

Title: Quantum 5

Date: Aug 01, 2008 02:00 PM

URL: <http://pirsa.org/08080006>

Abstract:

The Physics of Spin

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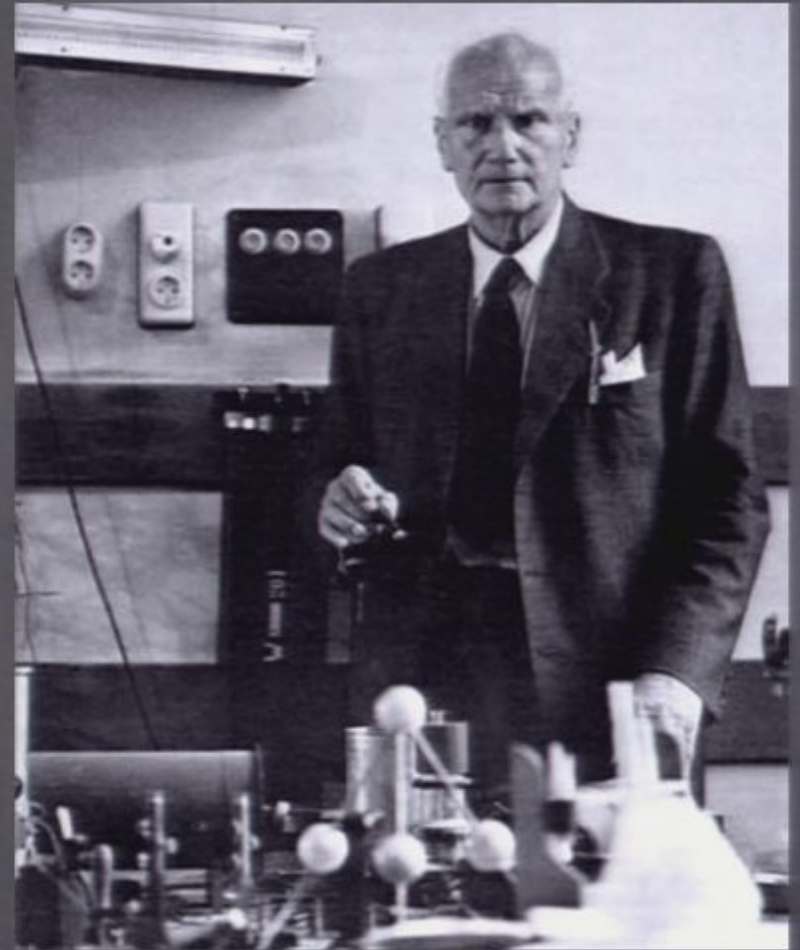


Otto Stern

The Physics of Spin



Otto Stern



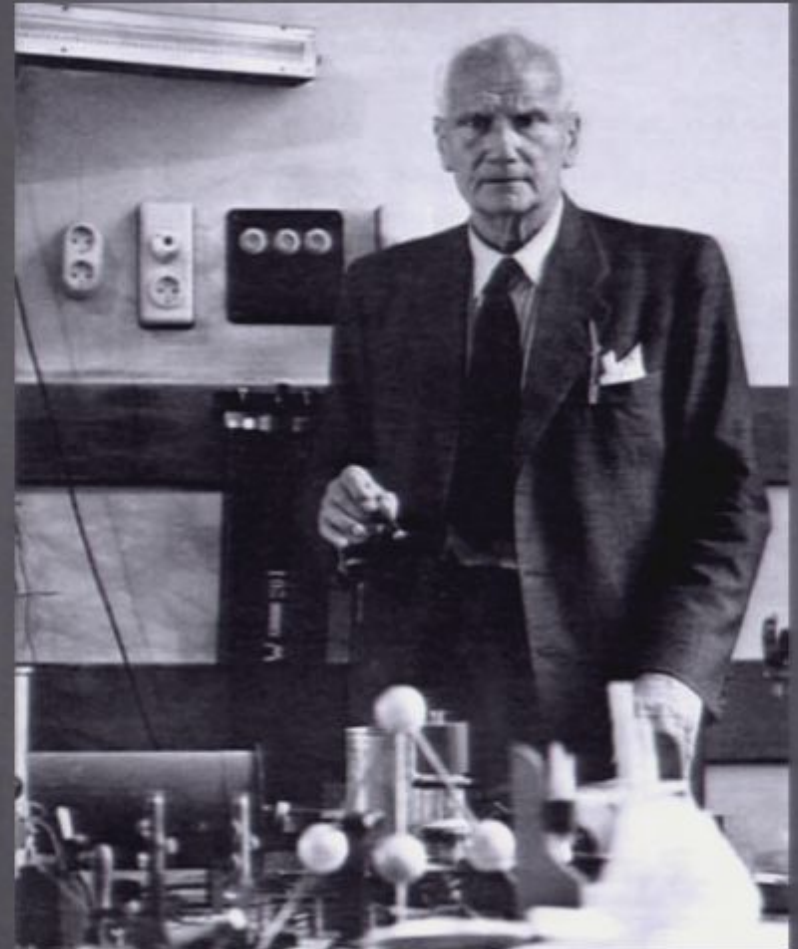
Walther Gerlach

The Physics of Spin

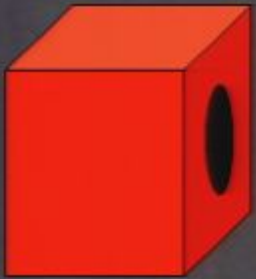


Otto Stern

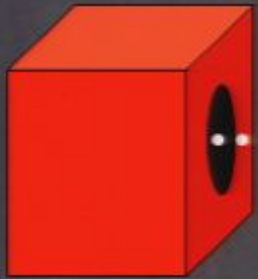
1922: Wrong theory
→ right experiment



Walther Gerlach

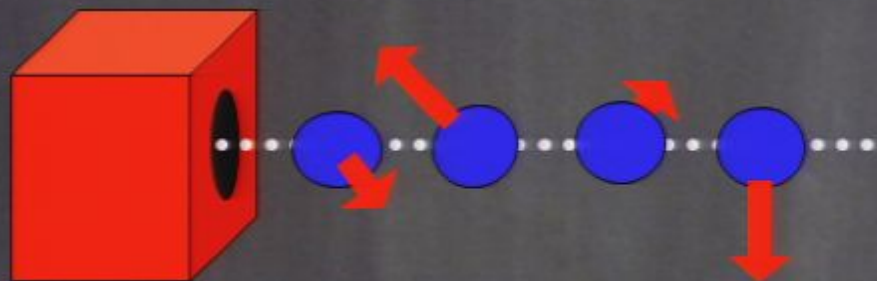


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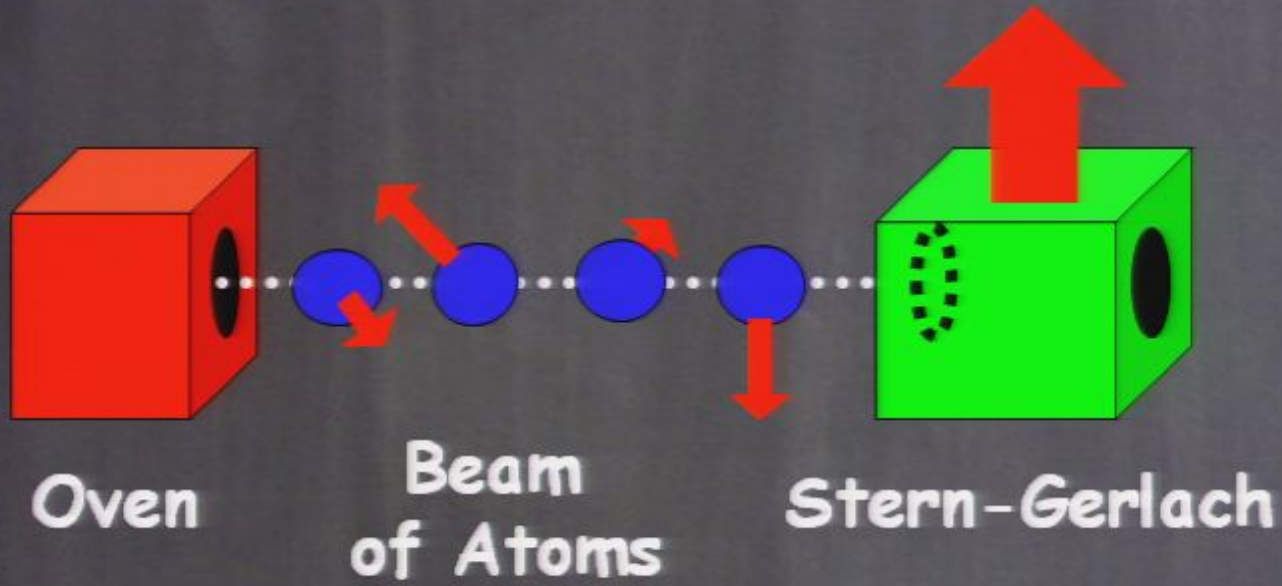
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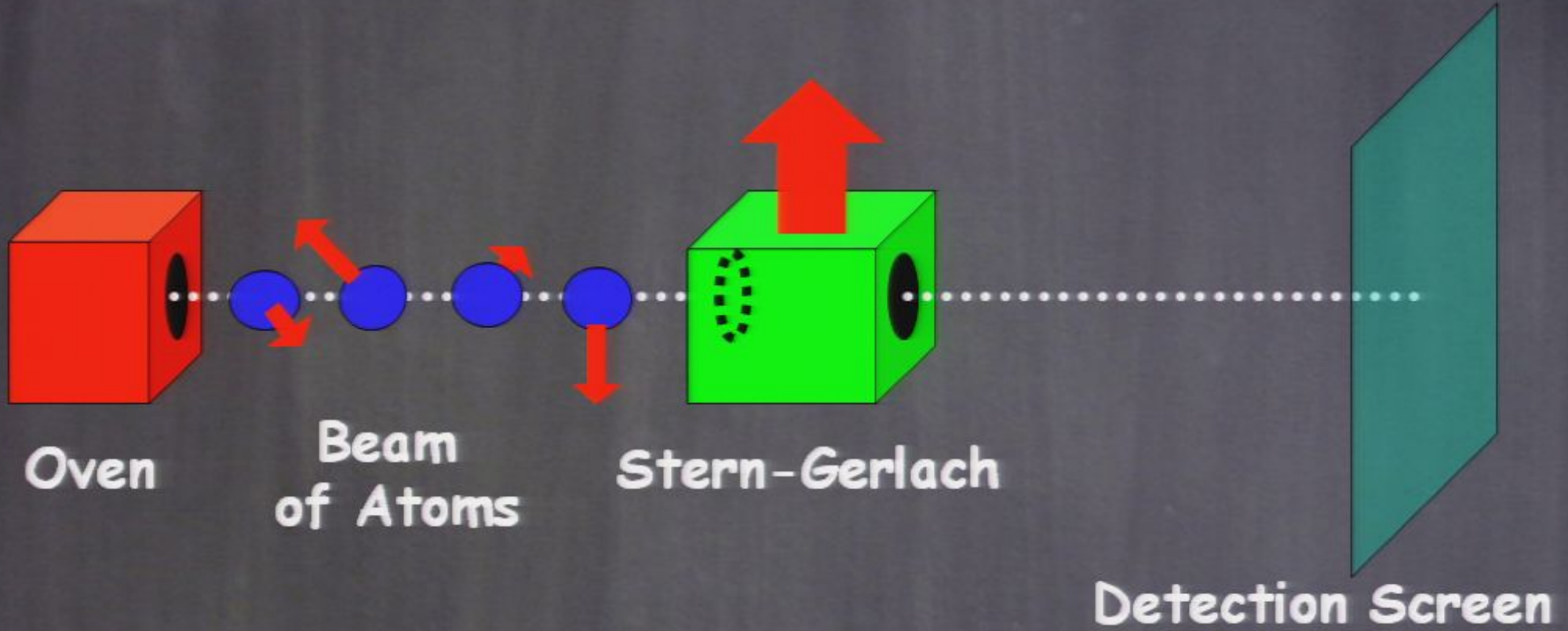
Beam
of Atoms

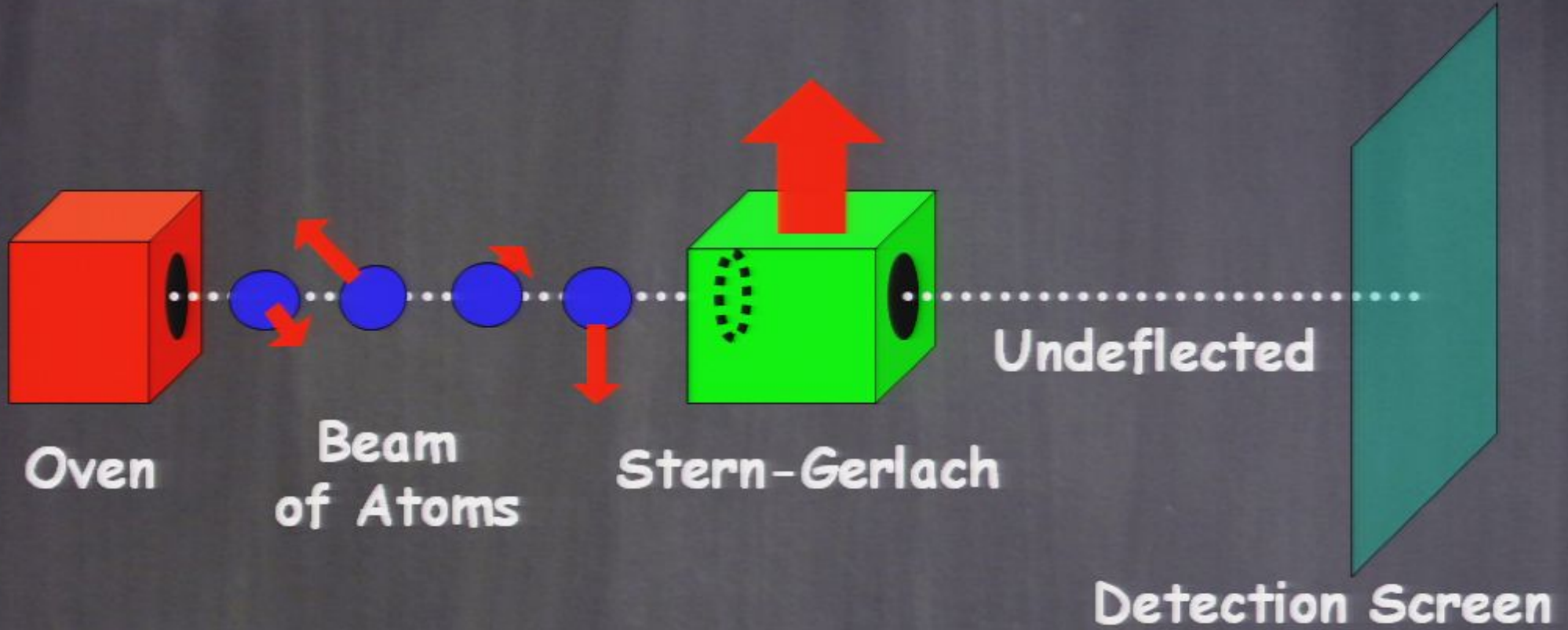


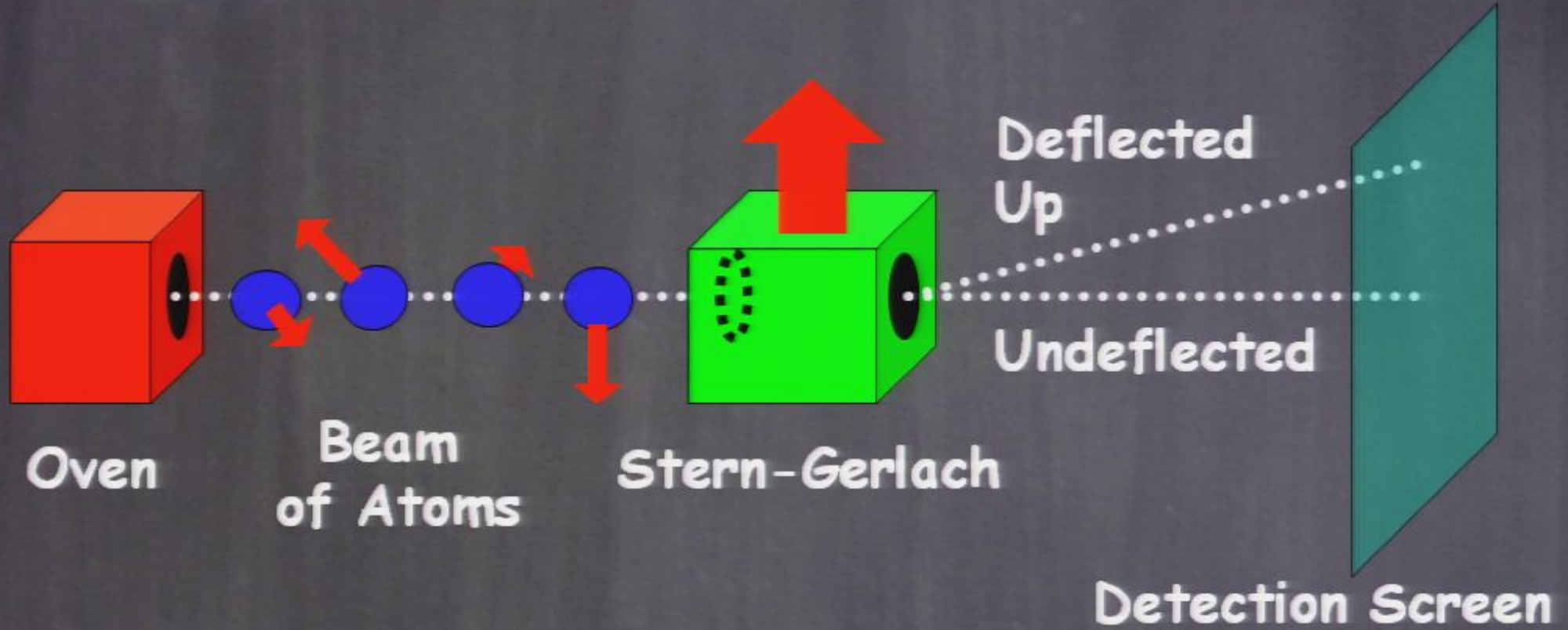
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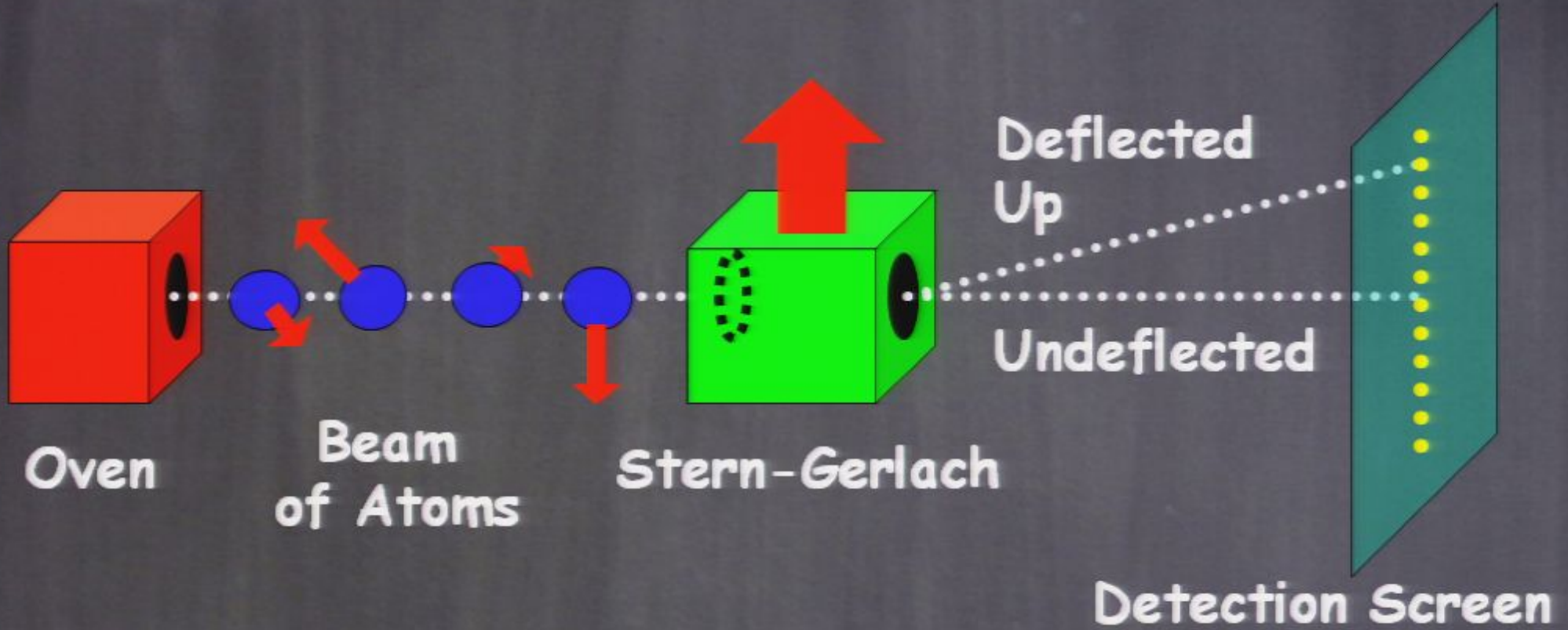
Beam
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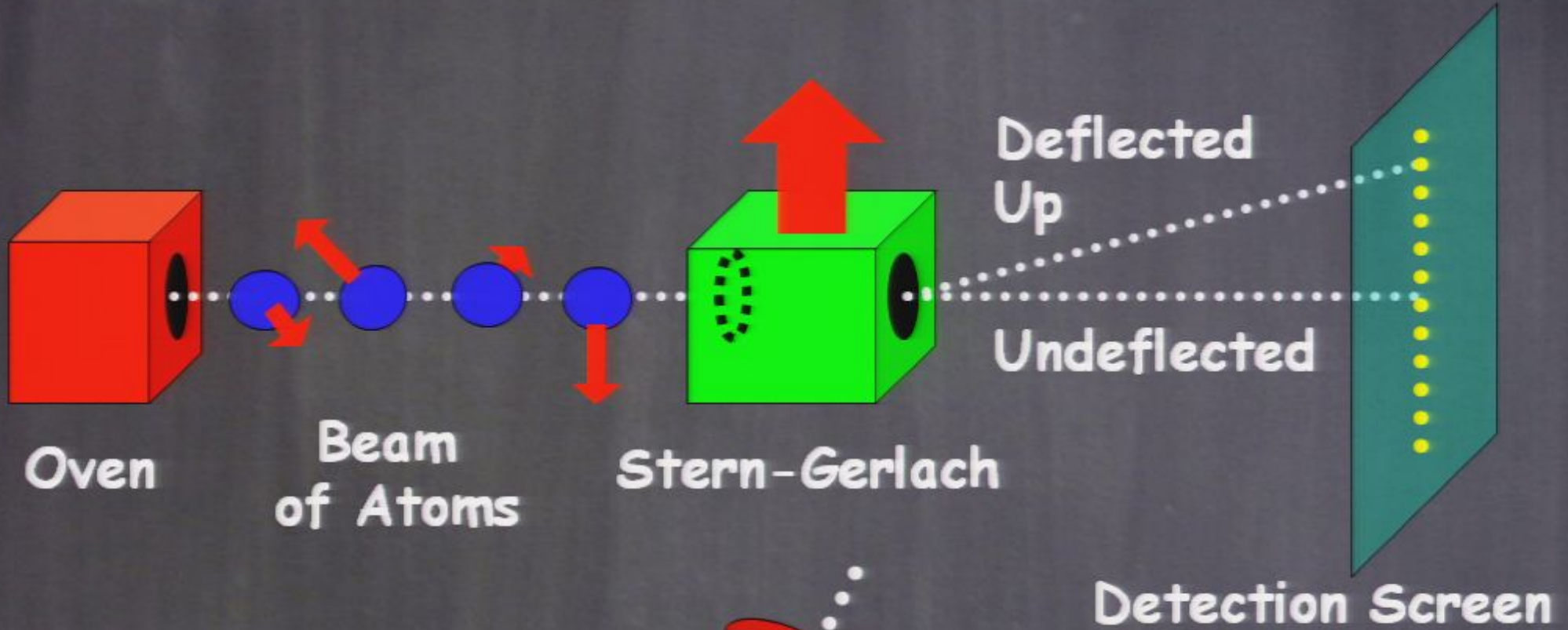








