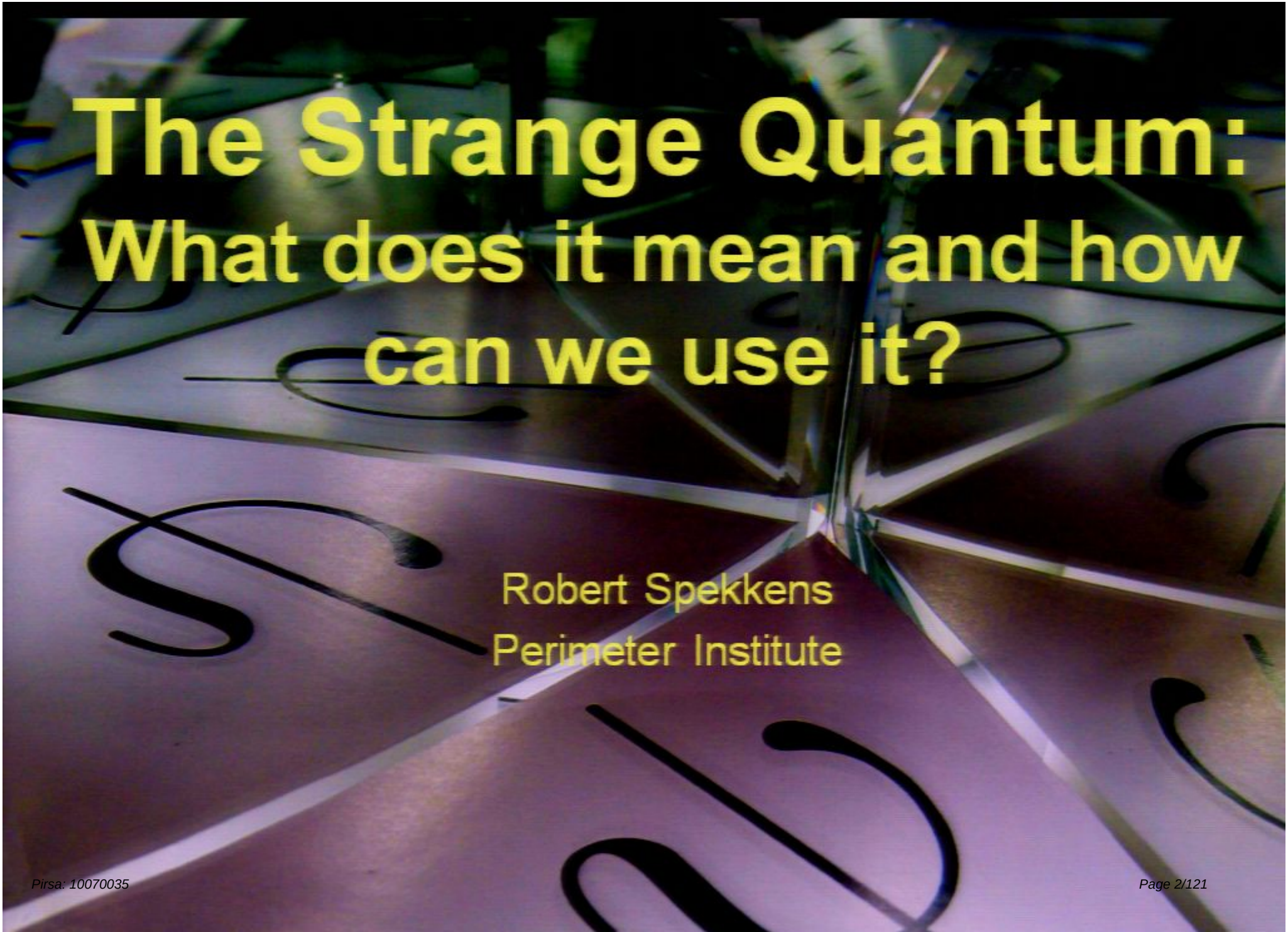
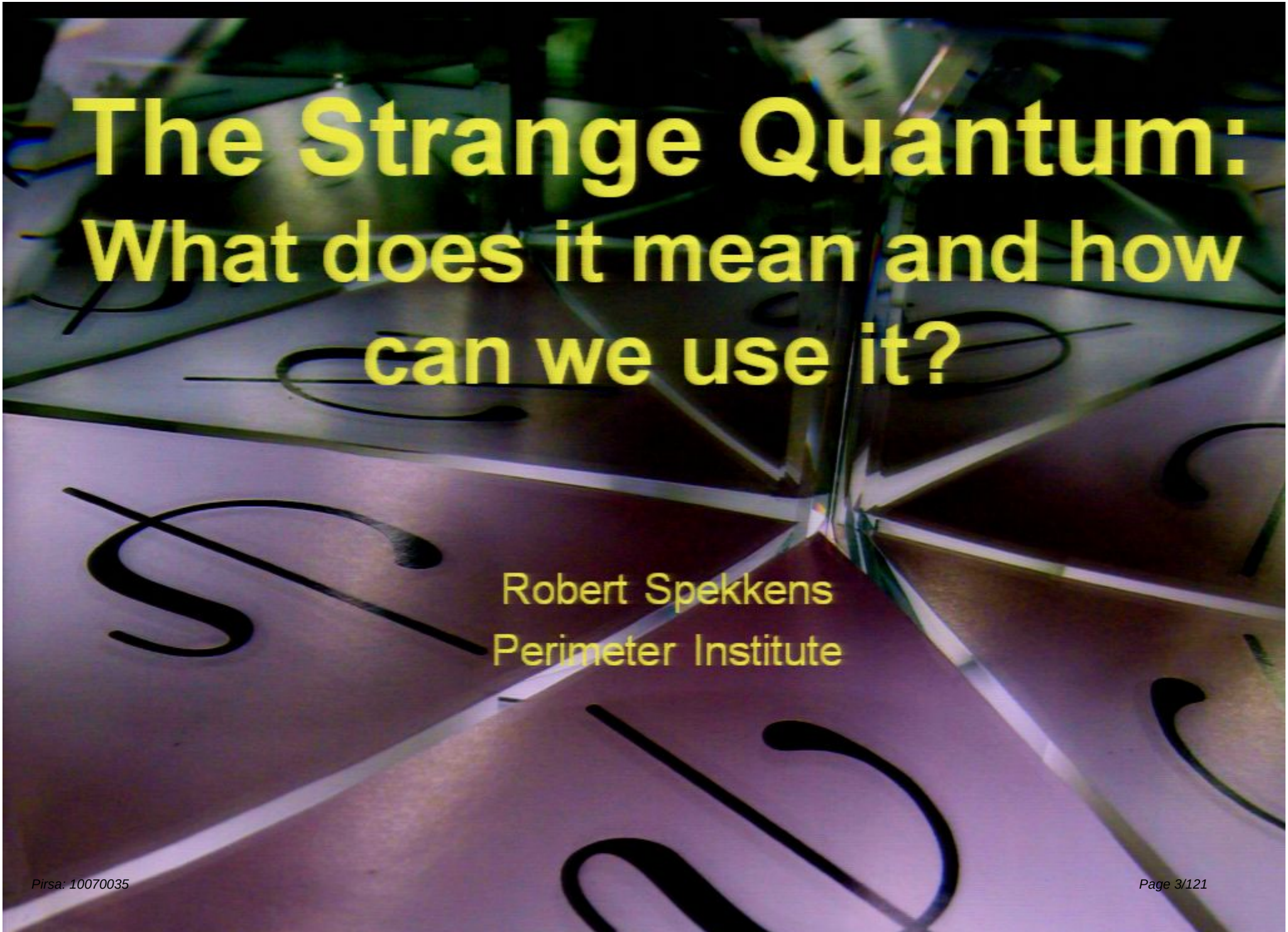
Title: ISSYP 2010 - The Strange Quantum: What does it mean and how can we use it?

Date: Jul 20, 2010 10:30 AM

URL: http://pirsa.org/10070035

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 it


The Strange Quantum:
What does it mean and how can we use it?
Robert Spekkens
Perimeter Institute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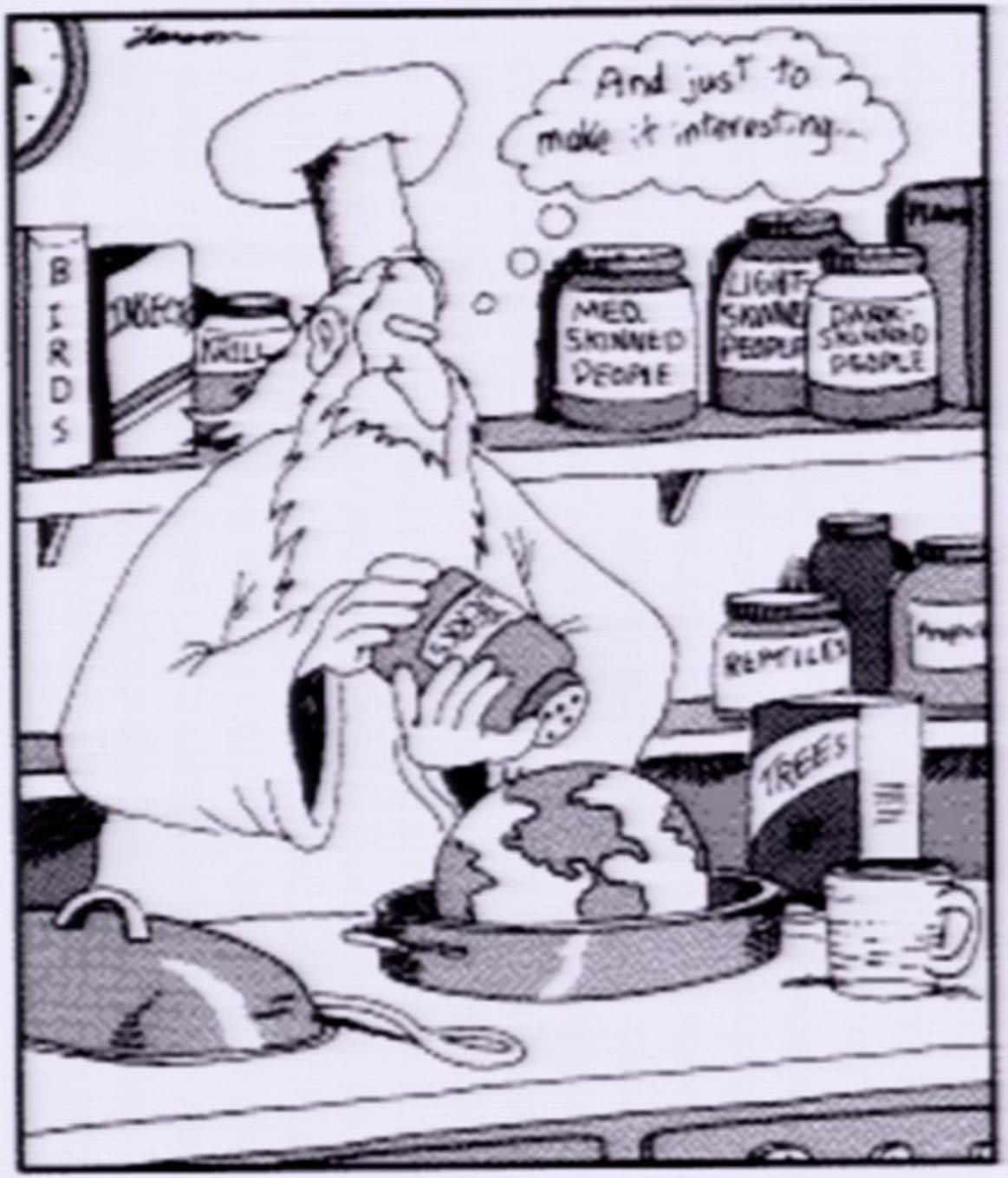
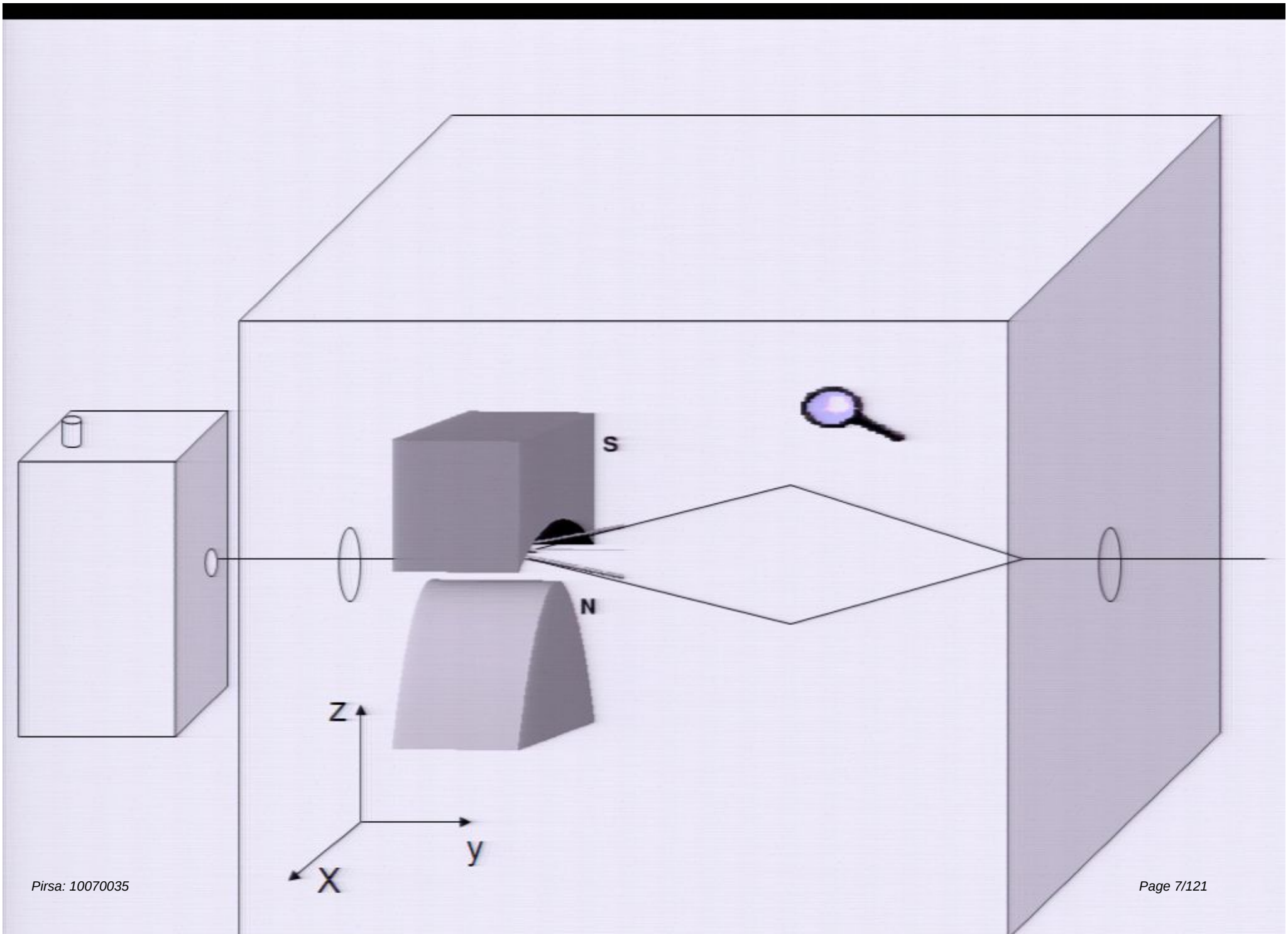

And just to make it interesting...
BIRDS
MED. SKINNED PEOPLE
LIGHT SKINNED PEOPLE
DARK SKINNED PEOPLE
REPTILES
TREES

The Solvay Congress of 1927

Some simple quantum phenomena


S
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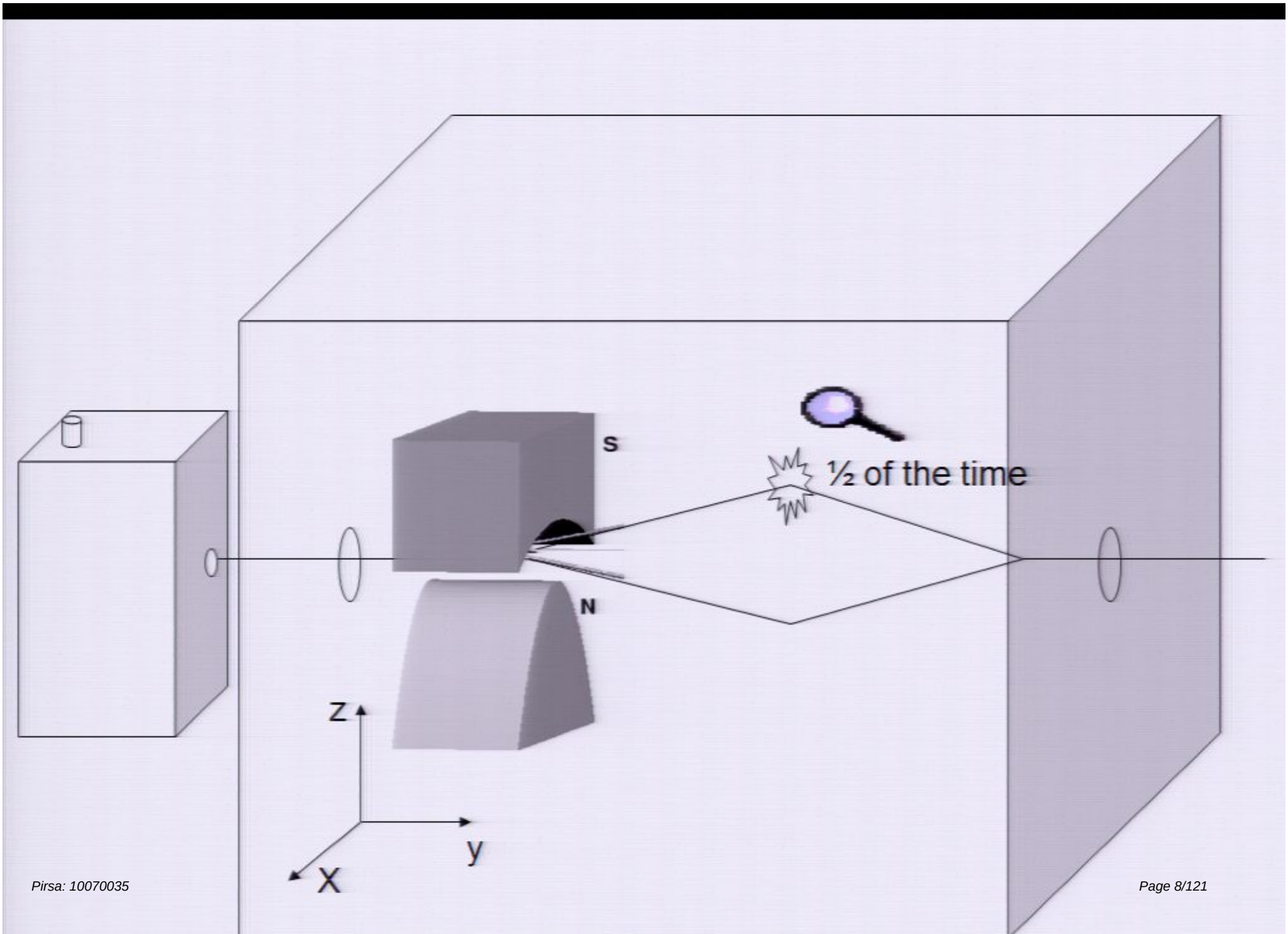
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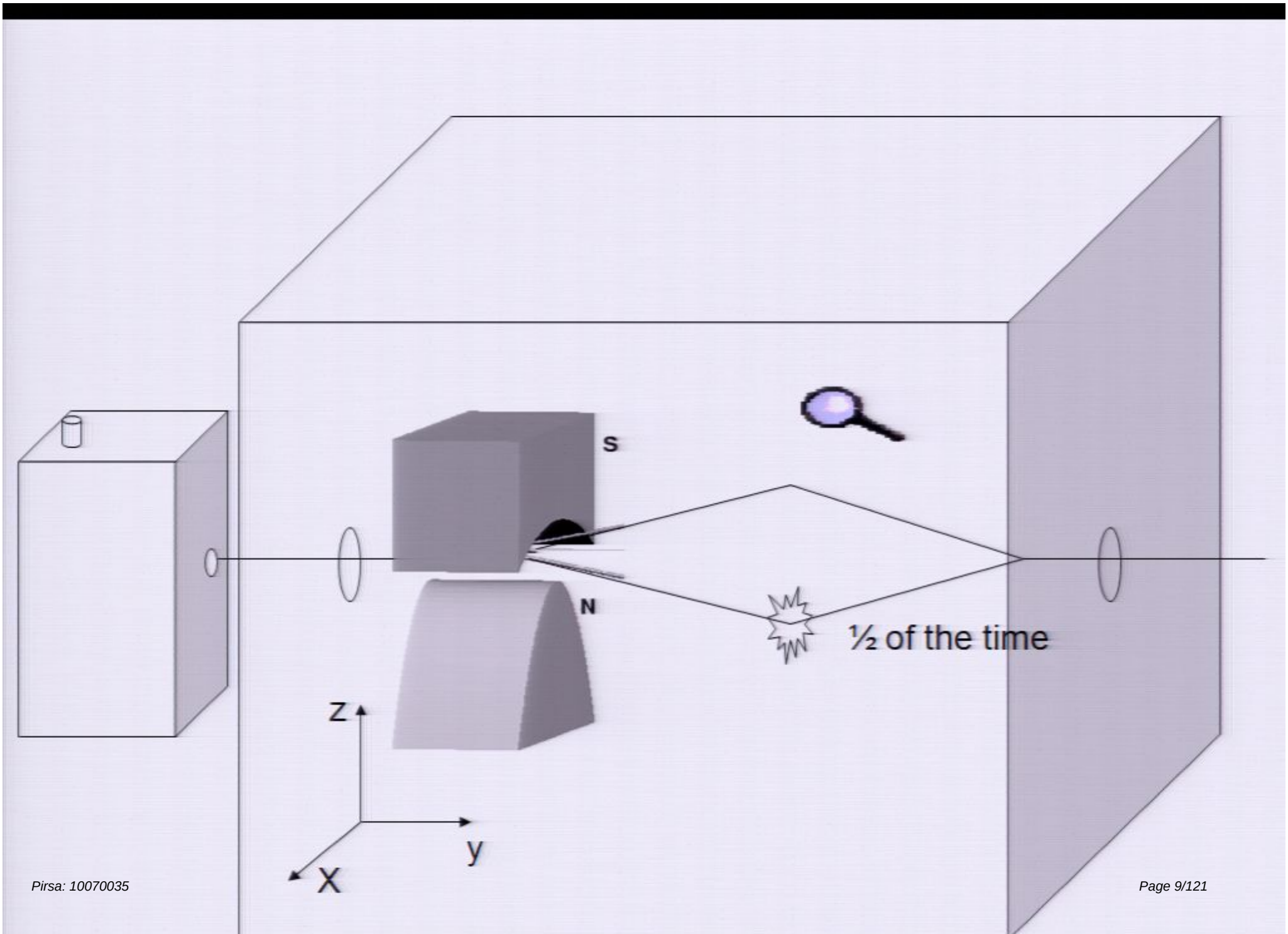
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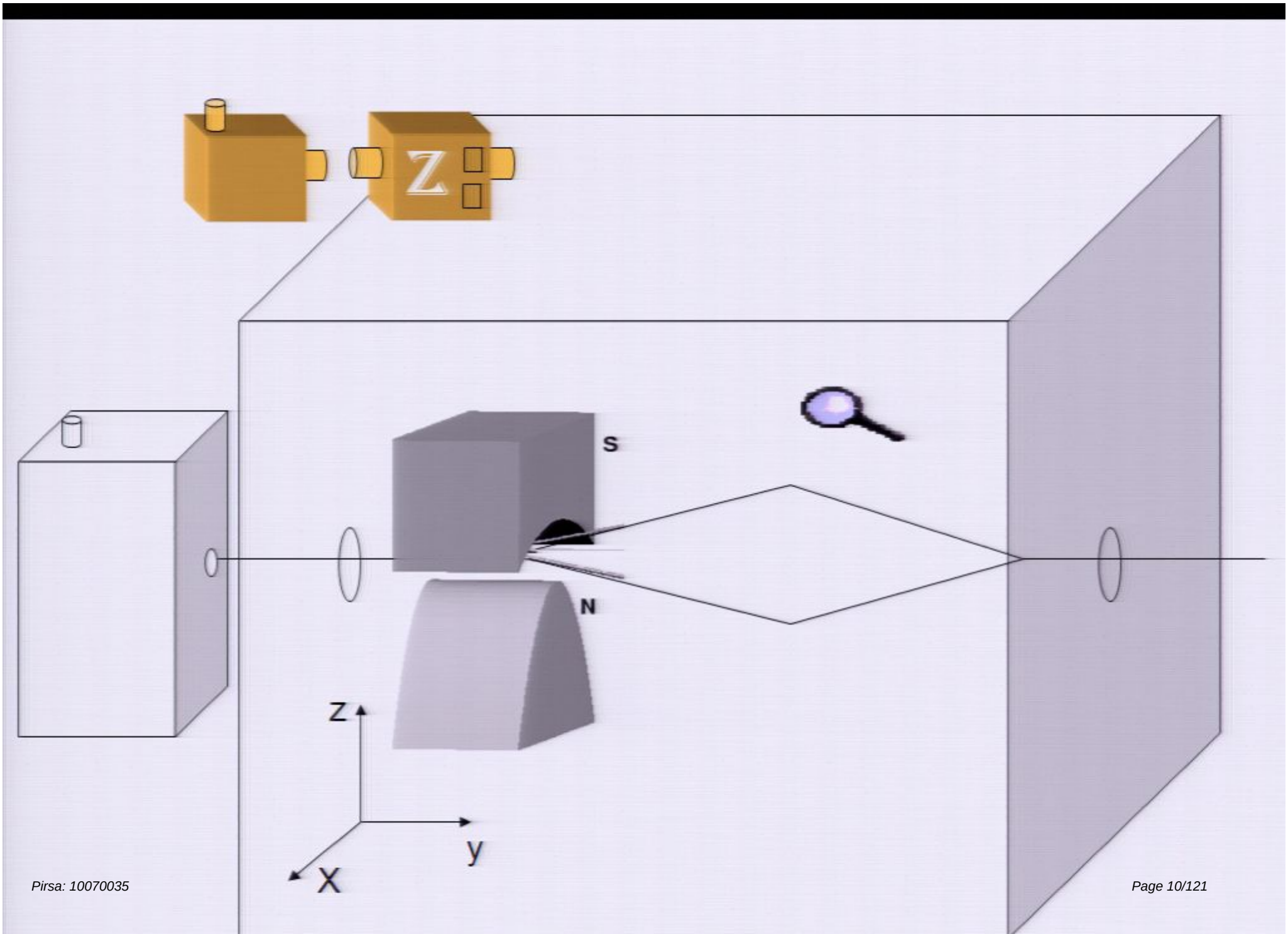
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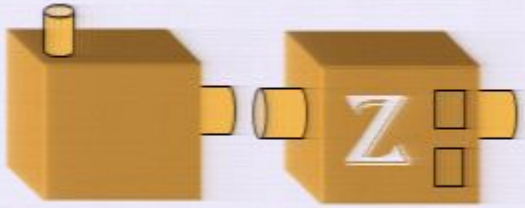
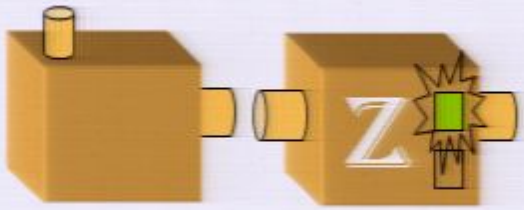

