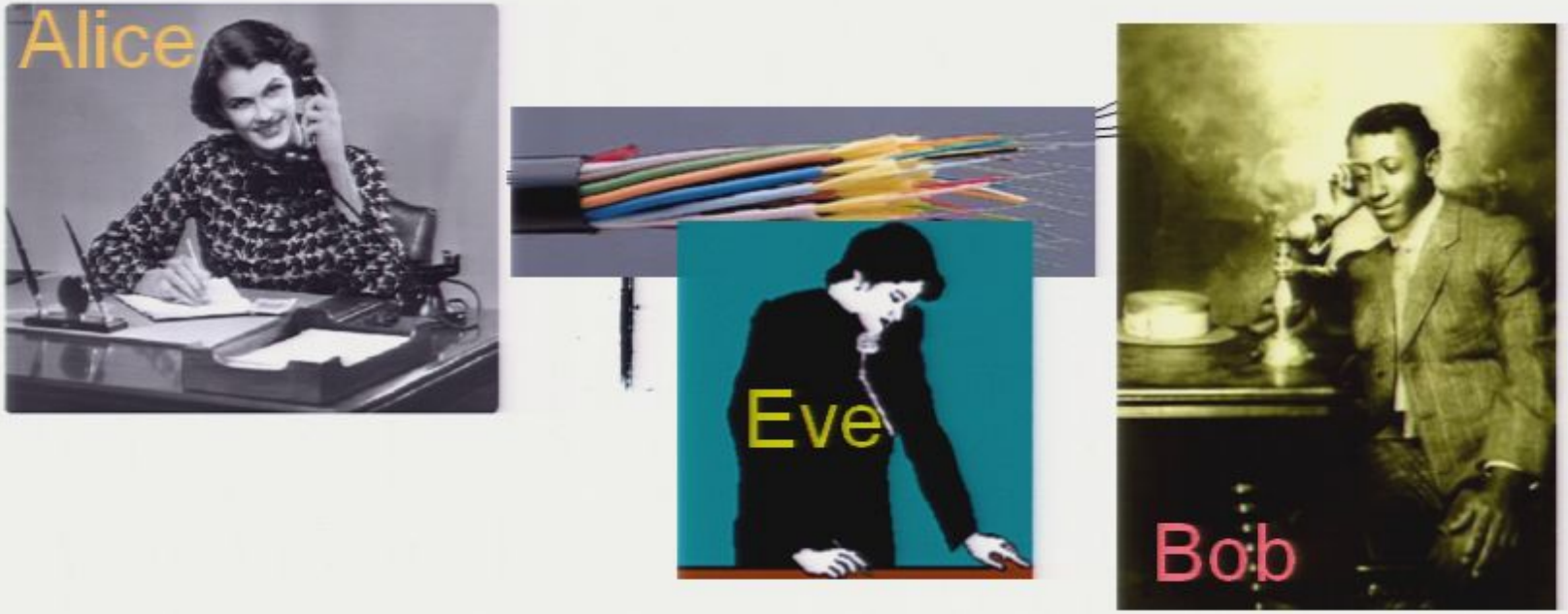
plain-text: "MEETMEATTHERIVER"

shift letter $i$ by $x_i \in \{0,\ldots, 26\}$
key: 7 20 4 12 14 23 19 8 1 2 11 19 23 ...

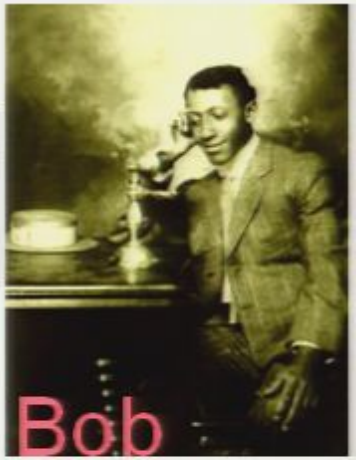
cipher-text: "TYIQZBWYURLCJRSE"