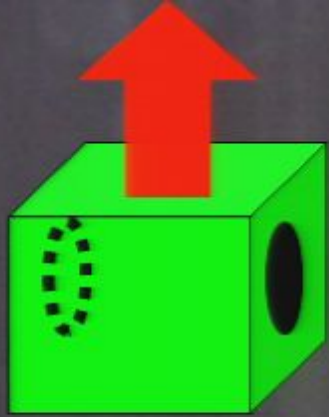
Silver
Atom

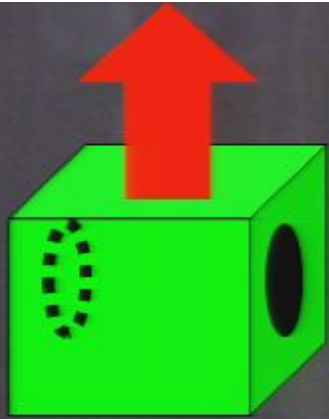


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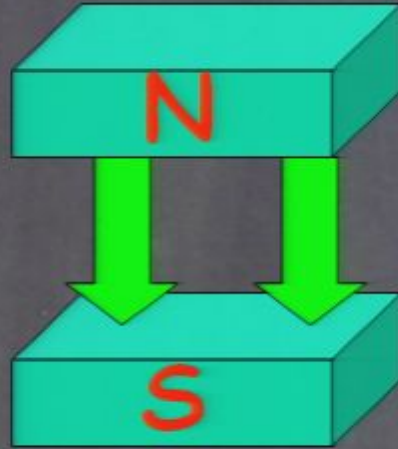


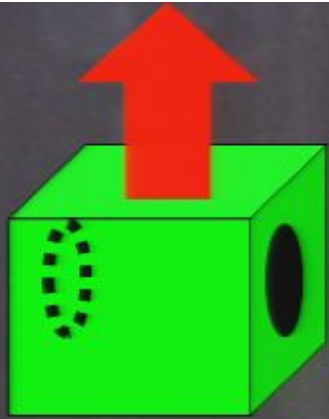
Tiny **Spinning**
Bar Magnet



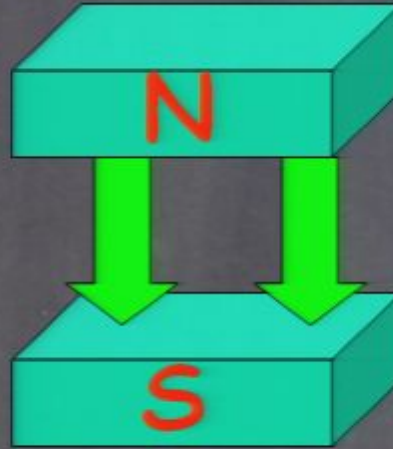


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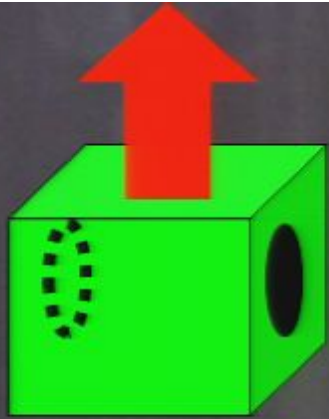




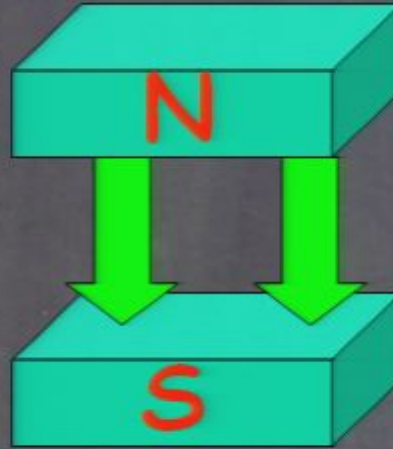
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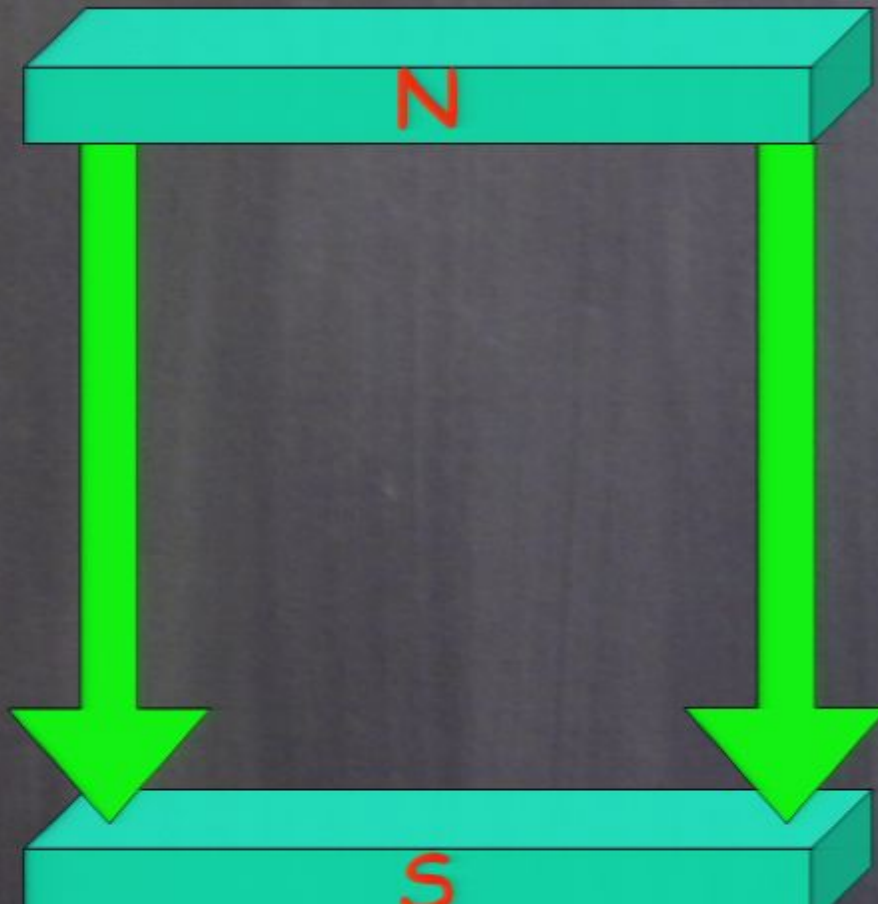
Nonuniform
Magnetic
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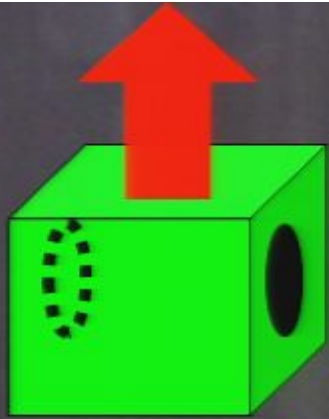


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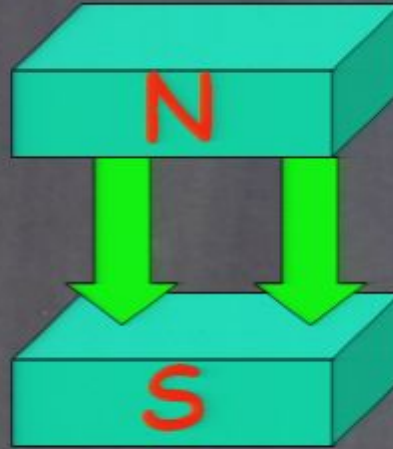


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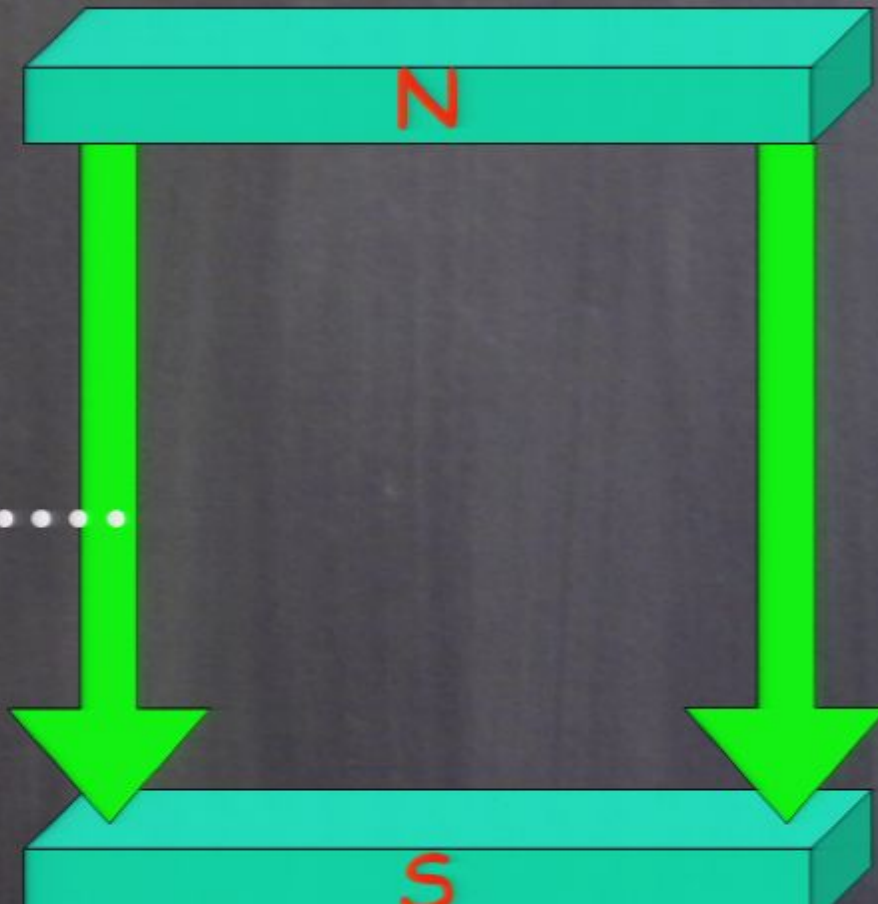


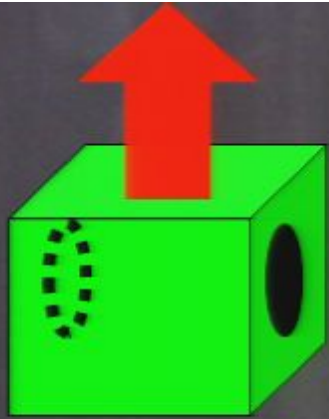


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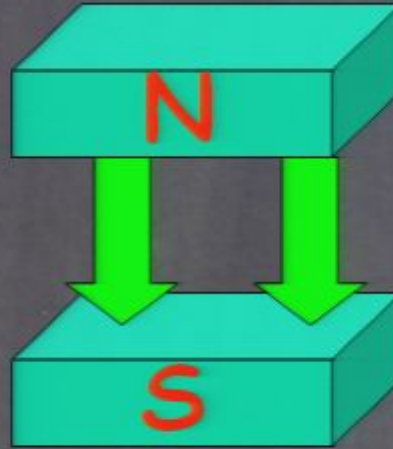


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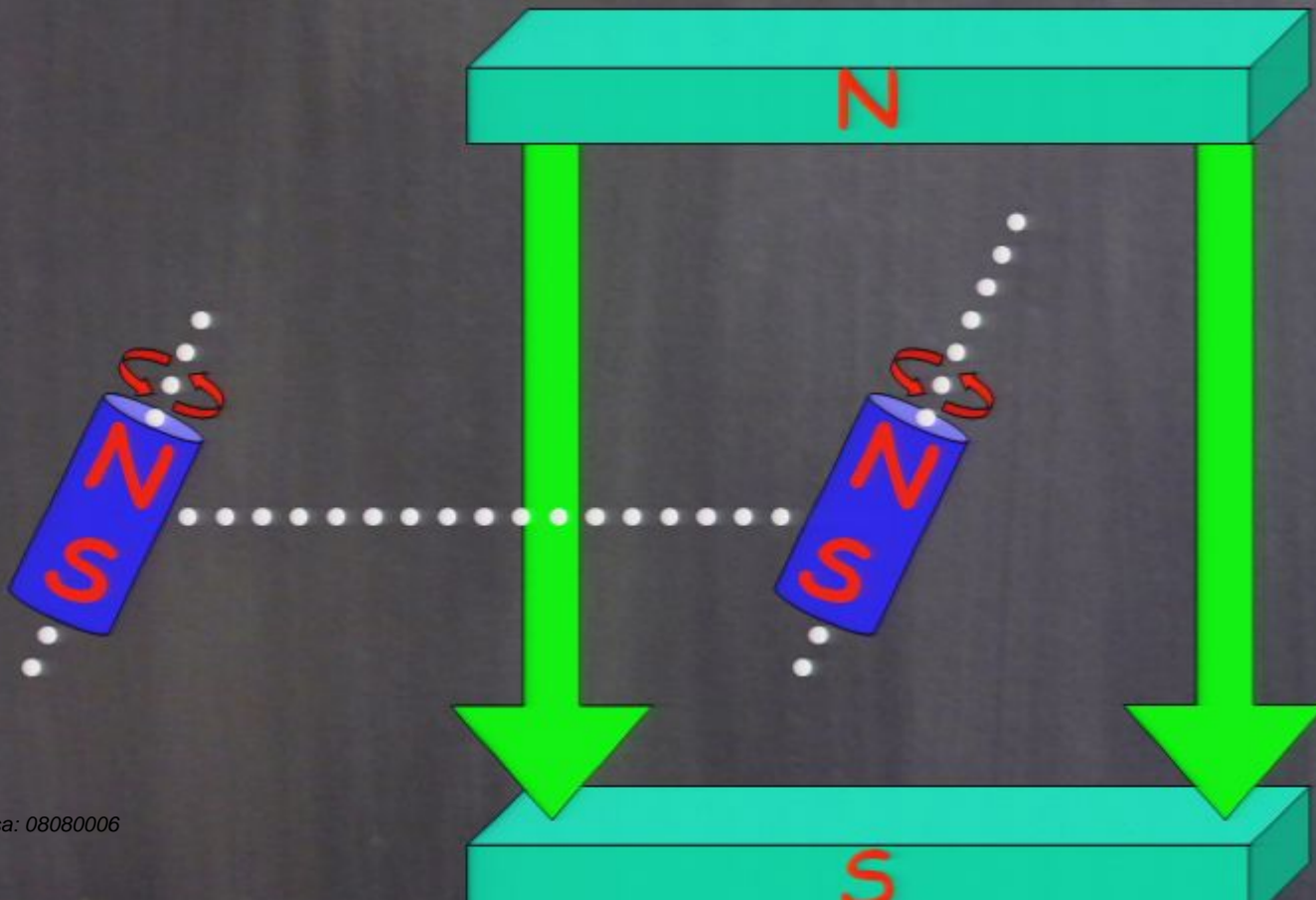


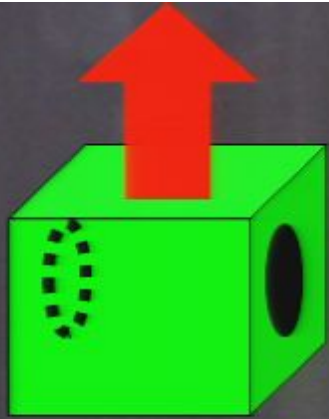


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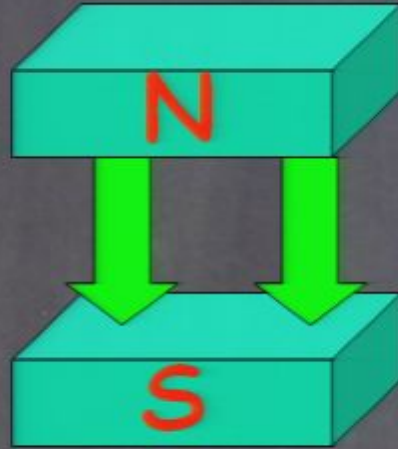


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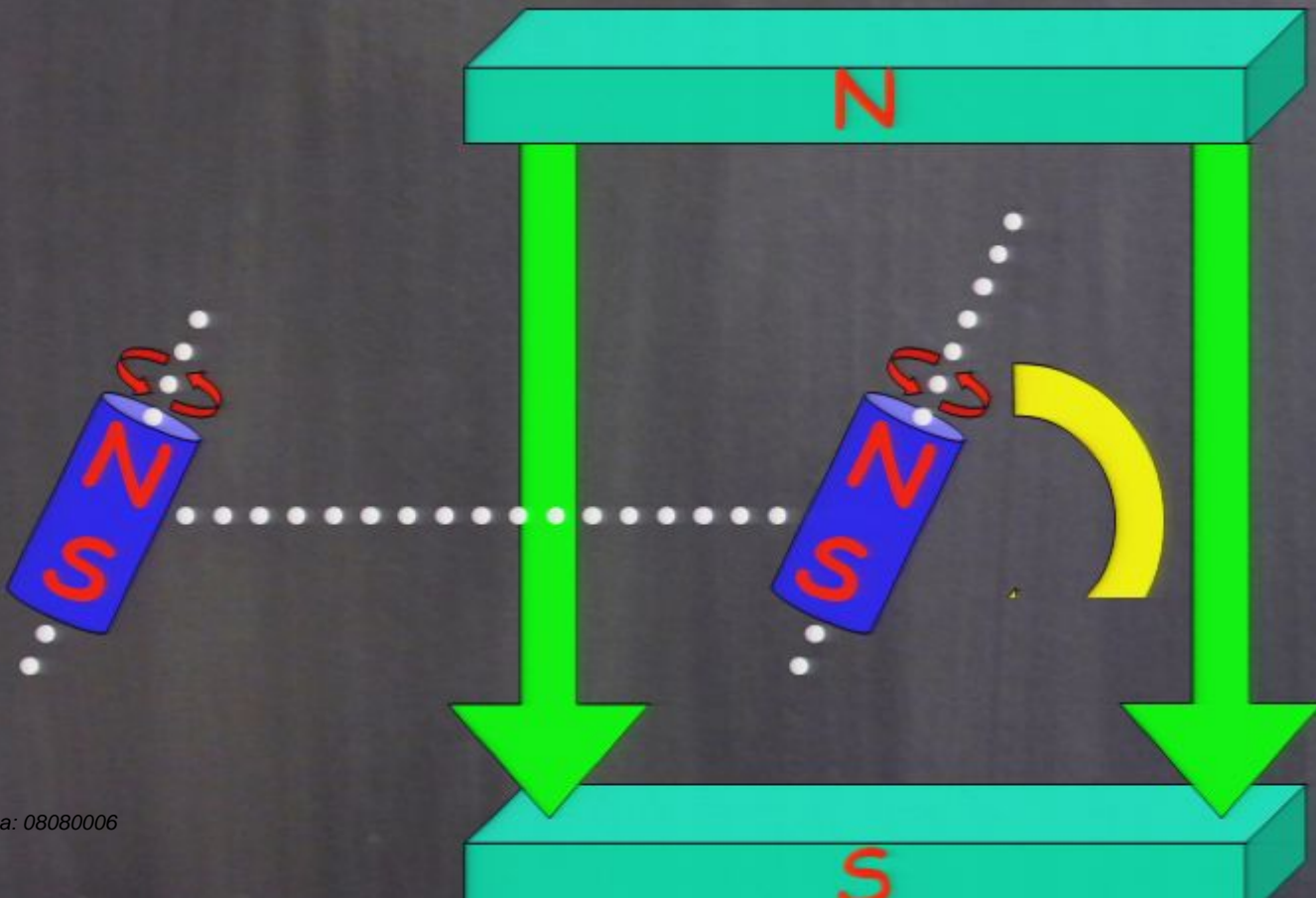