Z



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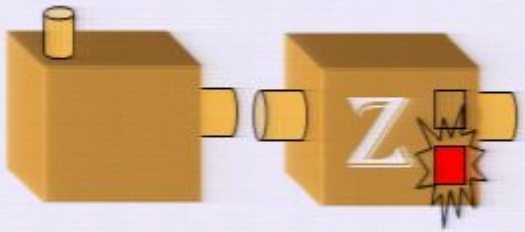

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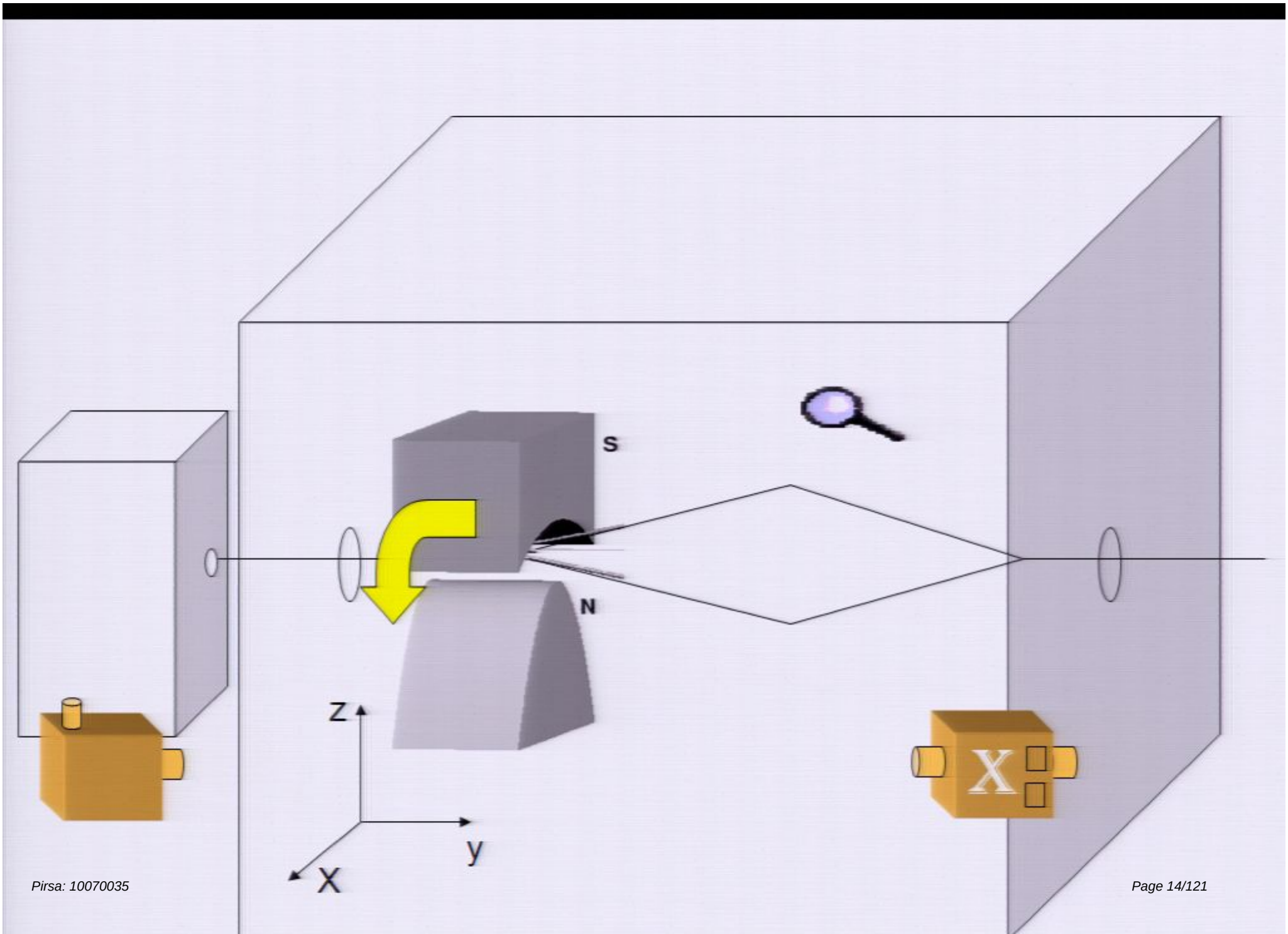
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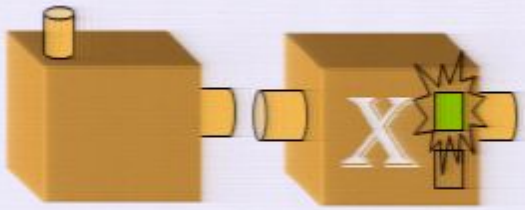

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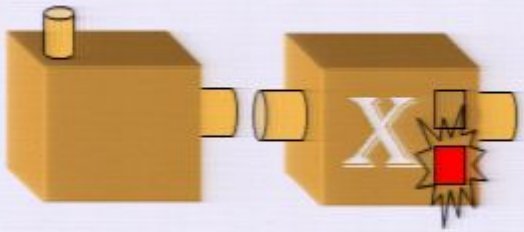

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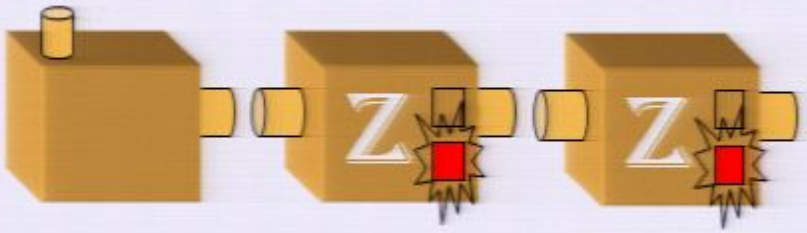
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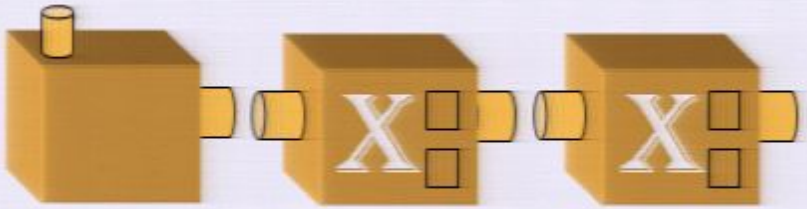
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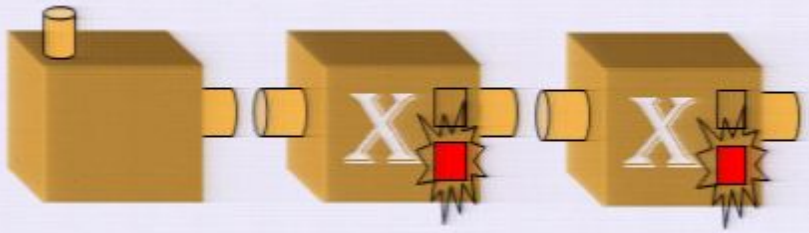
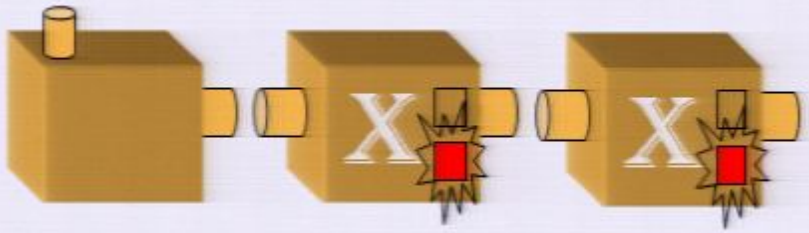
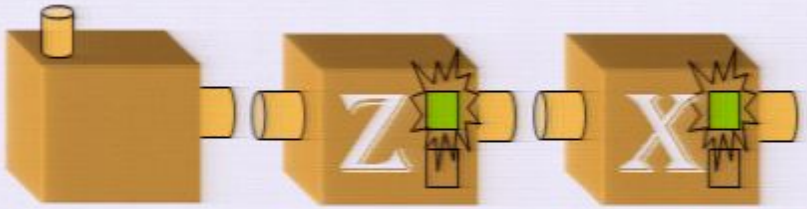

X
X



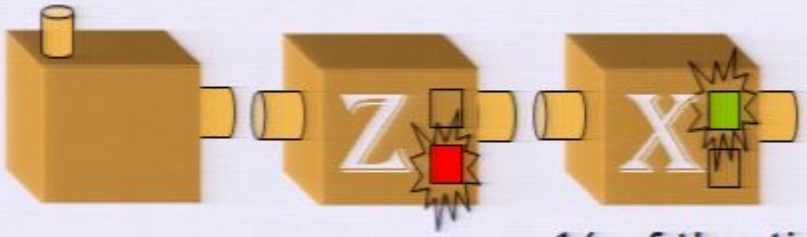
Consecutive identical measurements always yield the same outcome


Z
X



½ of the time


Z
X



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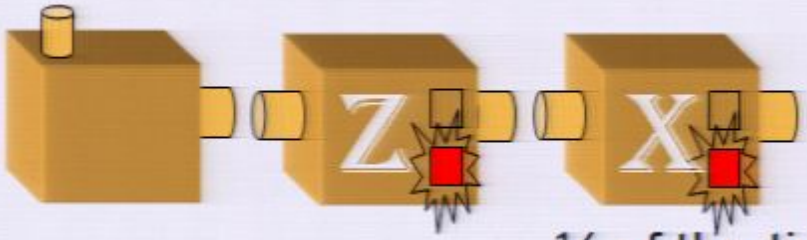
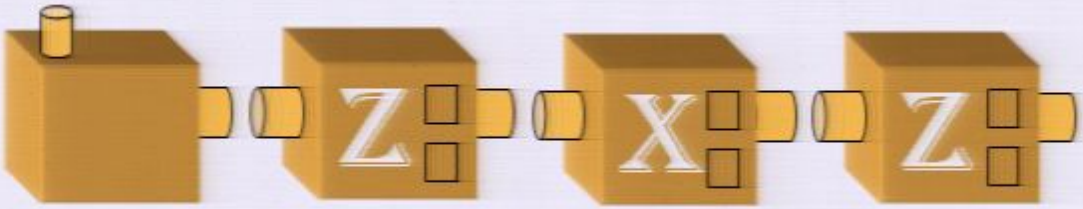
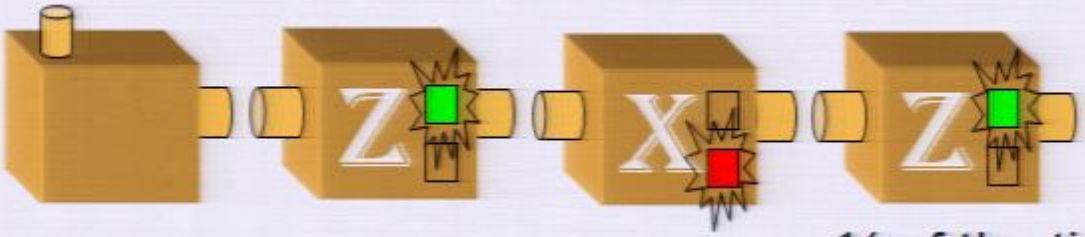


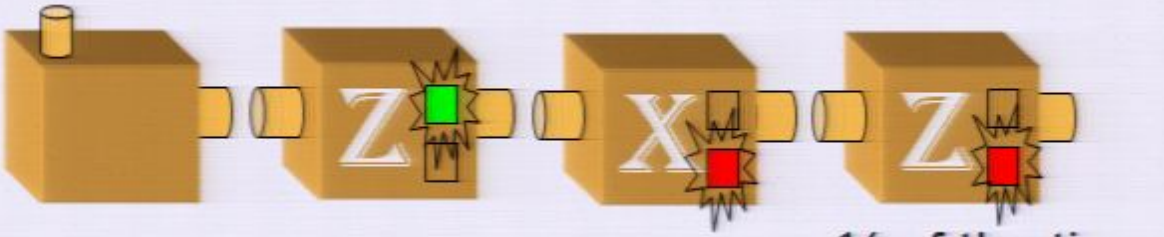
The outcome of an X measurement is uncorrelated with the outcome of an immediately preceding Z measurement