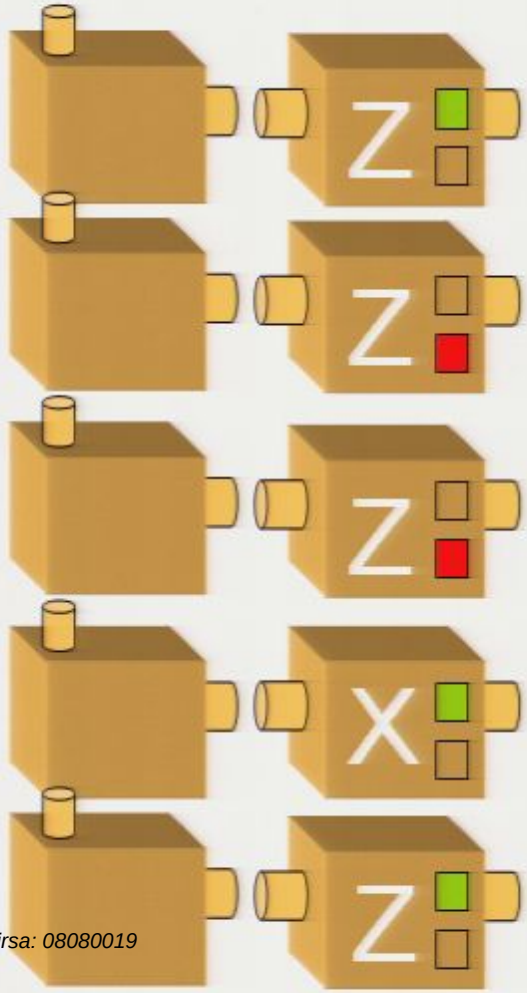
# Quantum Key distribution

# Quantum Key distribution



Alice

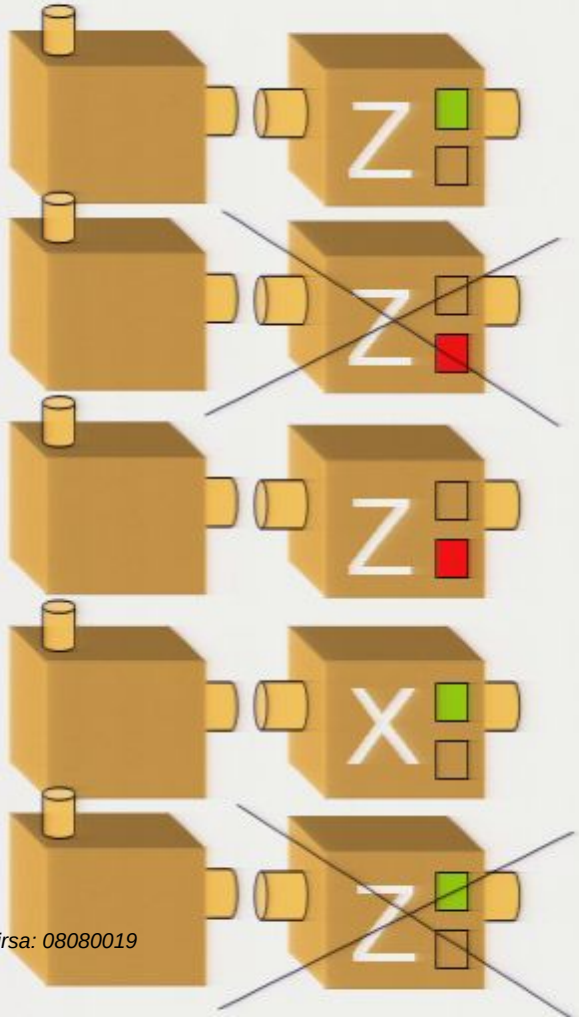

Bob

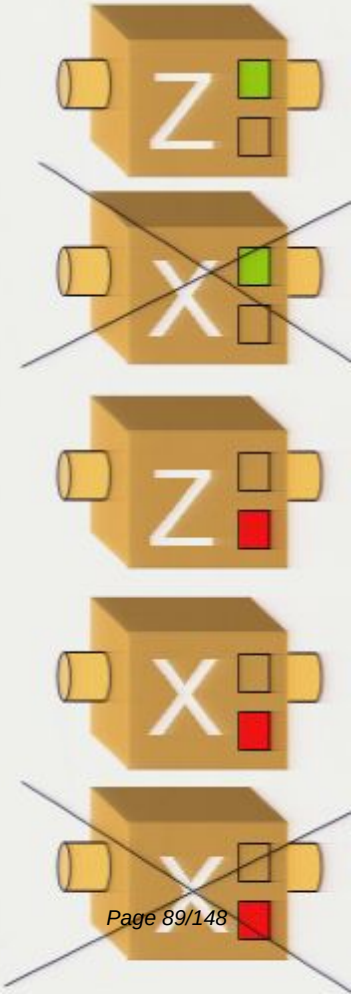

Z
Z
Z
X
Z

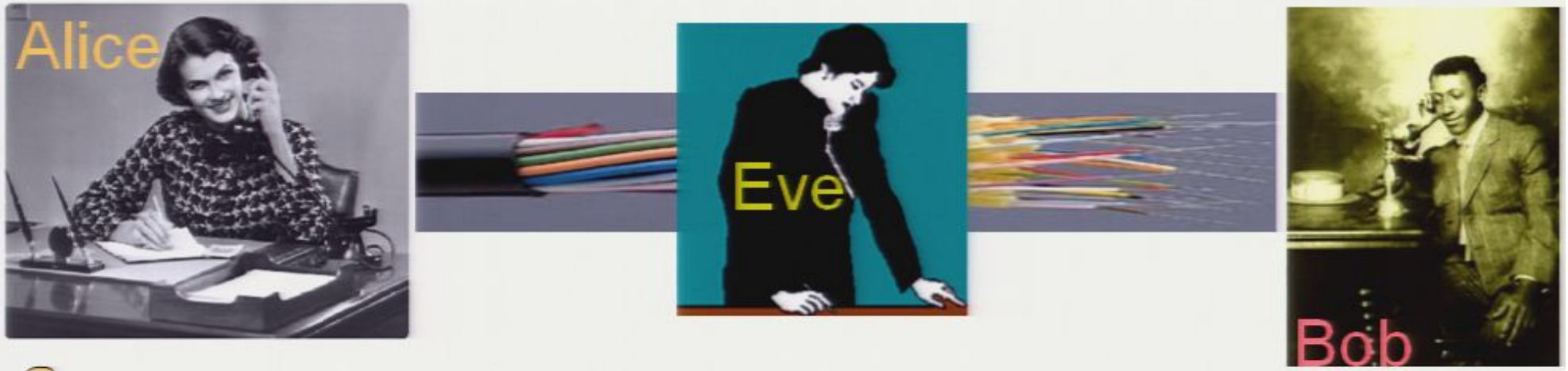
Z
X
Z
X
X

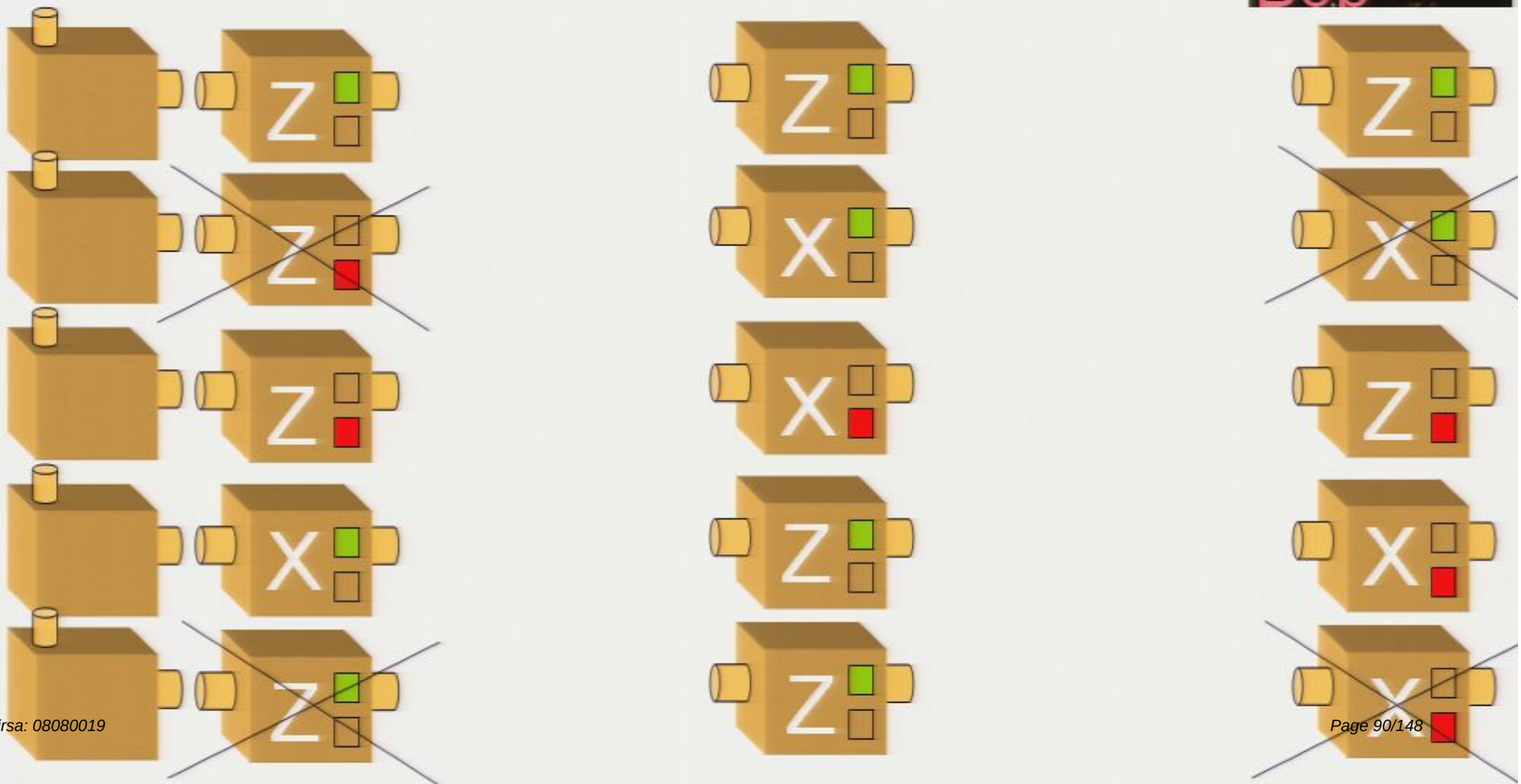
Alice

Bob


Z
Z
Z
X
Z


Z
X
Z
X
X


Alice
Eve
Bob


Z
Z
Z
X
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X
X
Z
Z
Z
X
X
Z

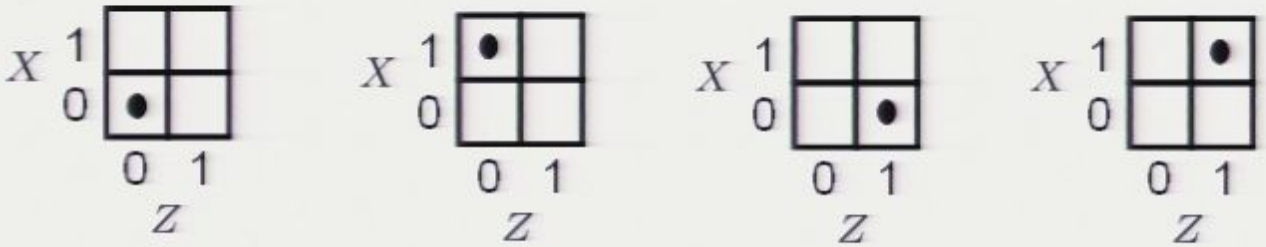
The idea behind
hidden variable models
of
quantum mechanics

# Plato's allegory of the cave

# A toy world with a restriction on knowledge

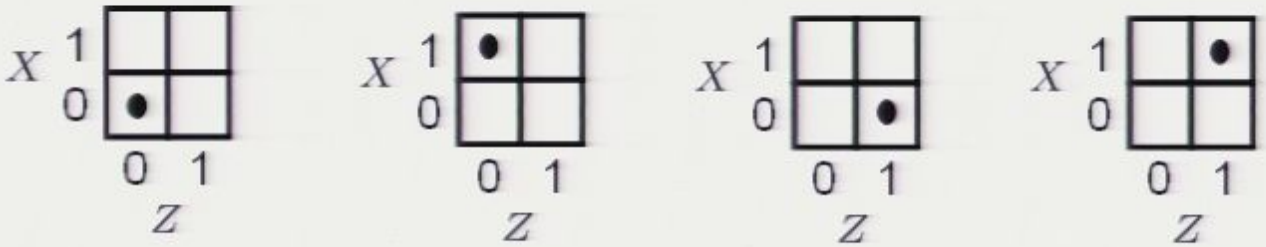
Every system has a pre-existing value of X and Z

4 physical states



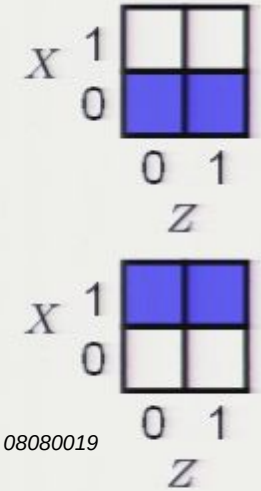
# A toy world with a restriction on knowledge