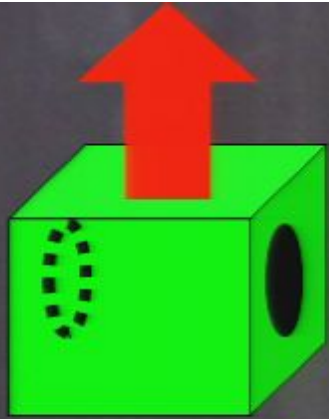


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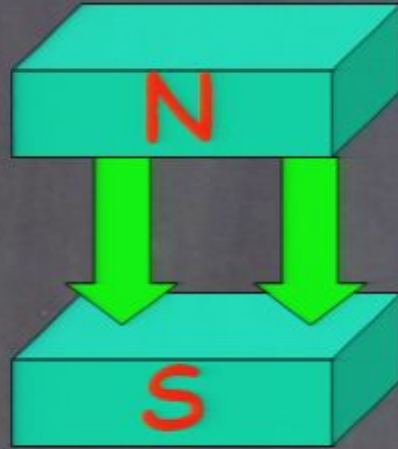


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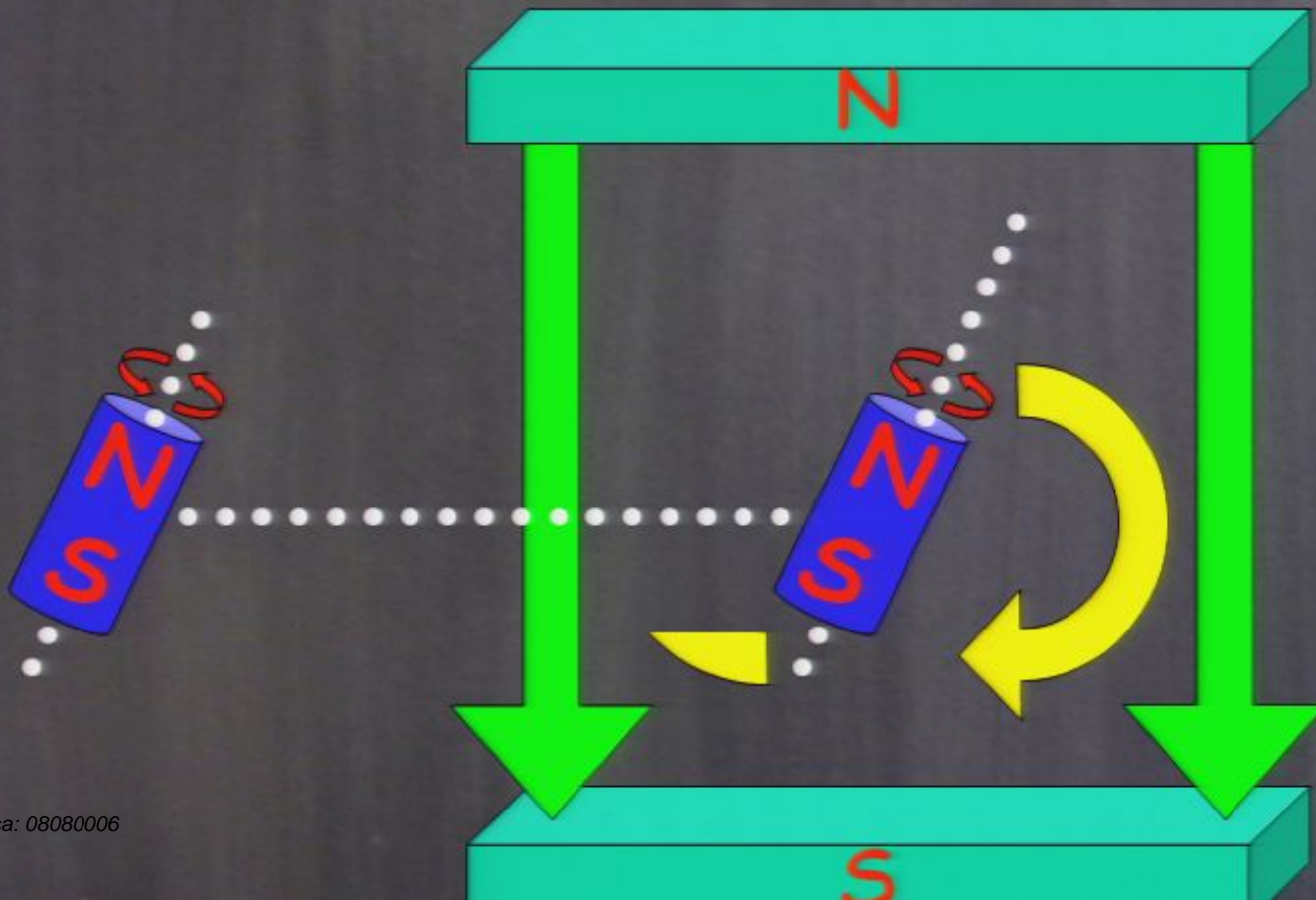


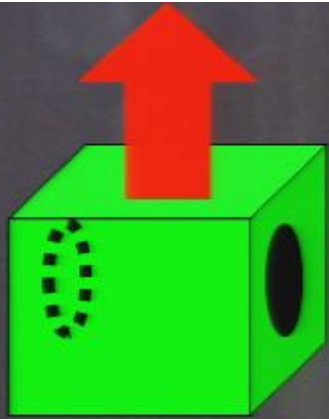


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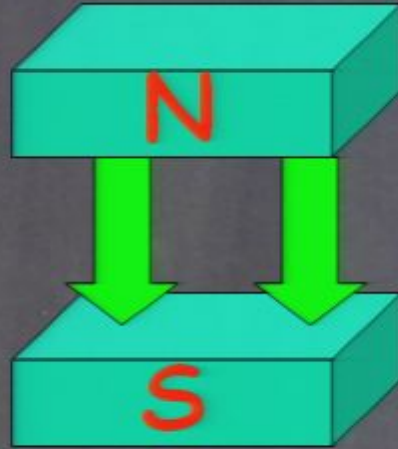


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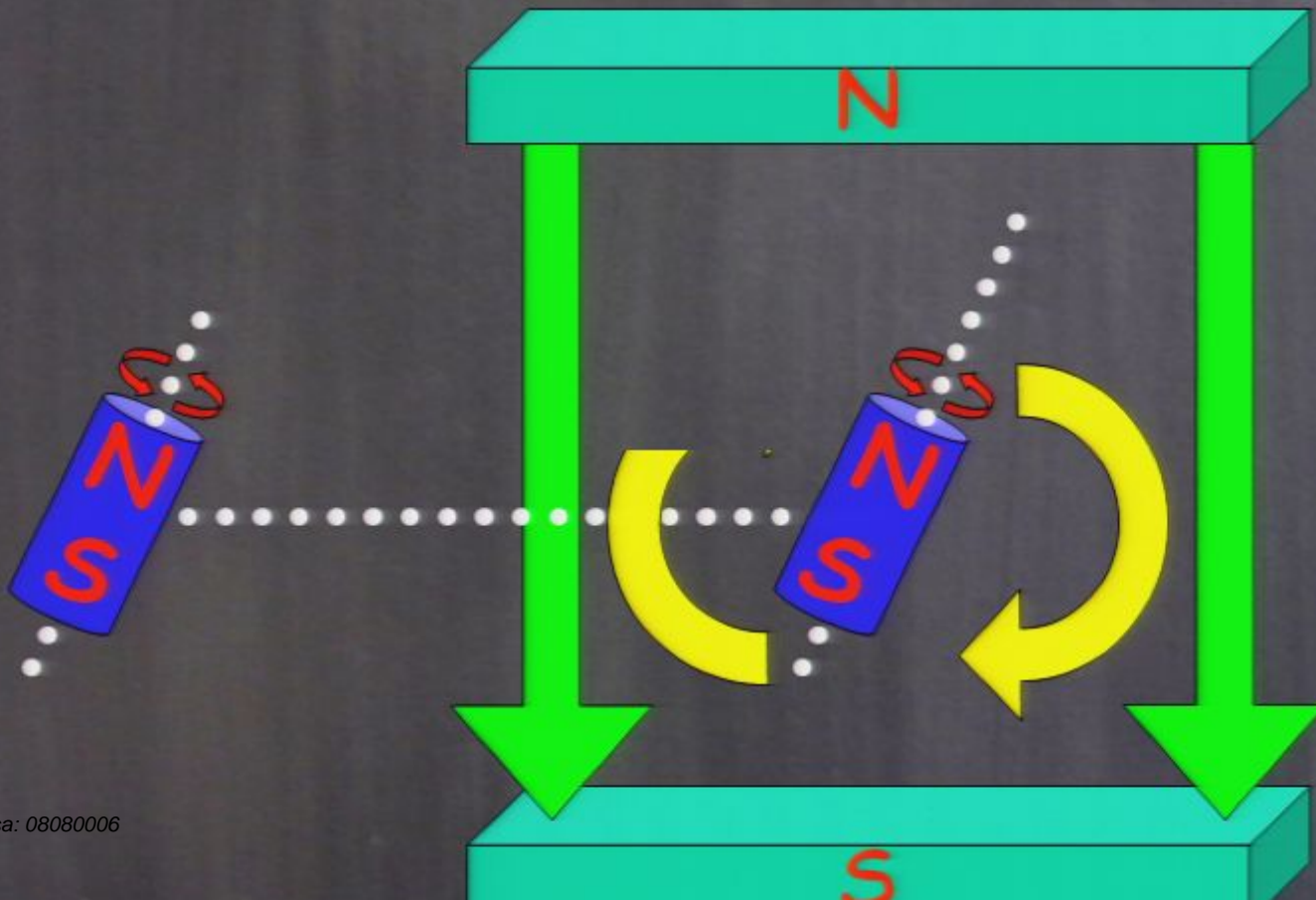


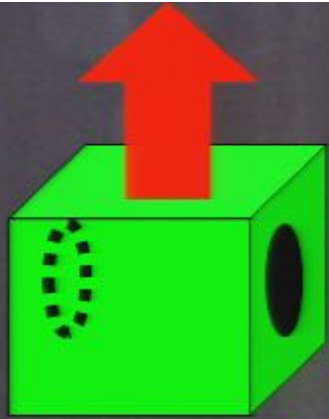


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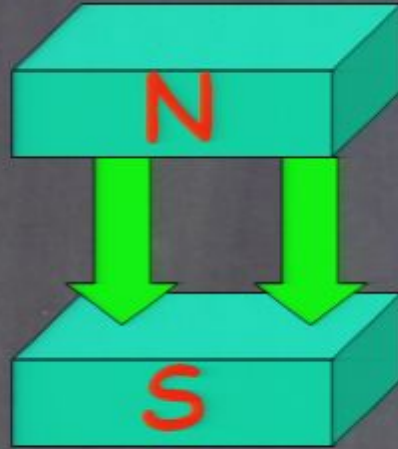


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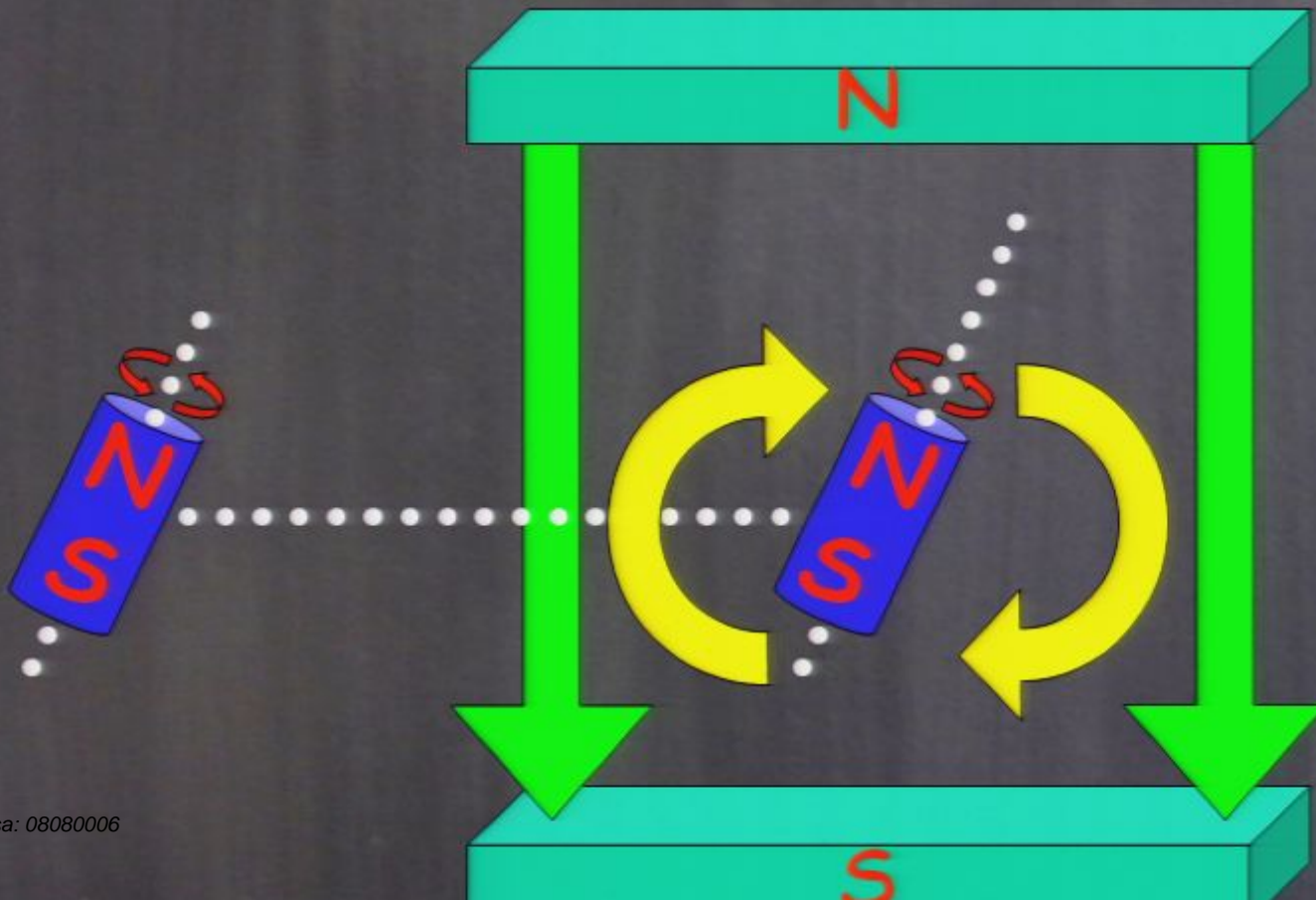


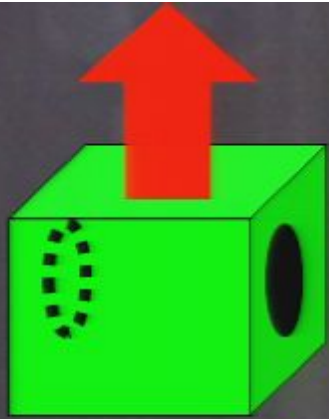


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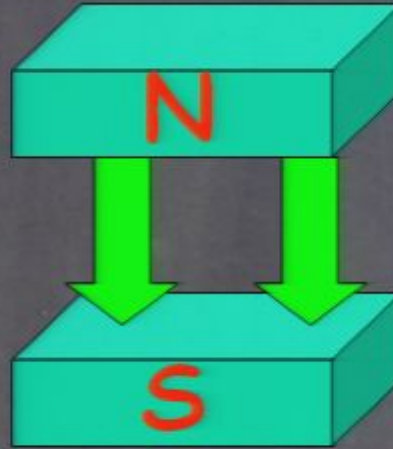


Nonuniform
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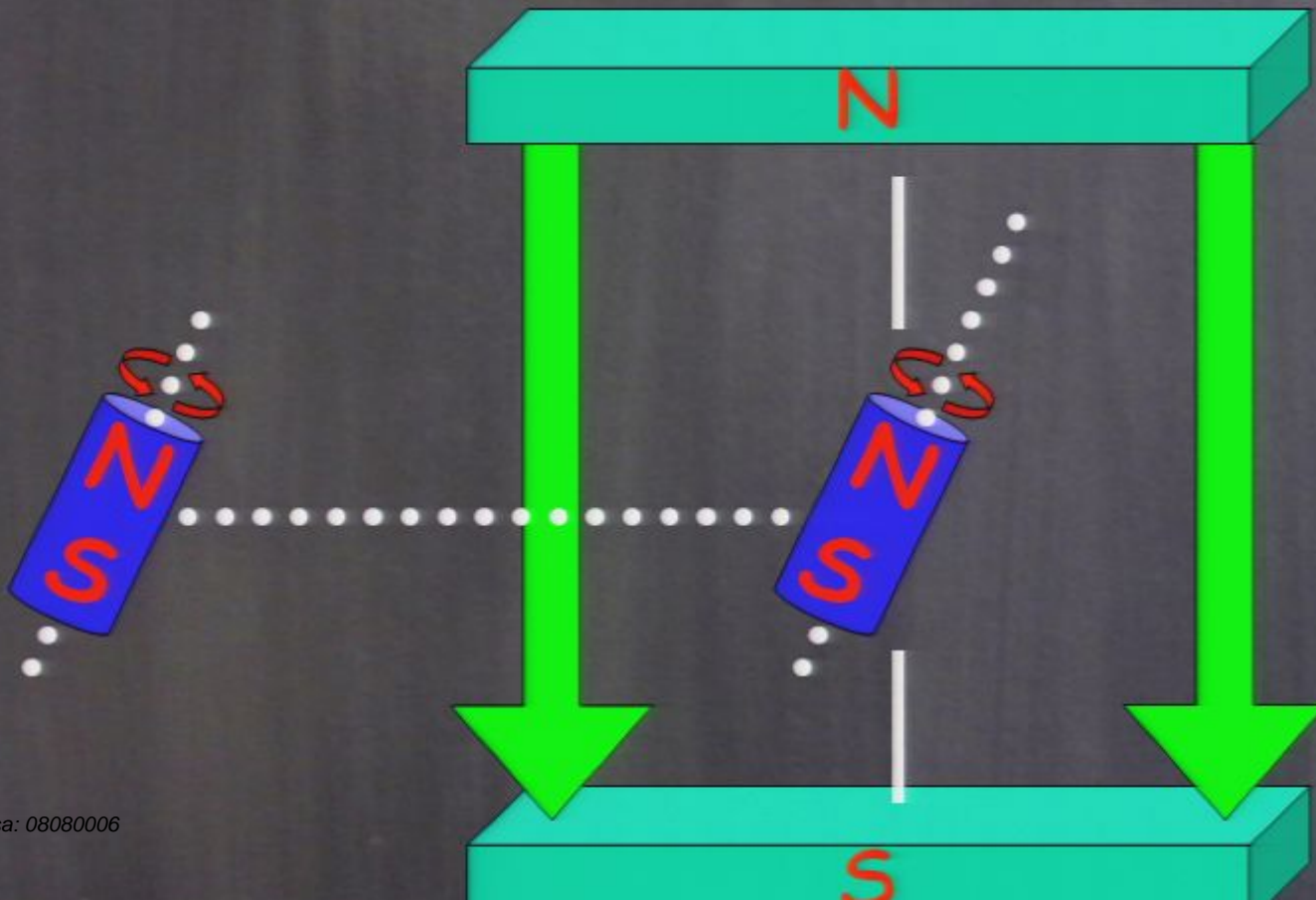


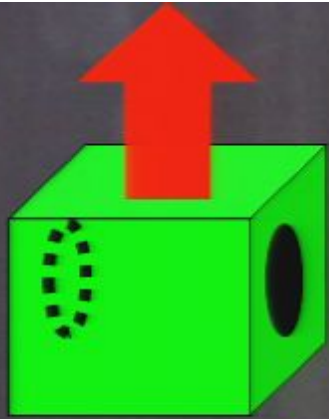


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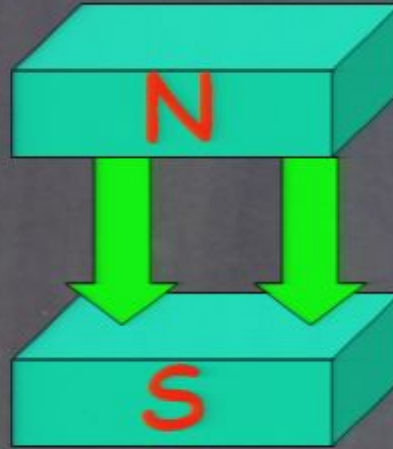


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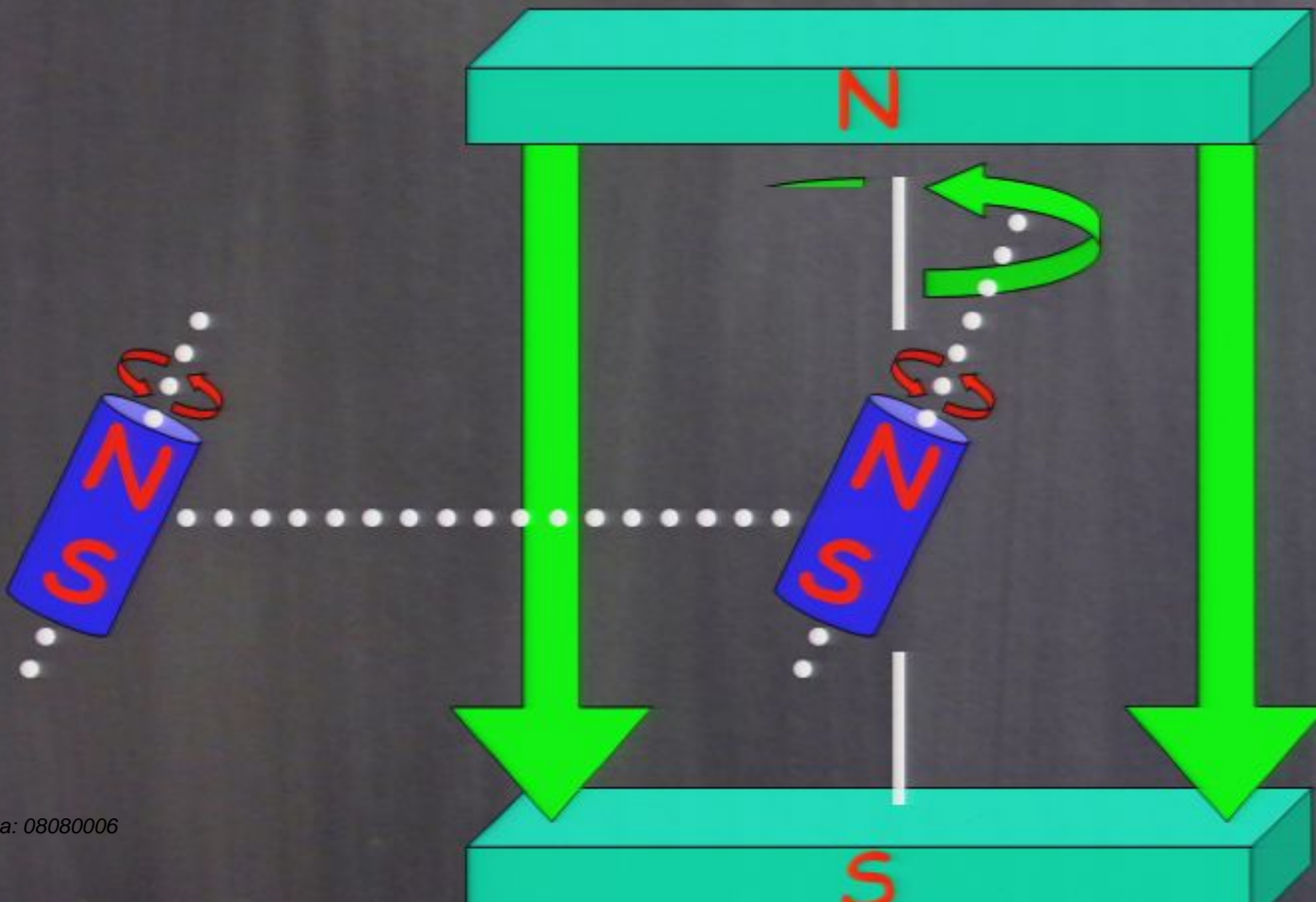