Same thing for X then Z


Z
X
Z



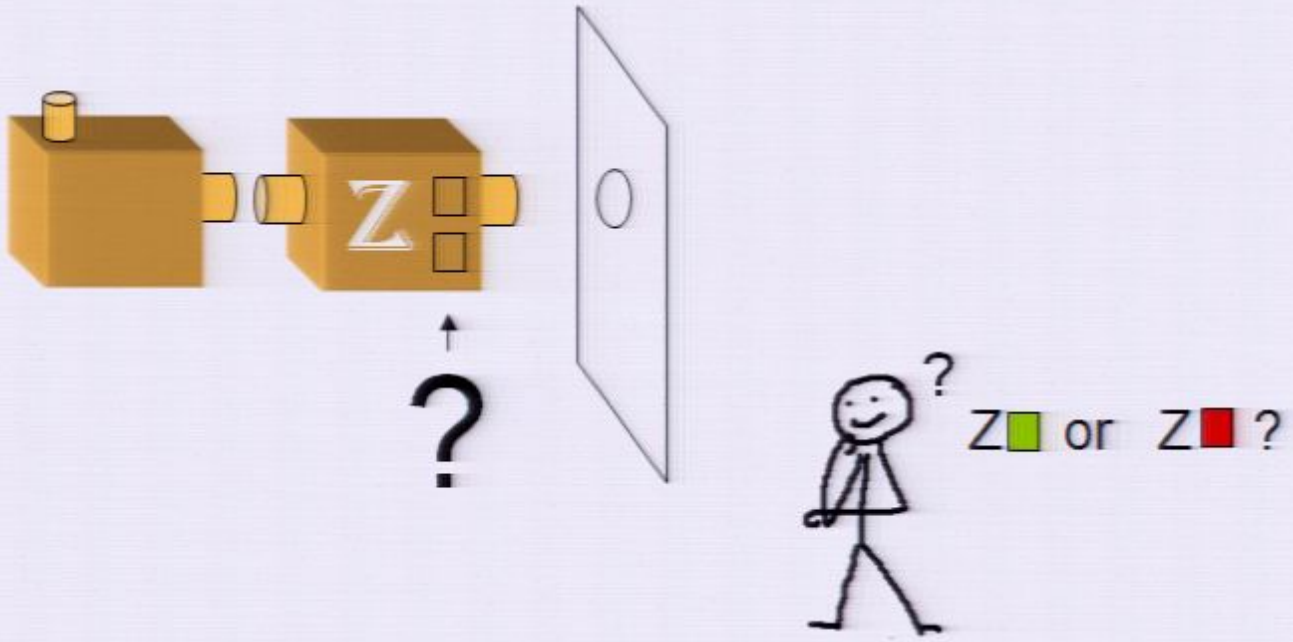
½ of the time

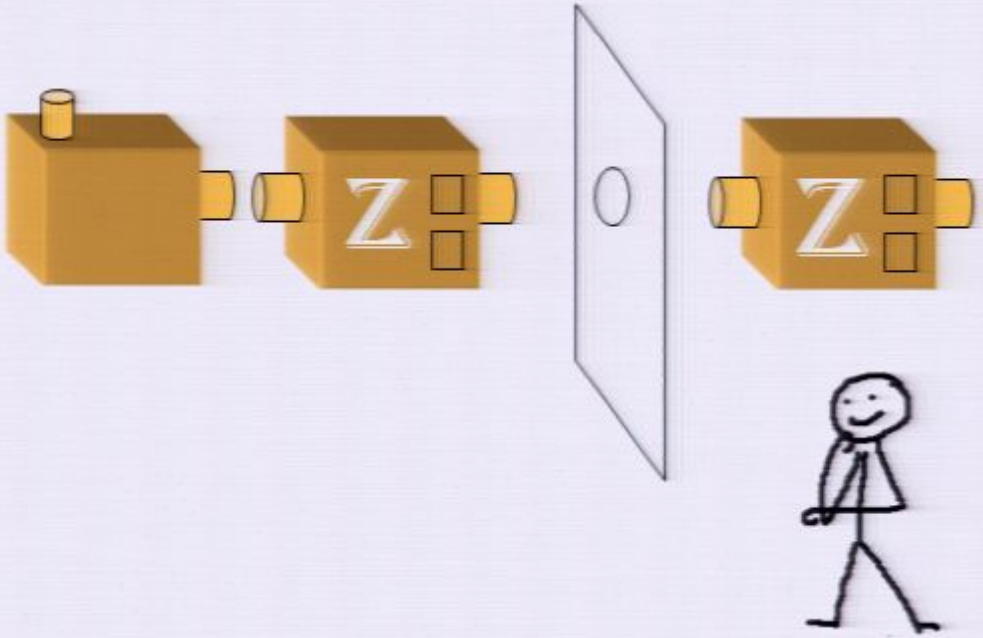


½ of the time

An intervening X measurement randomizes the outcome of a Z measurement

Same thing for X Z X


Z
?
?
Z or Z ?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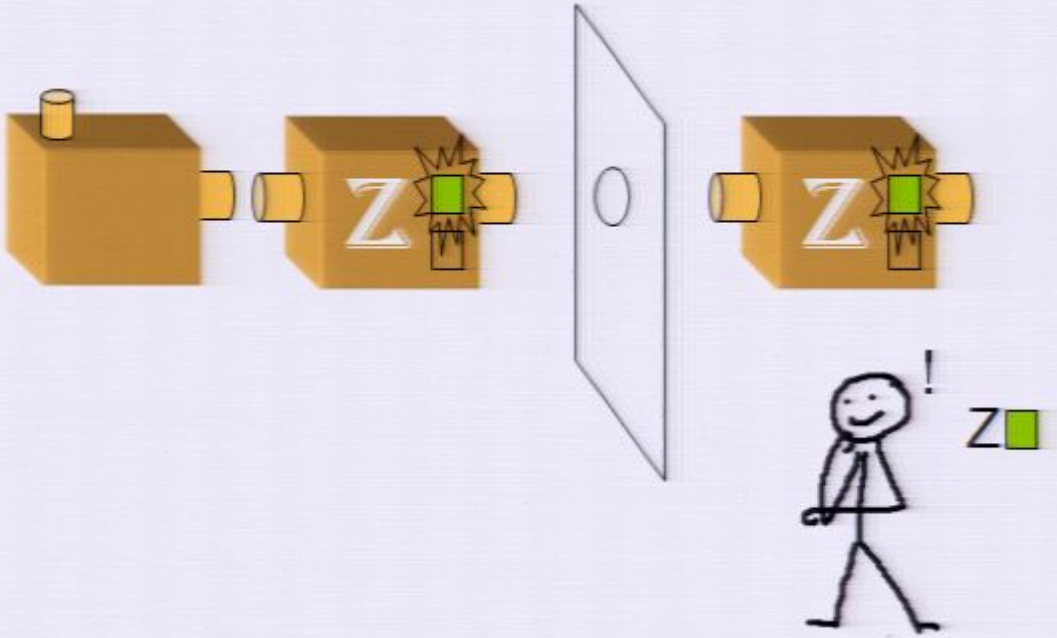
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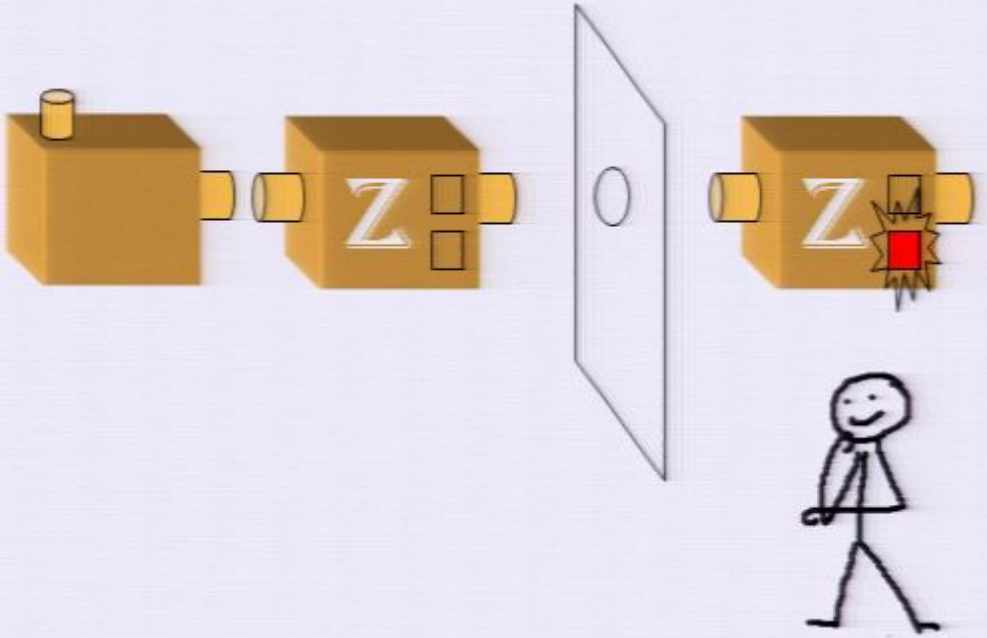
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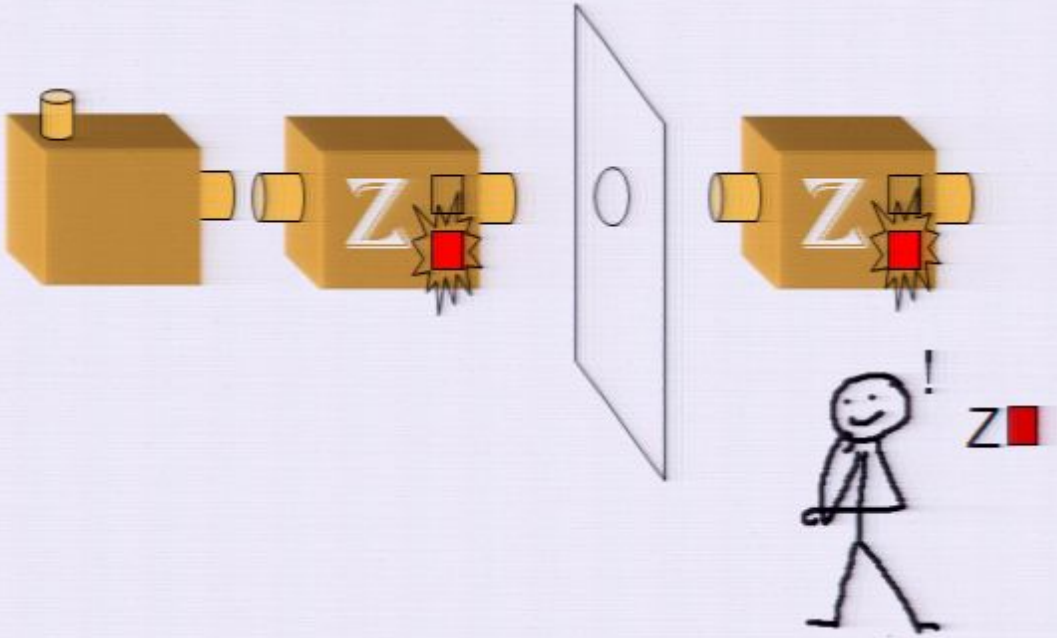
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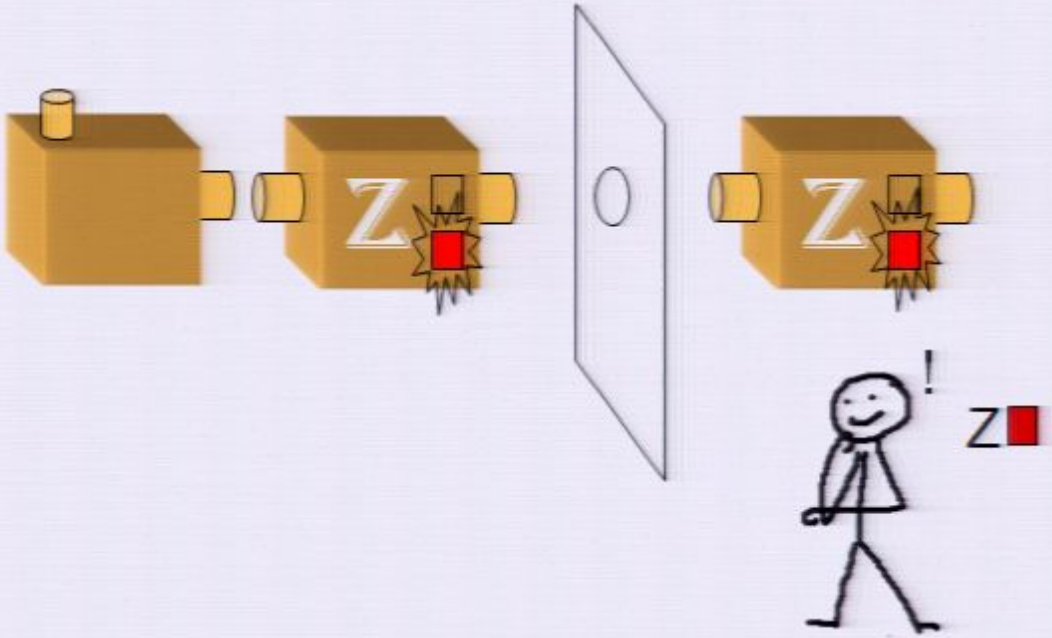
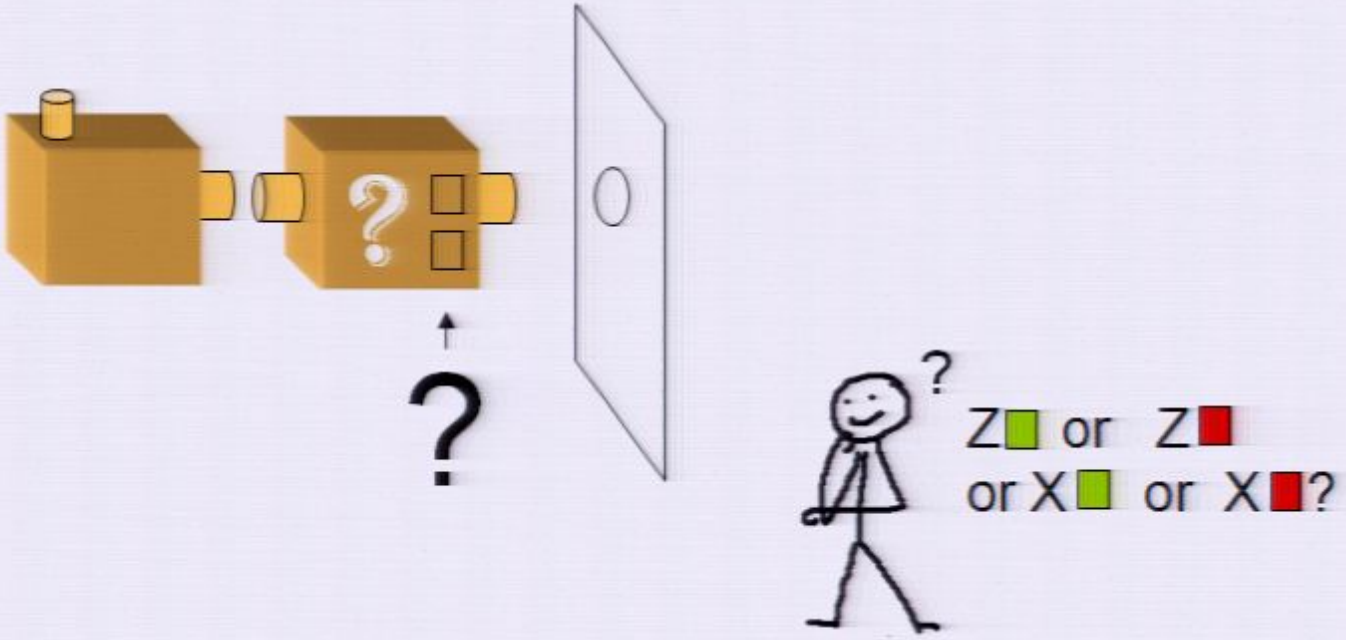
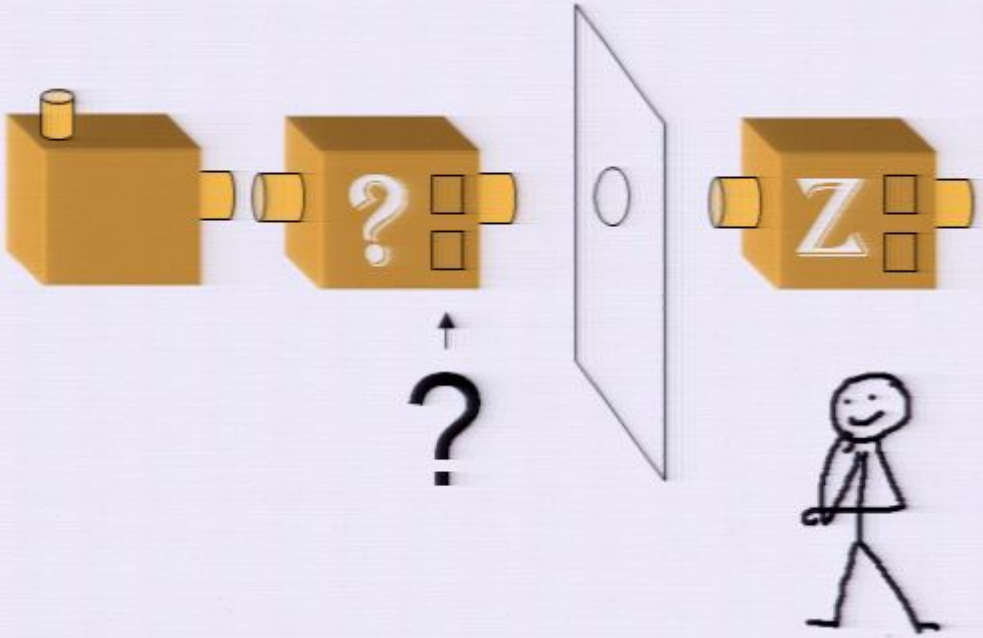
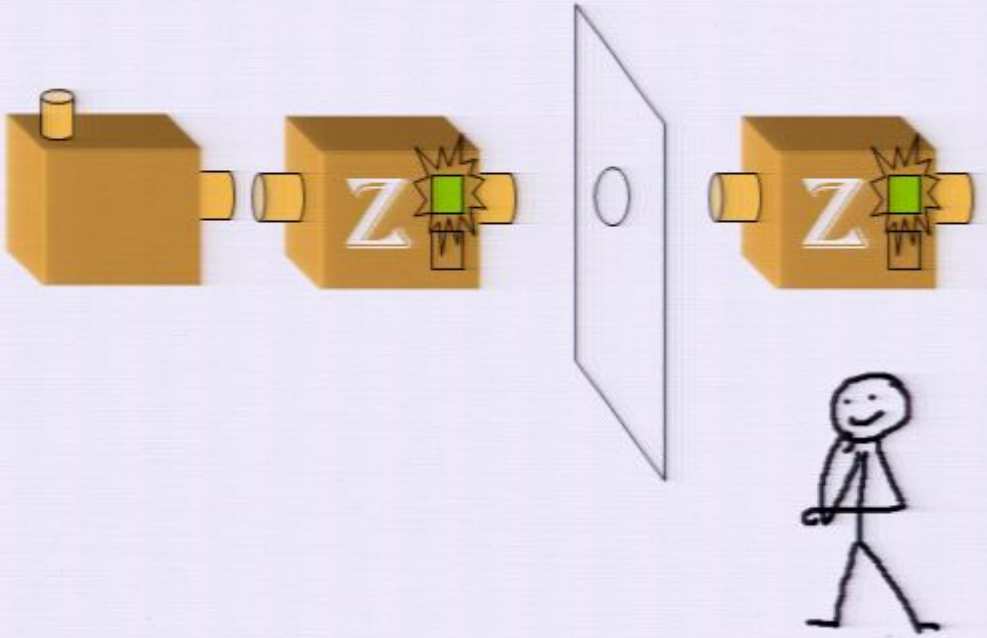
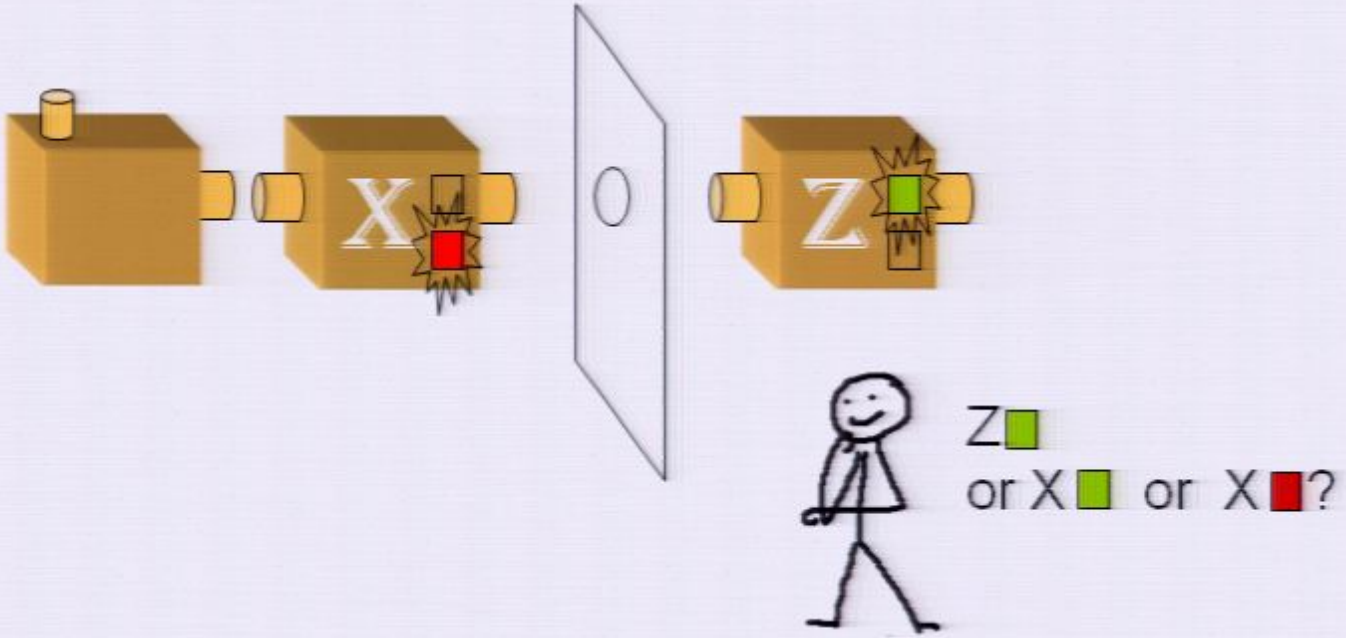


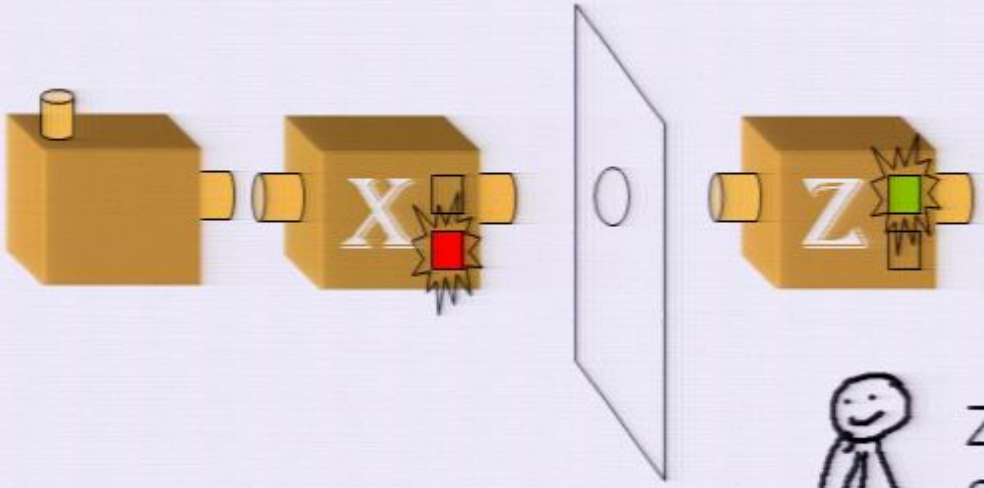
It is possible to distinguish between
Z Green and Z Red
(The same is true for X Green and X Red)

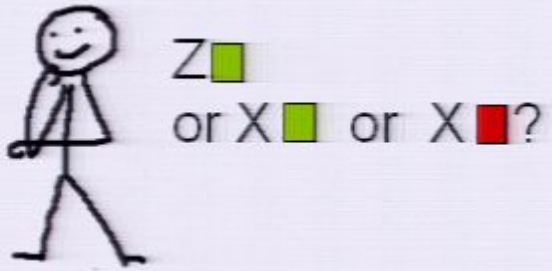

?
?
?
Z or Z
or X or X?


?
Z
?

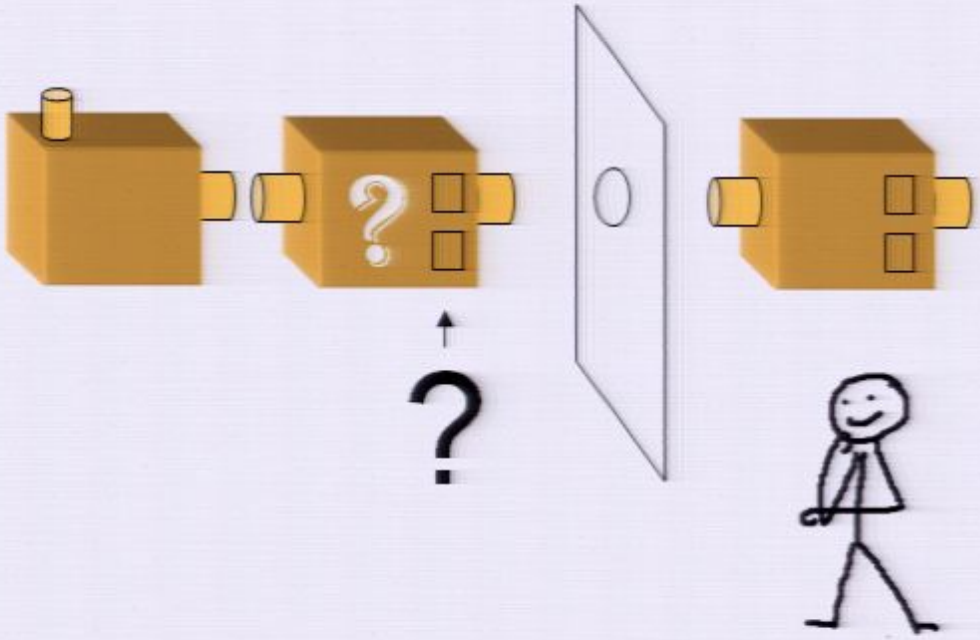

Z
Z


X
Z
Z
or X or X ?