Every system has a pre-existing value of X and Z
4 physical states

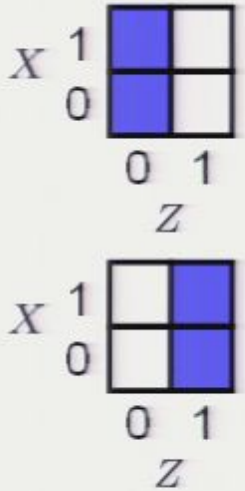



## Possible states of knowledge

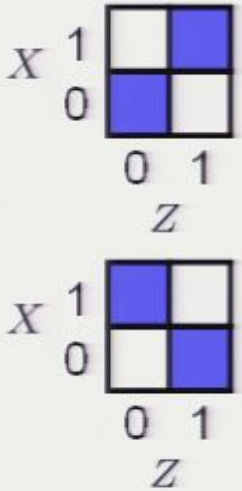
X known



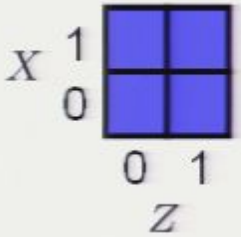

Z known




(X+Z)mod2 known

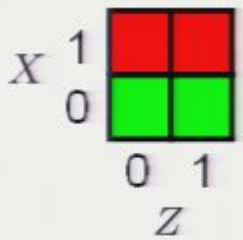



nothing known

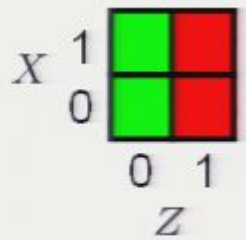


# Possible measurements

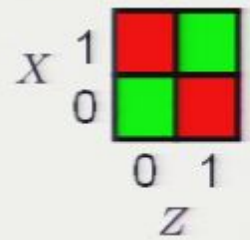
Measure X

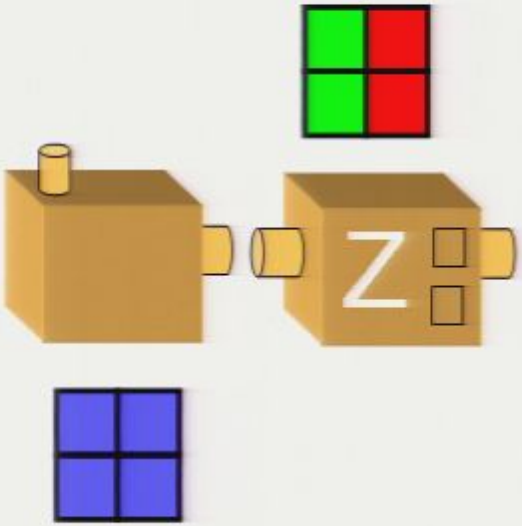


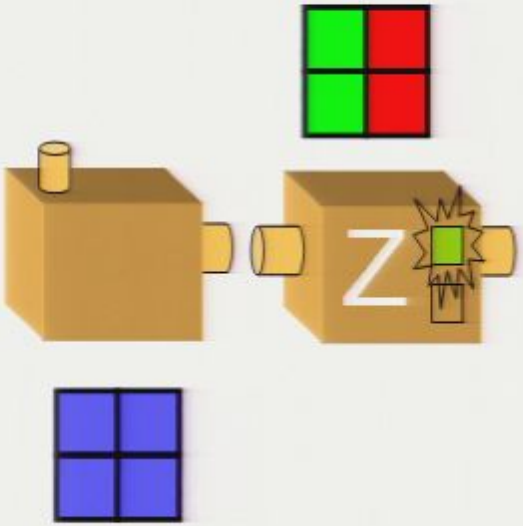

Measure Z



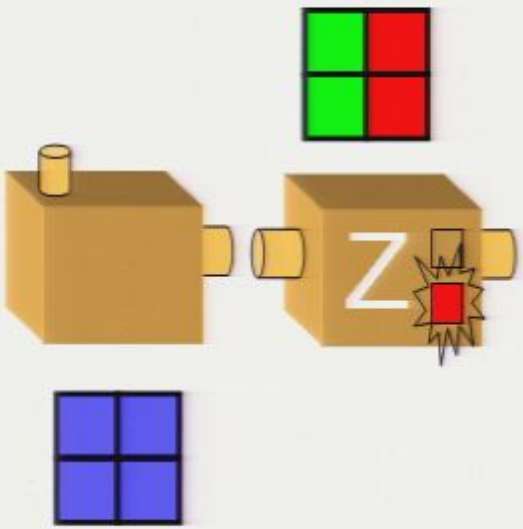

Measure (X+Z)mod2



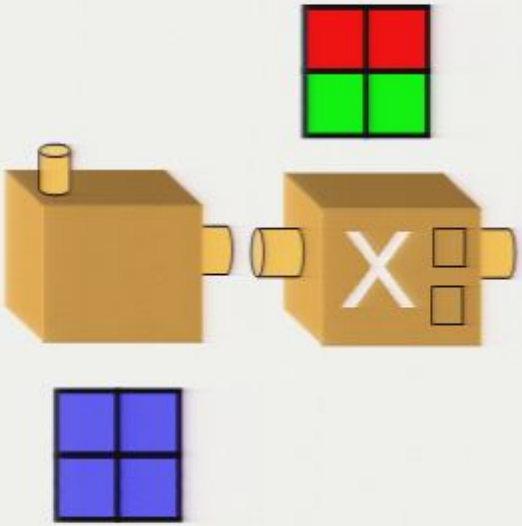

Z

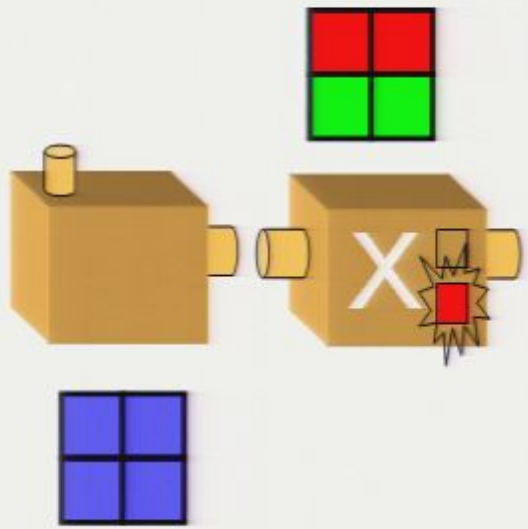



½ of the time



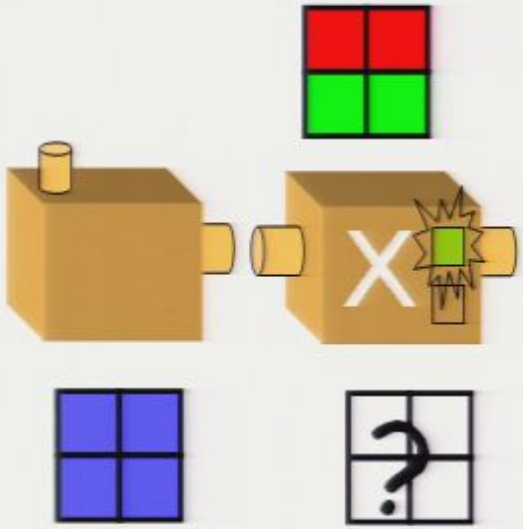

½ of the time

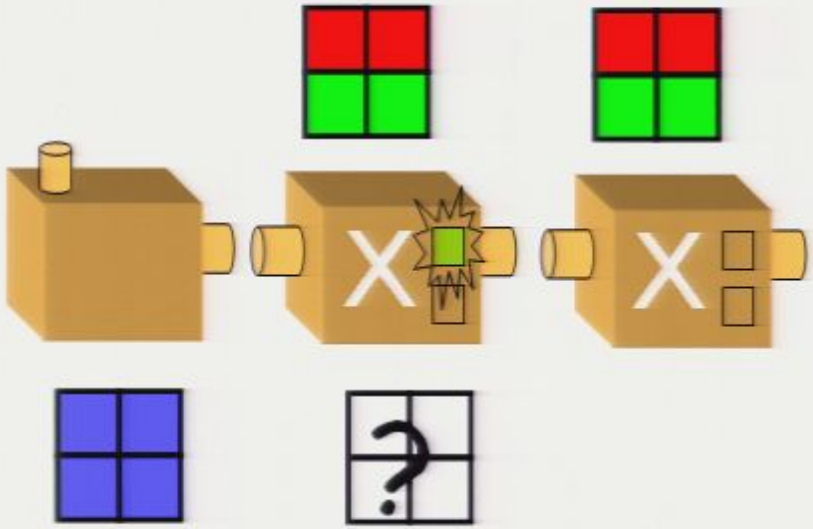

X

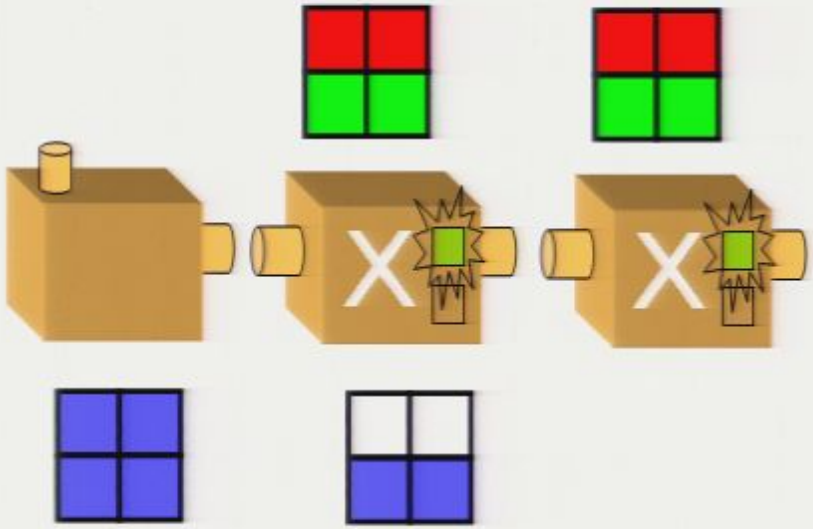


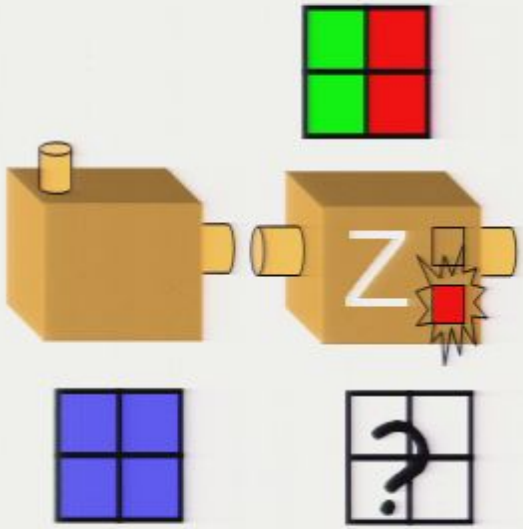

½ of the time

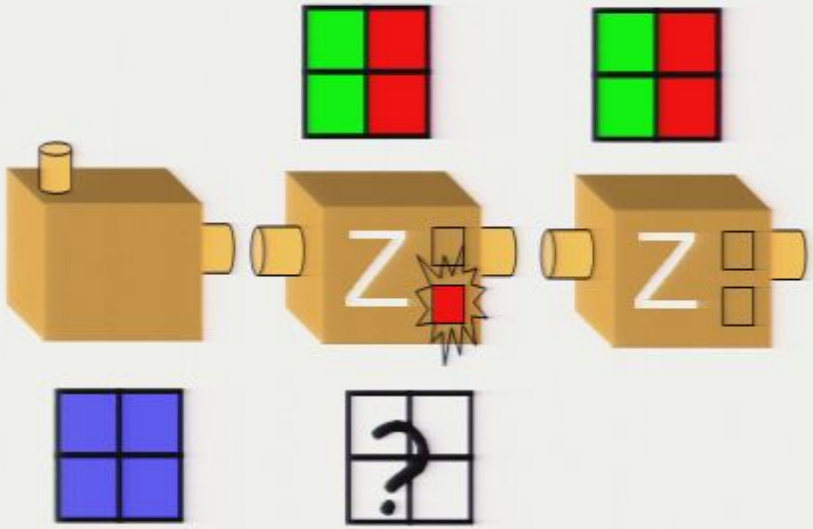
# Updating the probability distribution after a measurement

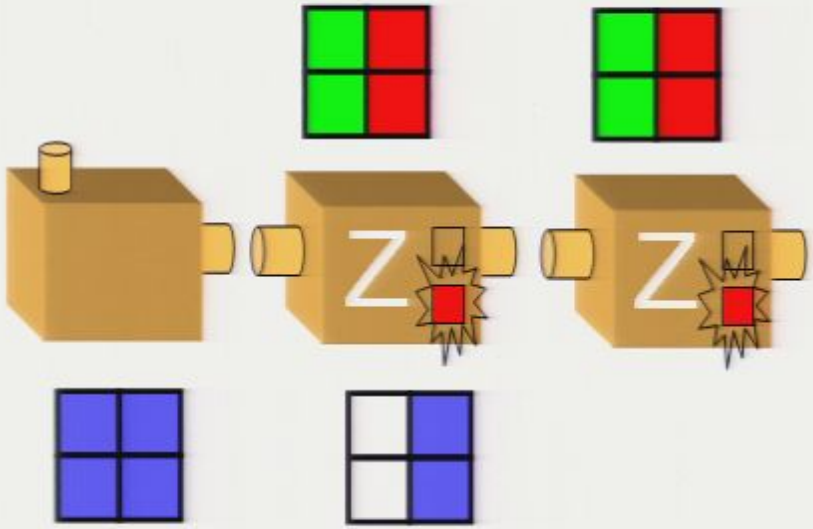


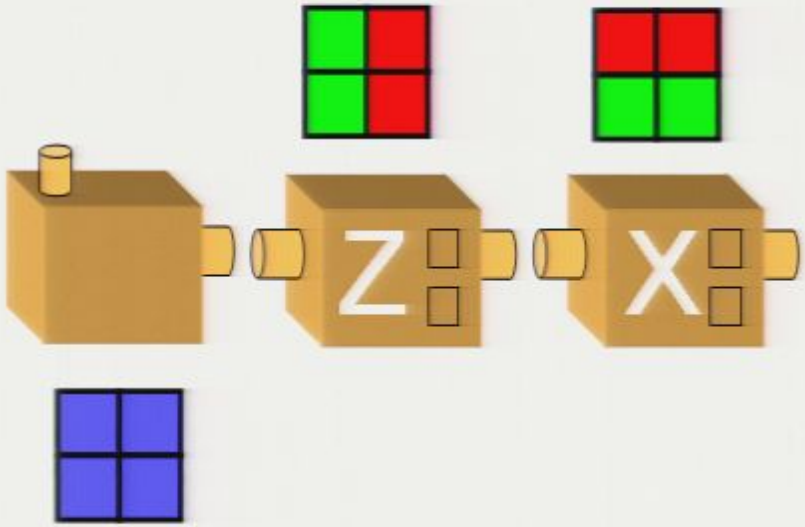

X
X
?

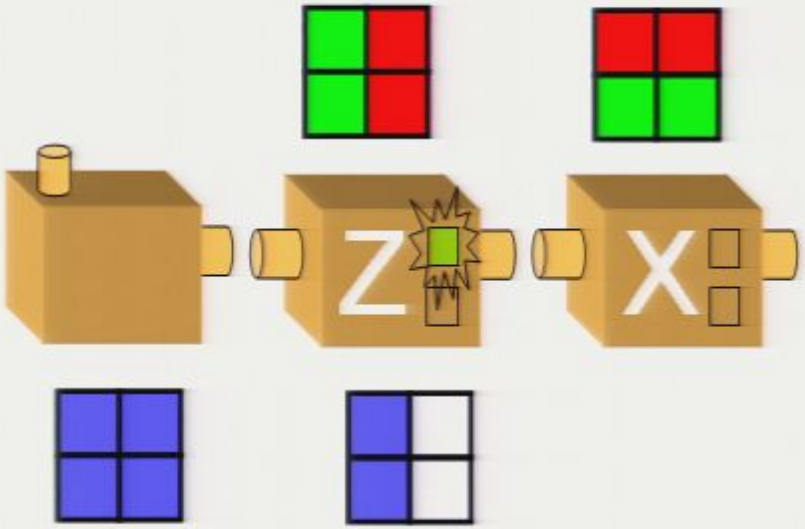

X
X

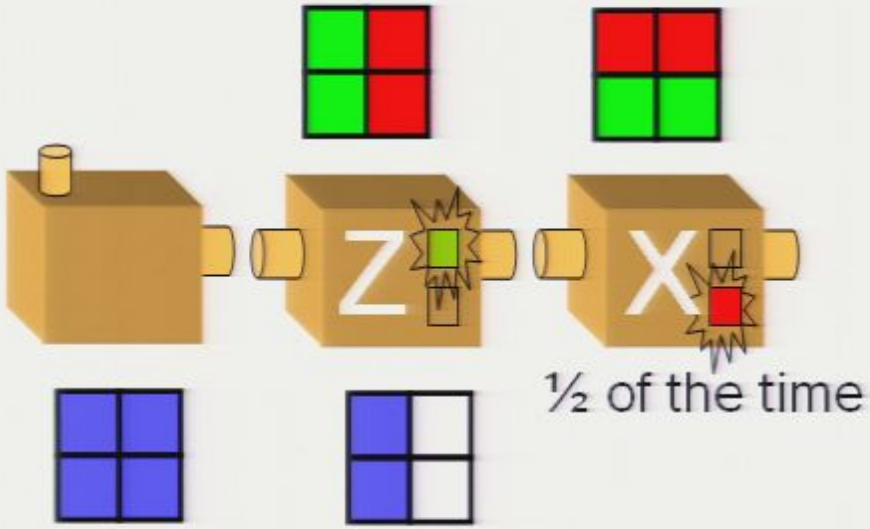

Z
?


Z
Z
?