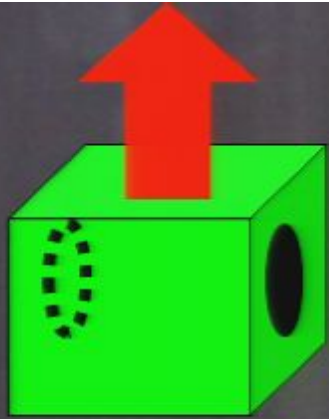


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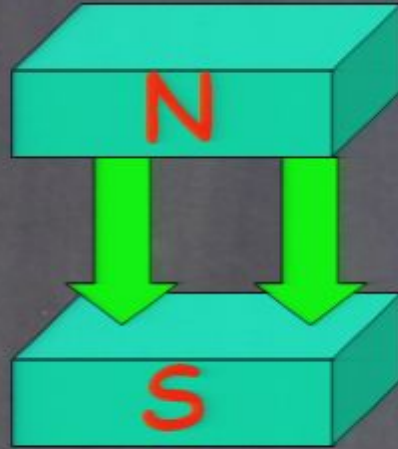


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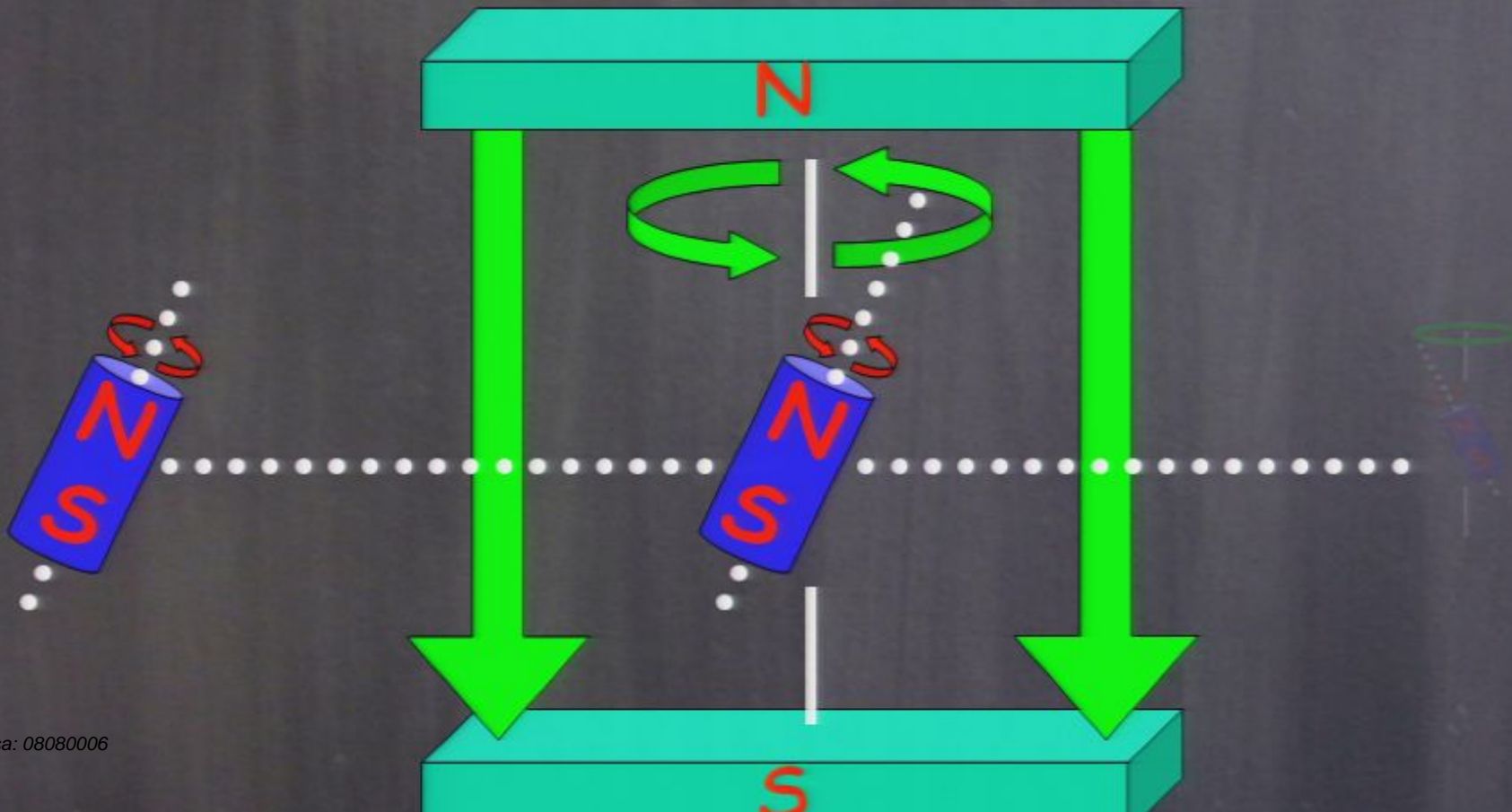


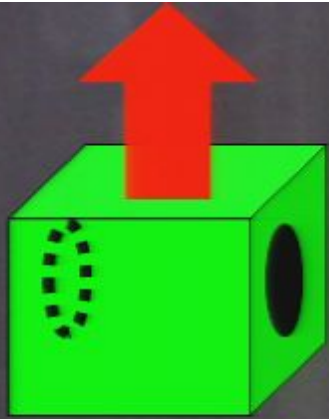


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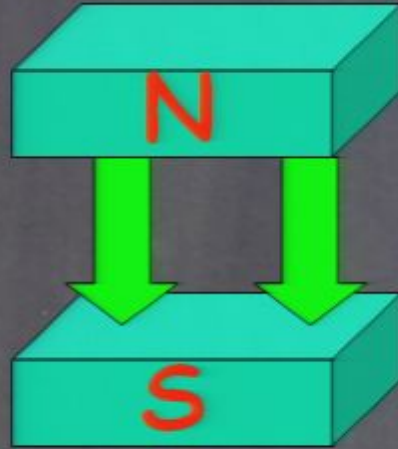


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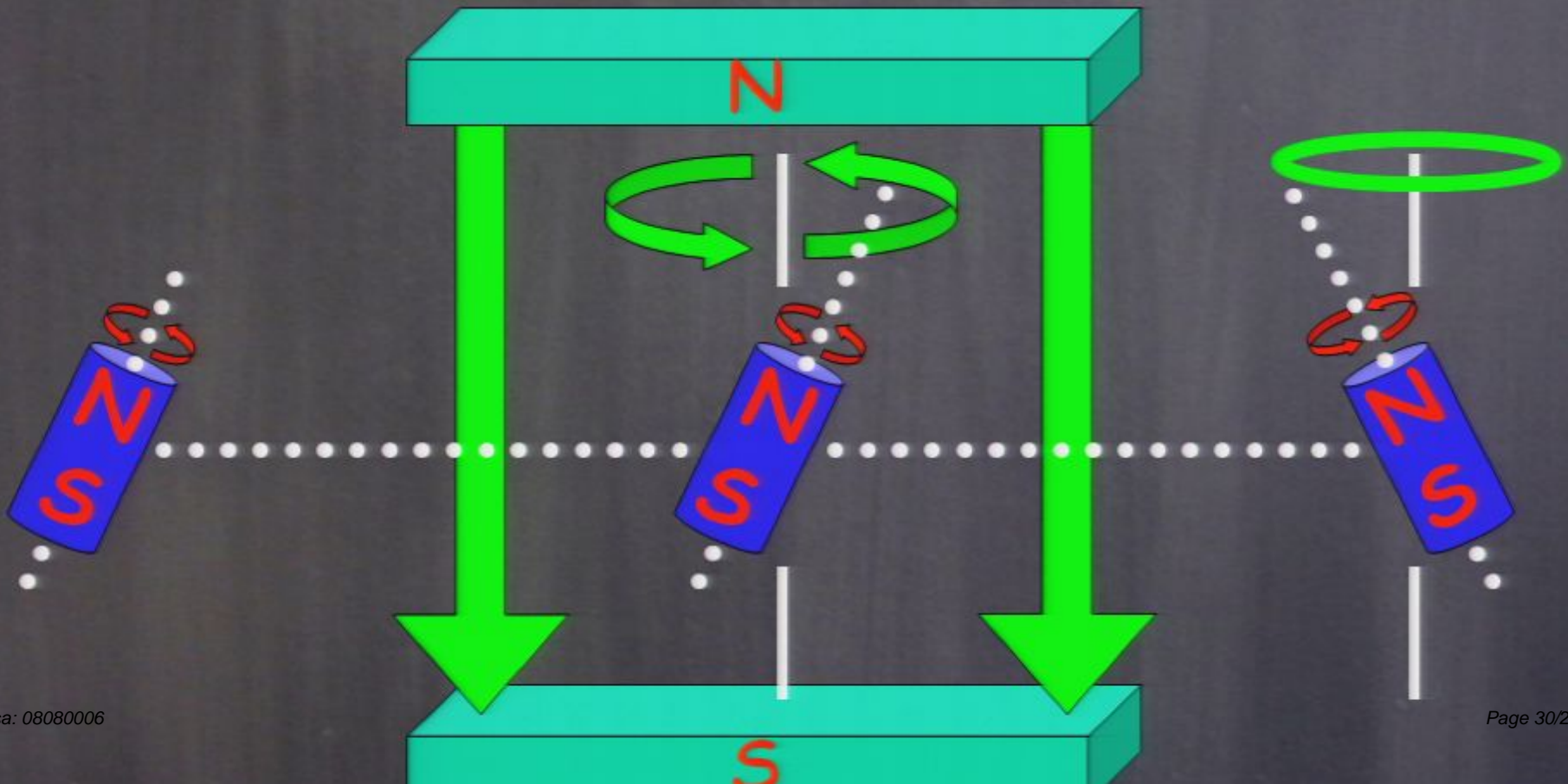


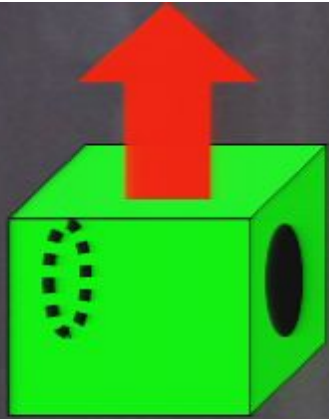


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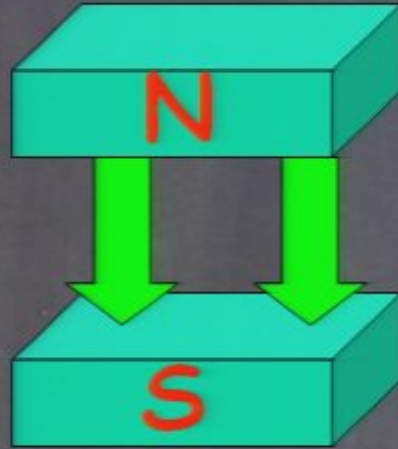


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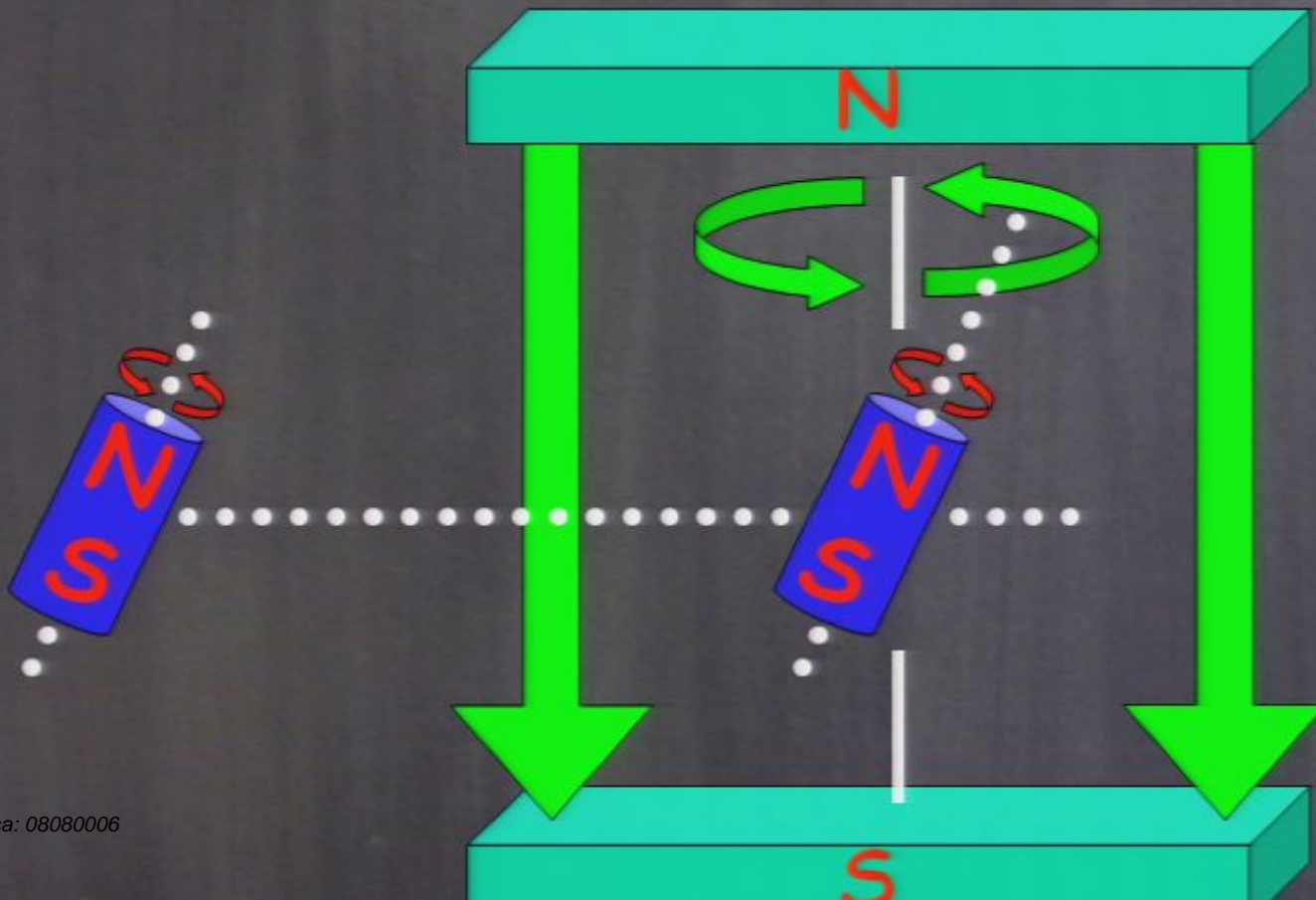


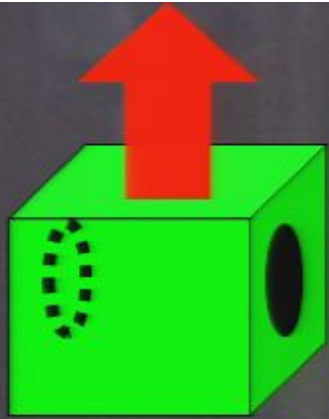


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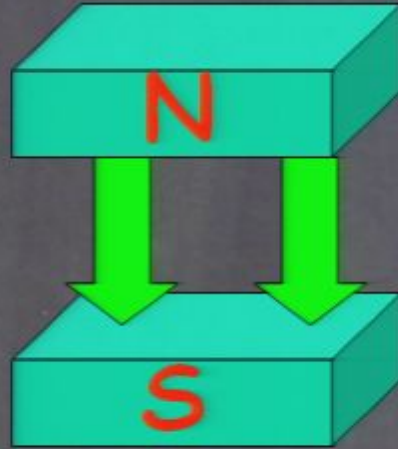


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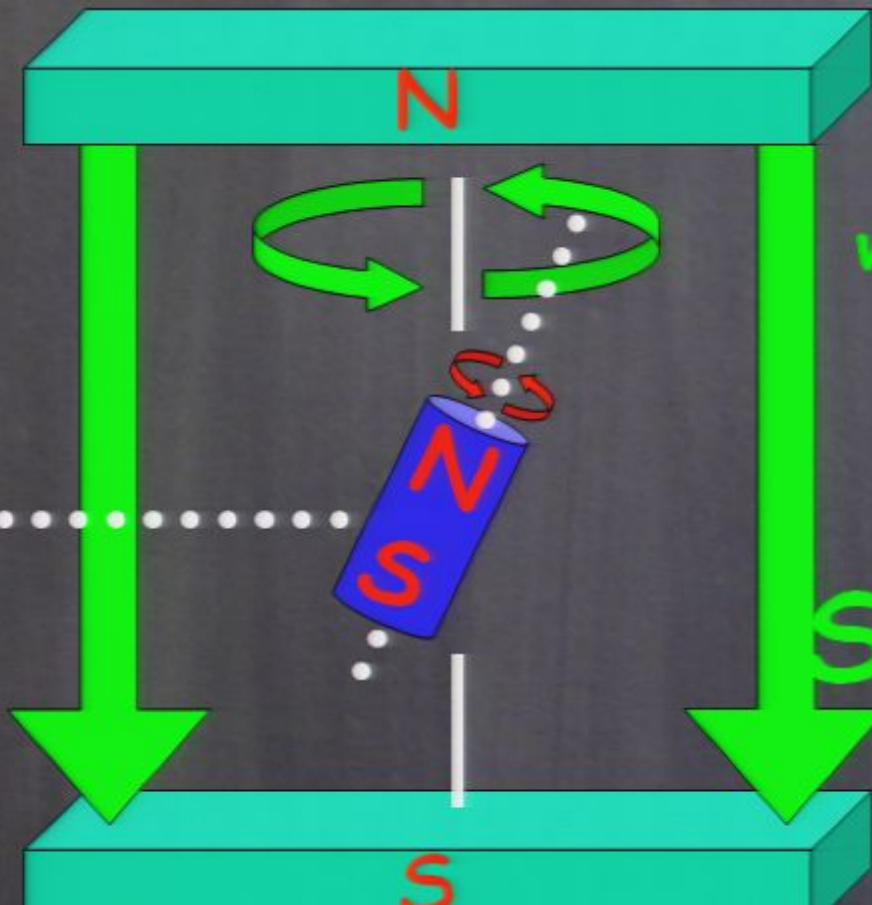




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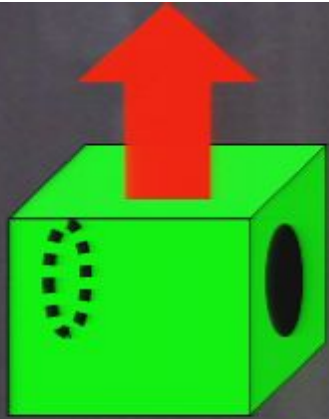