It is impossible to distinguish between
Z Green, Z Red, X Green and X Red
No information about Z vs. X



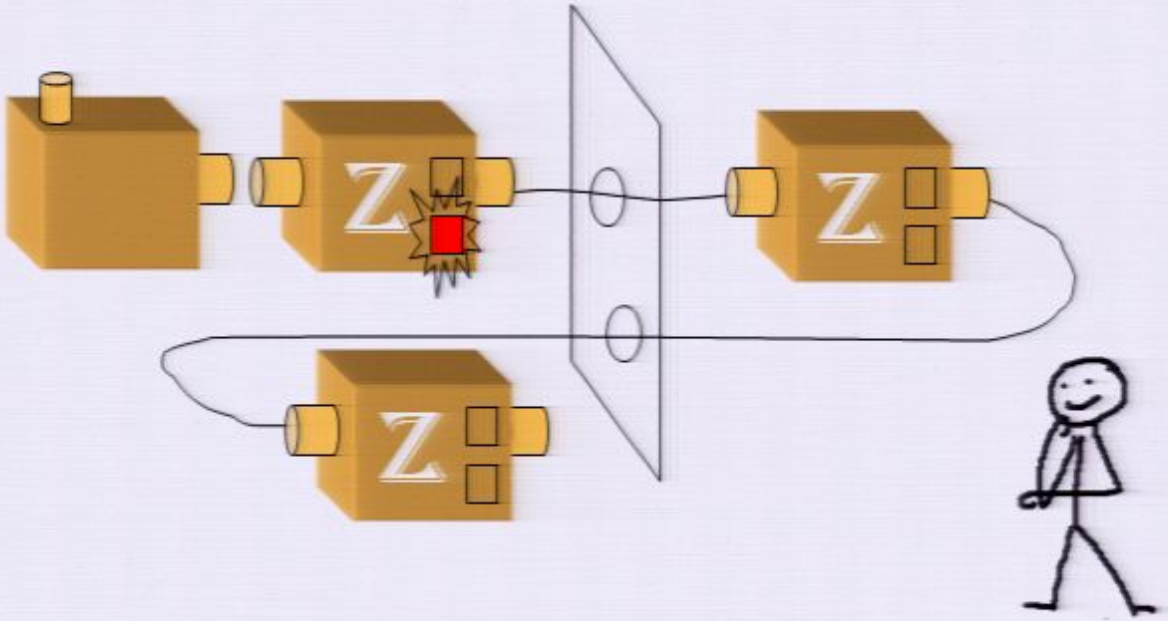
Probability of estimating correctly

= 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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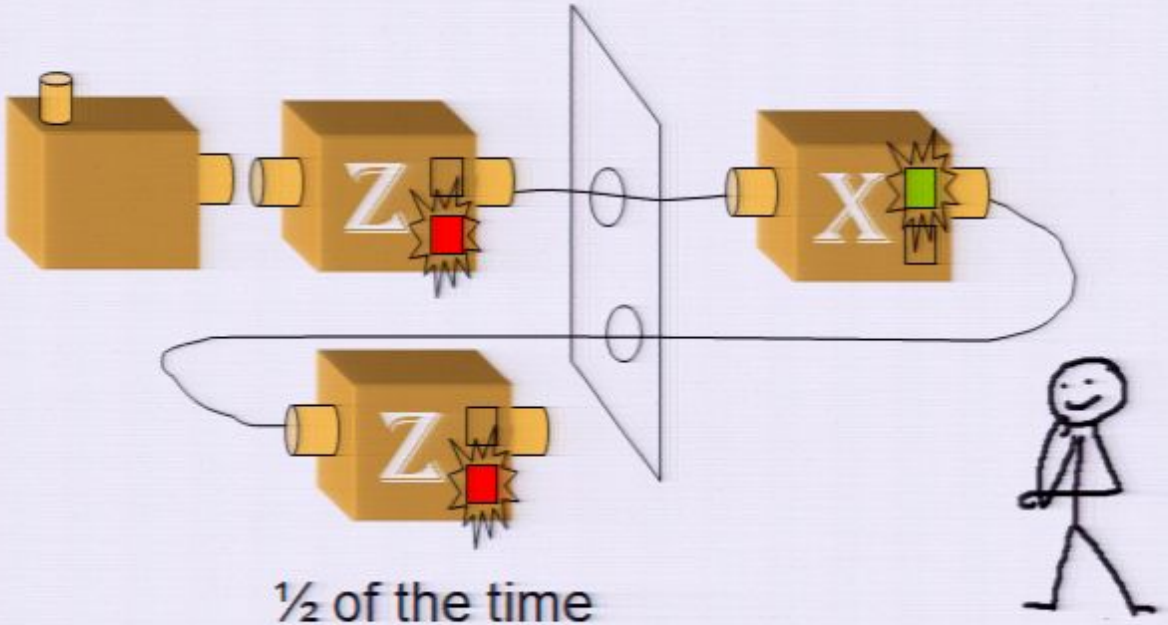
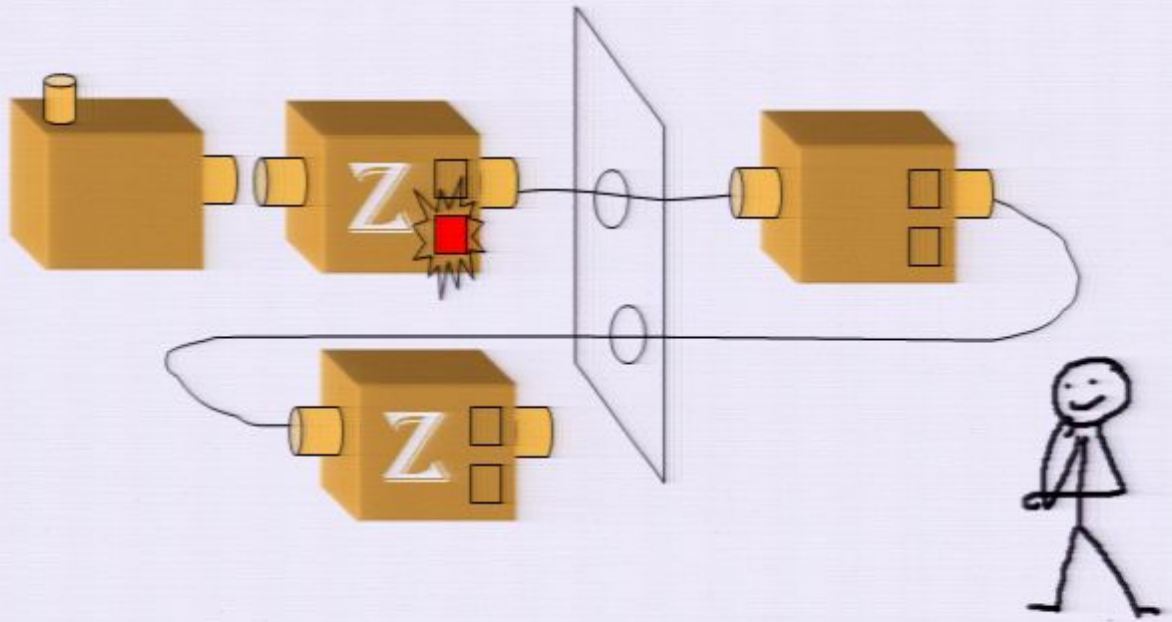

Z
X
Z
½ of the time



Probability of passing test

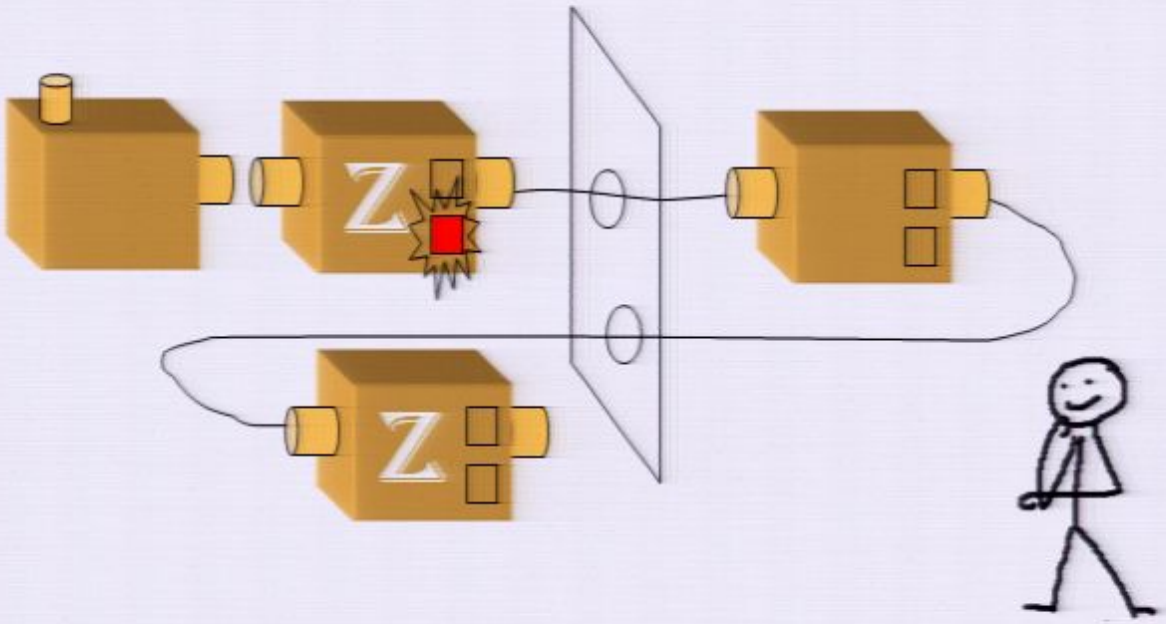
= P(get Z vs. X right) X P(pass the test | you got Z vs. X right)

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

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

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

$= \frac{3}{4}$



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)

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

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

$= \frac{3}{4}$

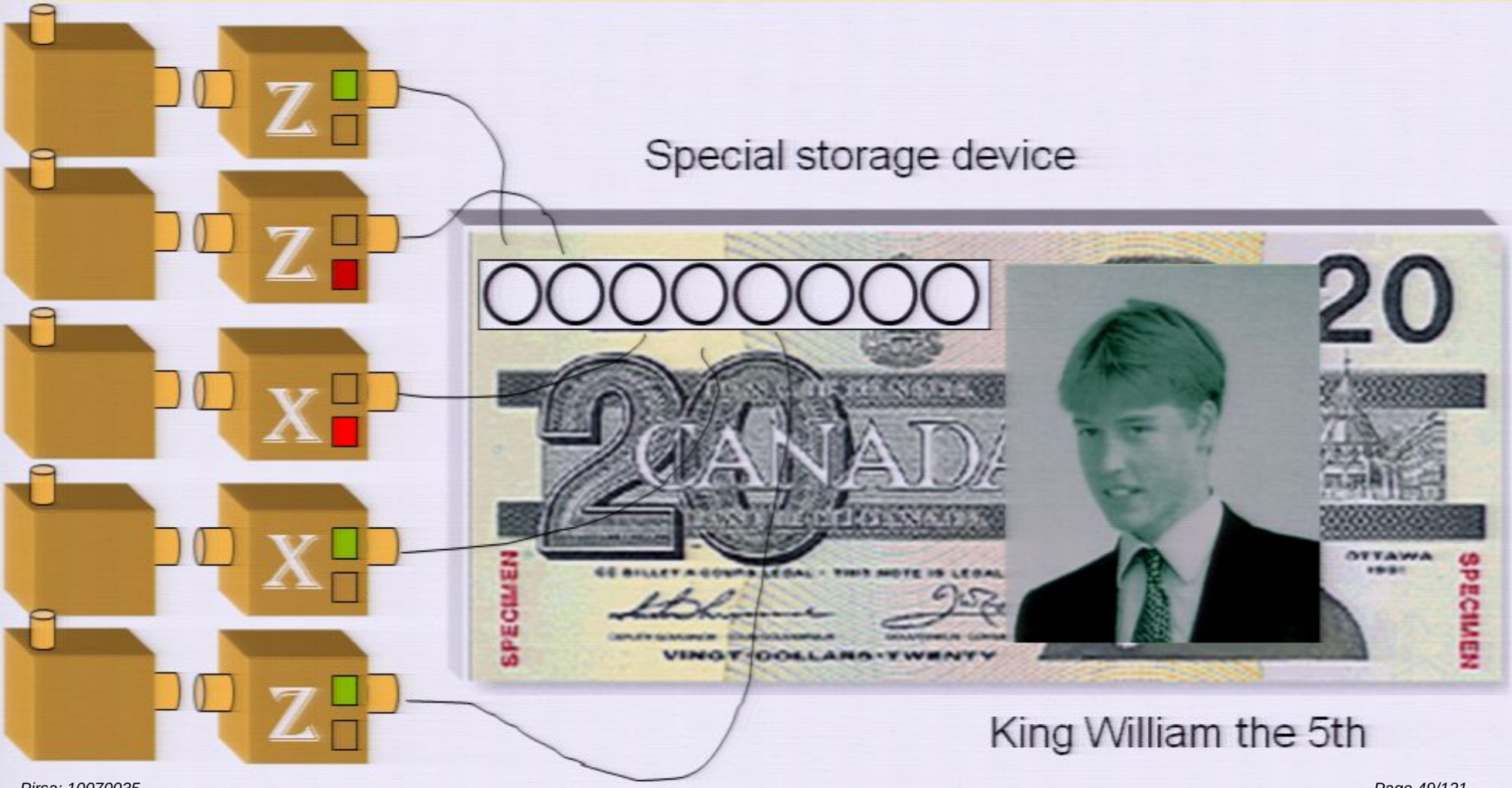
Information gain causes a disturbance

Some applications of these phenomena to cryptography

Quantum counterfeit-proof money

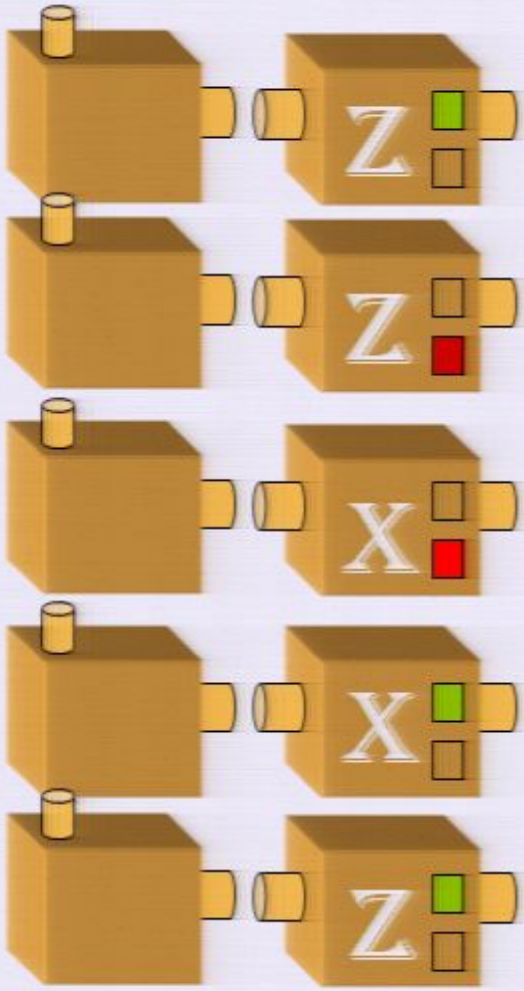
QUANTUM COUNTERFEIT-PROOF MONEY

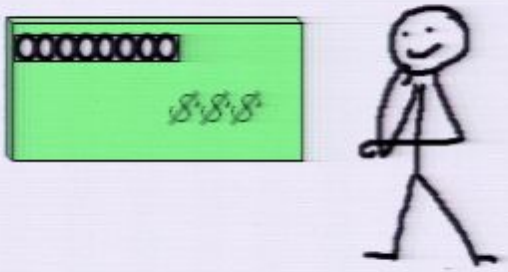
QUANTUM COUNTERFEIT-PROOF MONEY



The Mint

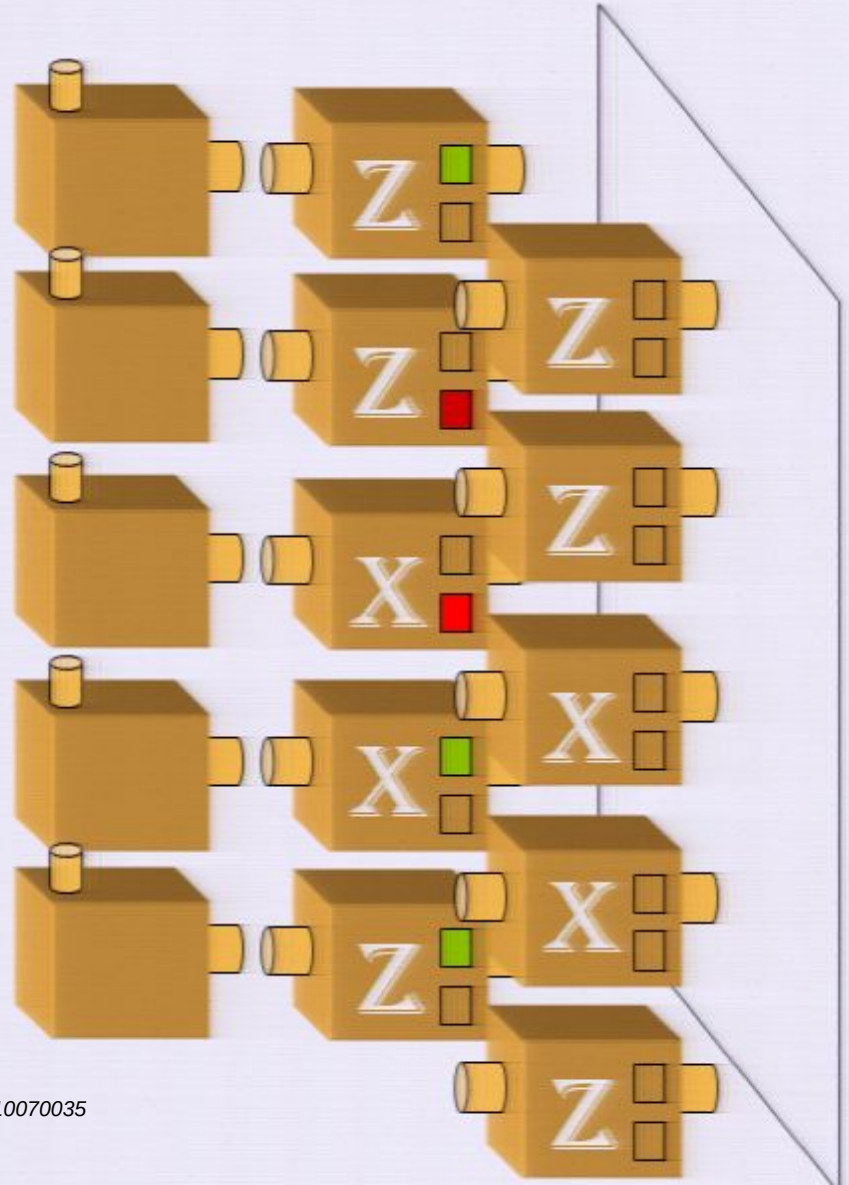
The rest of the world

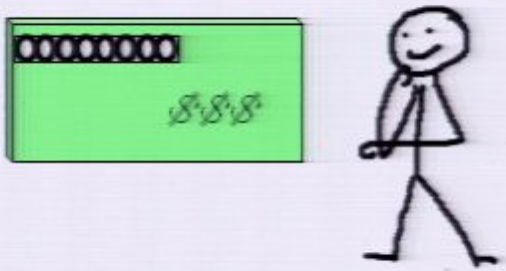


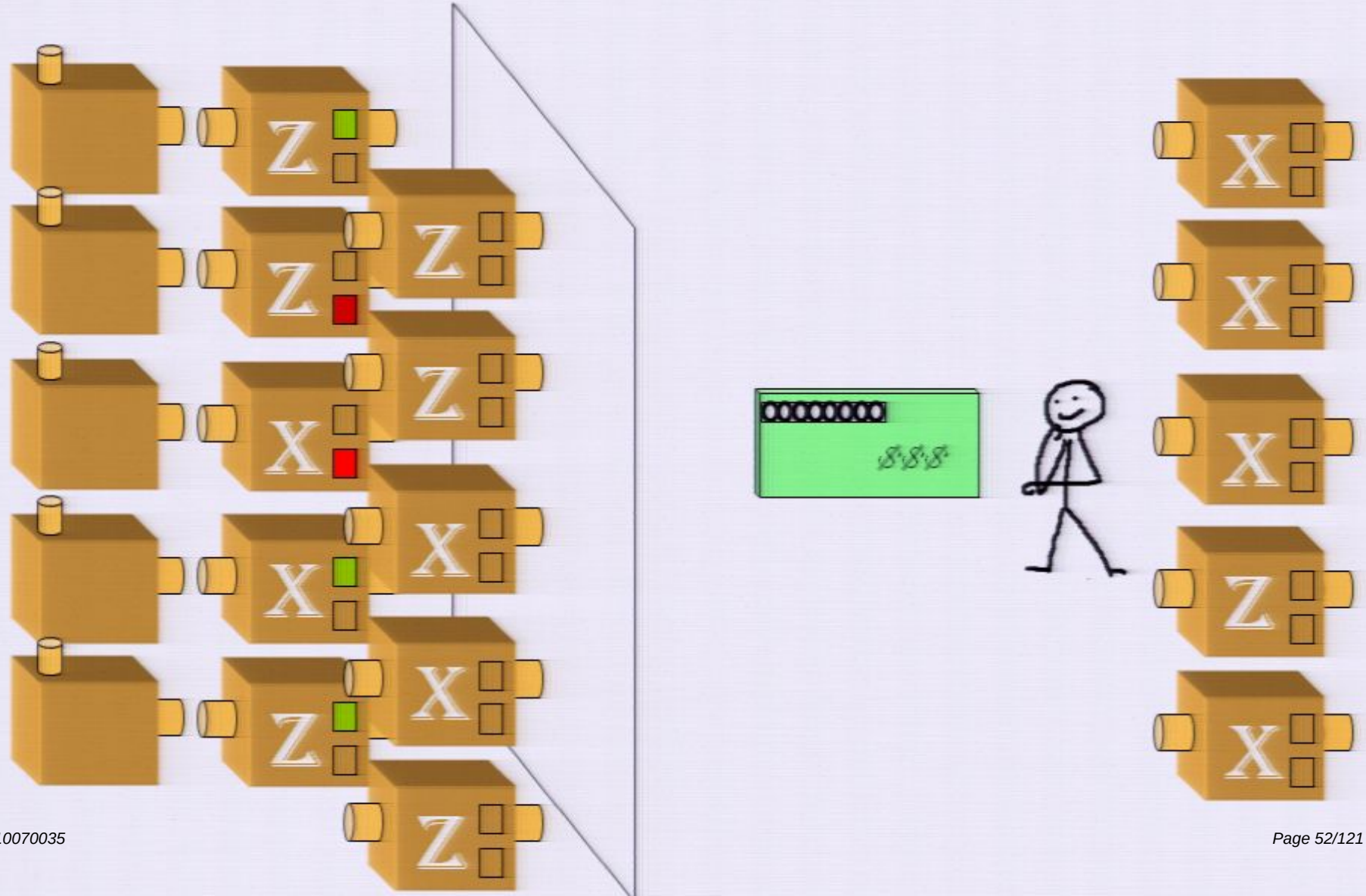


The Mint

The rest of the world






The Mint
The rest of the world
Z
Z
Z
Z
X
Z
X
X
Z
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 $x \in \{0,\ldots, 25\}$
key: 2

cipher-text: “OGGVOGCVVJGTKXGT”