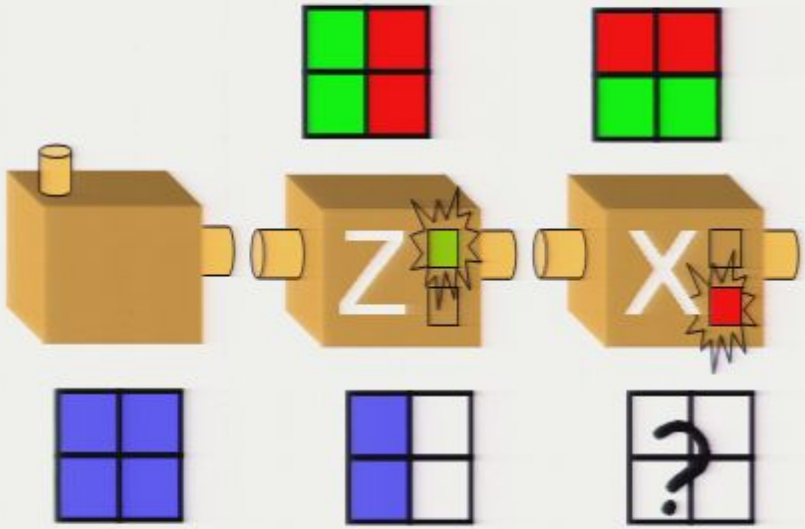

Z
Z

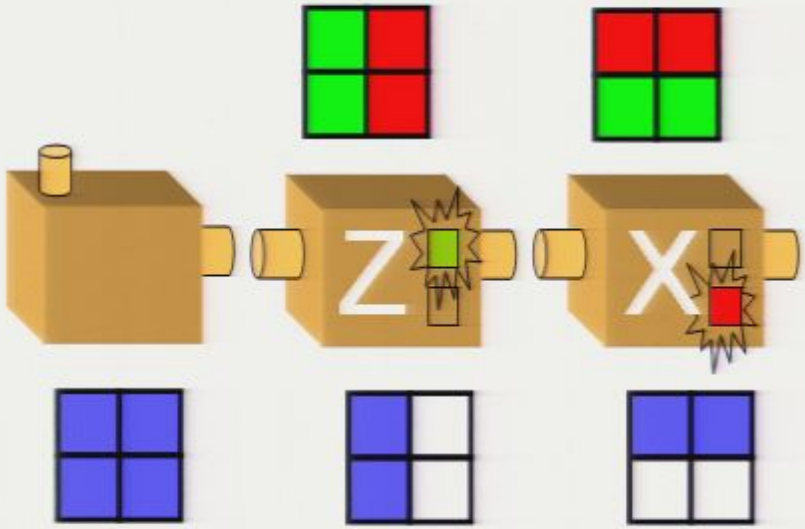

Z
X

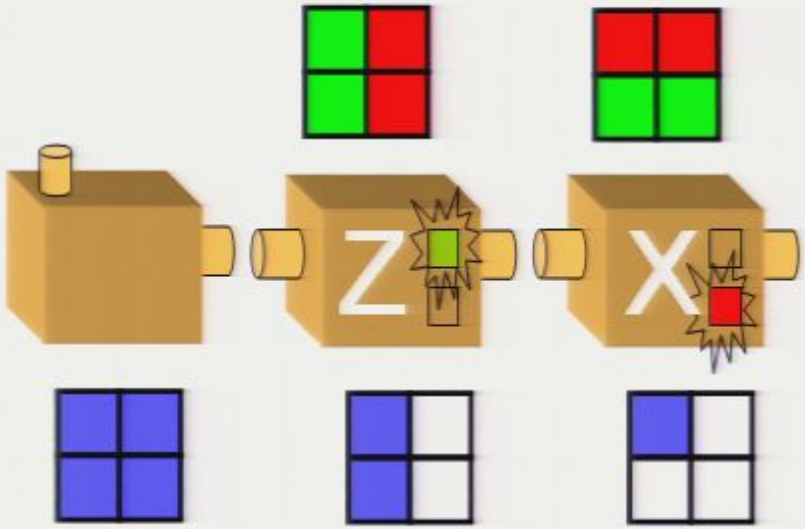

Z
X


Z
X
½ of the time

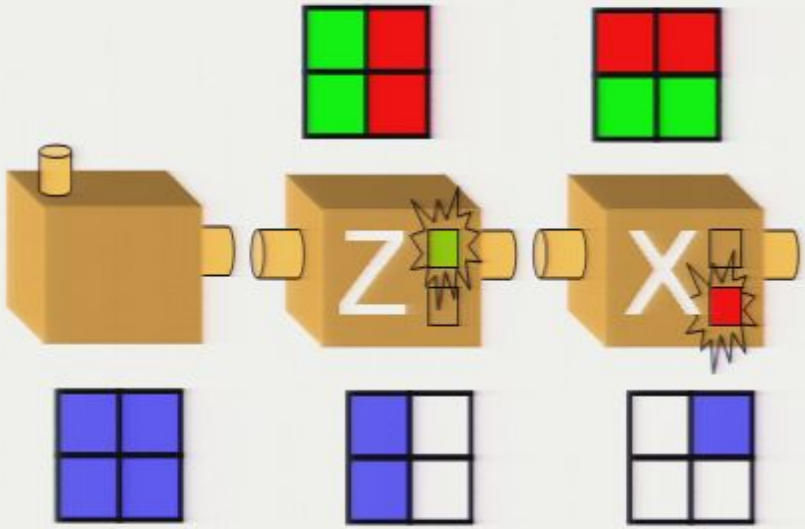
# Updating after a measurement, take 2



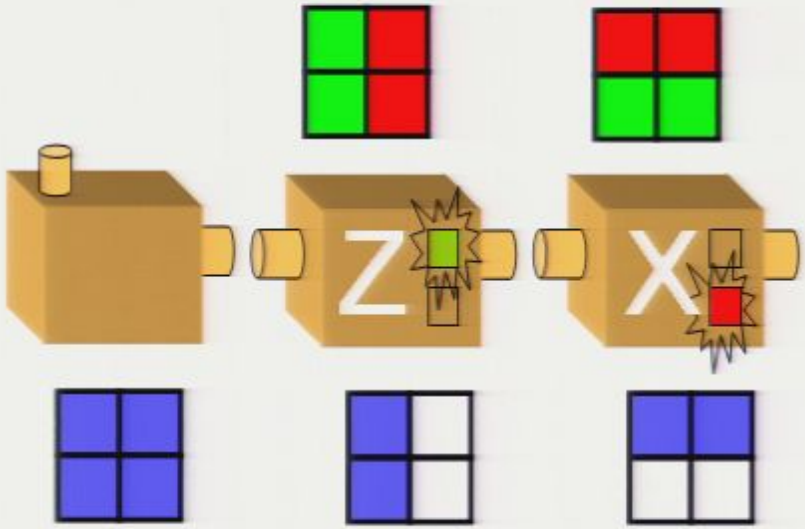

Z
X




What the final probability distribution would be if there was no physical disturbance



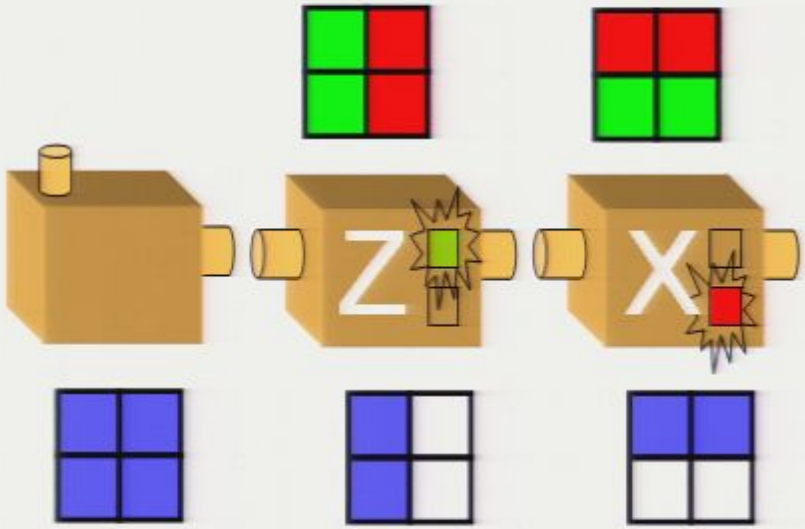

What the final probability distribution would be if there was a physical disturbance that flips the value of Z




To get the proper final distribution, we require:

Prob. 1/2 no physical disturbance

Prob. 1/2 a physical disturbance that flips the value of Z

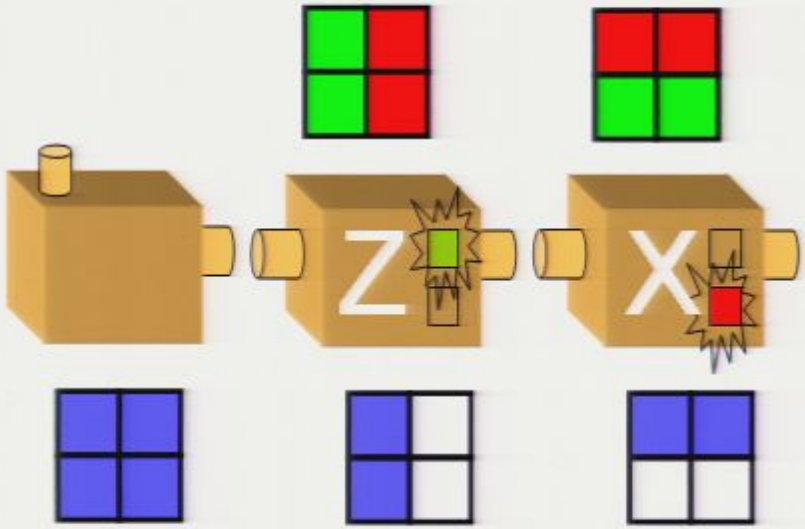



To get the proper final distribution, we require:

Prob. 1/2 no physical disturbance

Prob. 1/2 a physical disturbance that flips the value of Z

A measurement of X changes the value of Z with prob. 1/2




To get the proper final distribution, we require:

Prob. 1/2 no physical disturbance

Prob. 1/2 a physical disturbance that flips the value of Z

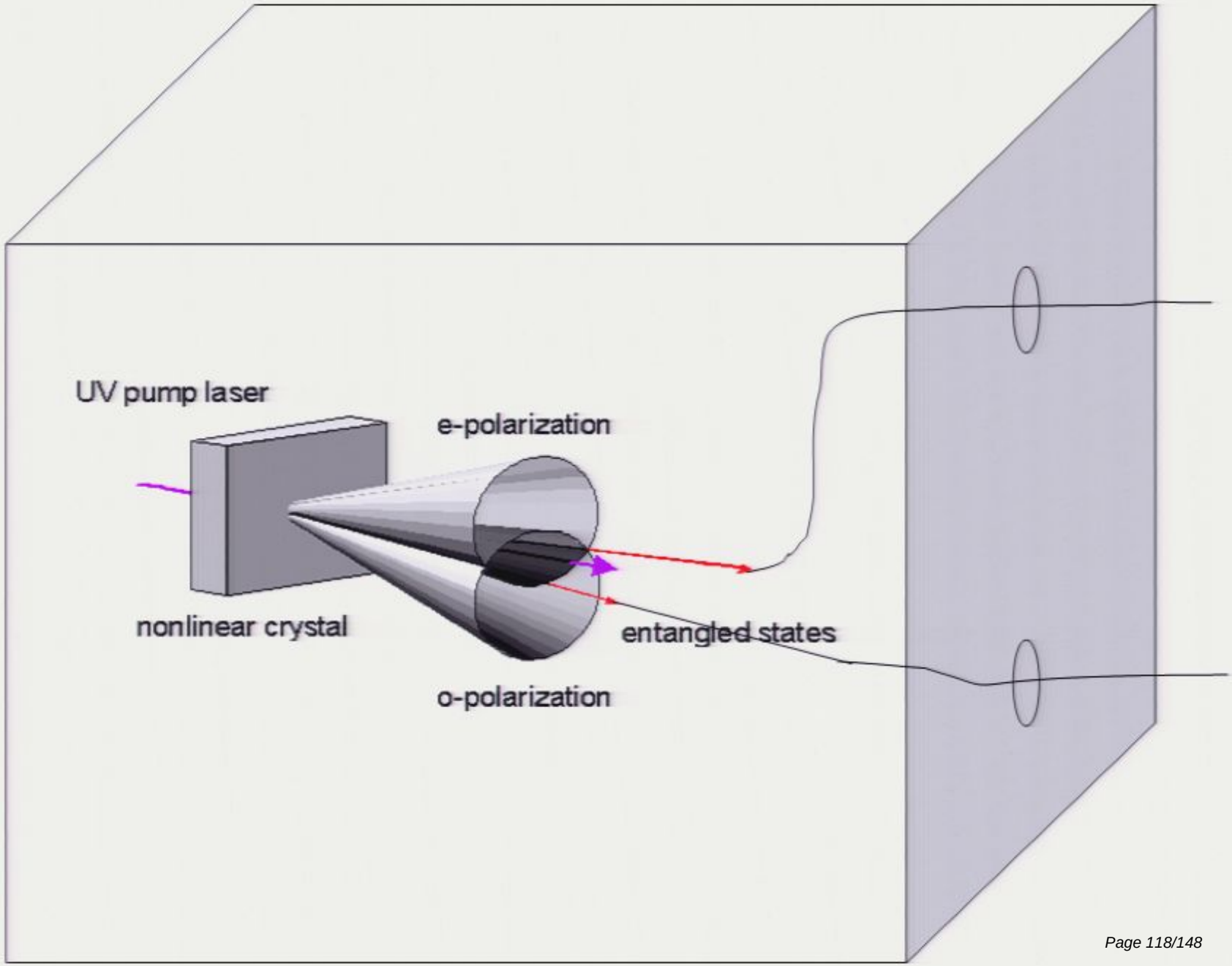
A measurement of X changes the value of Z with prob. 1/2