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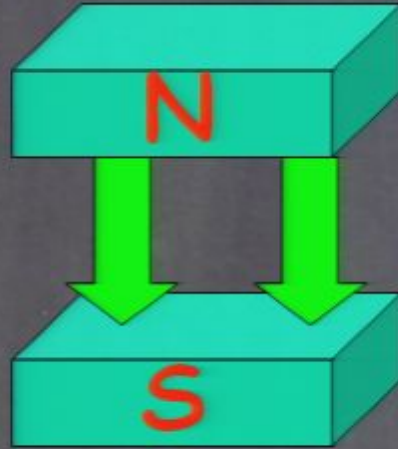


weaker

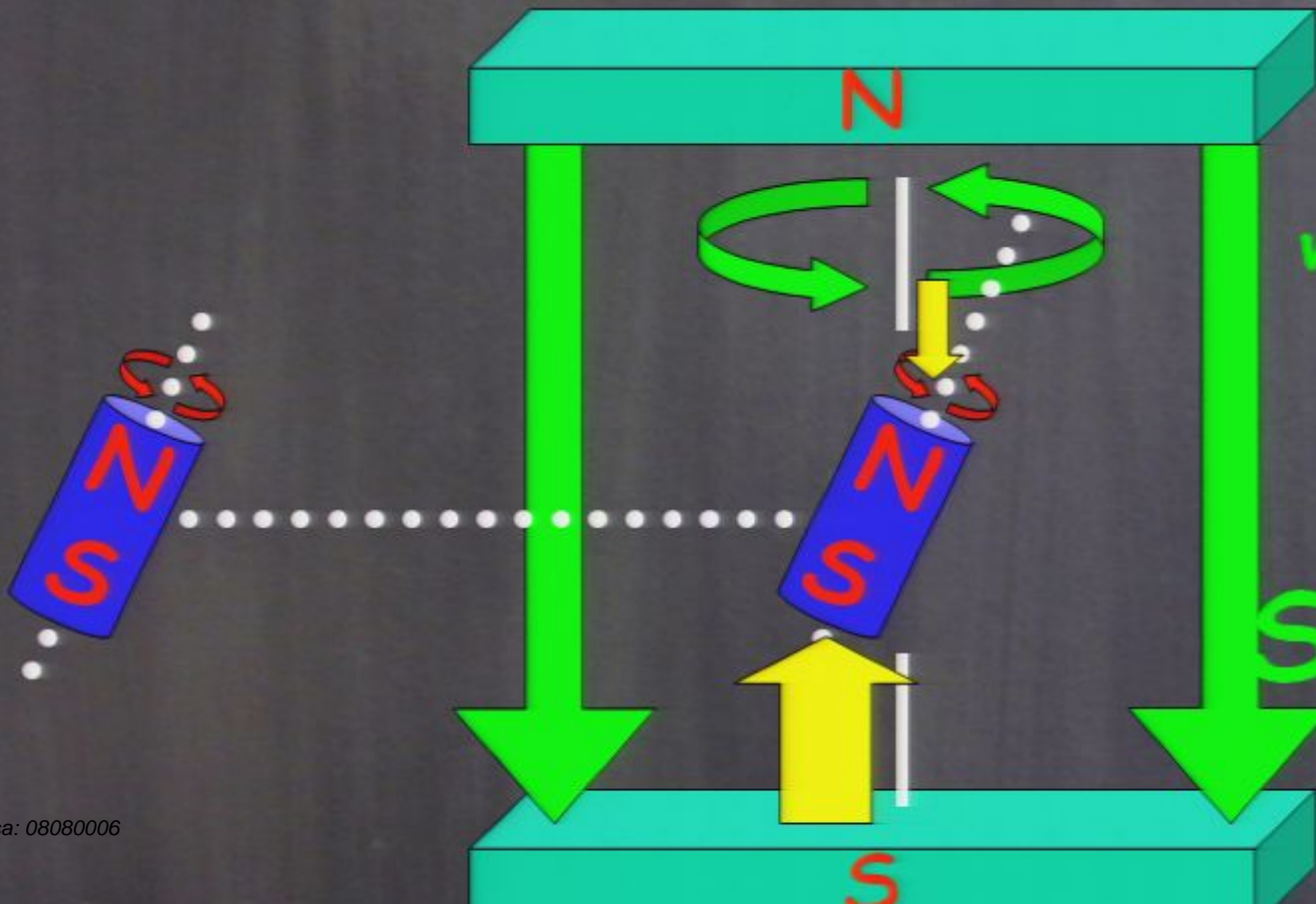
STRONGER



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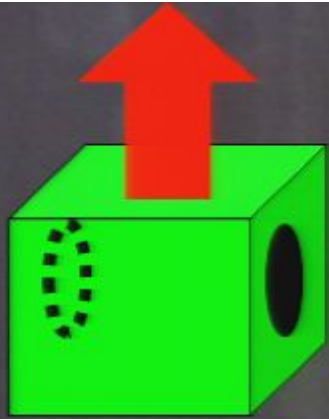


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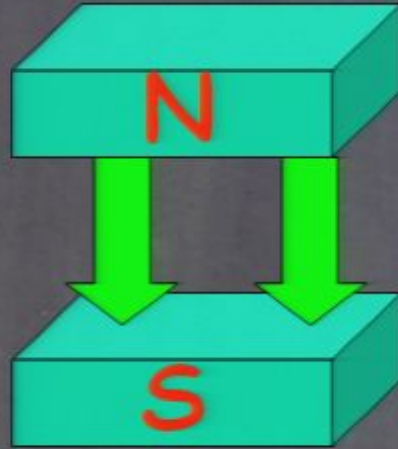


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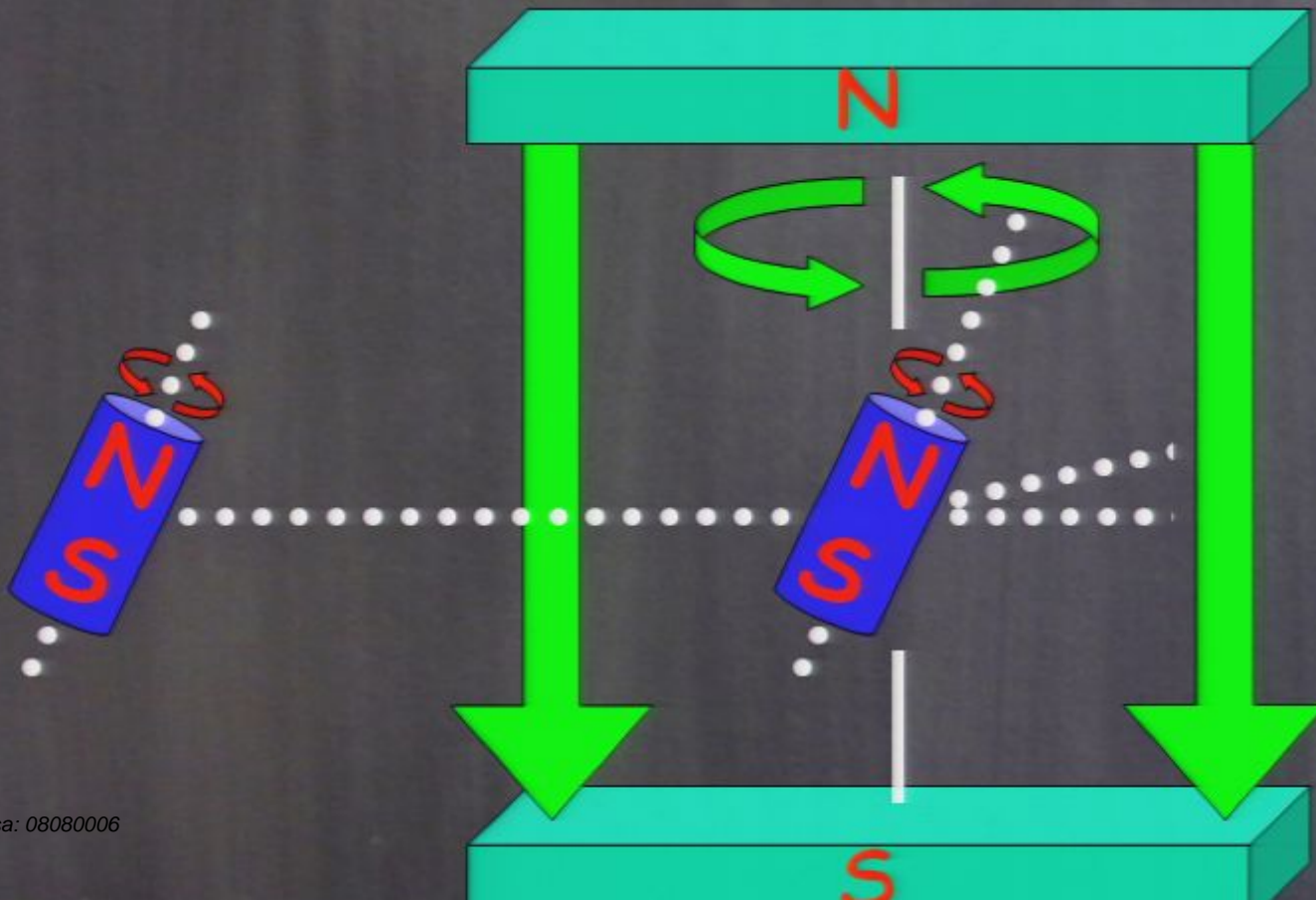
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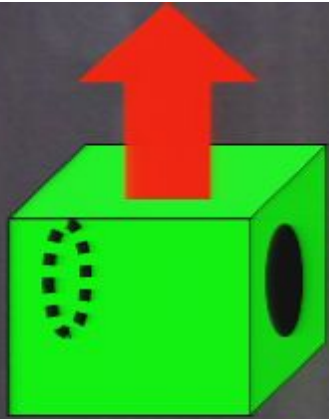


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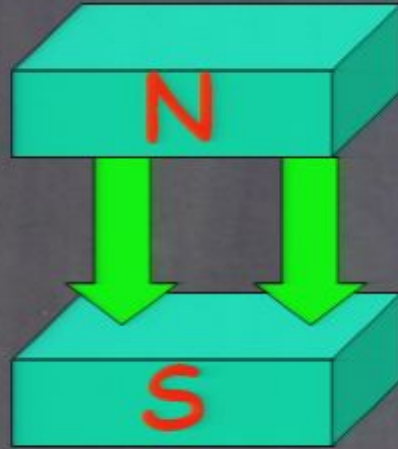


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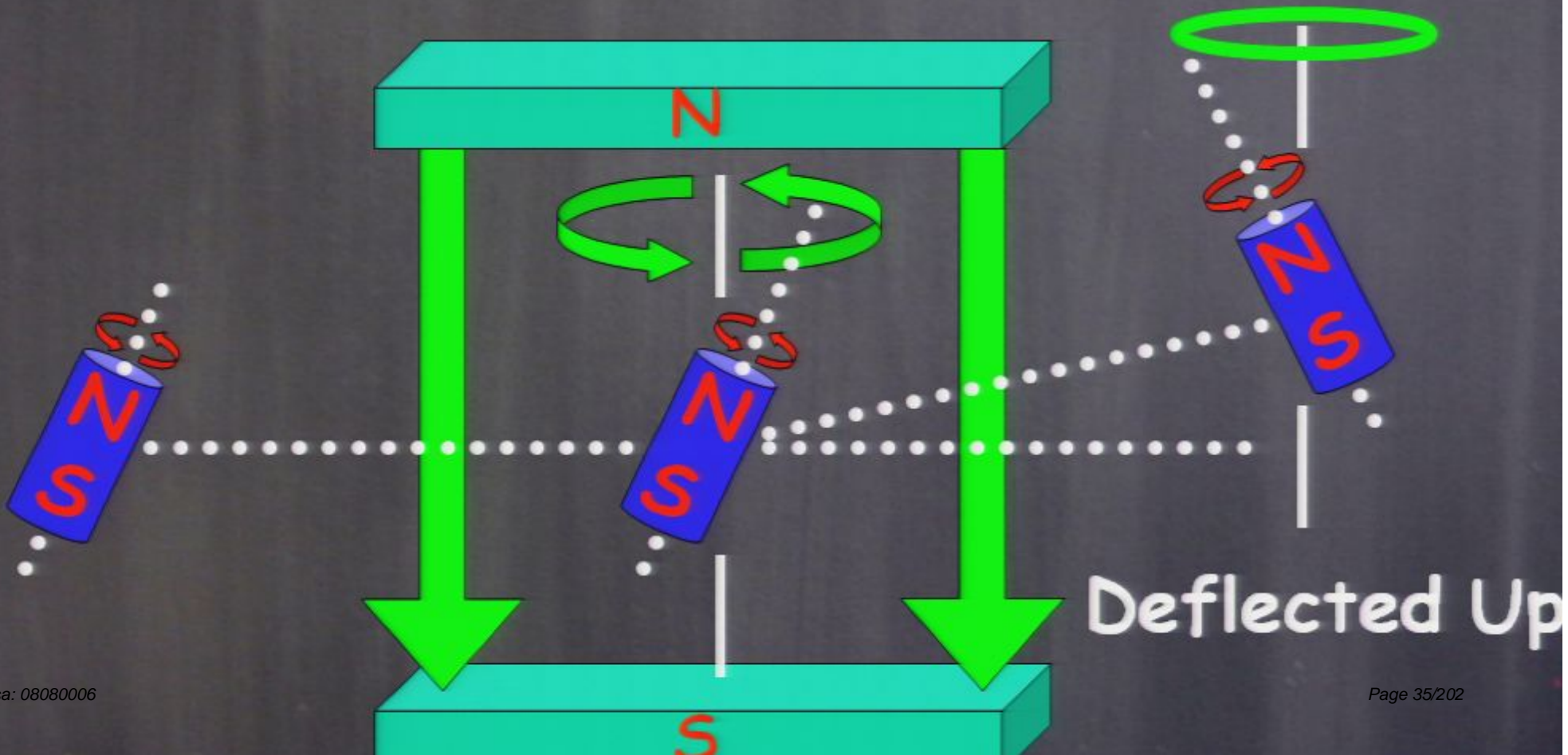




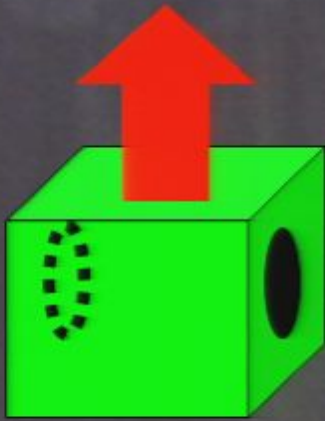
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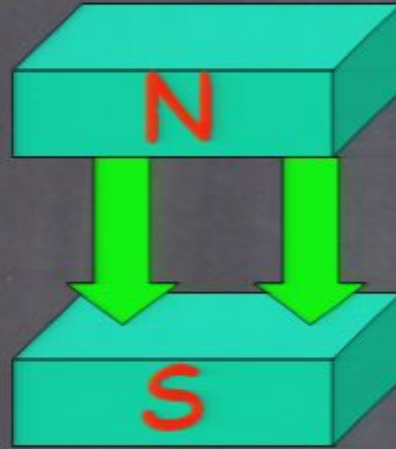
Nonuniform
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Field



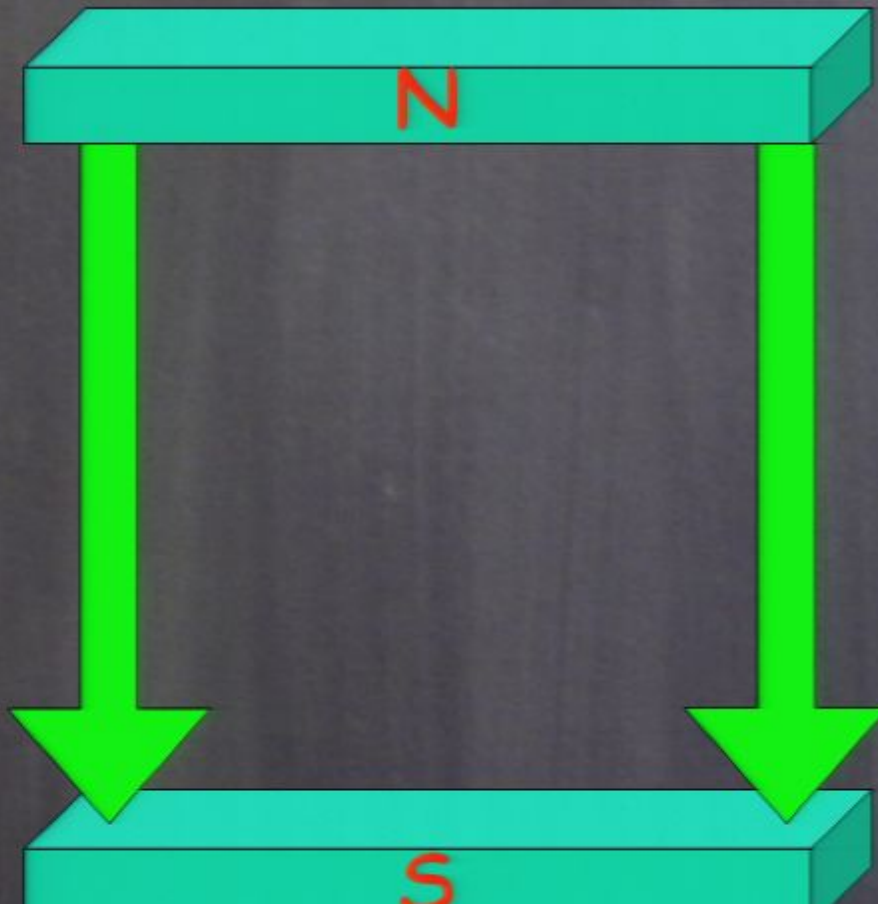
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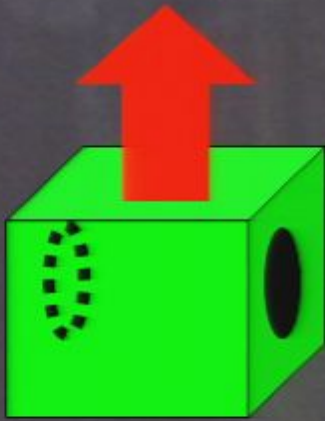


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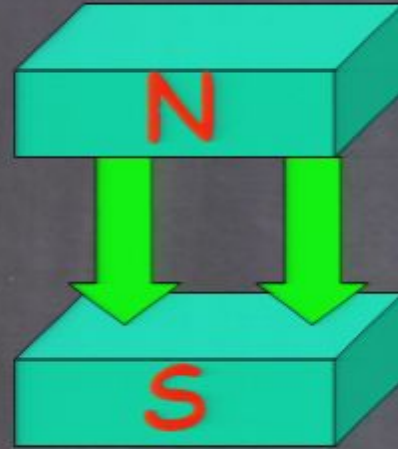


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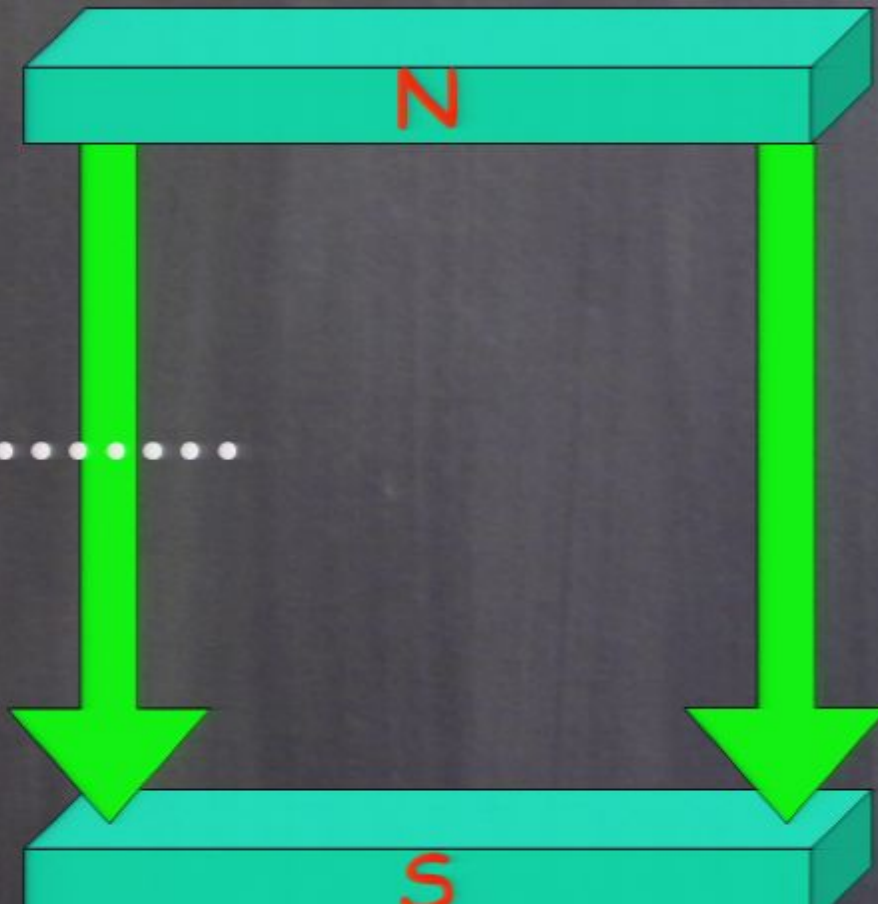


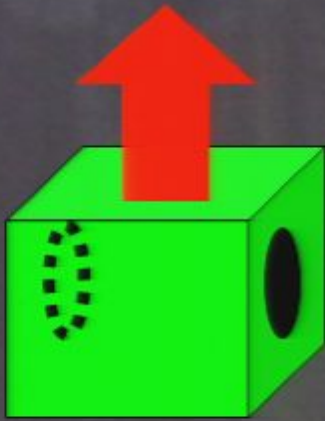


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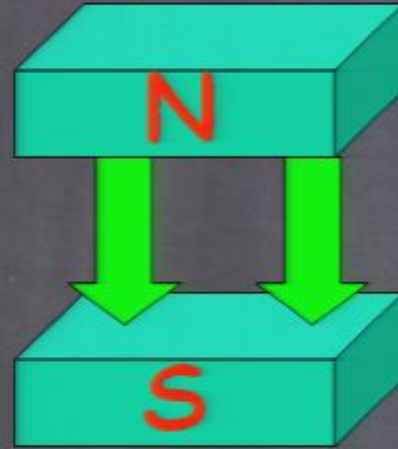


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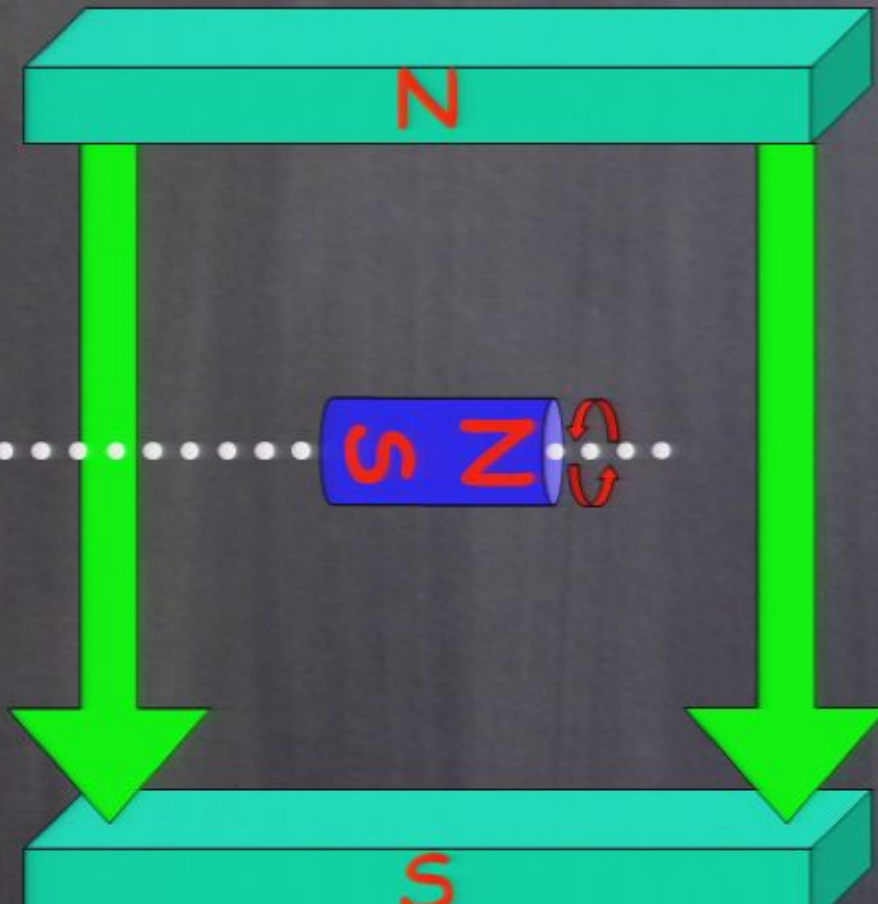