Caesar cipher

plain-text: "MEETMEATTHERIVER"

shift each letter by $x \in \{0,\ldots, 25\}$
key: 2

cipher-text: "OGGVOGCVVJGTKXGT"

Vernam cipher

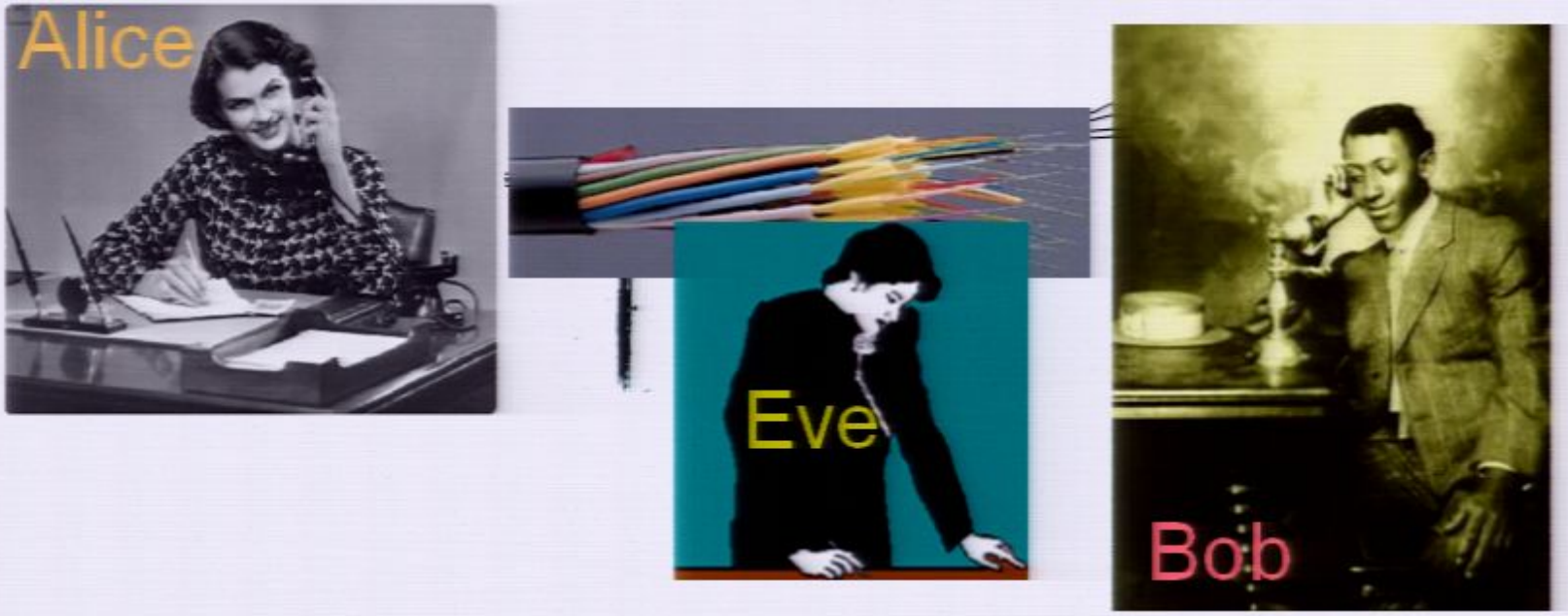
plain-text: "MEETMEATTHERIVER"

shift letter i by $x_i \in \{0,\ldots, 25\}$
key: 7 20 4 12 14 23 19 8 1 2 11 19 23 ...

cipher-text: "TYIQZBWYURLCJRSE"

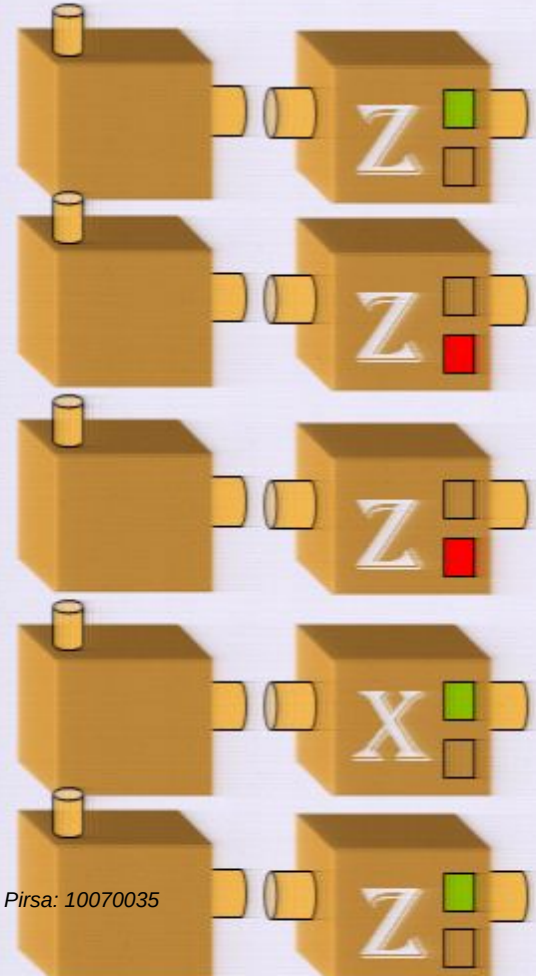
QUANTUM KEY DISTRIBUTION

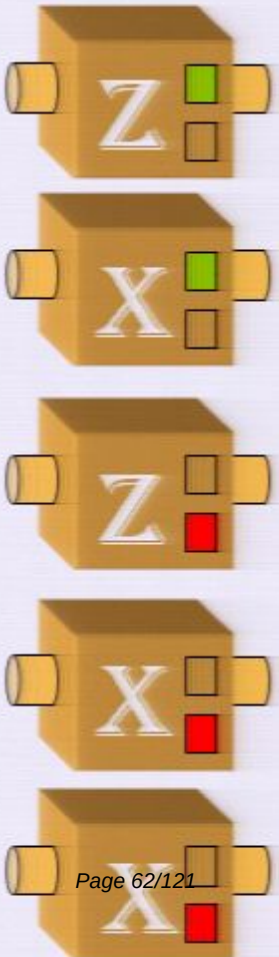
QUANTUM KEY DISTRIBUTION




Alice

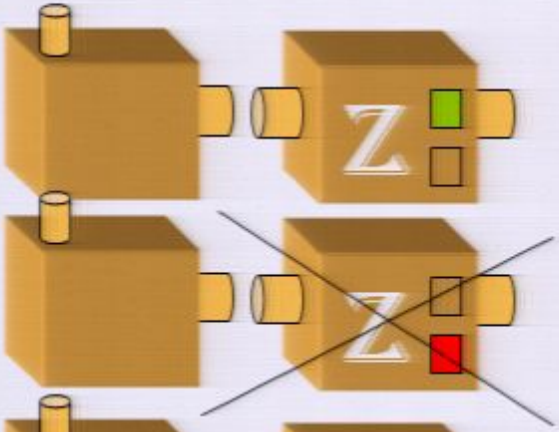

Bob


Z
Z
Z
X
Z


Z
X
Z
X
X


Alice


Bob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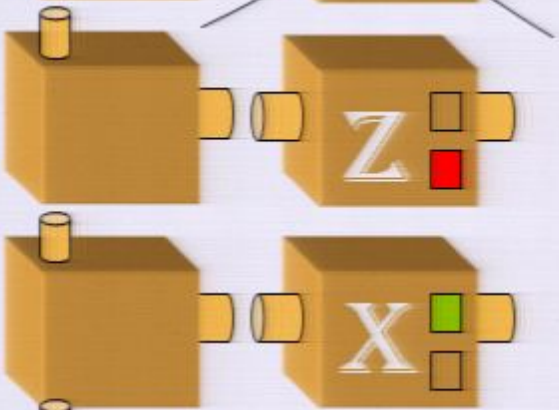
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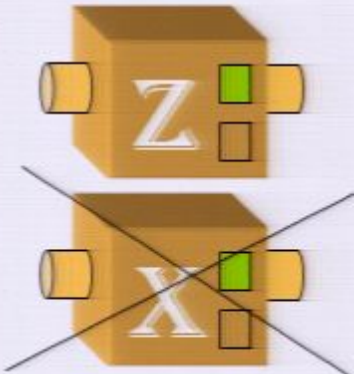
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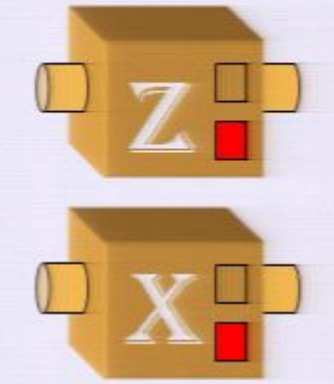
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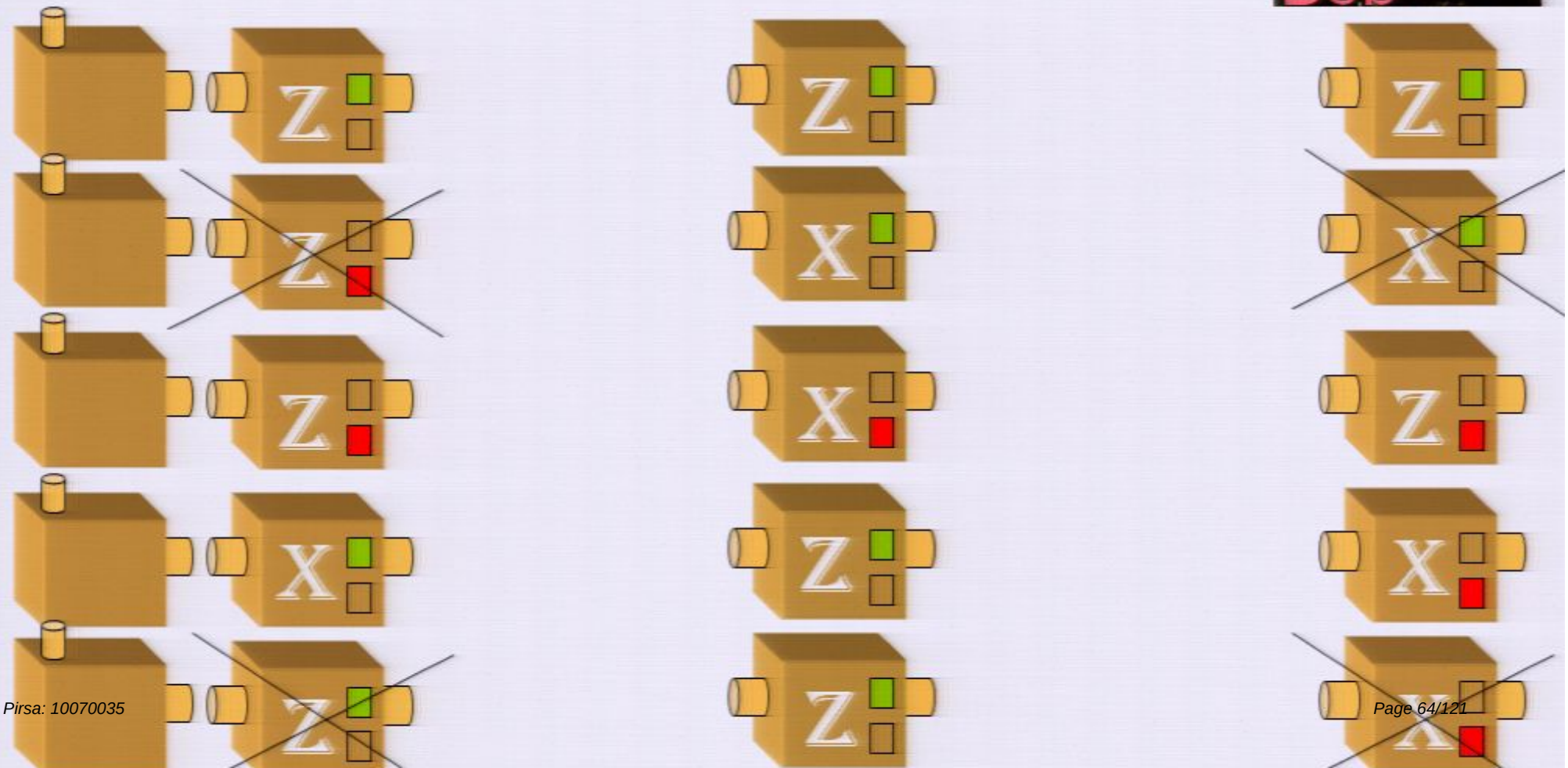
X


X


Alice
Eve
Bob


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

QUANTUM KEY DISTRIBUTION

Caesar cipher

plain-text: “MEETMEATTHERIVER”

shift each letter by $x \in \{0,\ldots, 25\}$
key: 2

cipher-text: “OGGVOGCVVJGTKXGT”

Caesar cipher

plain-text: "MEETMEATTHERIVER"

shift each letter by $x \in \{0,\ldots, 25\}$
key: 2

cipher-text: "OGGVOGCVVJGTKXGT"

Vernam cipher

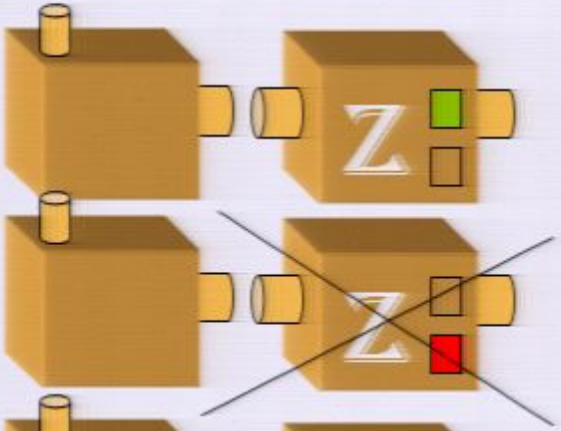
plain-text: "MEETMEATTHERIVER"

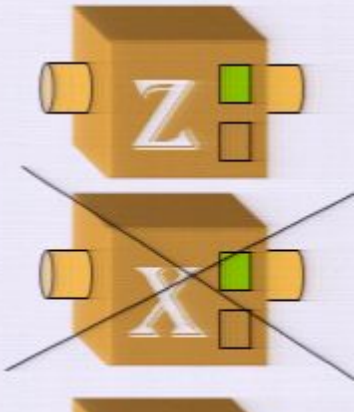
shift letter i by $x_i \in \{0,\ldots, 25\}$
key: 7 20 4 12 14 23 19 8 1 2 11 19 23 ...

cipher-text: "TYIQZBWYURLCJRSE"


Alice


Bob


Z
Z
Z
X
Z


Z
X
Z
X
X

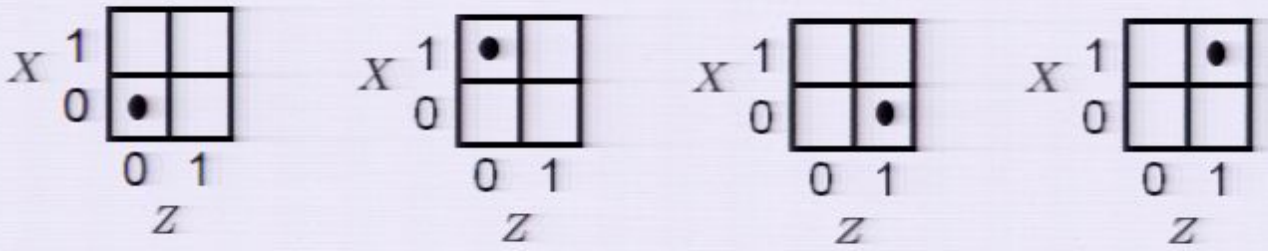
The idea behind hidden variable models of quantum mechanics


Plato's allegory of the cave
The fire
shadows cast on wall
Prisoners
Roadway where puppeteers perform

A toy world with a restriction on knowledge

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

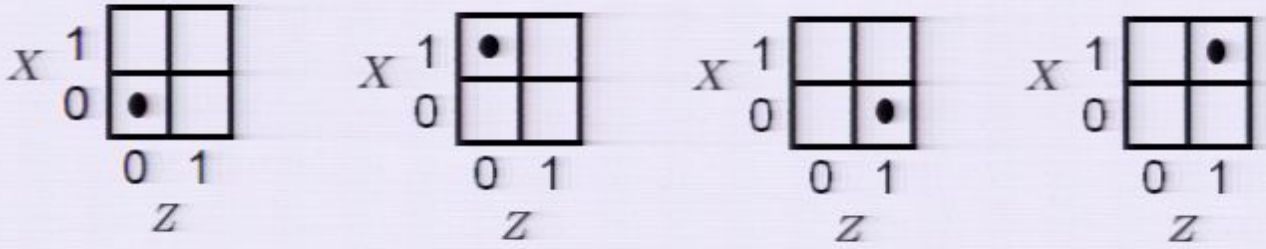
4 physical states



A toy world with a restriction on knowledge

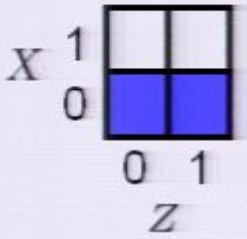
Every system has a pre-existing value of X and Z