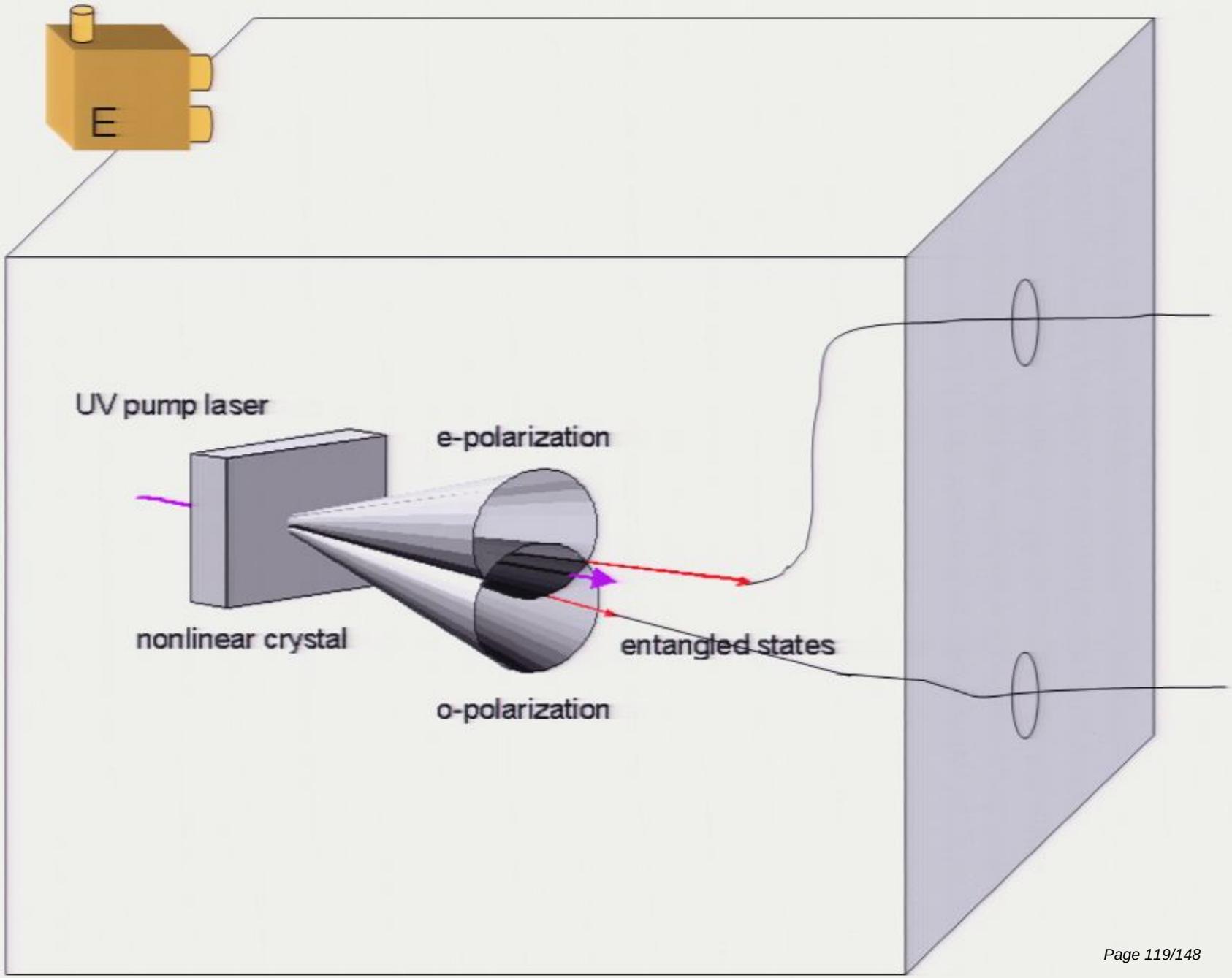
This is why a subsequent Z measurement would have a random outcome

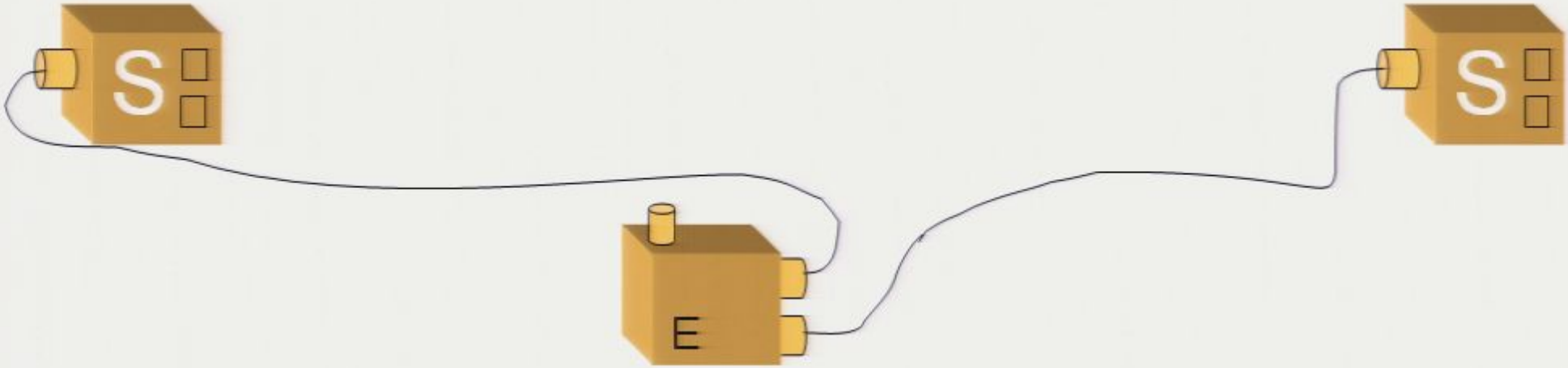
# Bell's theorem

or

why any realistic account
of quantum mechanics
(including hidden variable models)
must be nonlocal


UV pump laser
e-polarization
nonlinear crystal
entangled states
o-polarization


E
UV pump laser
e-polarization
nonlinear crystal
entangled states
o-polarization


S
S
E

There are two possible measurements, S and T, with two outcomes each: green or red

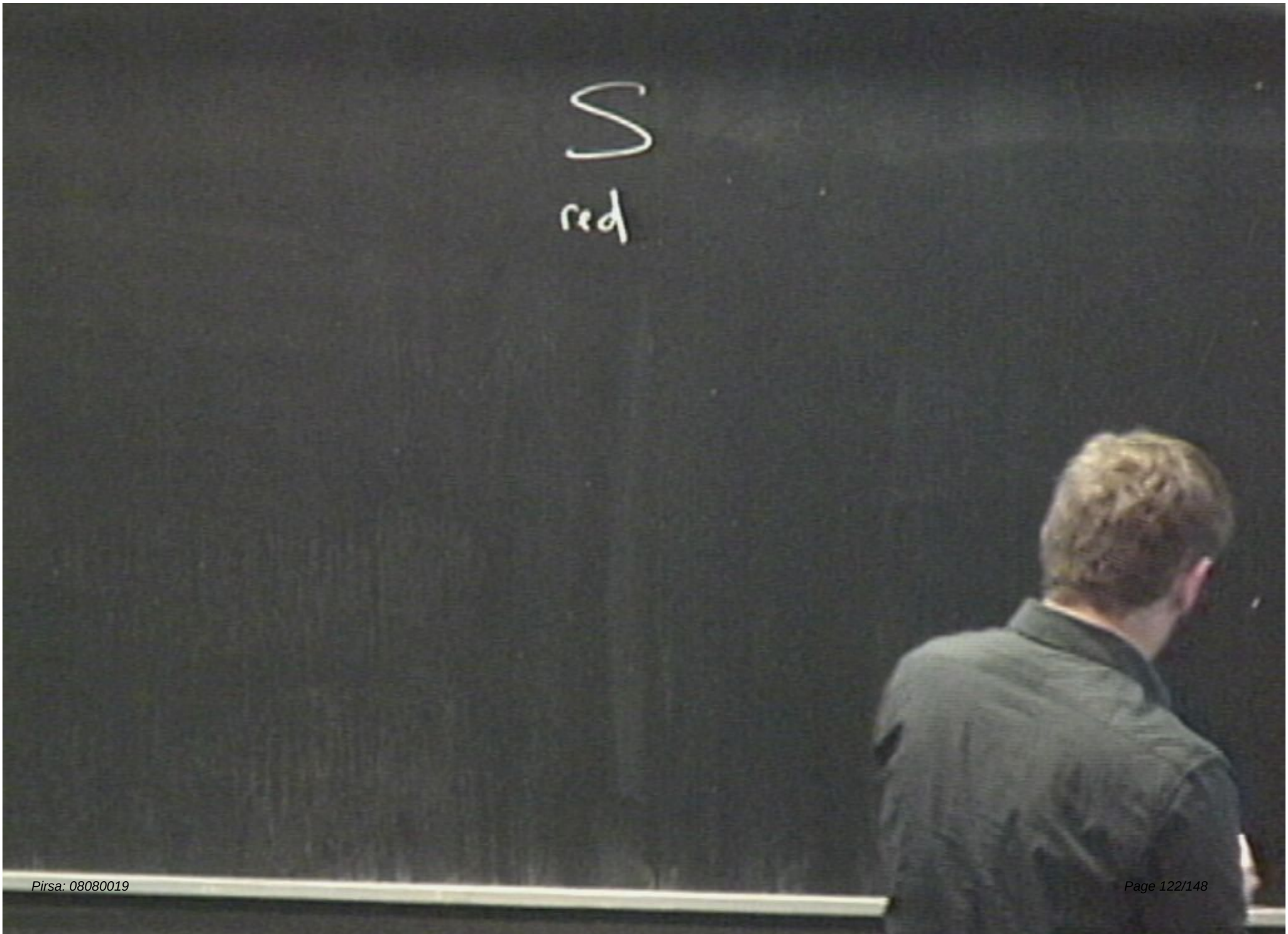
Suppose which of S or T occurs at each wing is chosen at random

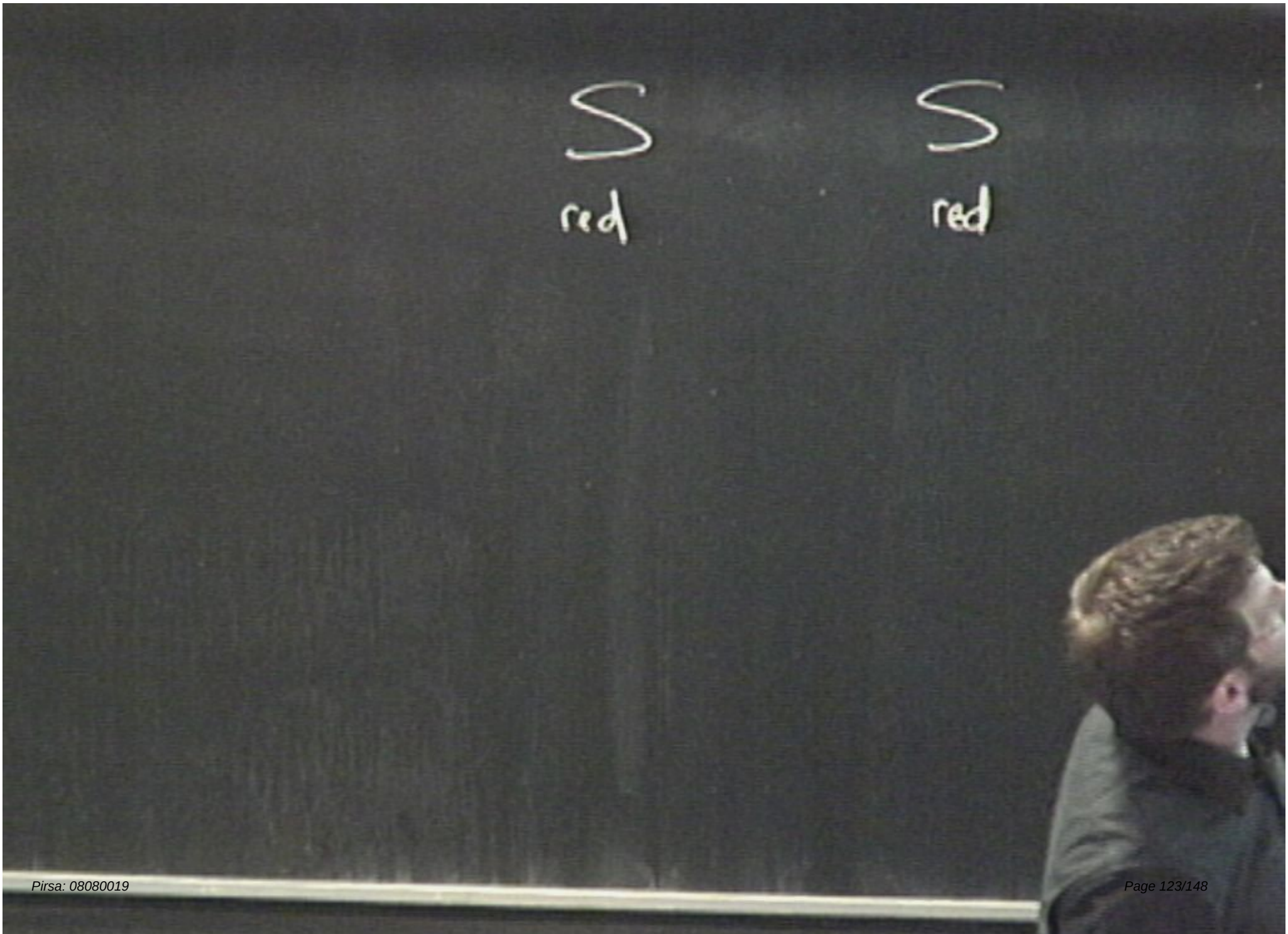
## Scenario 1

Features:

1. Whenever the same measurement is made on A and B, the outcomes always agree — S and S or T and T

2. Whenever different measurements are made on A and B, the outcomes always disagree — S and T or T and S


S
red


S
red
S
red

There are two possible measurements, S and T, with two outcomes each: green or red