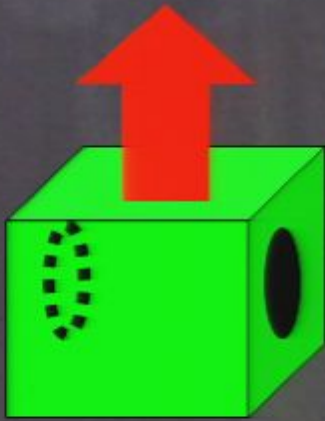


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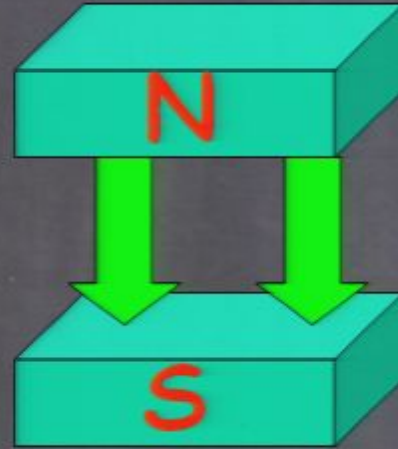


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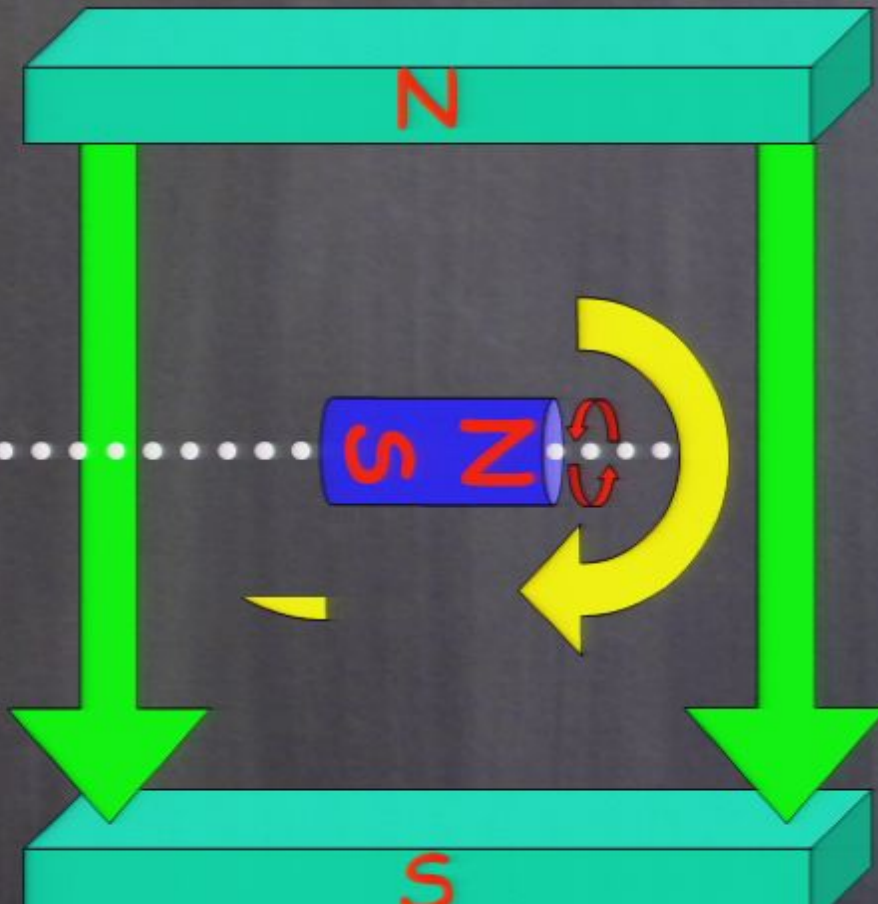


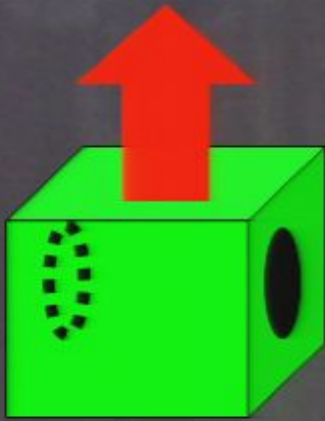


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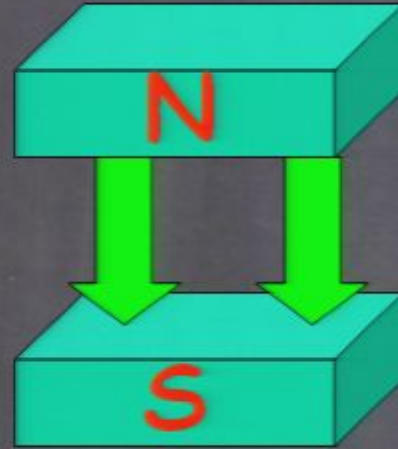


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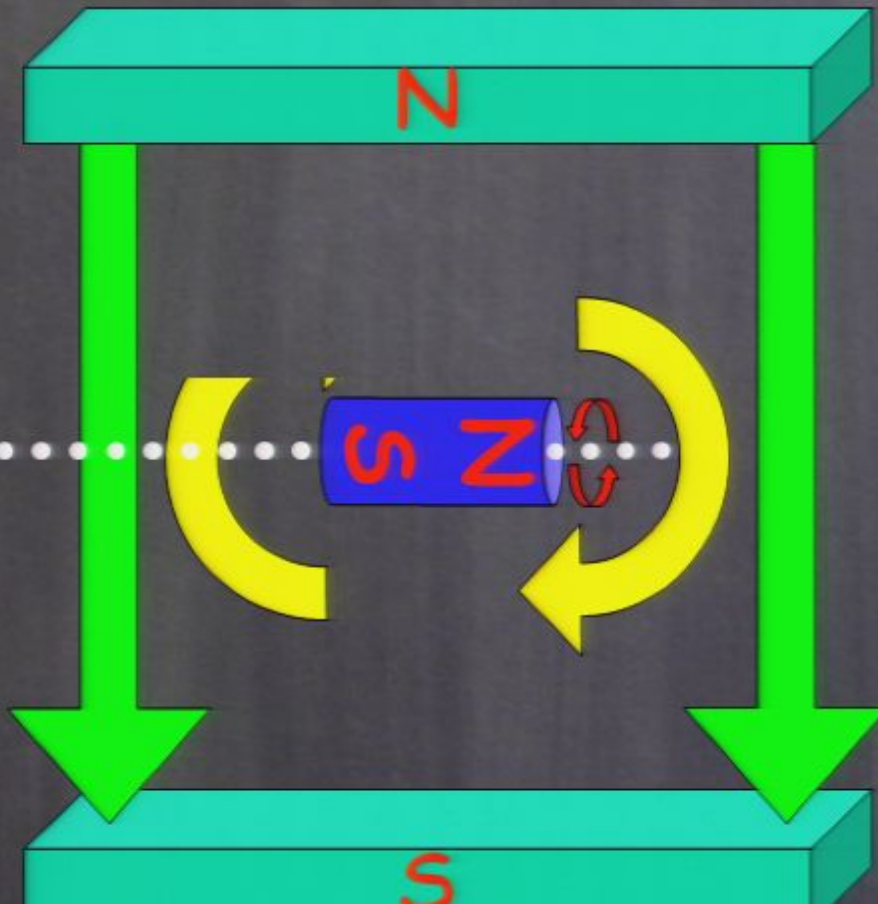


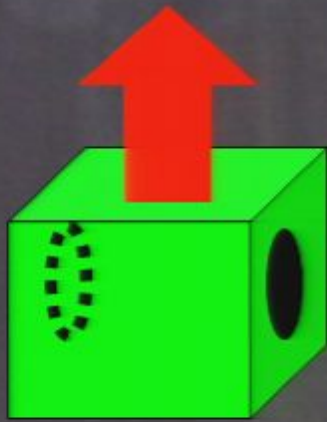


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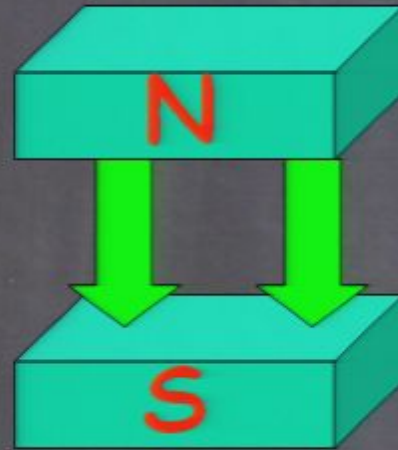


Nonuniform
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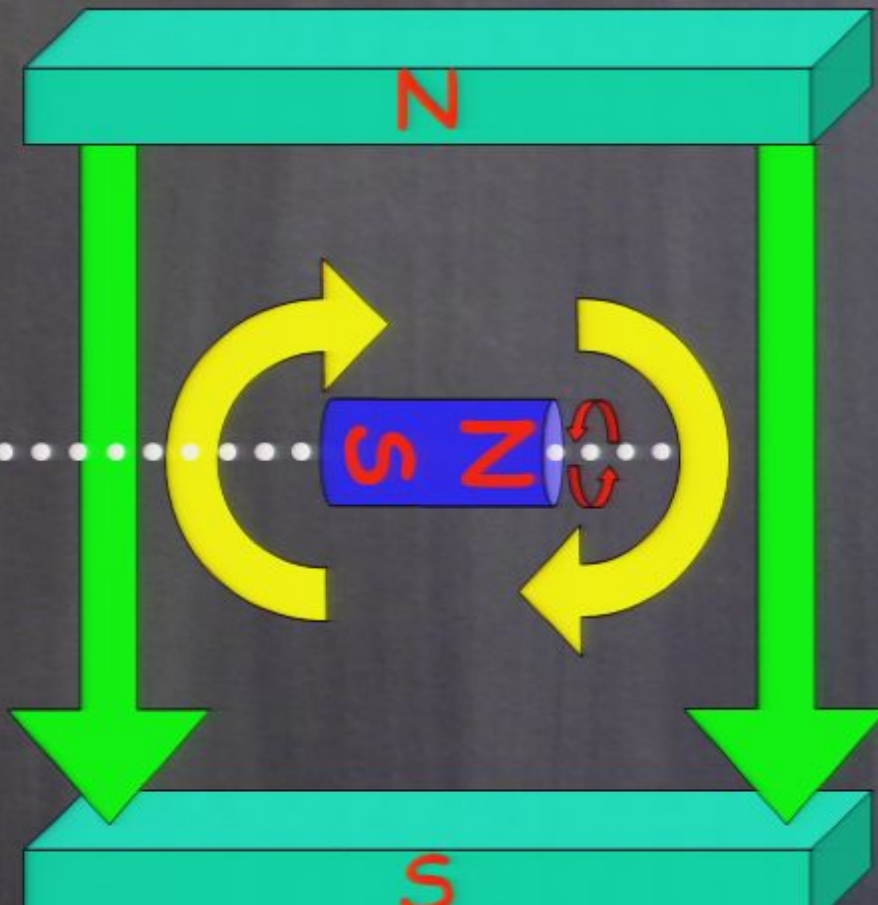


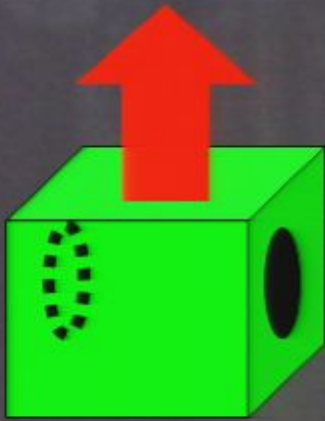


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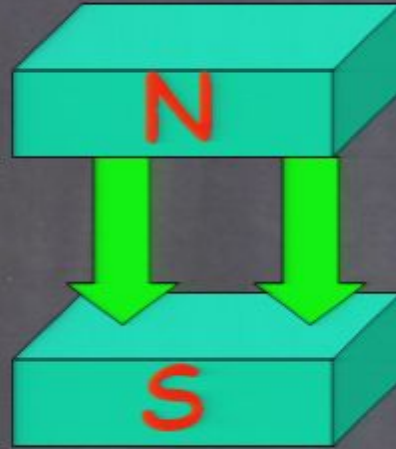


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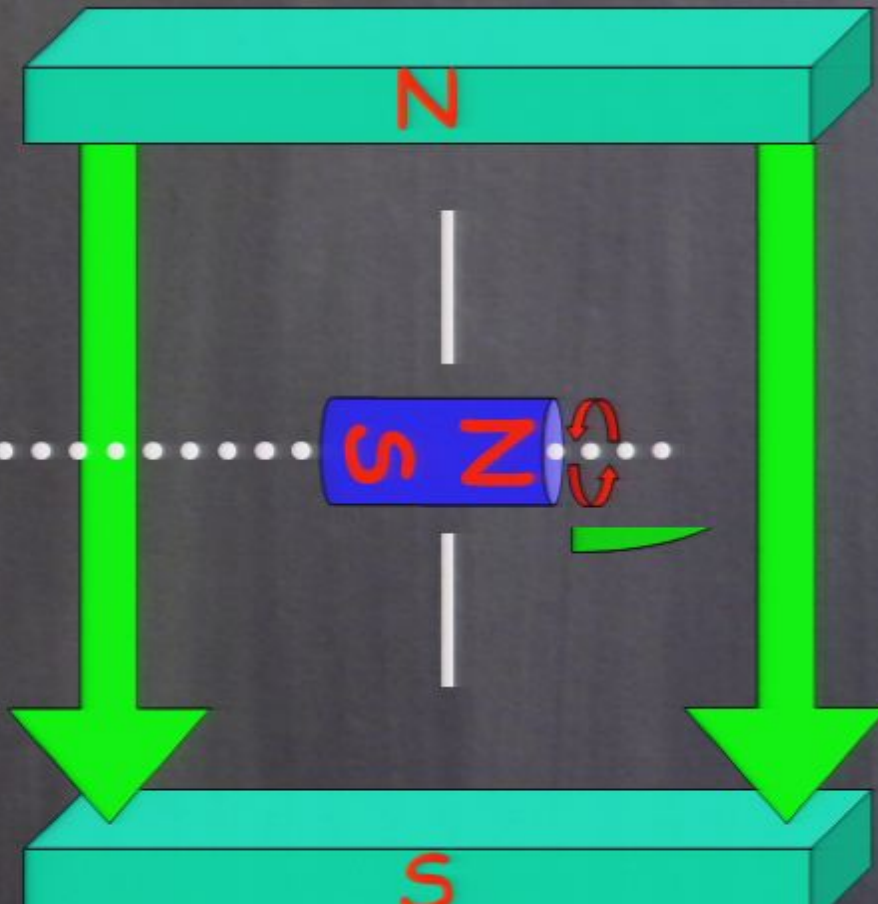


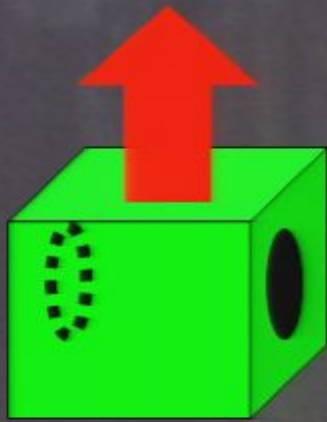


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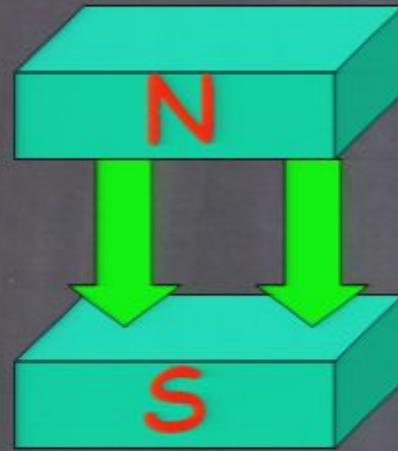


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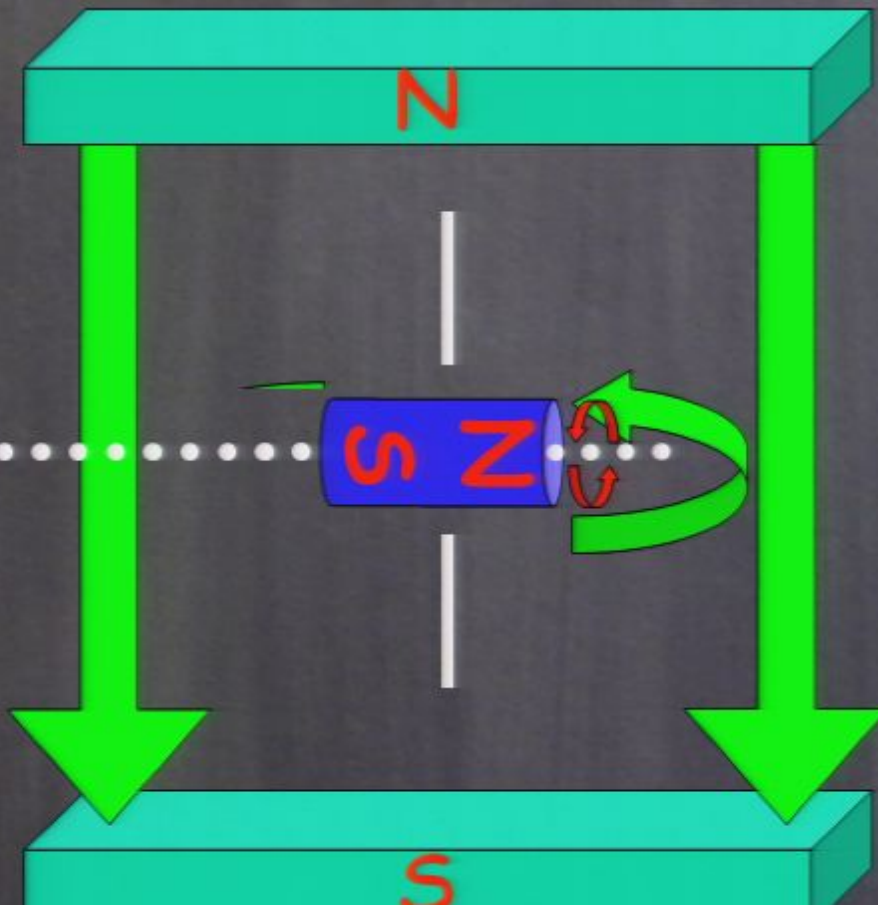


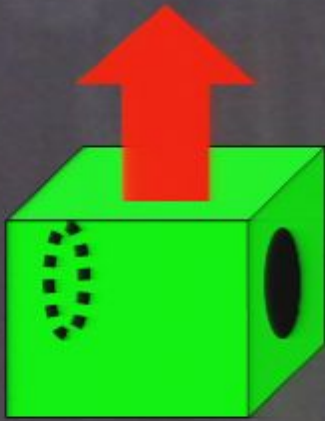


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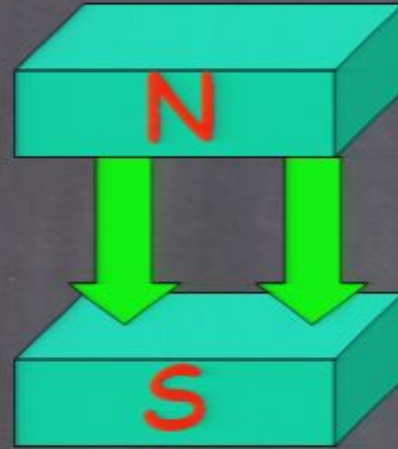


Nonuniform
Magnetic
Field

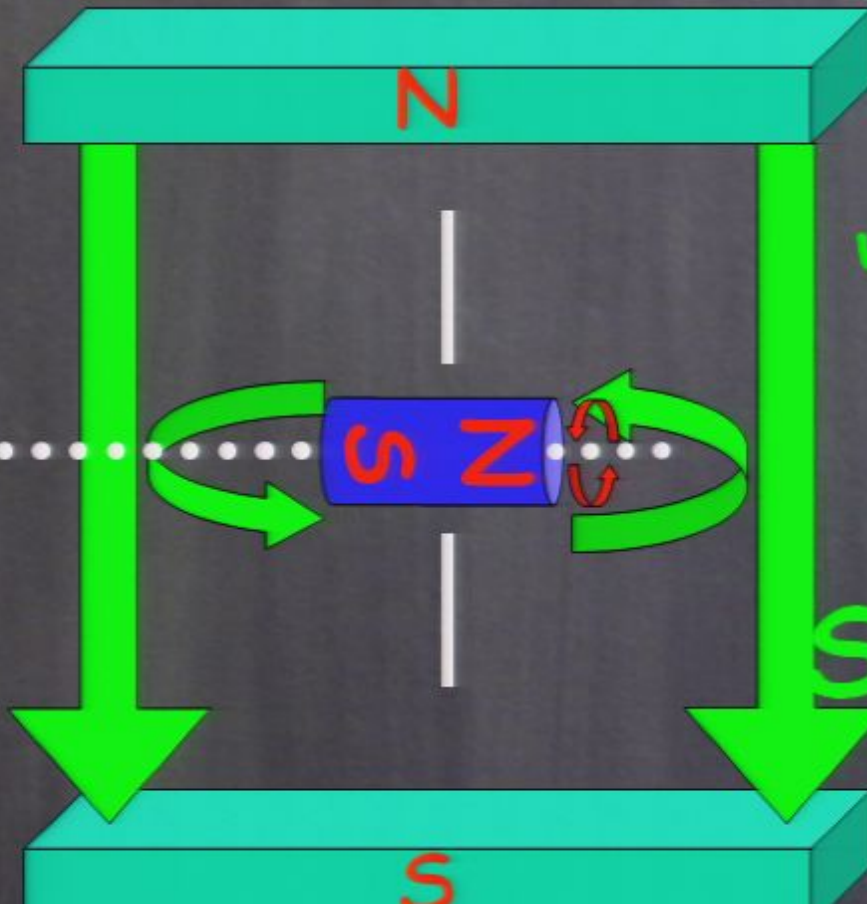




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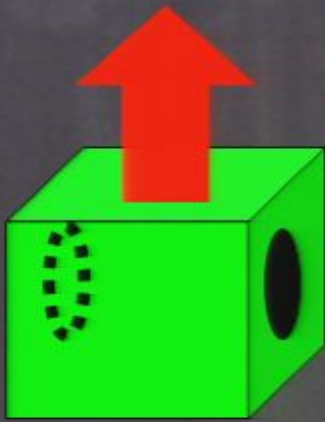