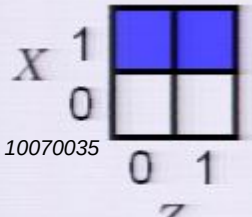
4 physical states



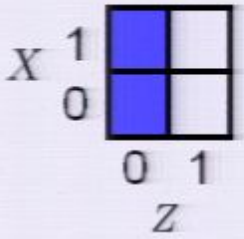
Possible states of knowledge

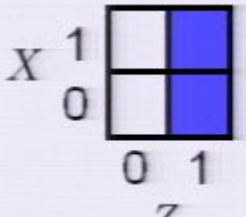
X known



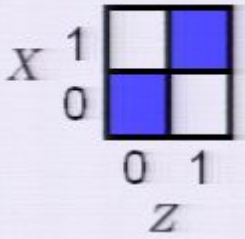


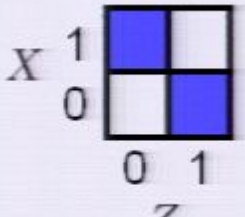
Z known



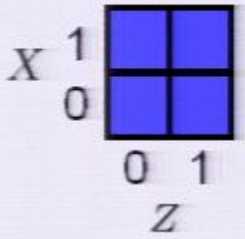


(X+Z)mod2 known



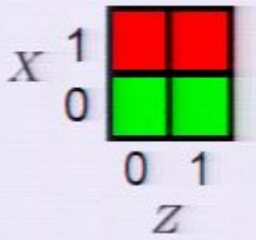


nothing known

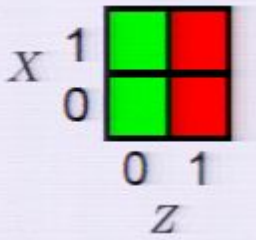


Possible measurements

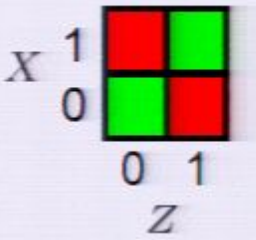
Measure X

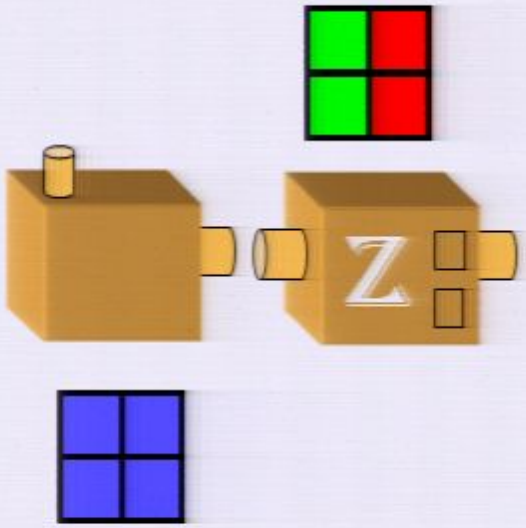


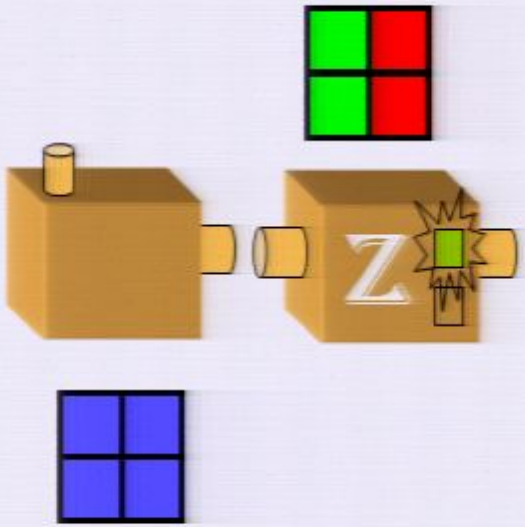
Measure Z



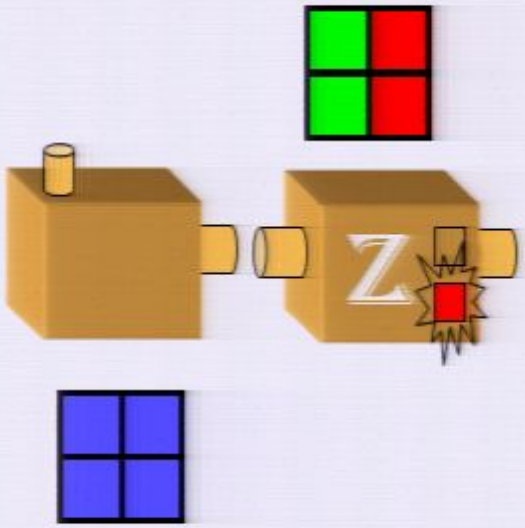
Measure (X+Z)mod2



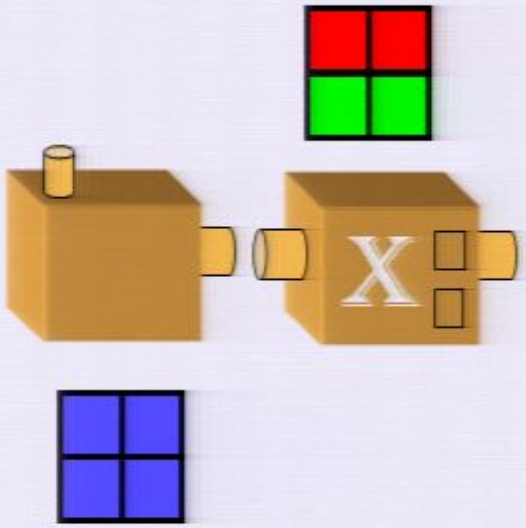

Z

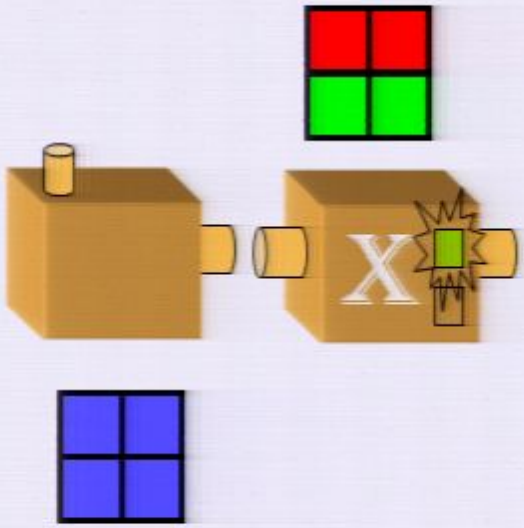


½ of the time



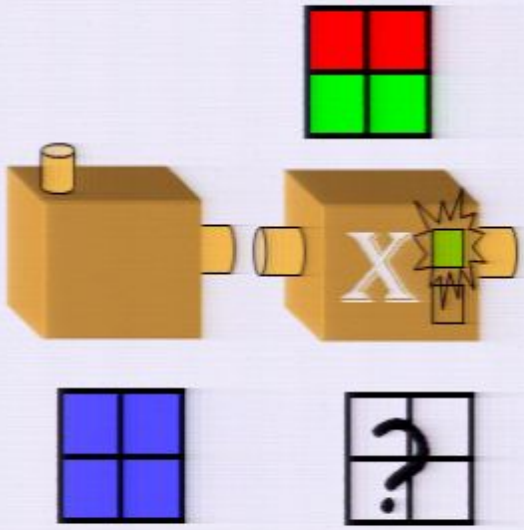
½ of the time

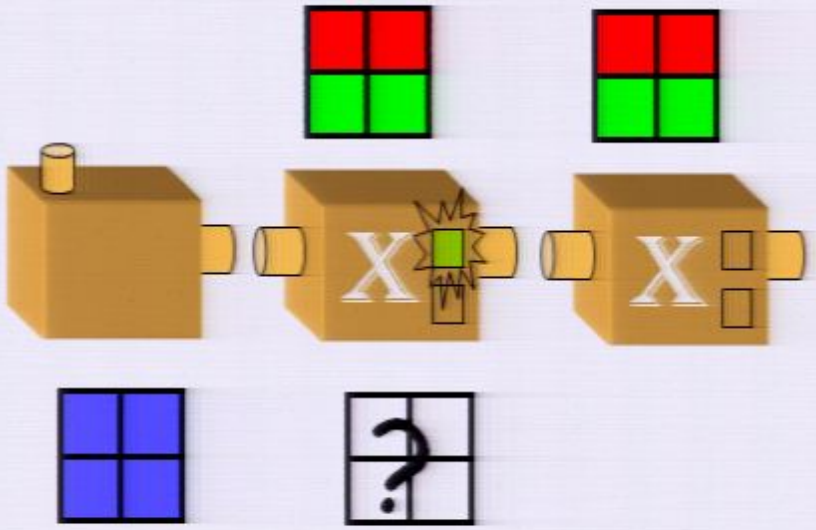

X

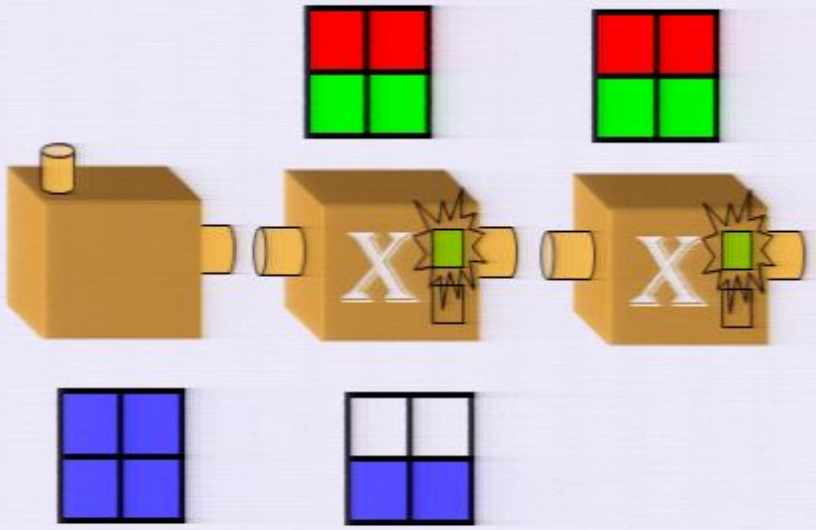


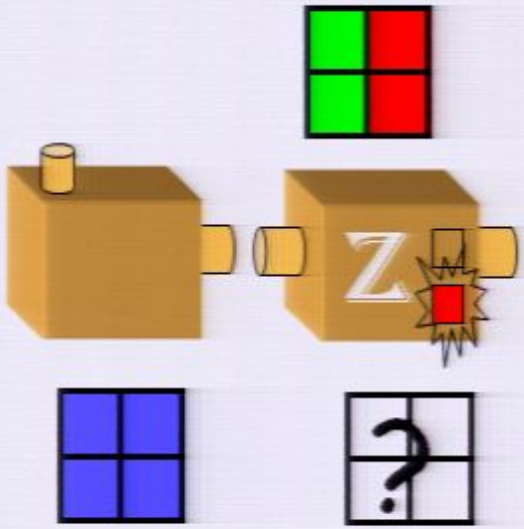
½ of the time

Updating the probability distribution after a measurement




X
X
?


X
X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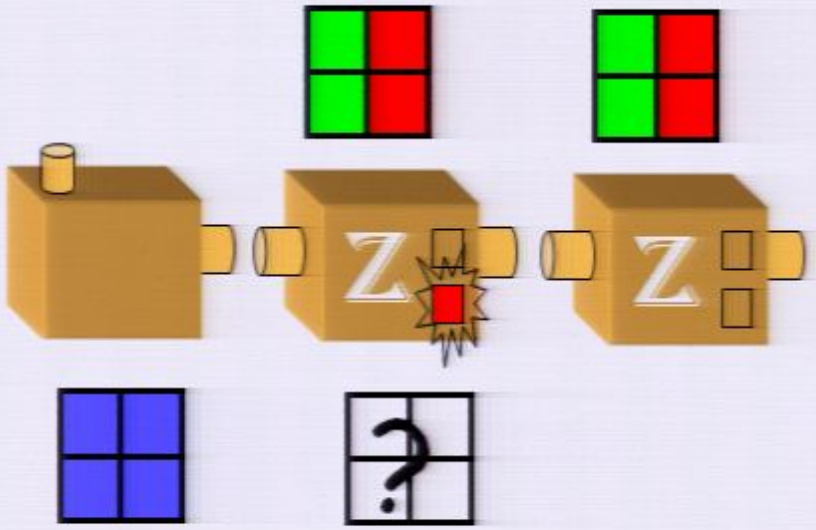
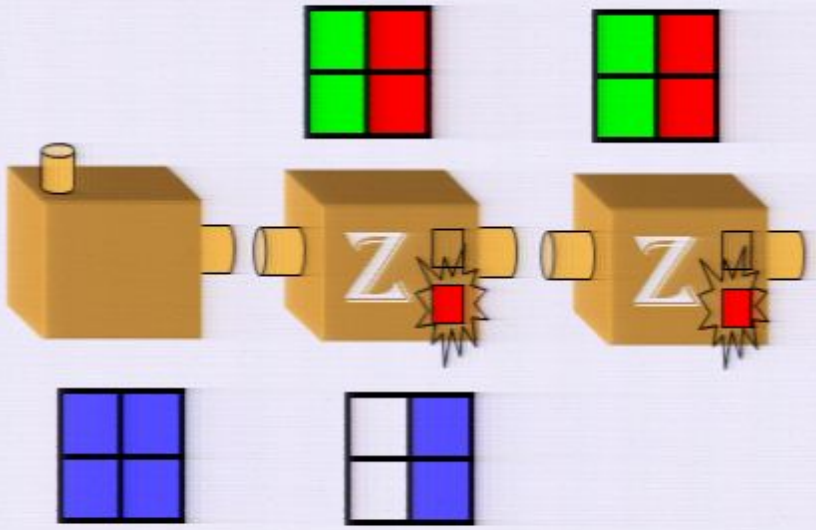
?


Z
Z
?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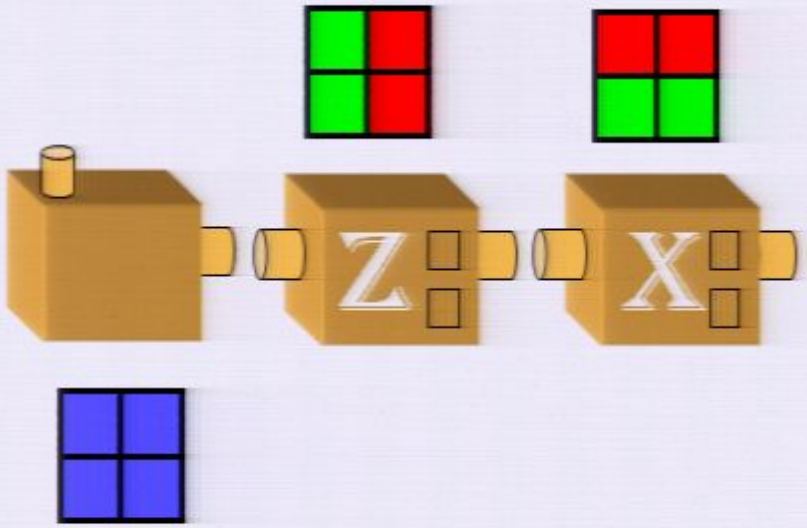
Z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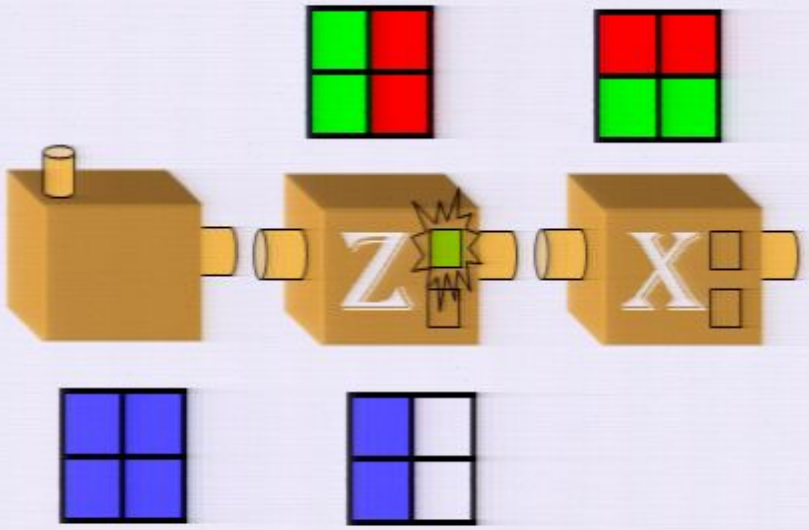
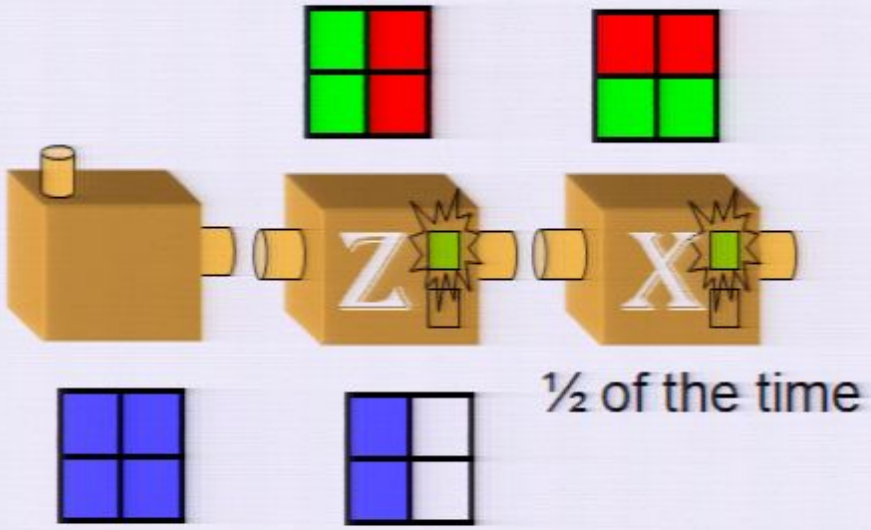
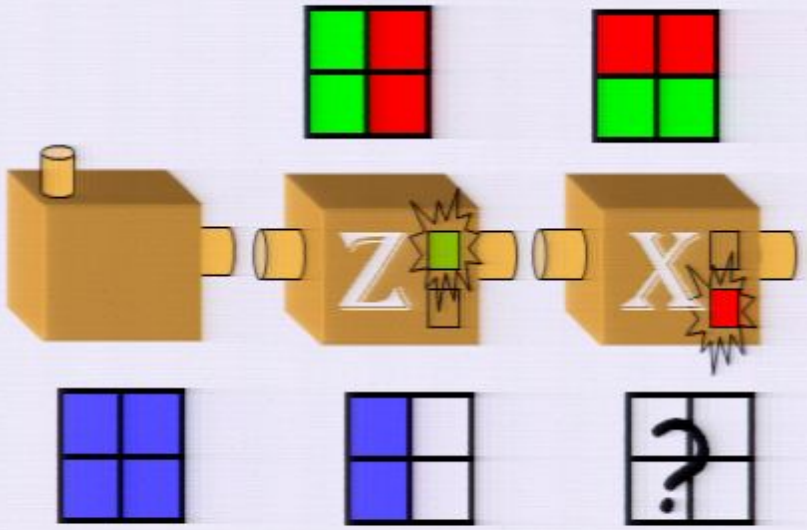
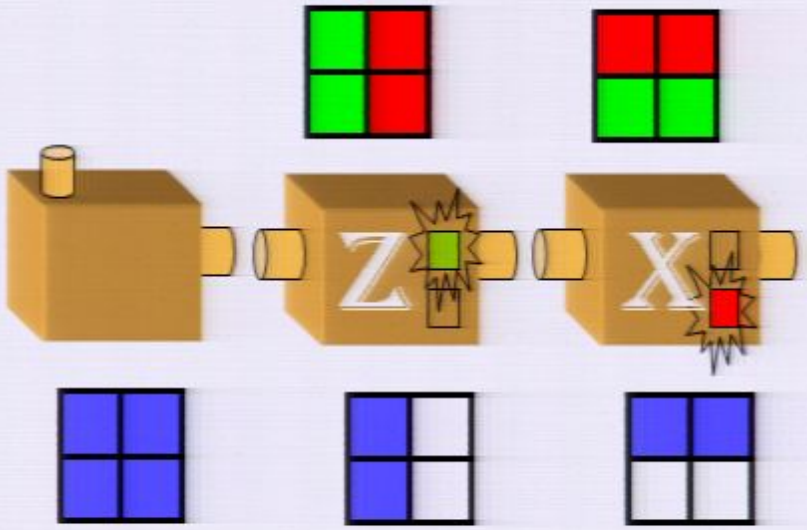

Z
X


Z
X
½ of the time

Updating after a measurement, take 2




Z
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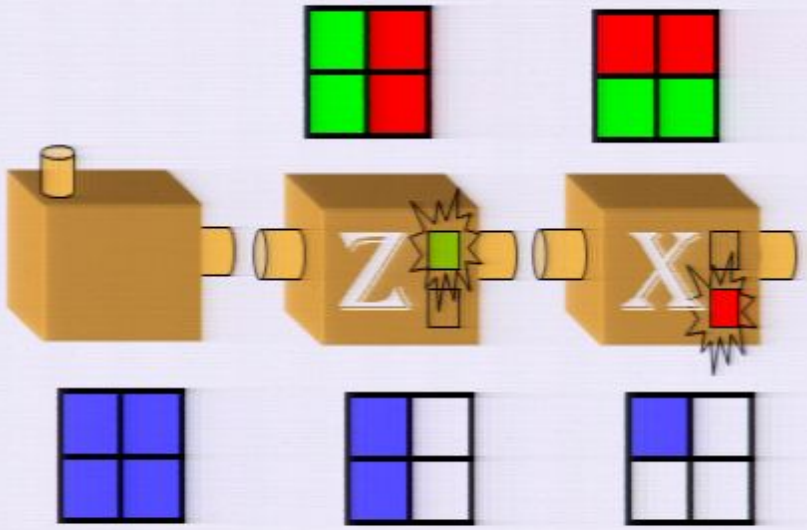
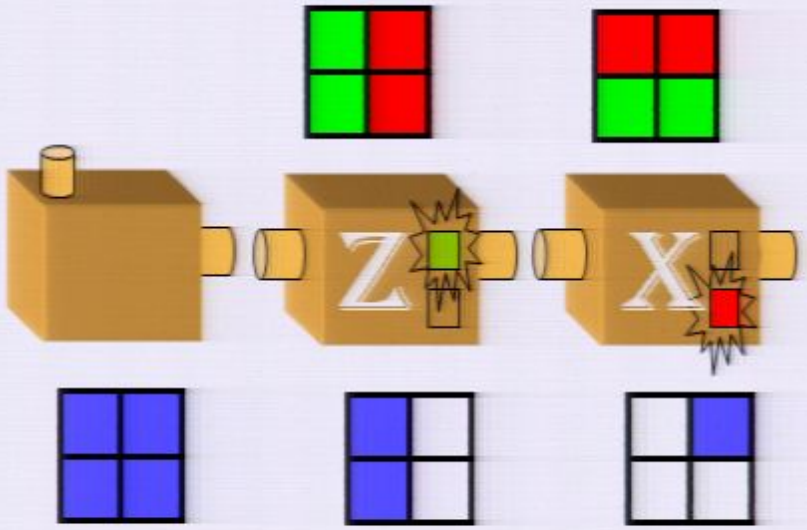
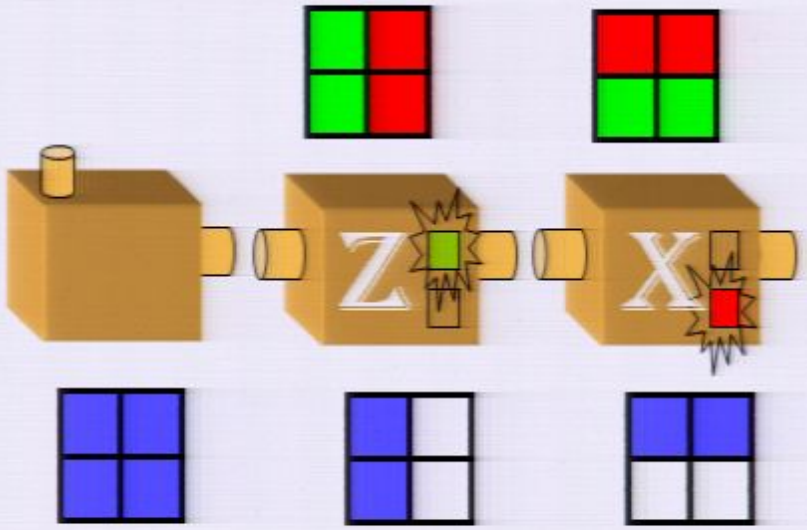


What the final probability distribution would be if there was no physical disturbance



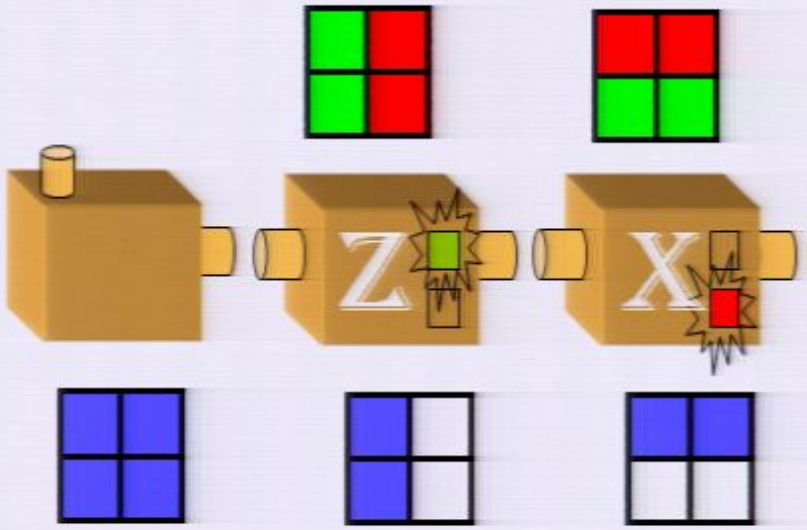
What the final probability distribution would be if there was a physical disturbance that flips the value of Z