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## Scenario 1

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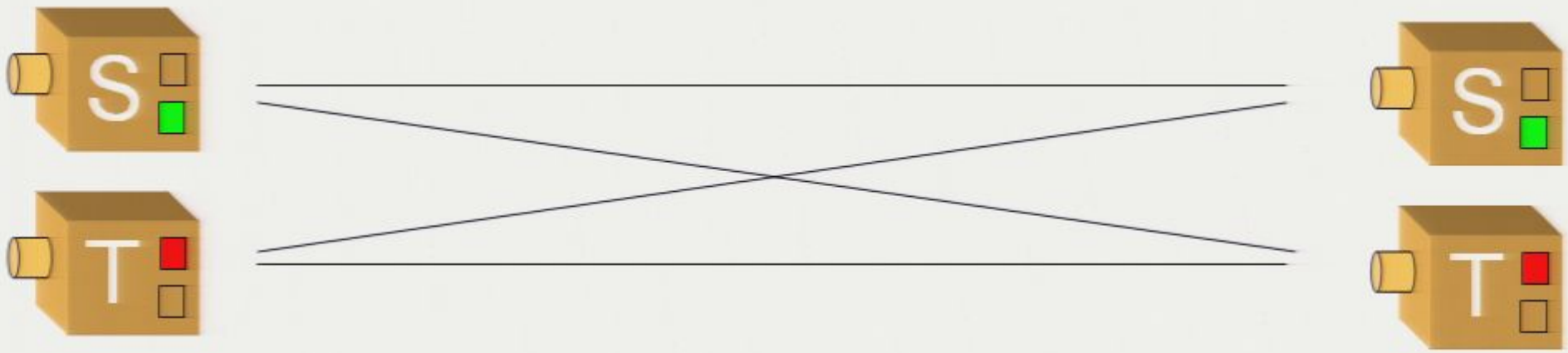
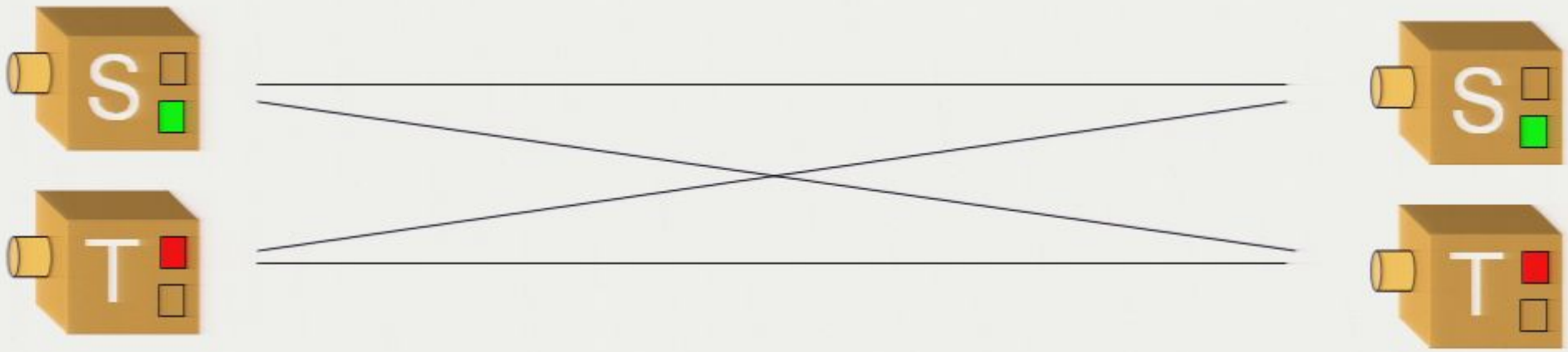

S
T
S
T


S
T
S
T

There are two possible measurements, S and T, with two outcomes each: green or red

Suppose which of S or T occurs at each wing is chosen at random

## Scenario 2

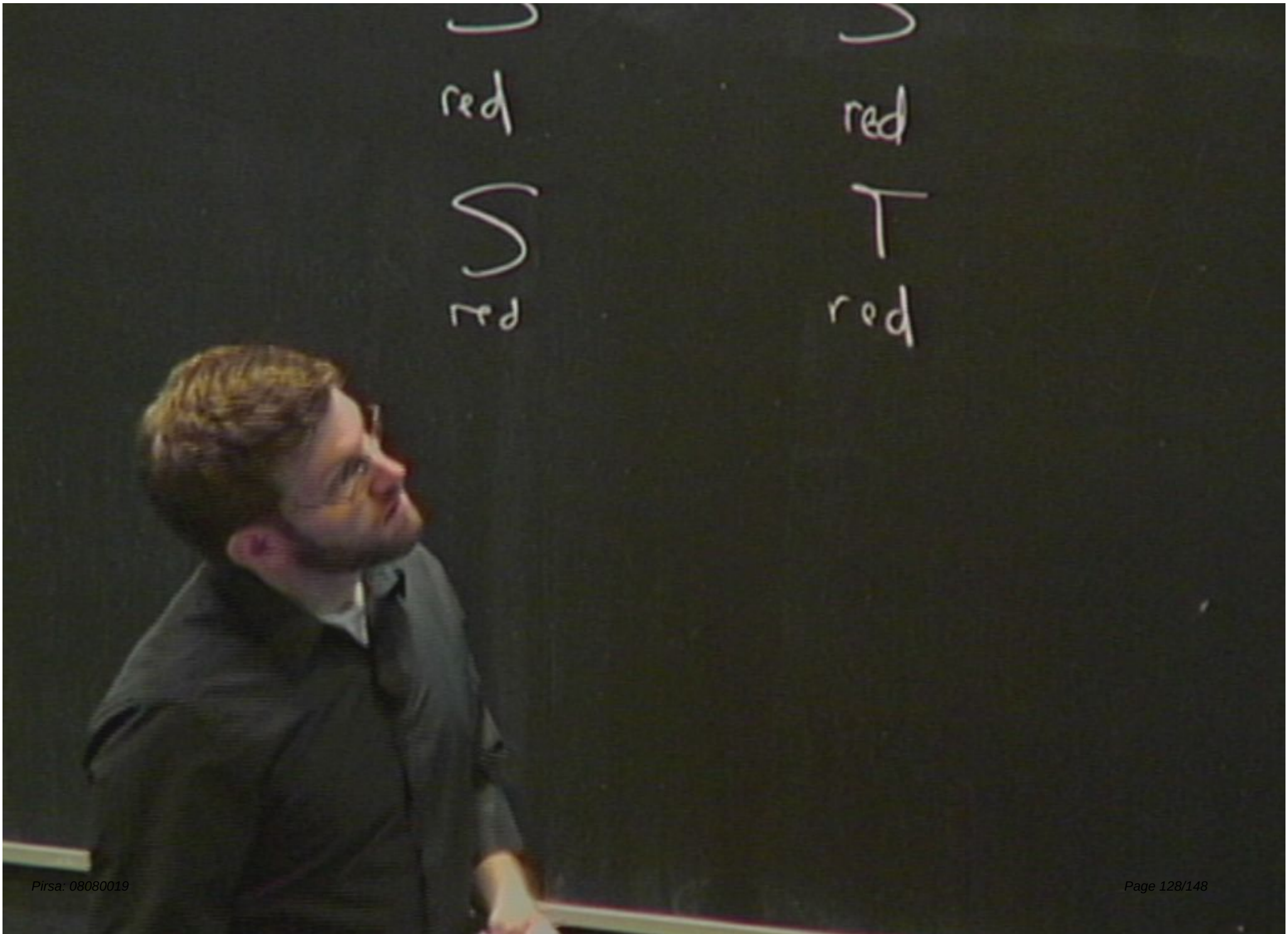
Features:

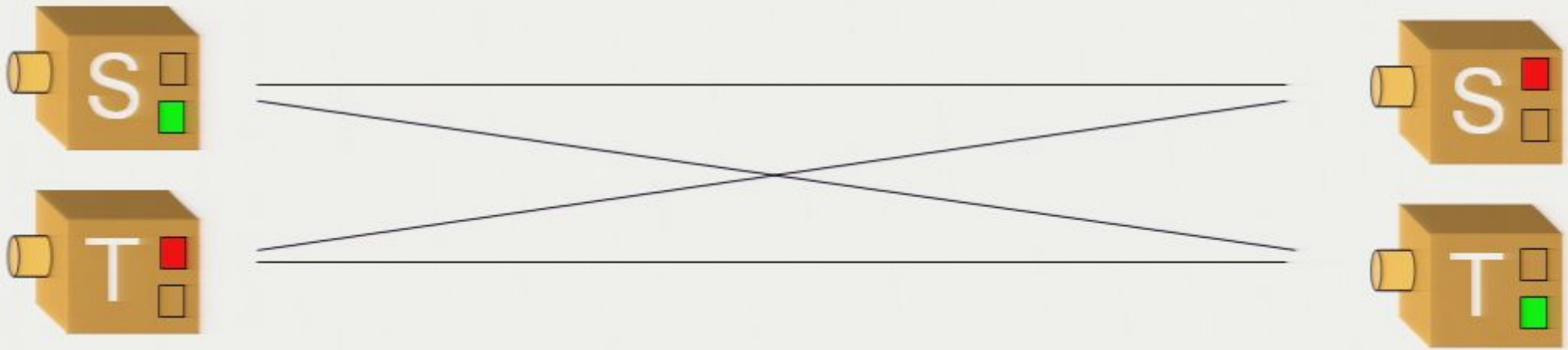
1. Whenever the same measurement is made on A and B, the outcomes always disagree

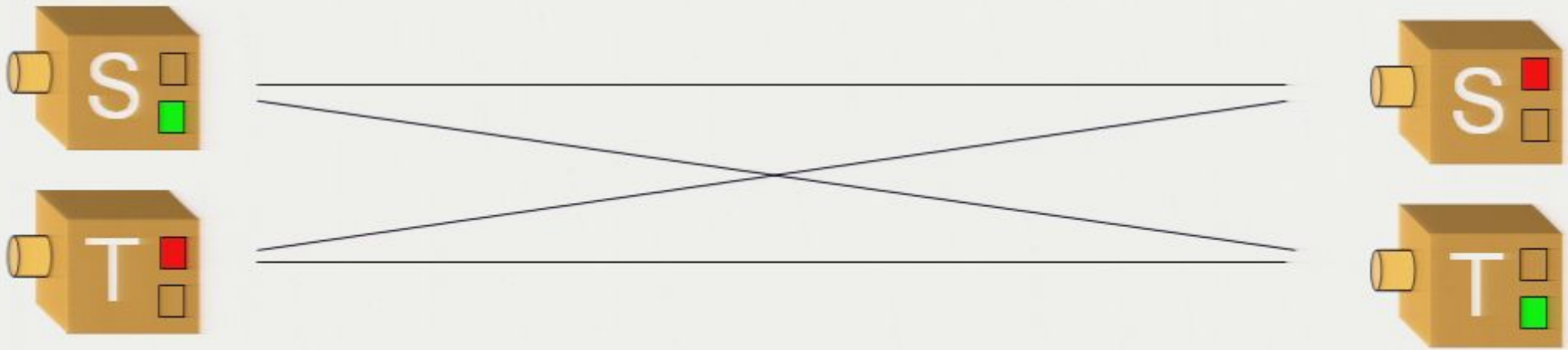
   S and S
   or
   T and T

2. Whenever different measurements are made on A and B, the outcomes always agree

   S and T
   or
   T and S


red
red
S
T
red
red


S
T
S
T


S
T
S
T

There are two possible "measurements", S and T, with two outcomes each: green or red

Suppose which of S or T occurs at each wing is chosen at random

## Scenario 3

Features:

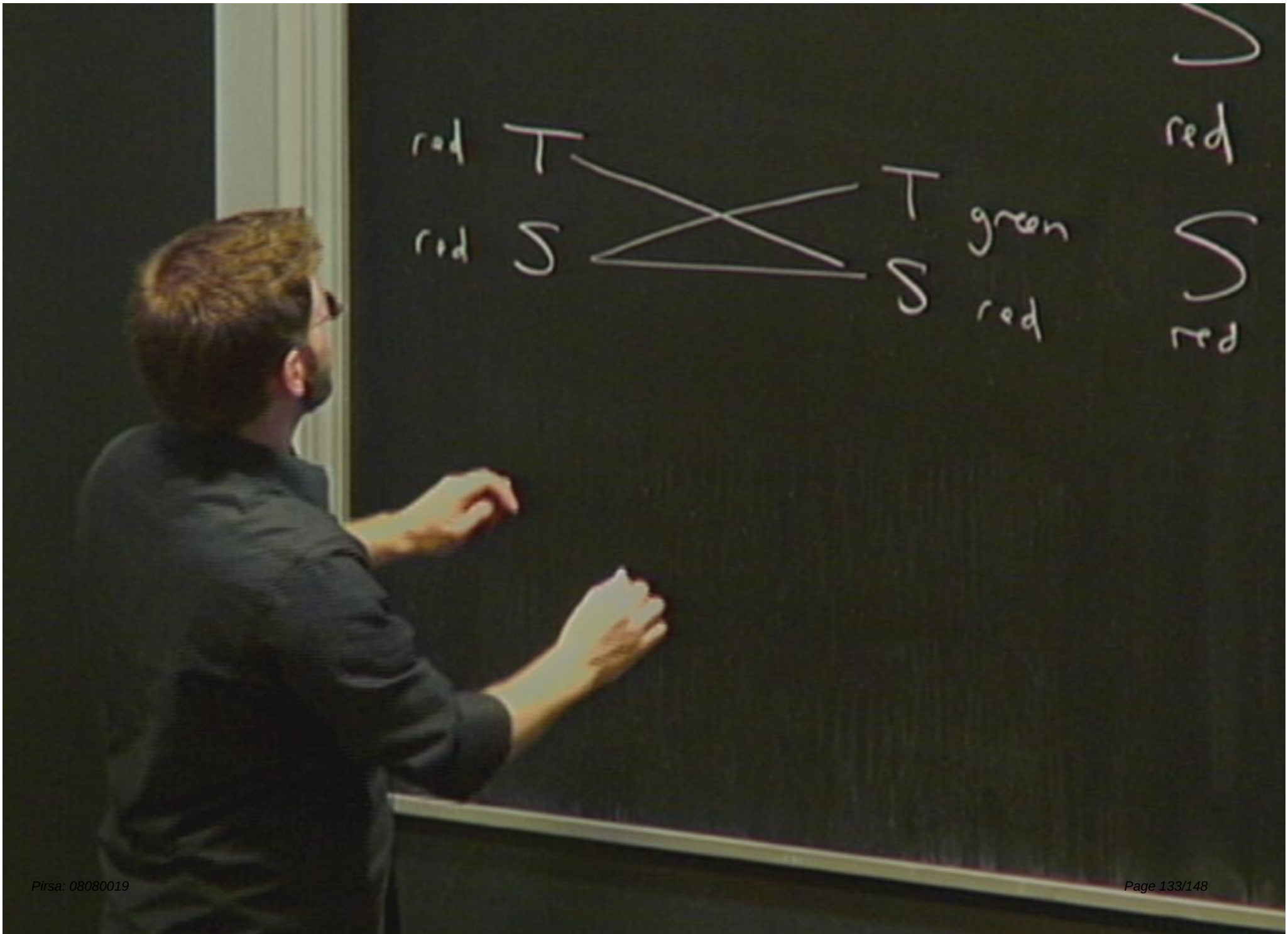
1. Whenever the measurement T is made on both A and B, the outcomes always disagree

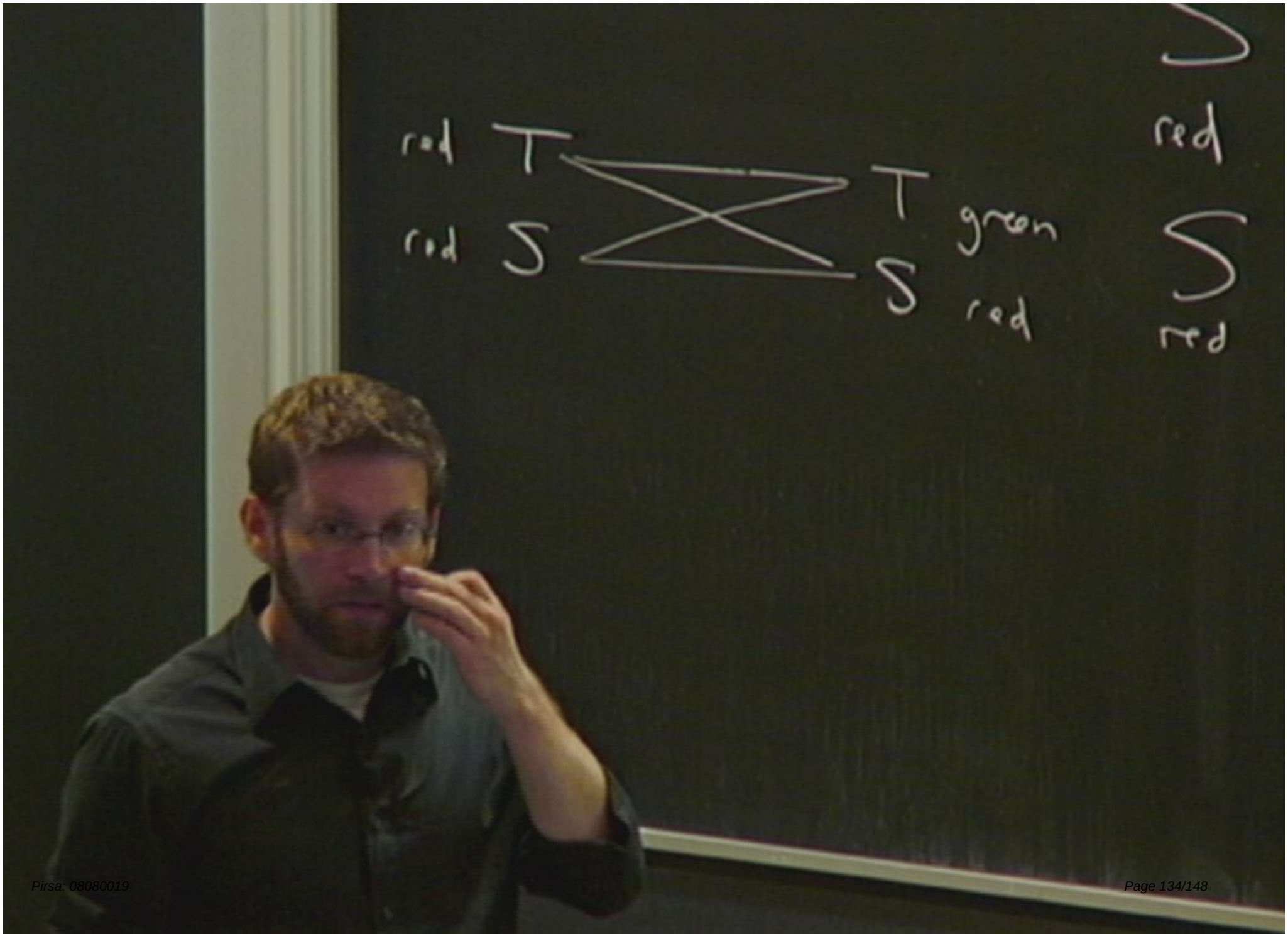
   T and T

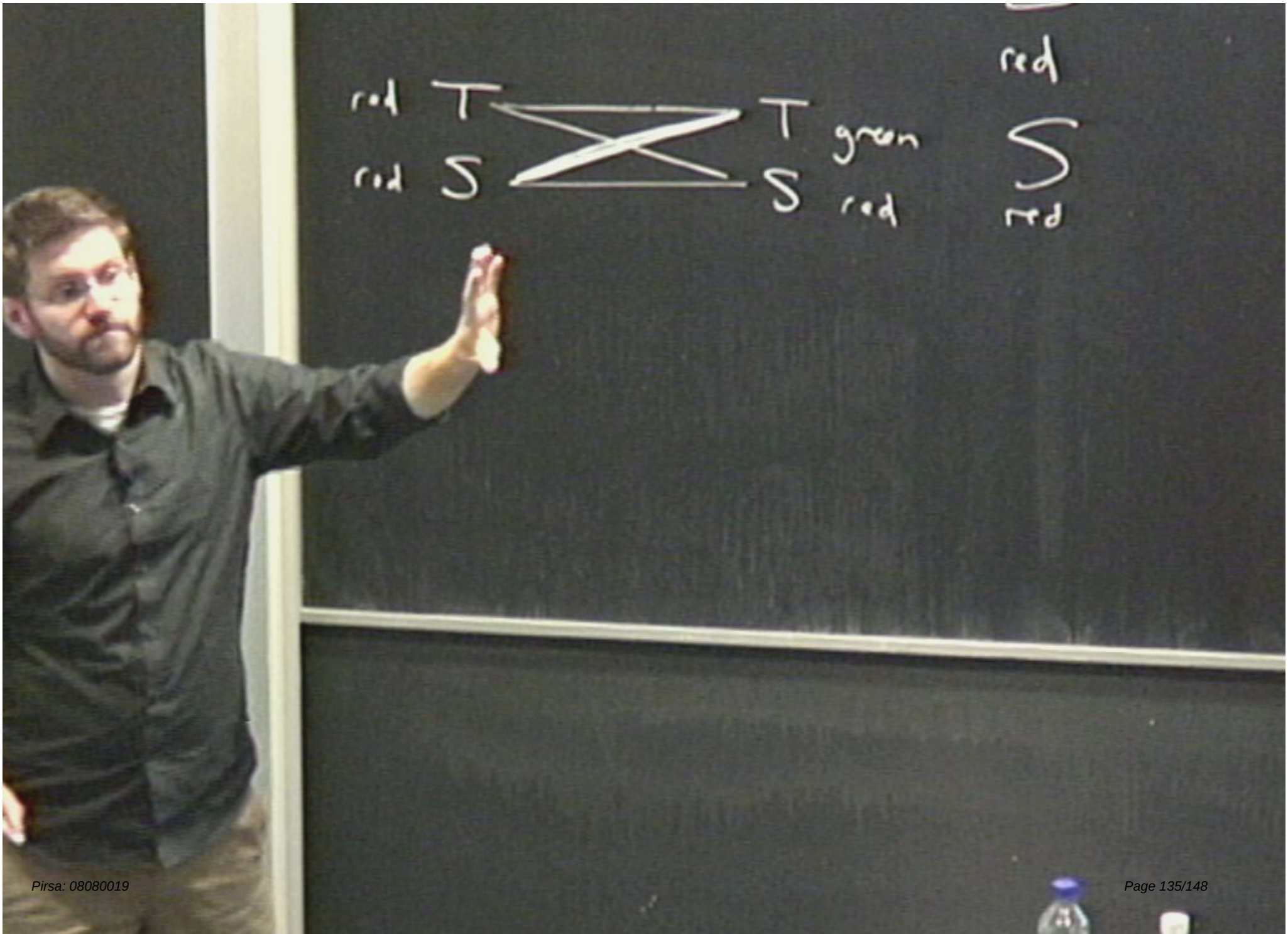
2. Otherwise, the outcomes always agree

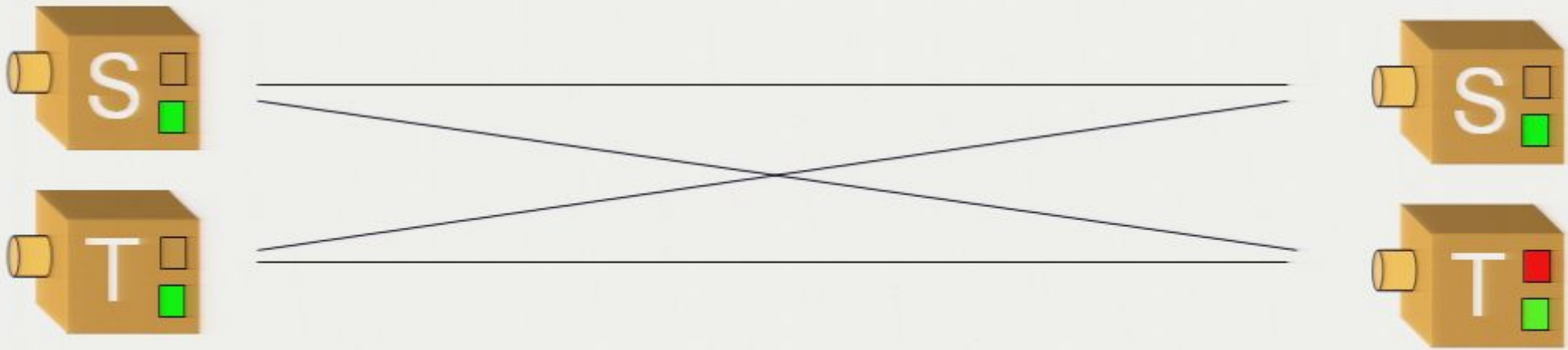
   S and S
   or
   S and T
   or
   T and S