Nonuniform
Magnetic
Field

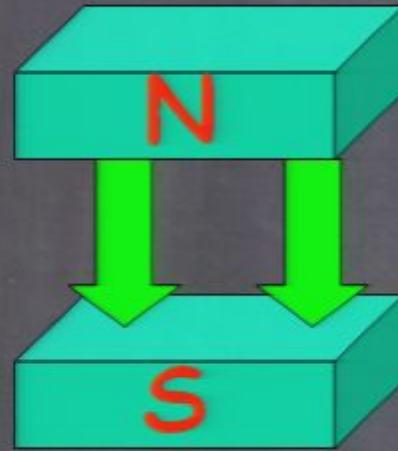


weaker

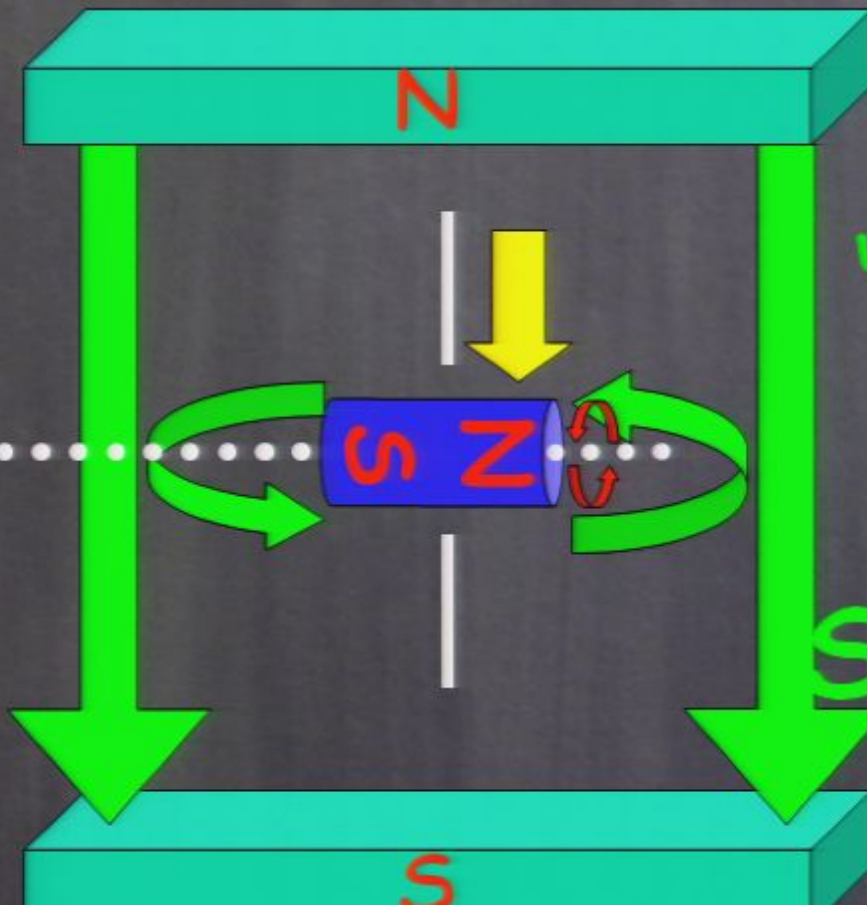
STRONGER



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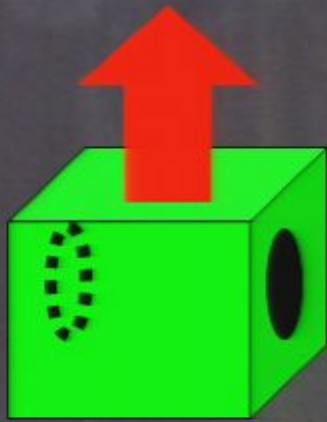


Nonuniform
Magnetic
Field

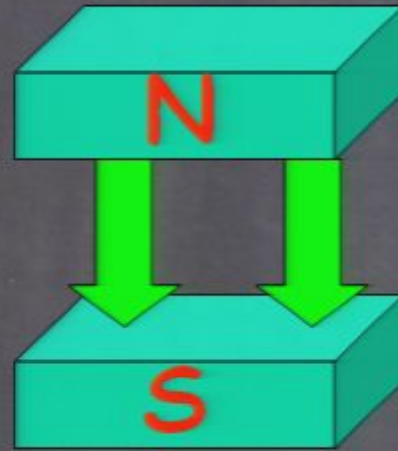


weaker

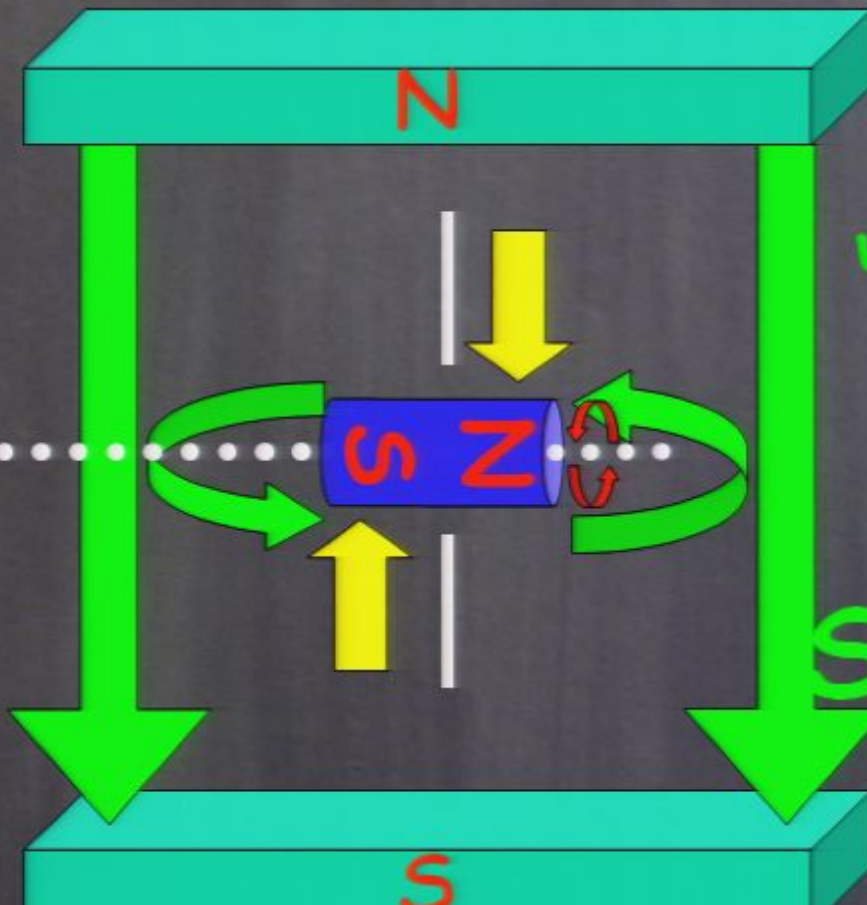
STRONGER



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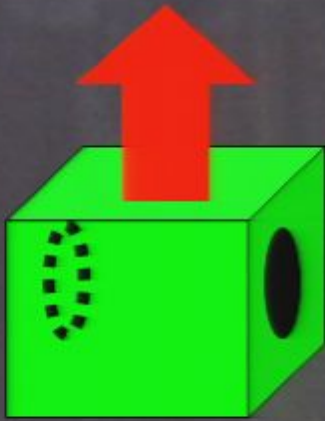


Nonuniform
Magnetic
Field

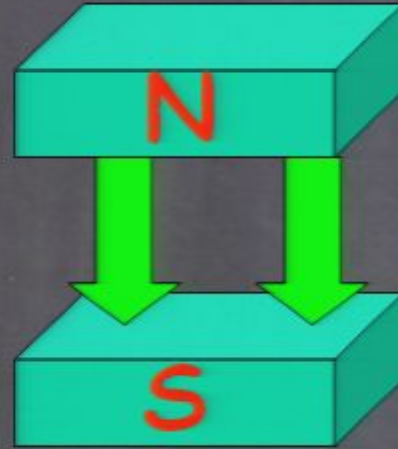


weaker

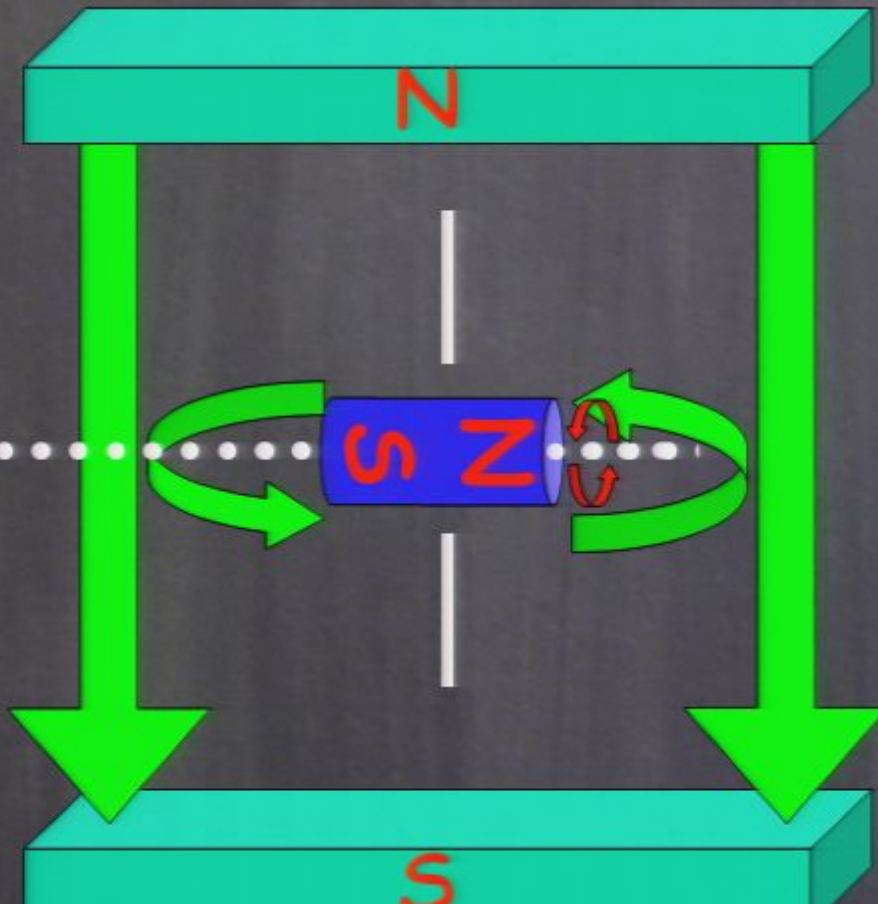
STRONGER

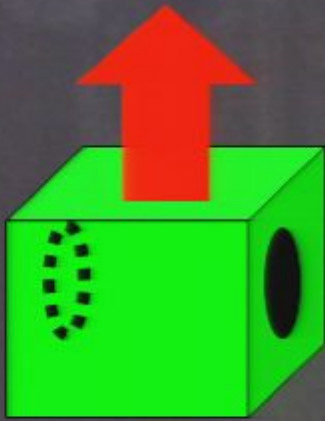


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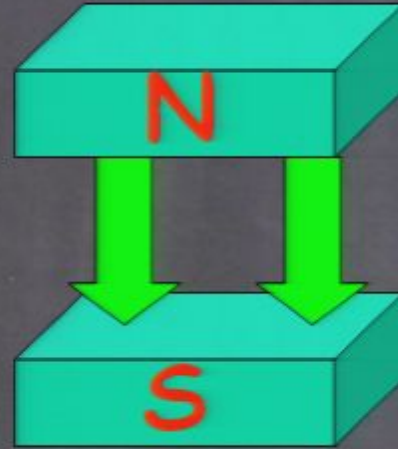


Nonuniform
Magnetic
Field

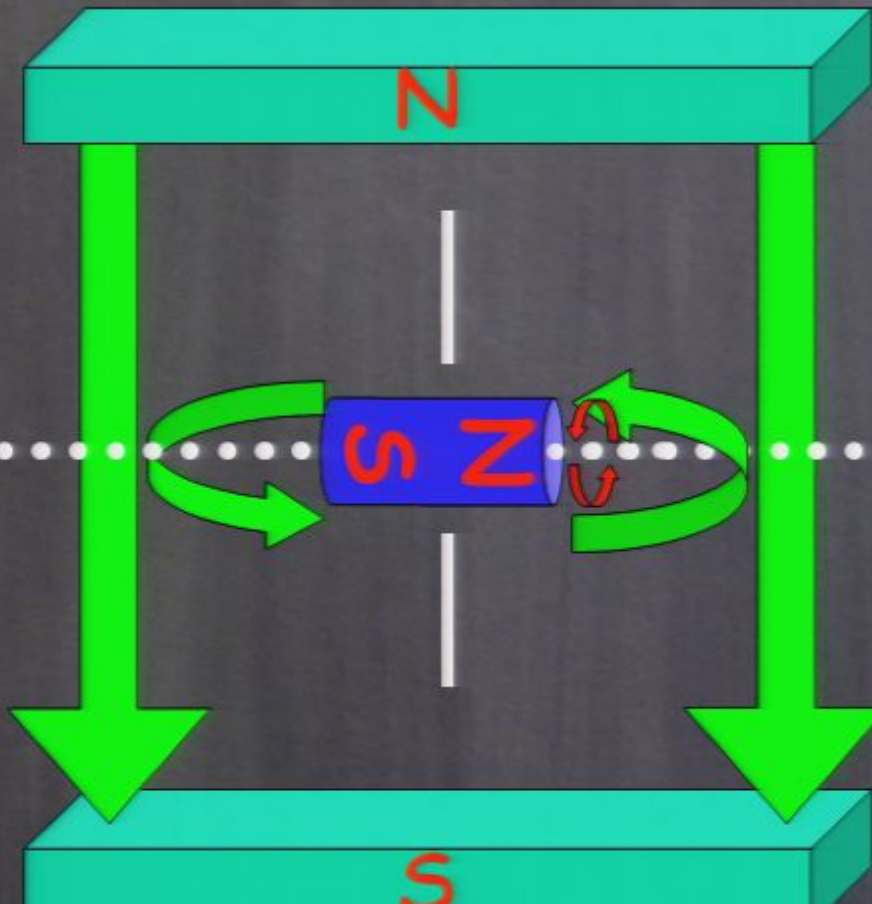


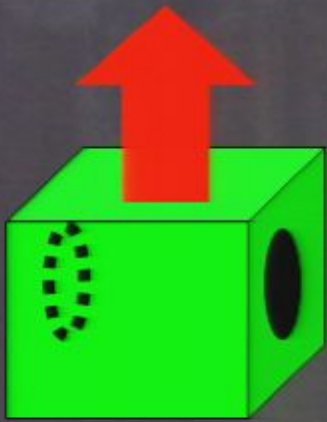


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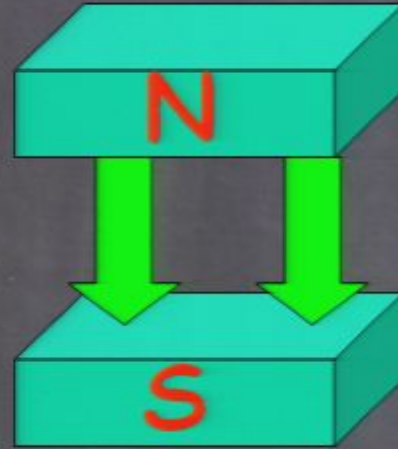


Nonuniform
Magnetic
Field

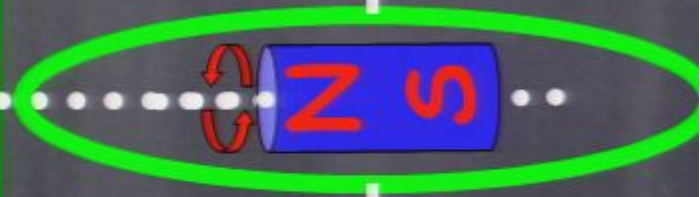
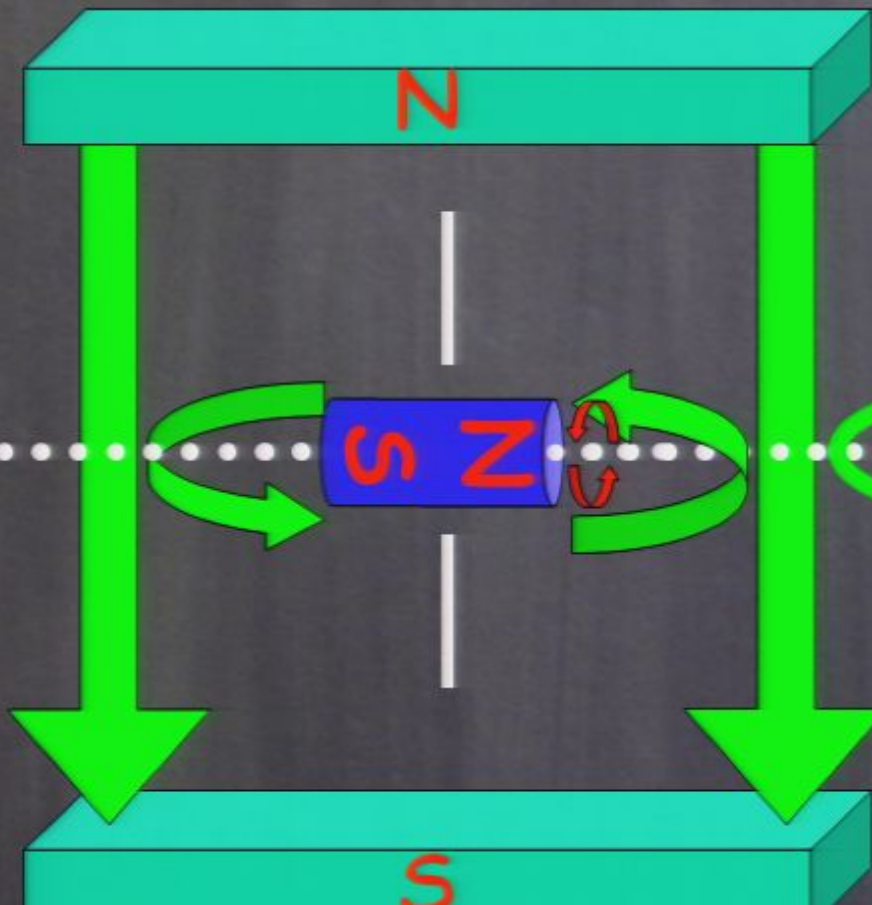




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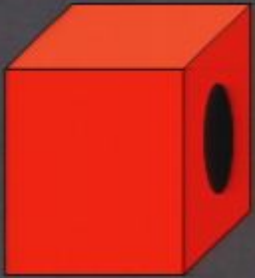
Nonuniform
Magnetic
Field