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

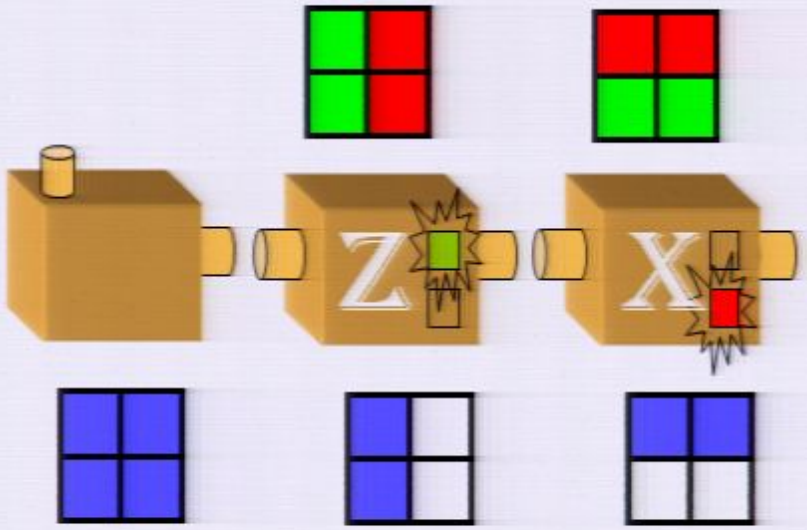


To get the proper final distribution, we require:

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

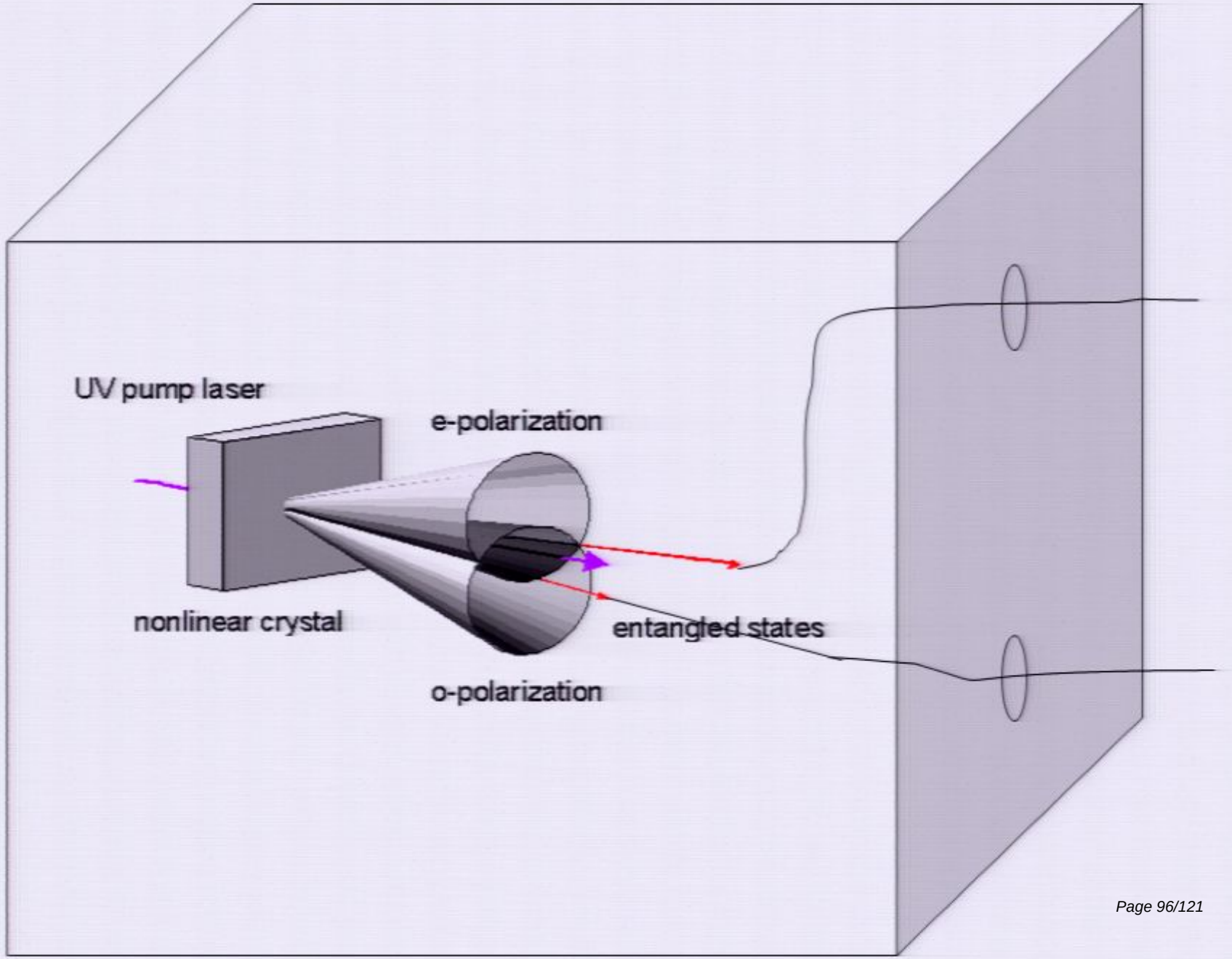
A measurement of X changes the value of Z with prob. 1/2.

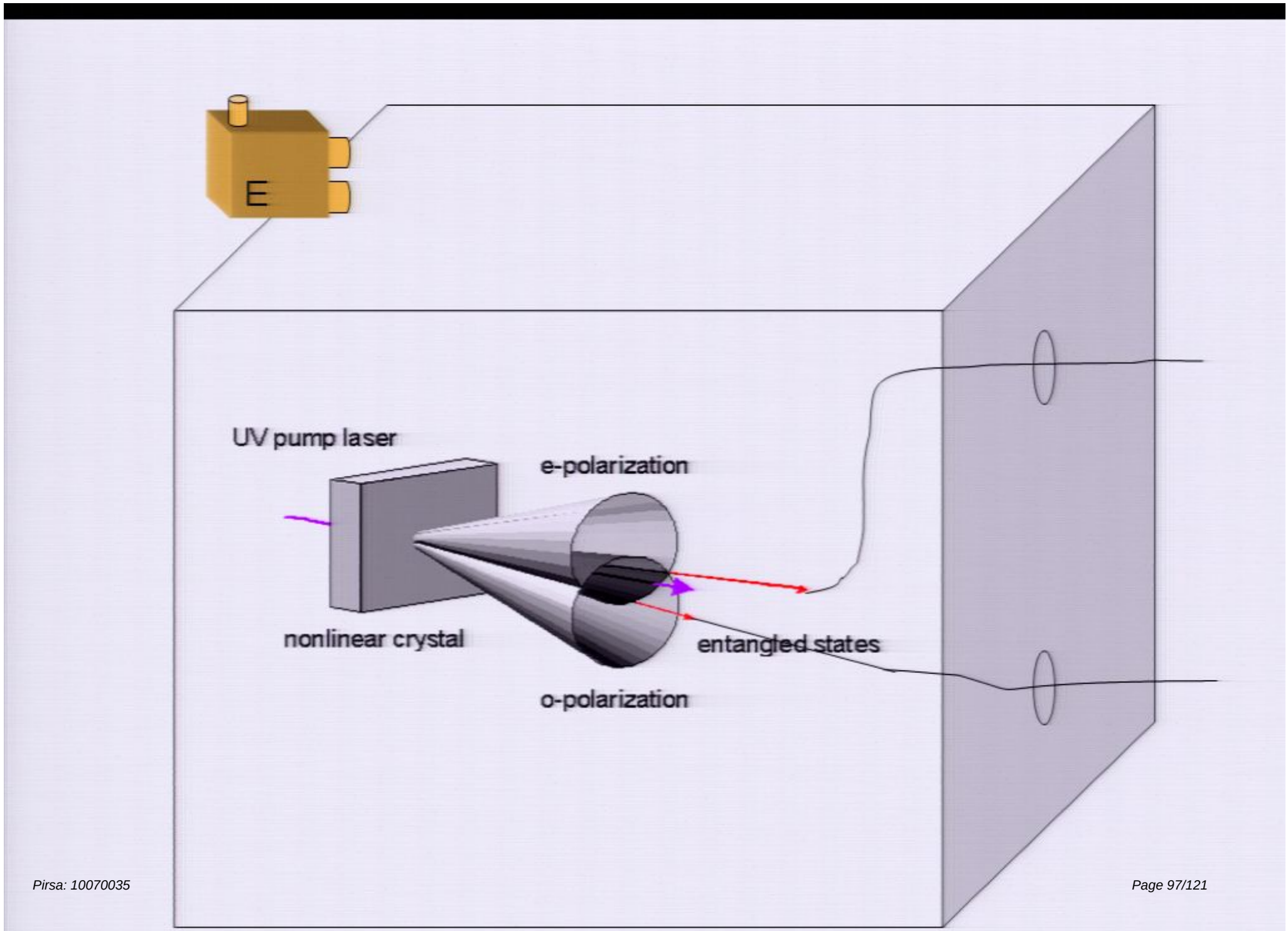
This is why a subsequent Z measurement would have a random outcome

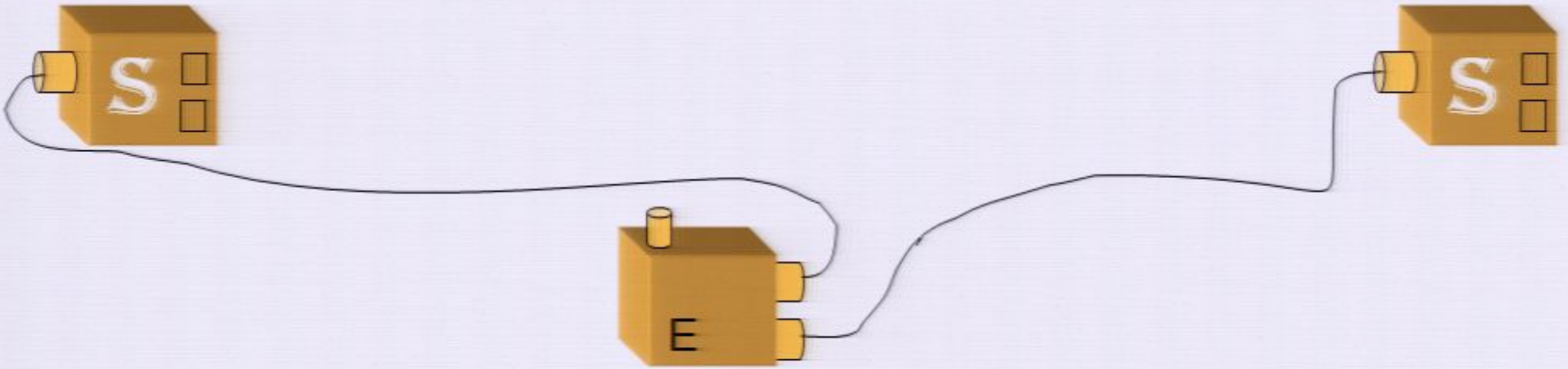
Bell's theorem

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
E
S

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

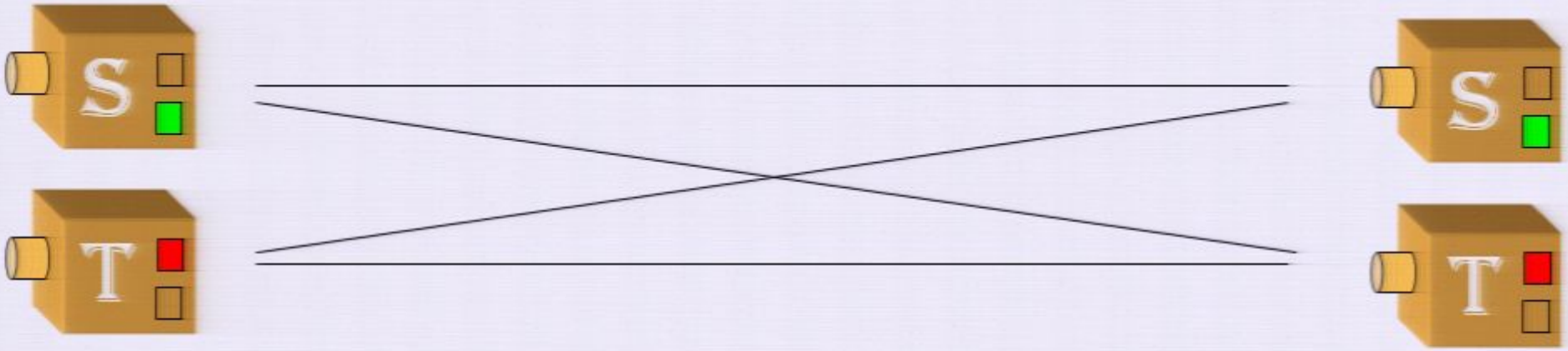
Suppose which of S or T occurs at each wing is chosen at random

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
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 1

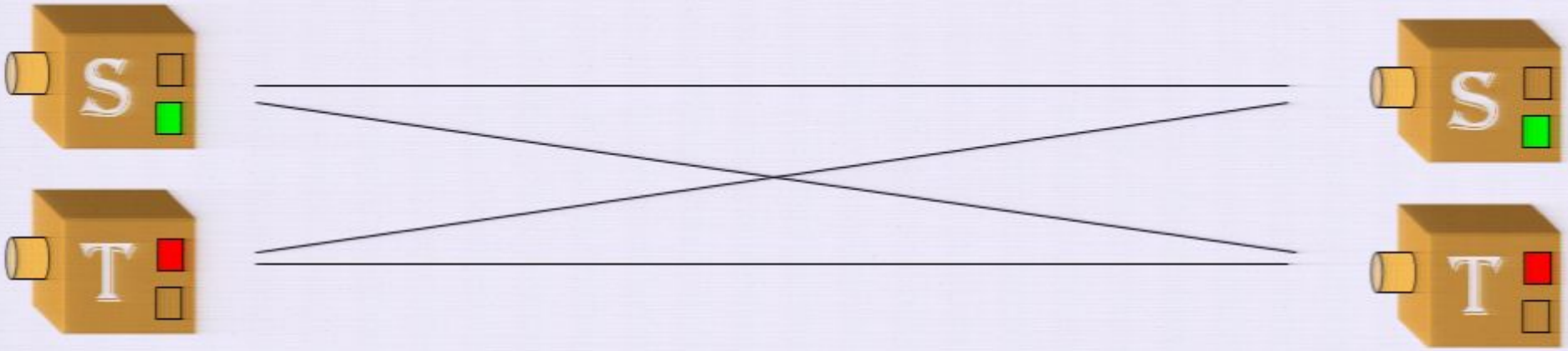
Features:

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
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

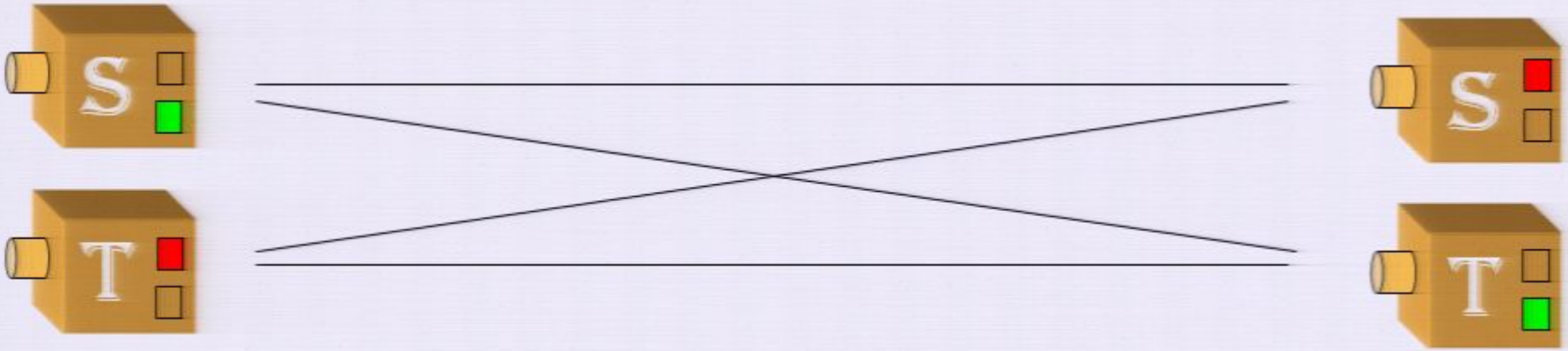
Features:

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


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

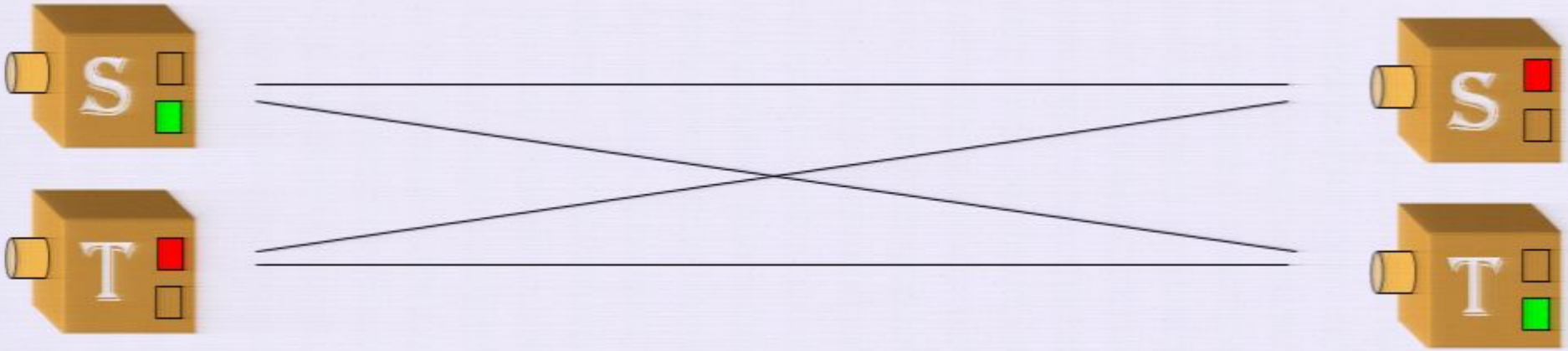
Features:

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


S
T
S
T

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

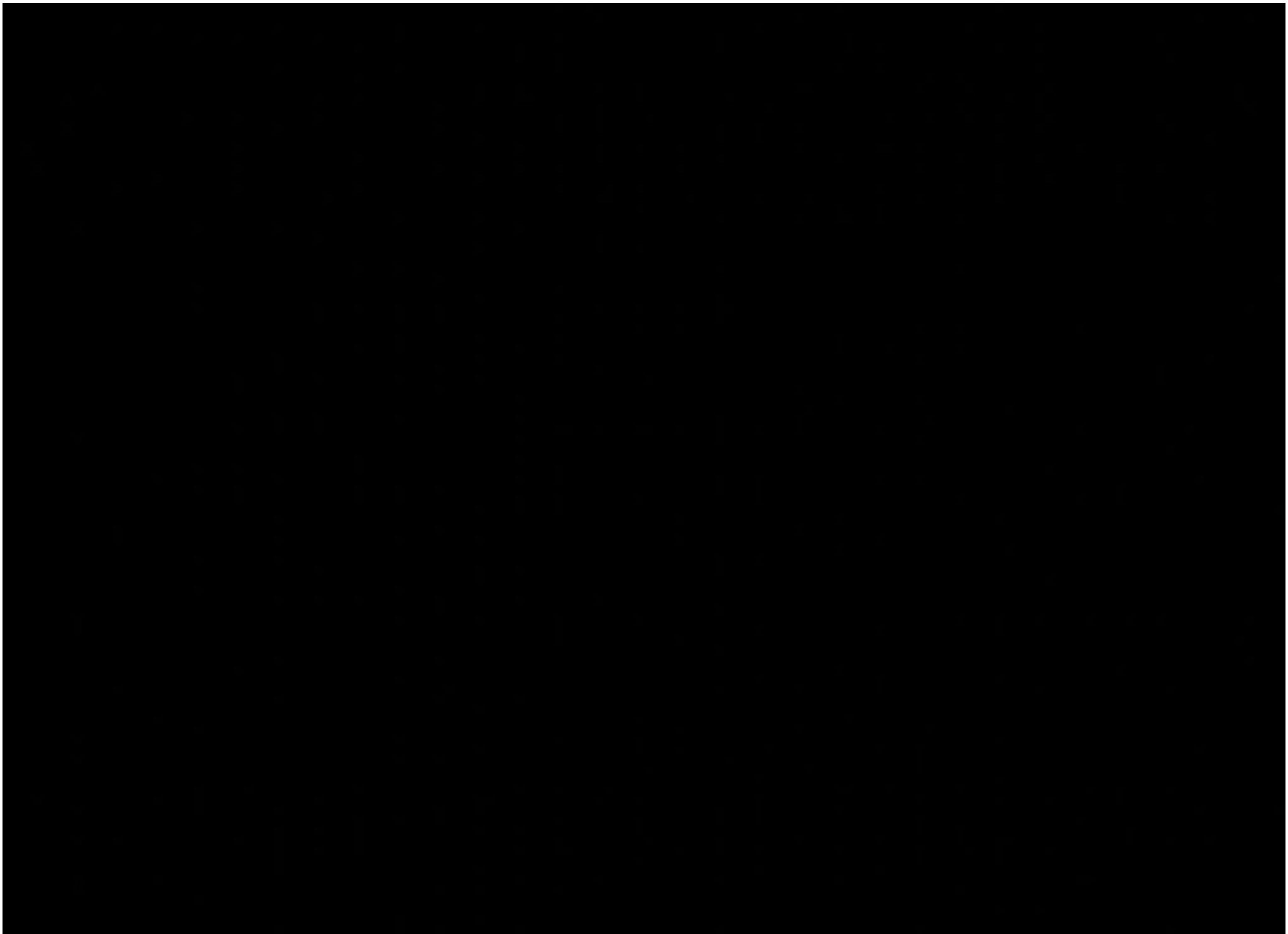
Suppose which of S or T occurs at each wing is chosen at random