red T
red S
T green
S red
red
S
red

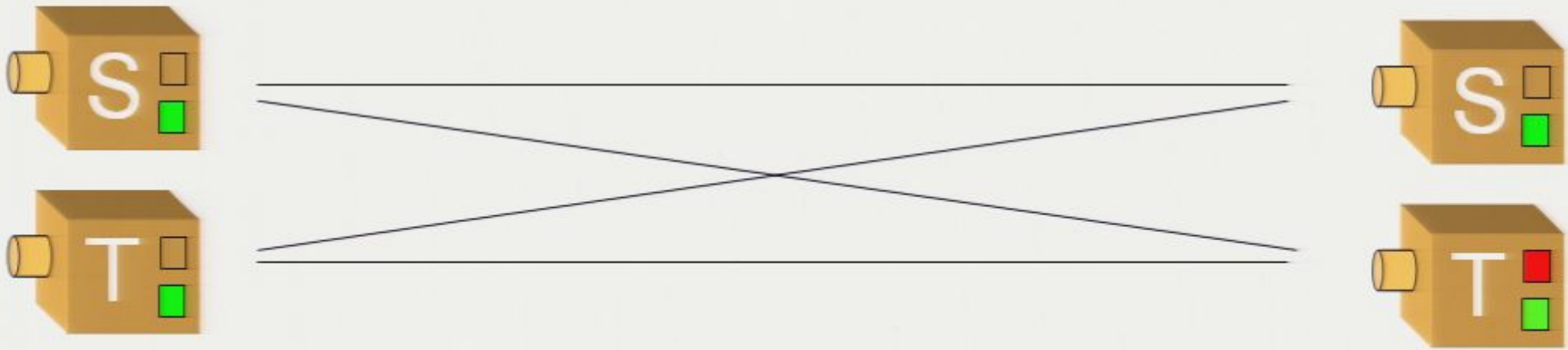

red T
red S
T green
S red
red
S
red


red T
red S
T green
S red
red
S
red


red T
red S
T green
S red
red
S
red

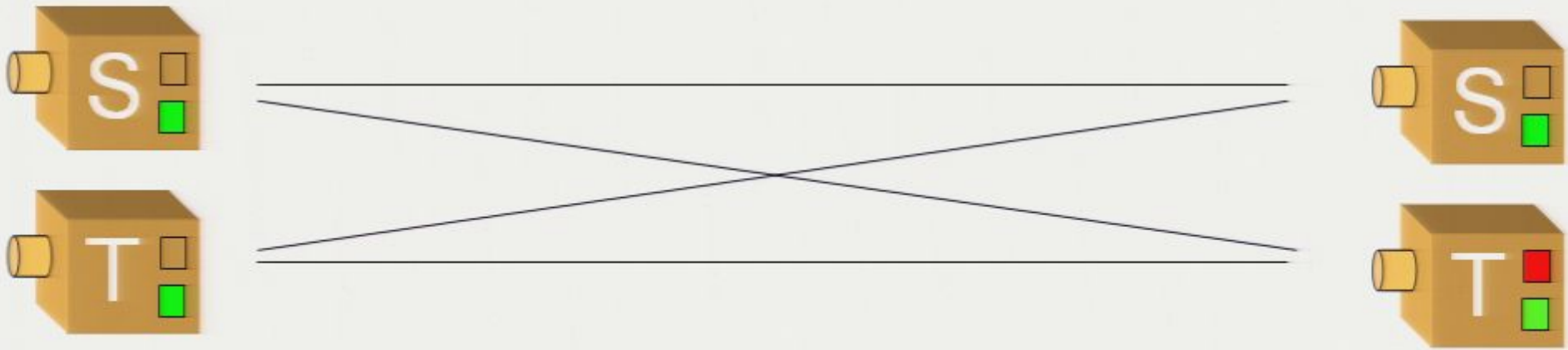



Q: What's the best probability of winning?




Q: What's the best probability of winning?

The best local strategies "win the game" only 75% of the time
Using quantum systems, one can win 85% of the time!

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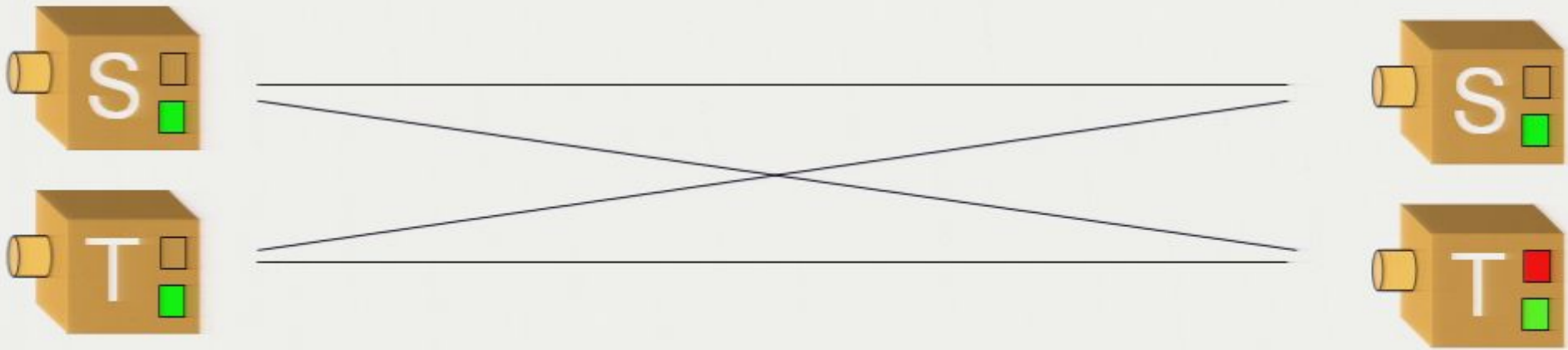
Q: How could you cheat and win the game all the time?

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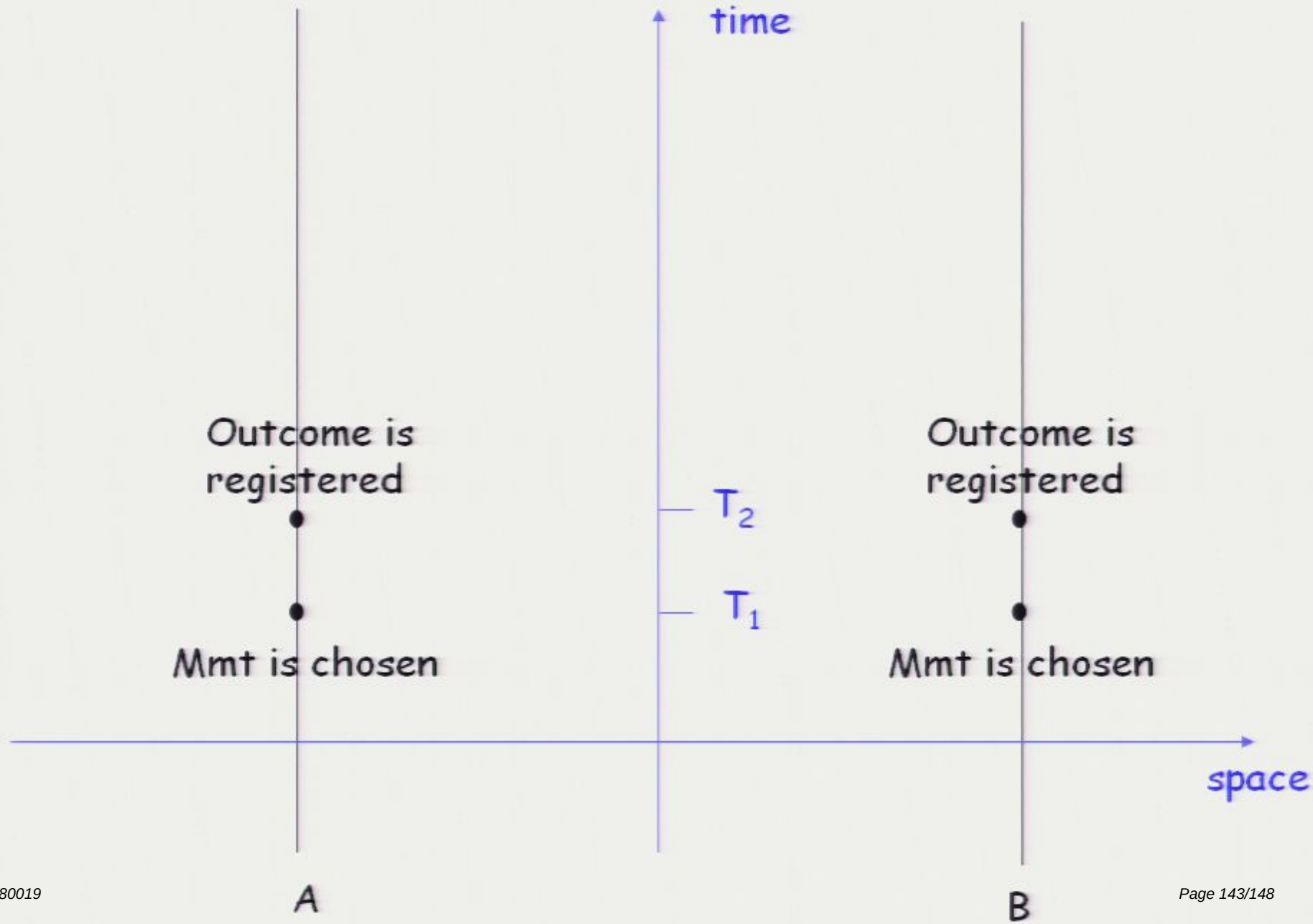
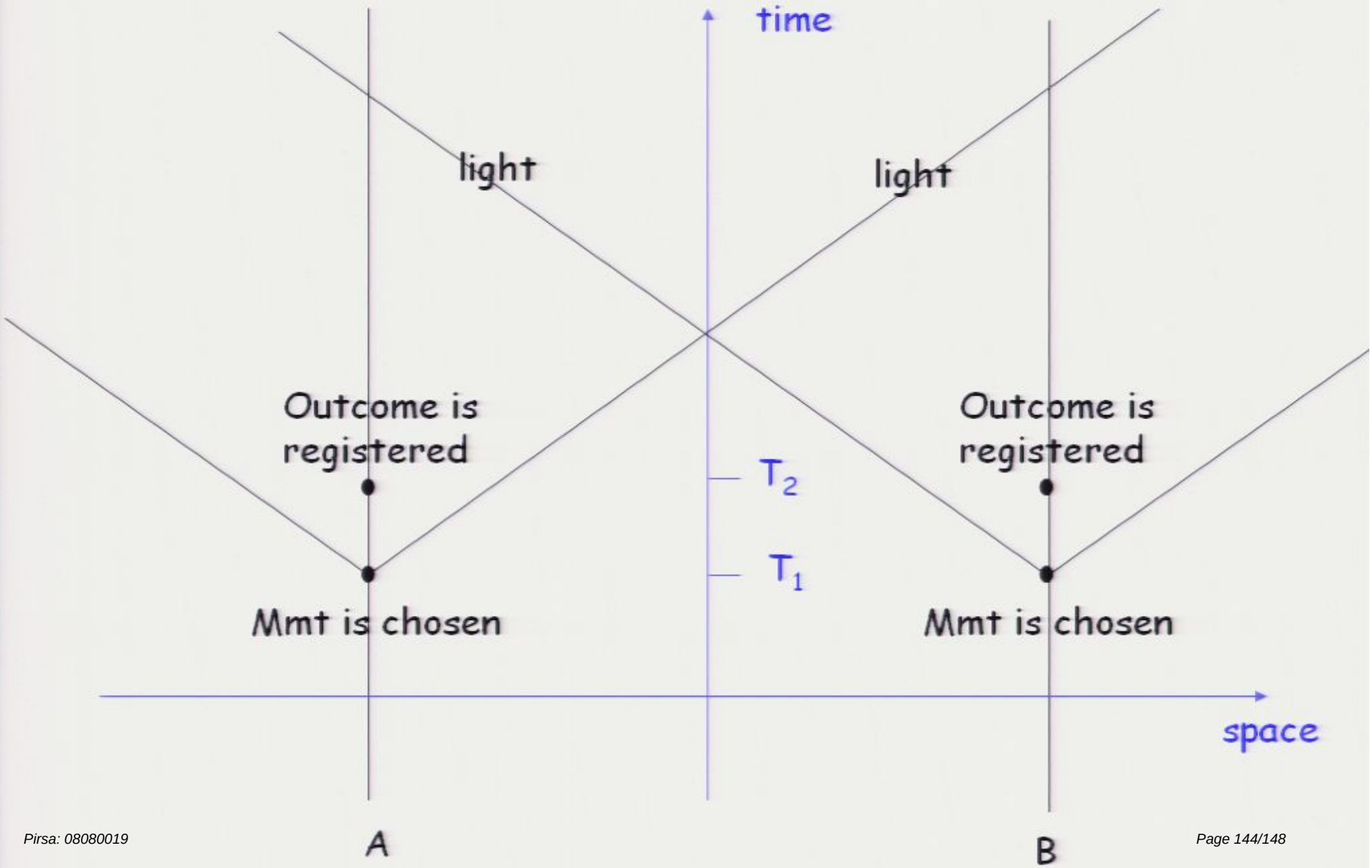
A: Communication of the choice of measurement in one wing to the system in the opposite wing

But there's a problem...

# Tension with the theory of relativity



# Tension with the theory of relativity



Experiment can distinguish:

1) the quantum predictions

2) the predictions of any locally causal theory

Experiment can distinguish:

1) the quantum predictions

2) the predictions of any locally causal theory

Quantum theory wins!

When seeking a realist explanation of Bell's theorem, the mystery is the tension between:

1) No superluminal signalling (independence of statistics at one wing on choice of measurement at the other)

2) The necessity of superluminal influences (dependence of particular outcomes at one wing on choice of measurement at the other)

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