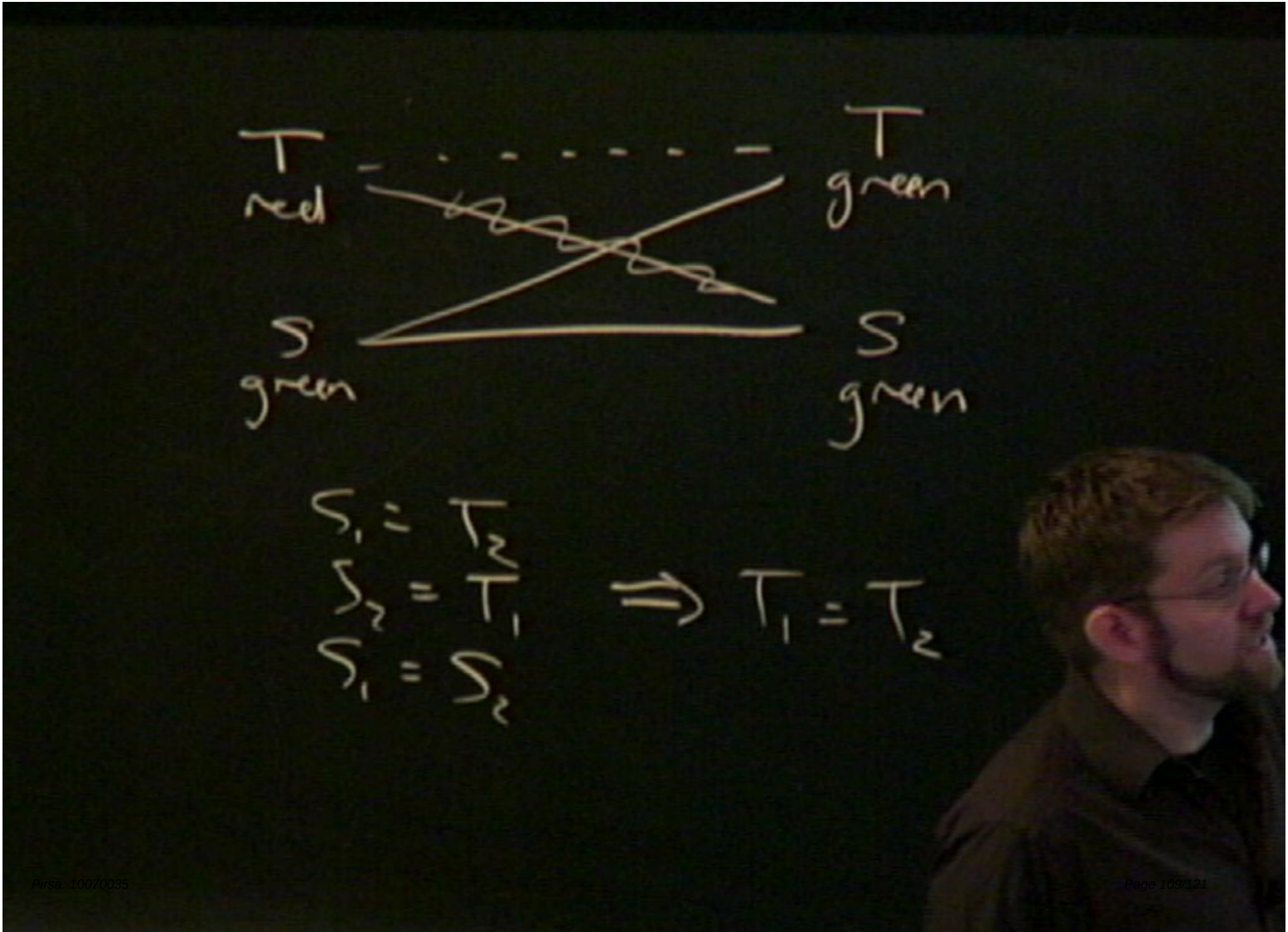
Scenario 3

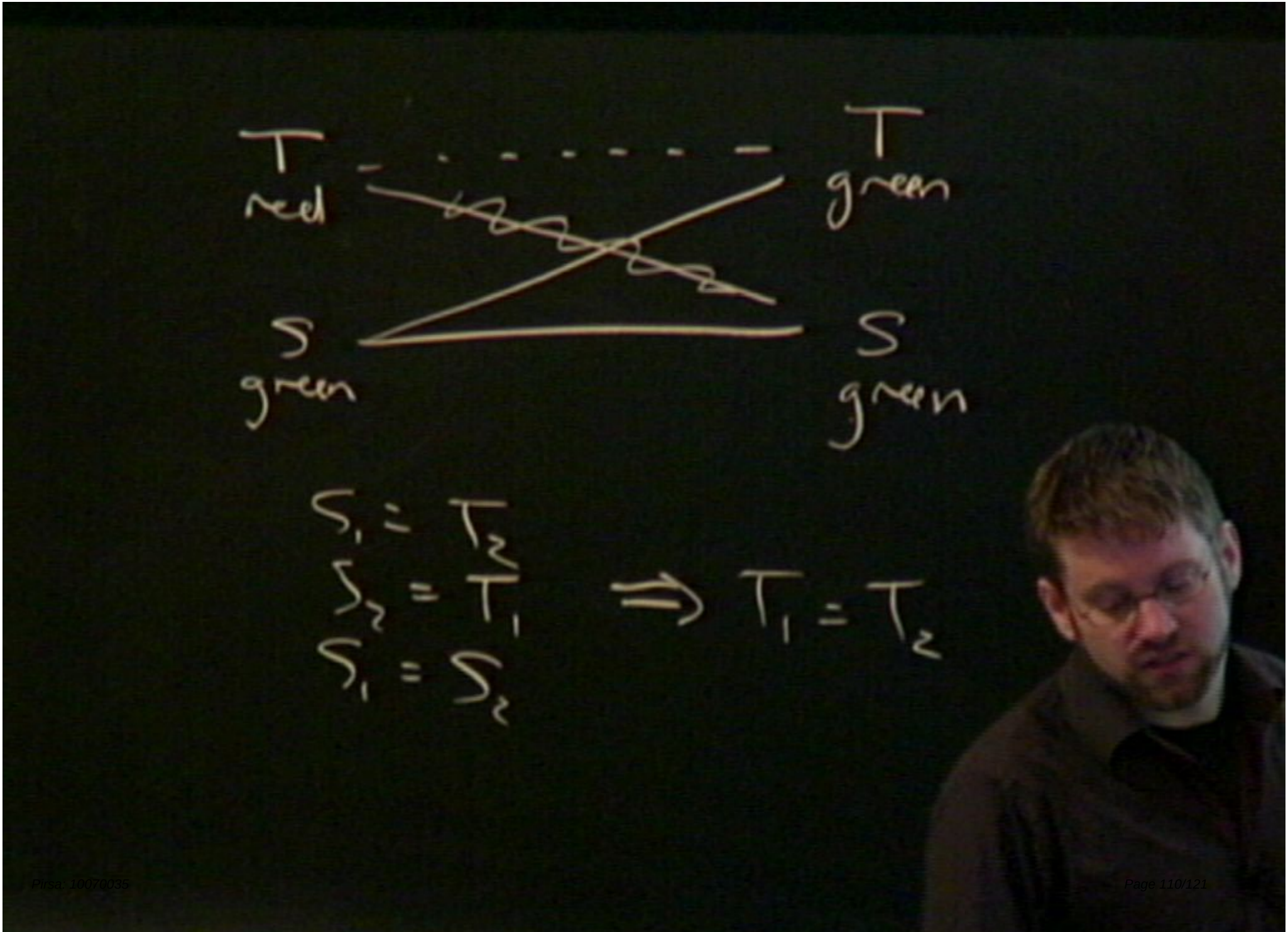
Features:

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




T
red
T
green
S
green
S
green
$S_1 = T_2$
$S_2 = T_1$
$S_1 = S_2$
$\Rightarrow T_1 = T_2$


T
red
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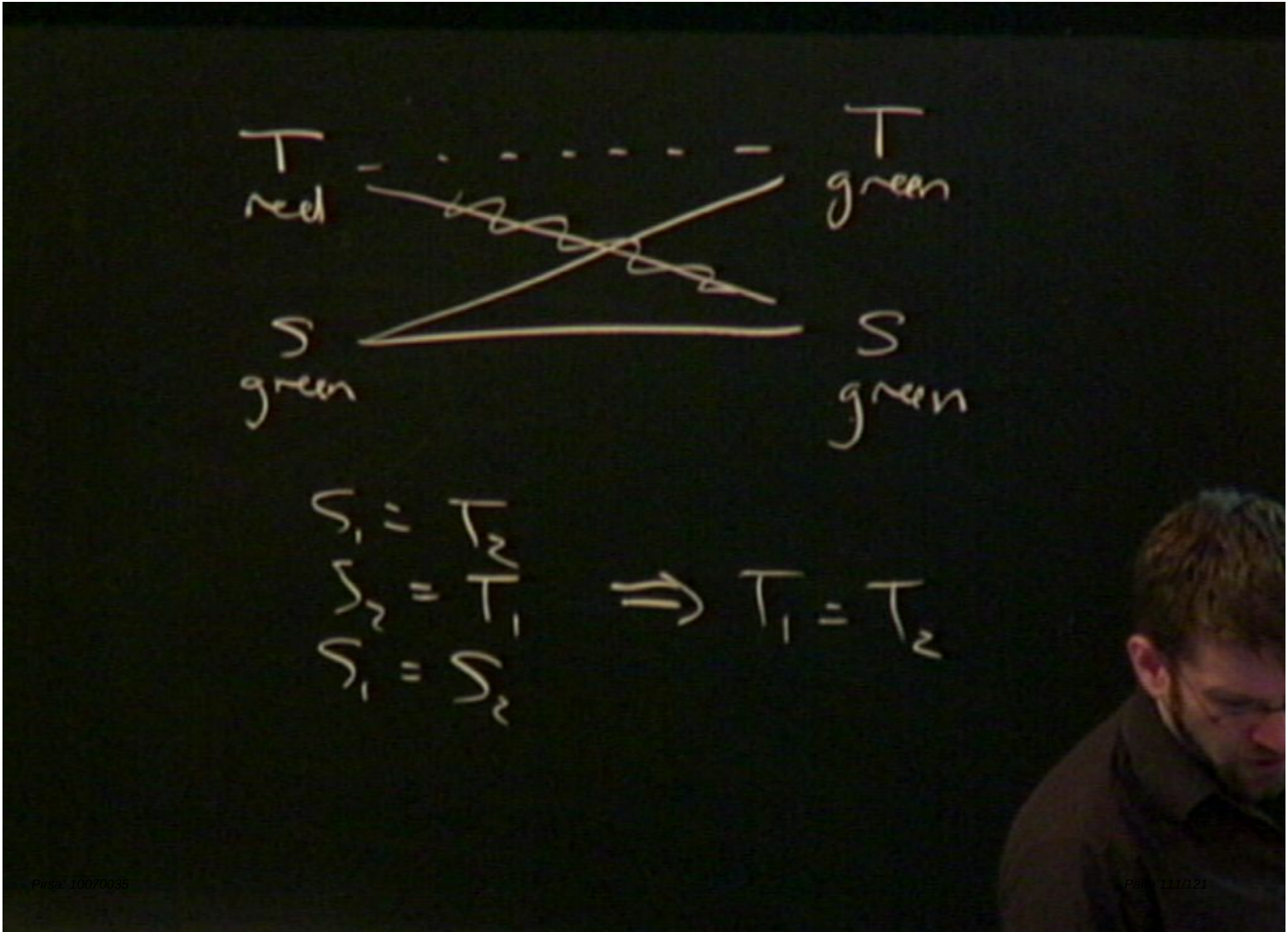
$S_1 = T_2$
$S_2 = T_1$
$S_1 = S_2$
$\Rightarrow T_1 = T_2$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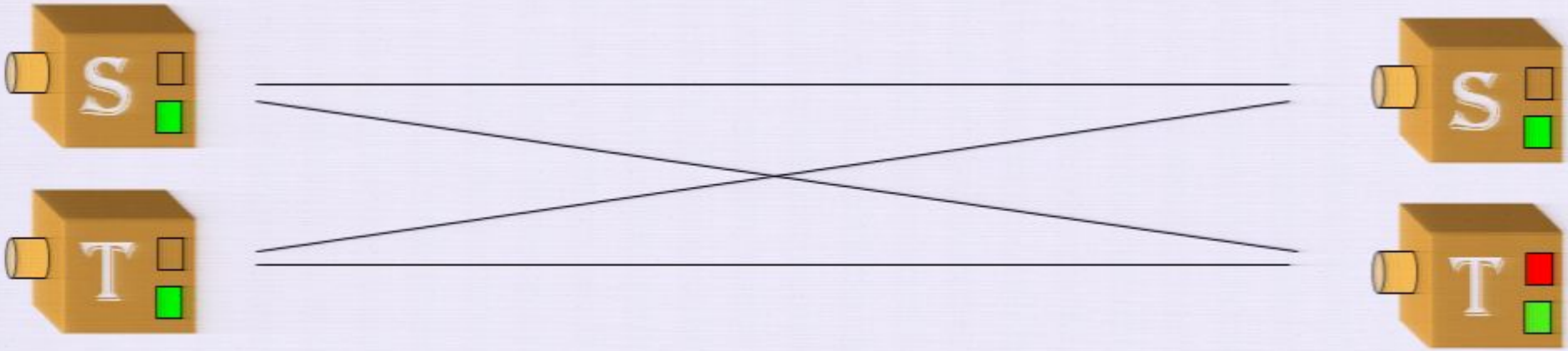

Q: What's the best probability of winning?

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

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

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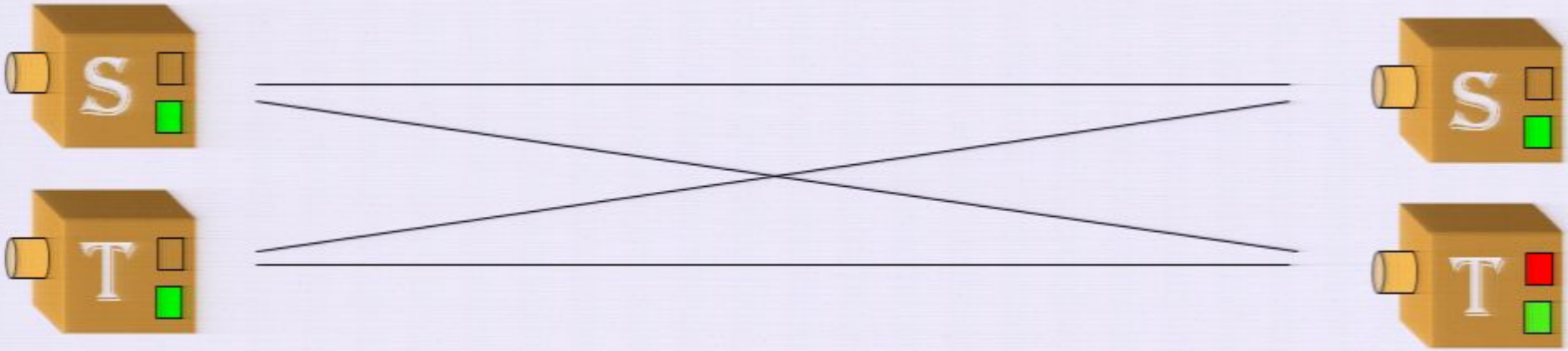
A: Communication of the choice of measurement in one wing to the system in the opposite wing

But there's a problem...



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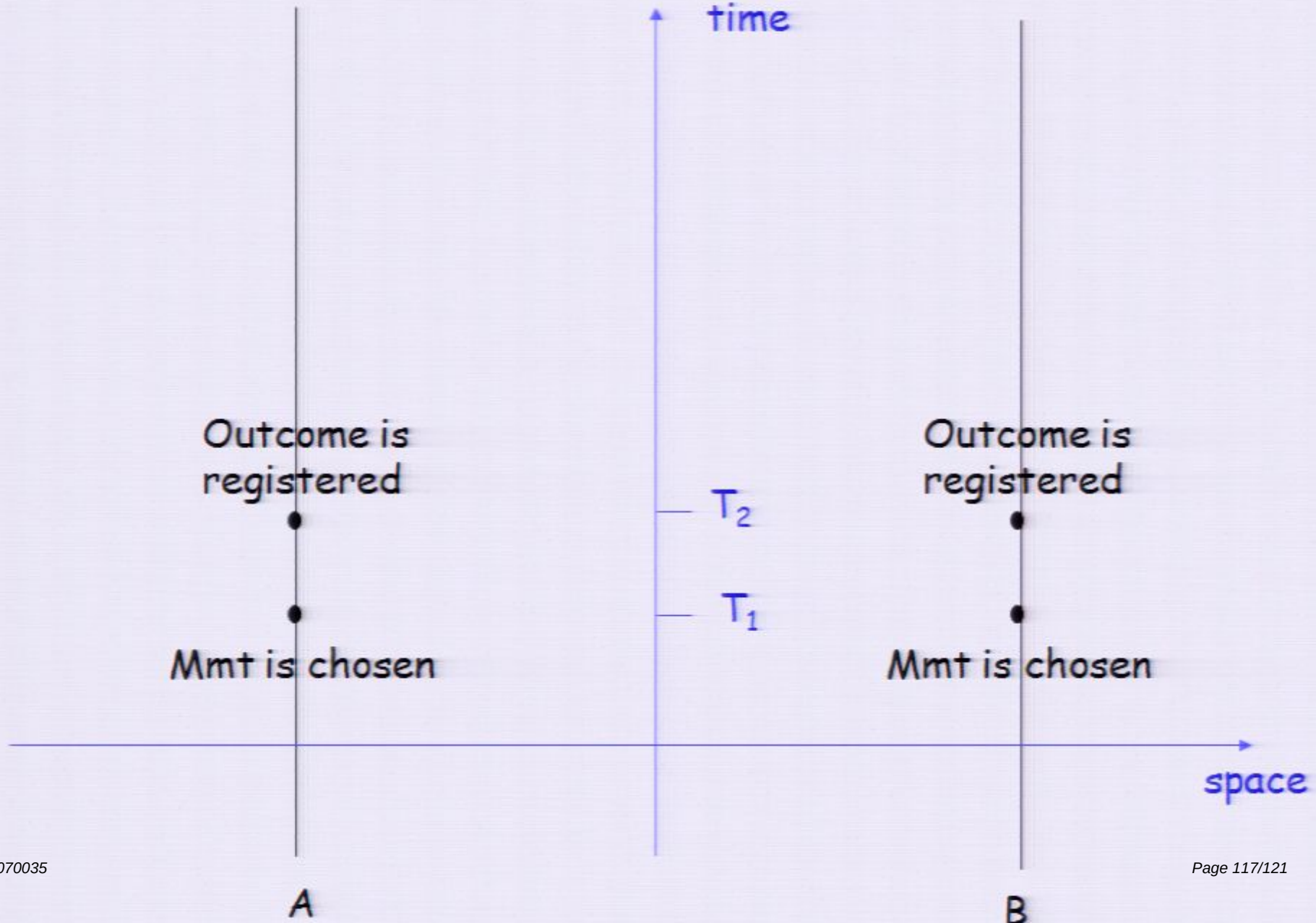
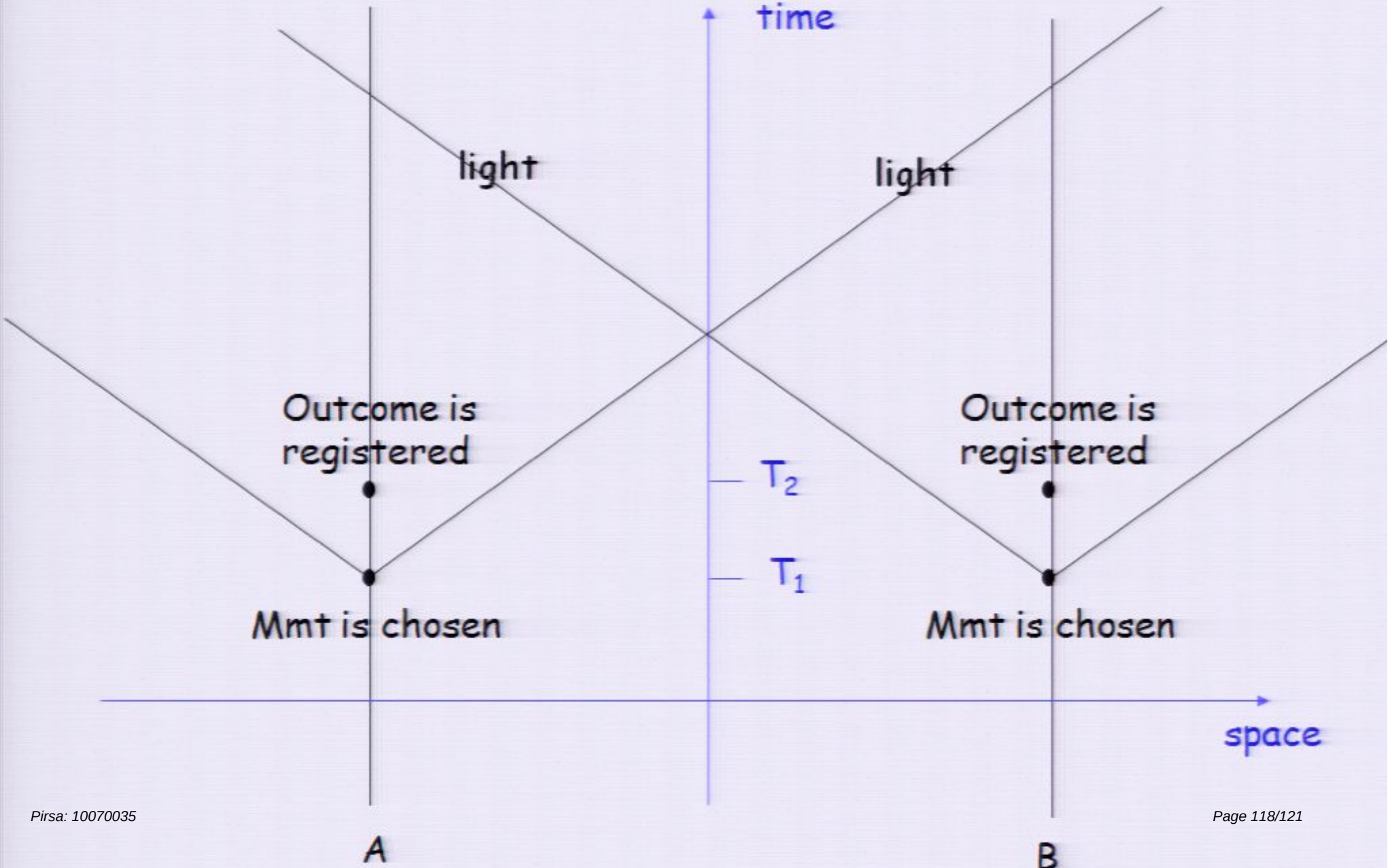
Tension with the theory of relativity



Tension with the theory of relativity



Experiment can distinguish:
1) the predictions of quantum theory
2) the predictions of any locally causal theory

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1) the predictions of quantum theory
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Quantum theory is corroborated!

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)

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