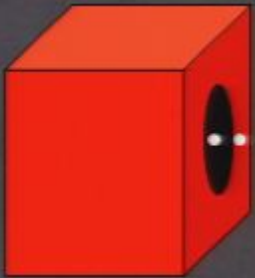
Undeflected

Experiment #1

Experiment #1



Experiment #1



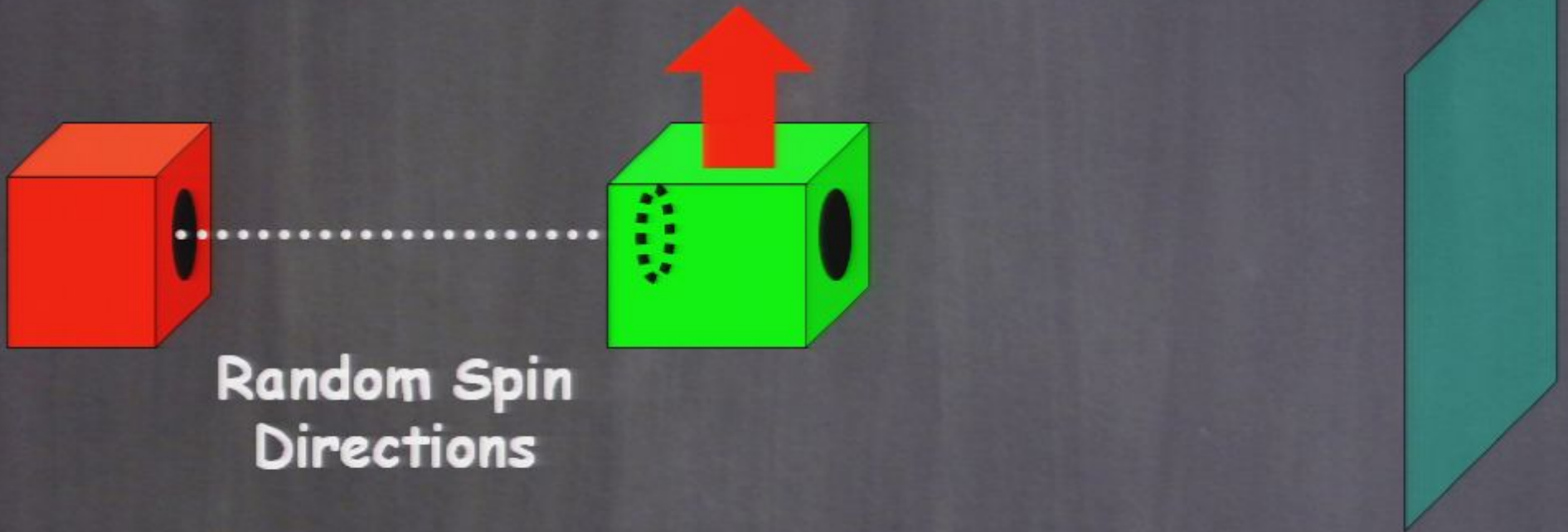
Random Spin
Directions

Experiment #1

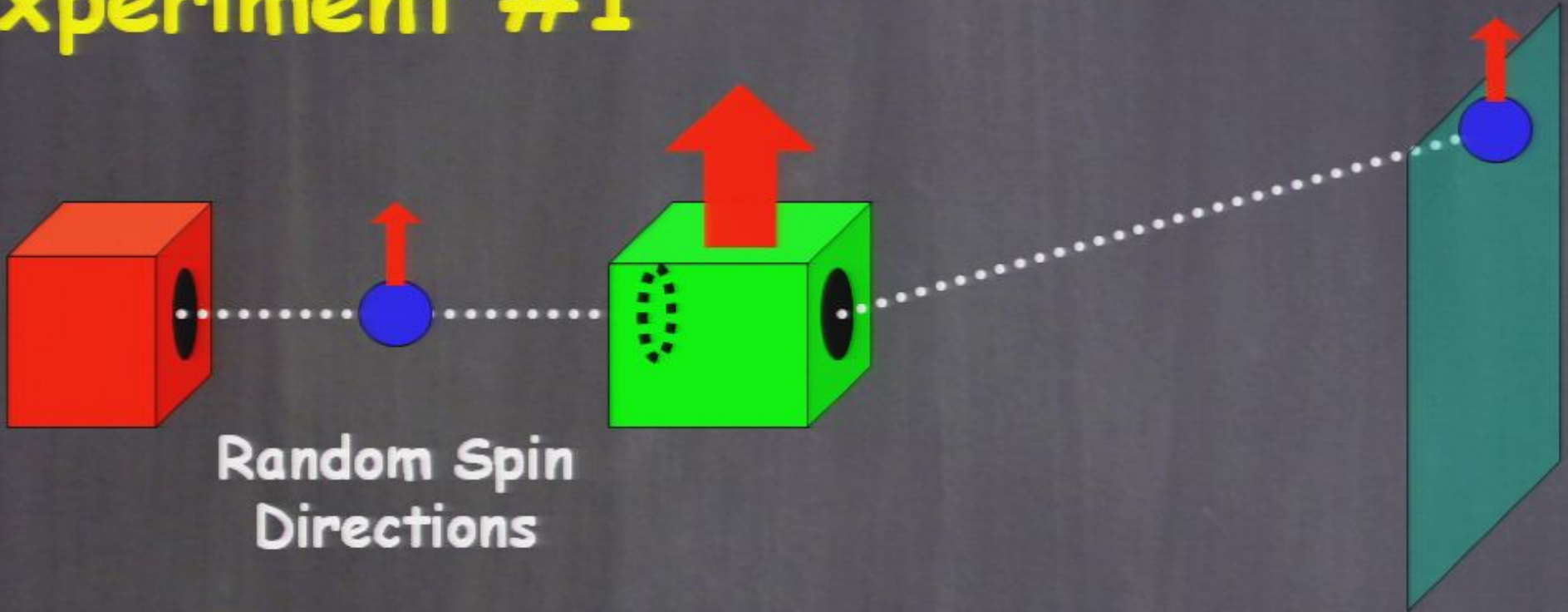


Random Spin
Directions

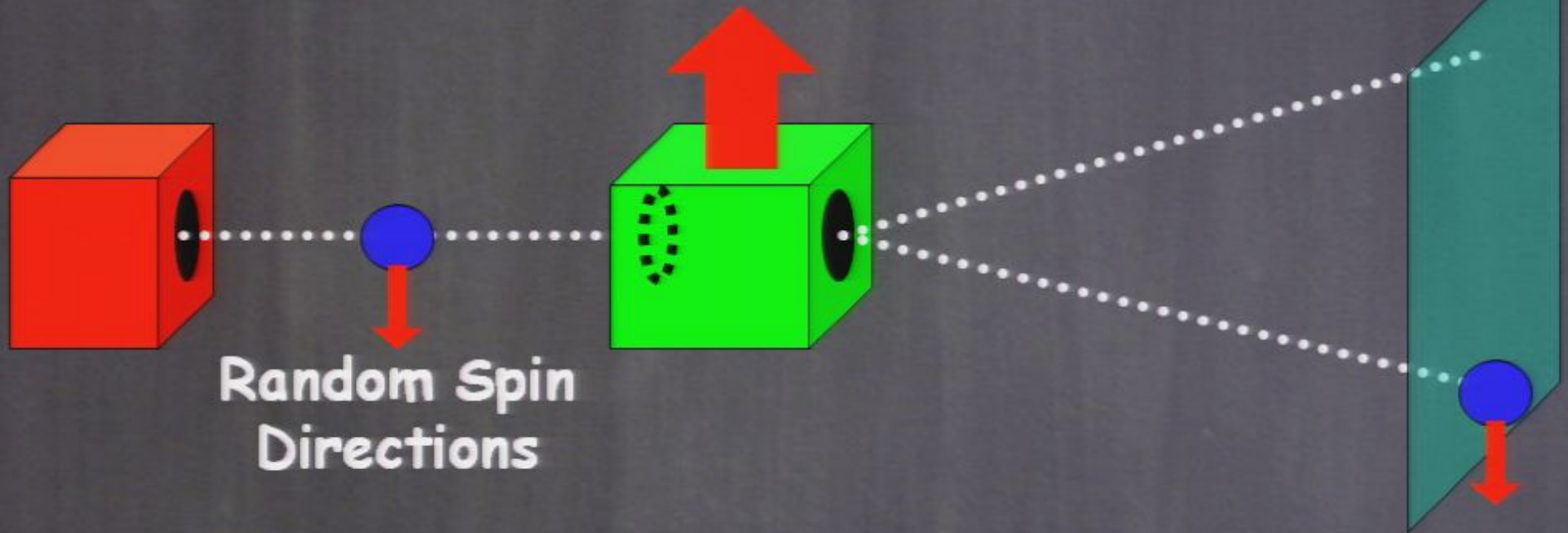
Experiment #1



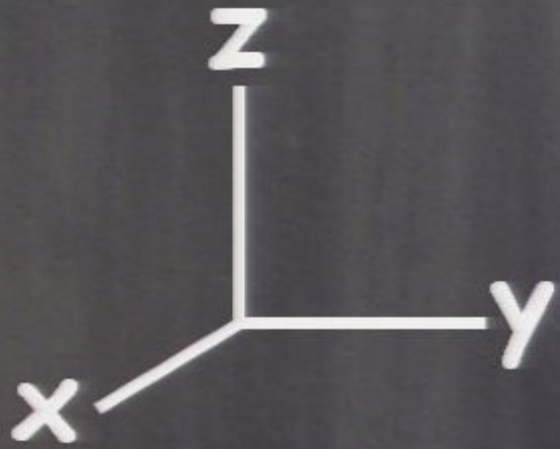
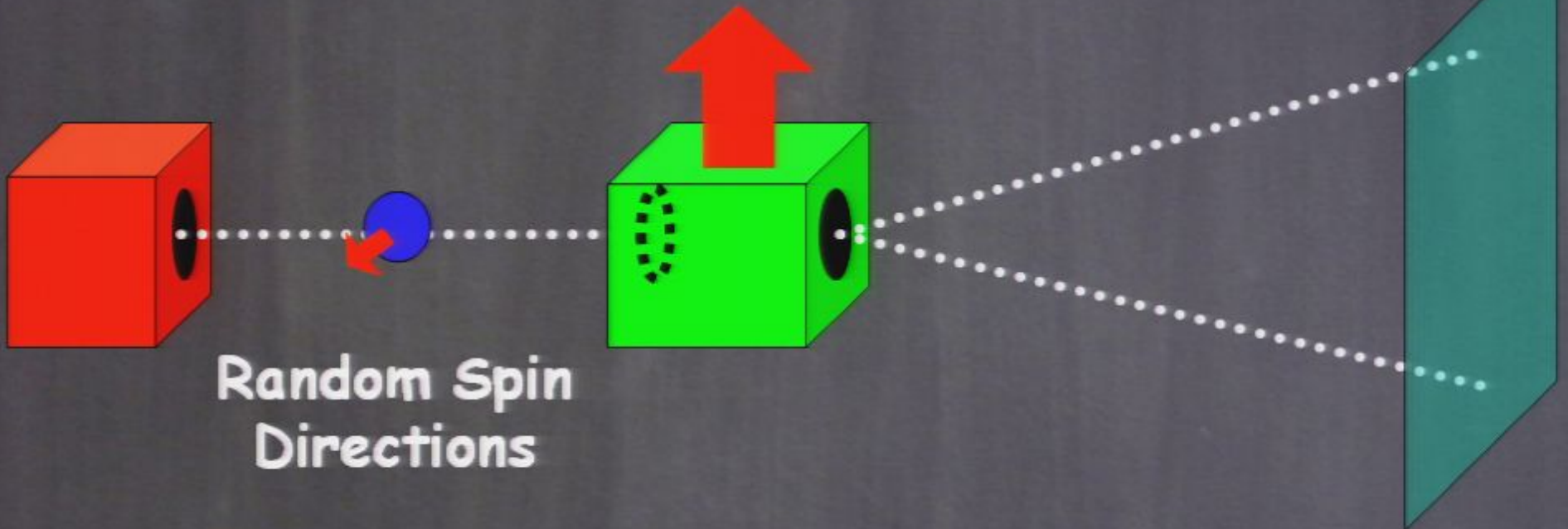
Experiment #1



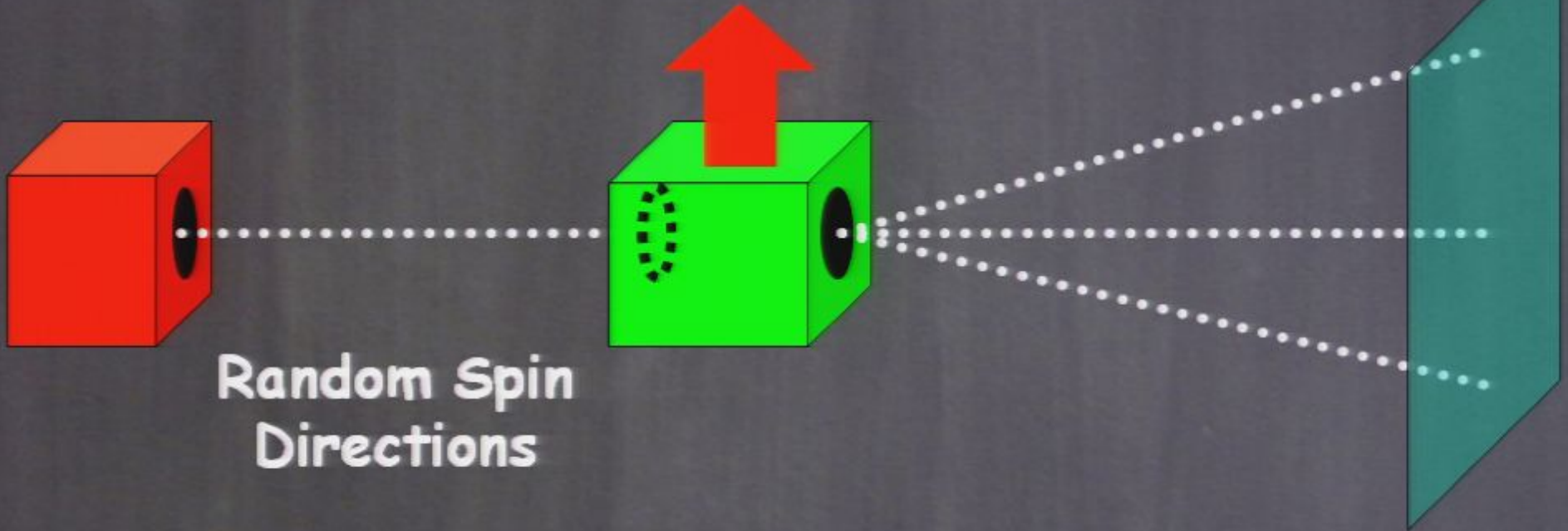
Experiment #1



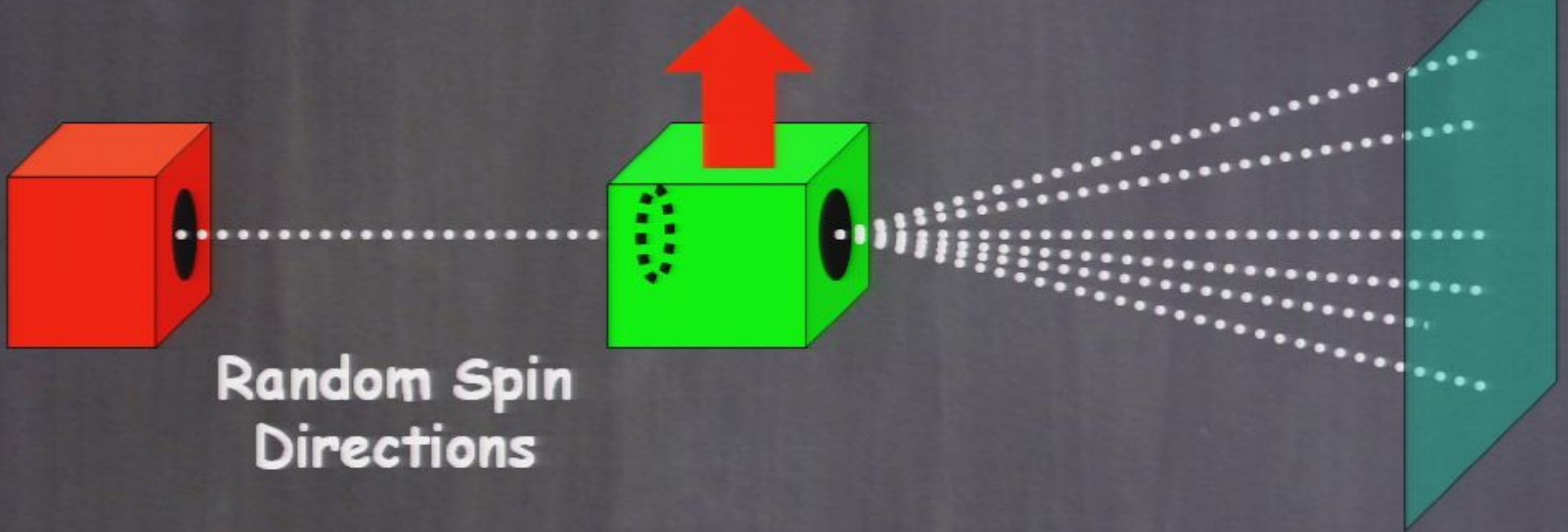
Experiment #1



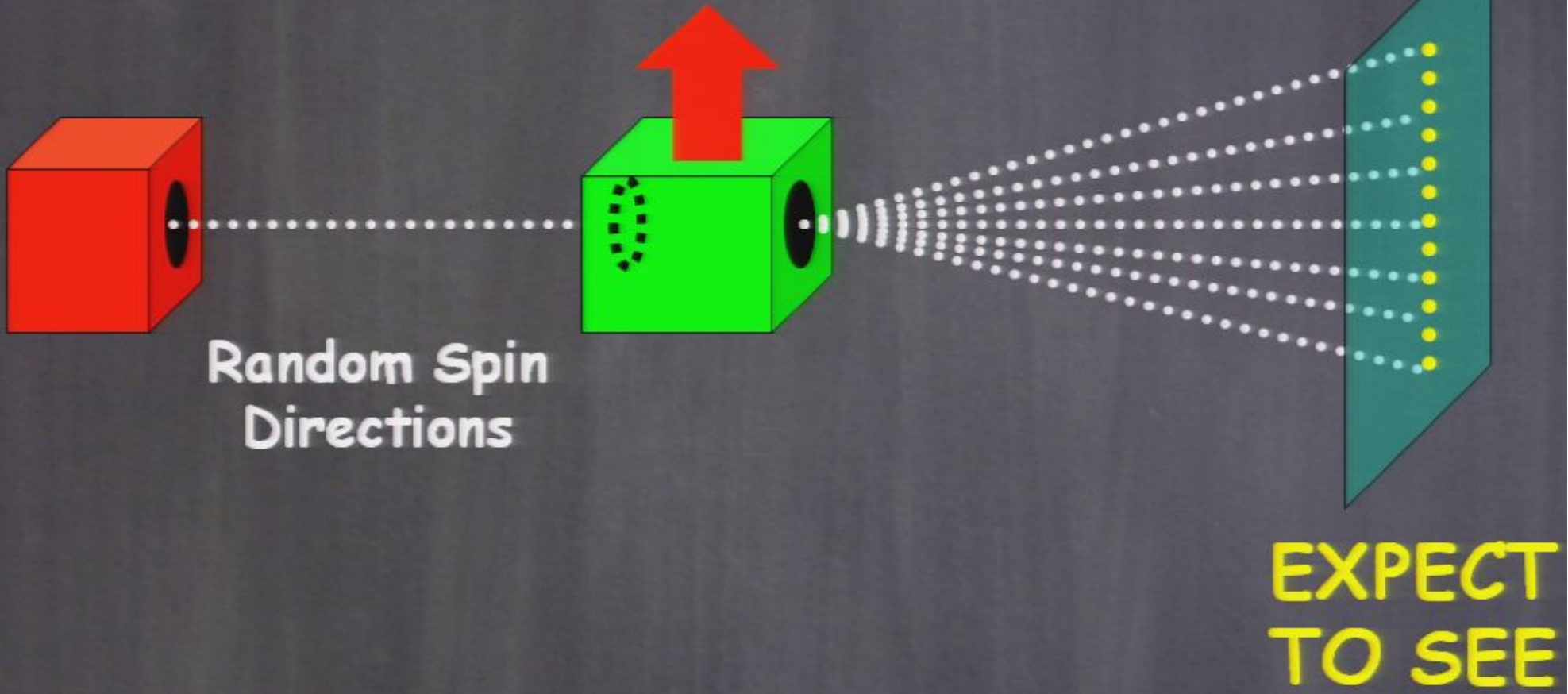
Experiment #1



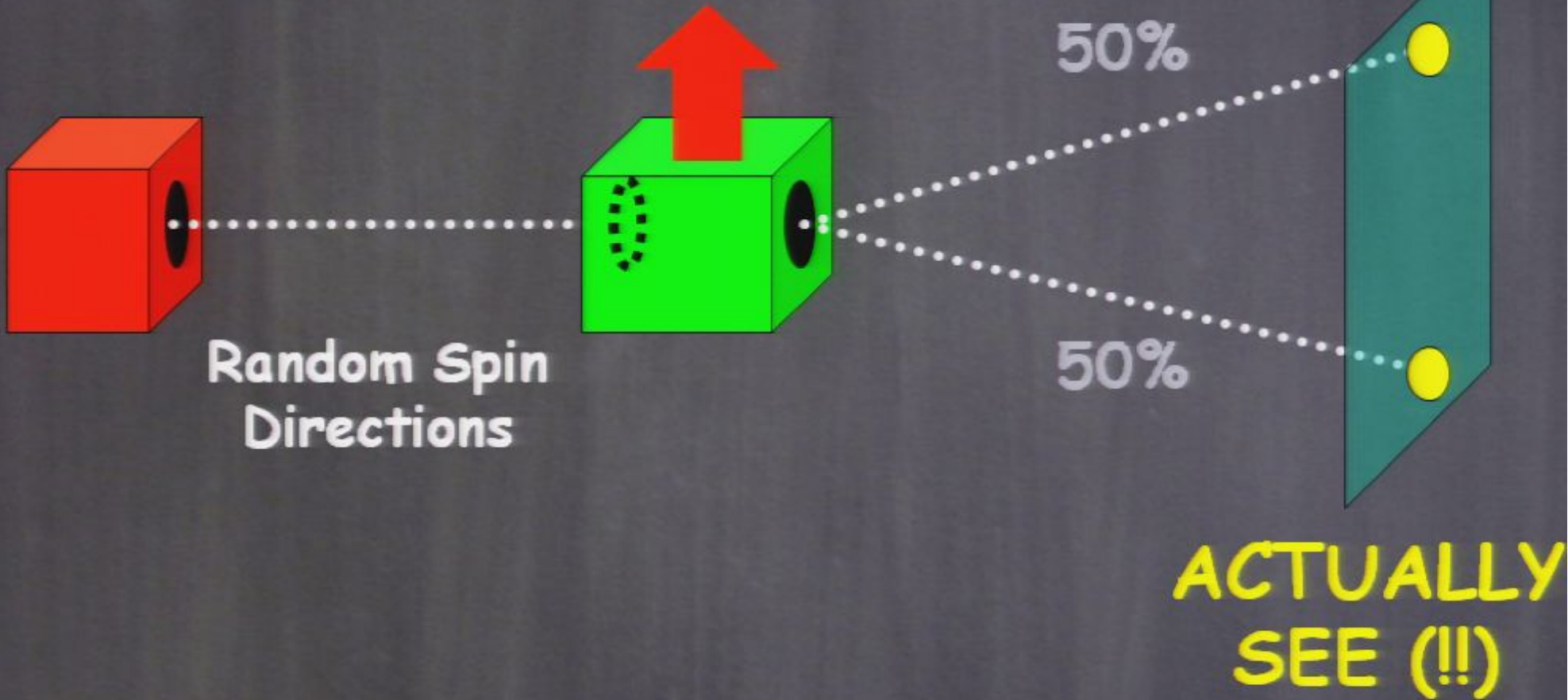
Experiment #1



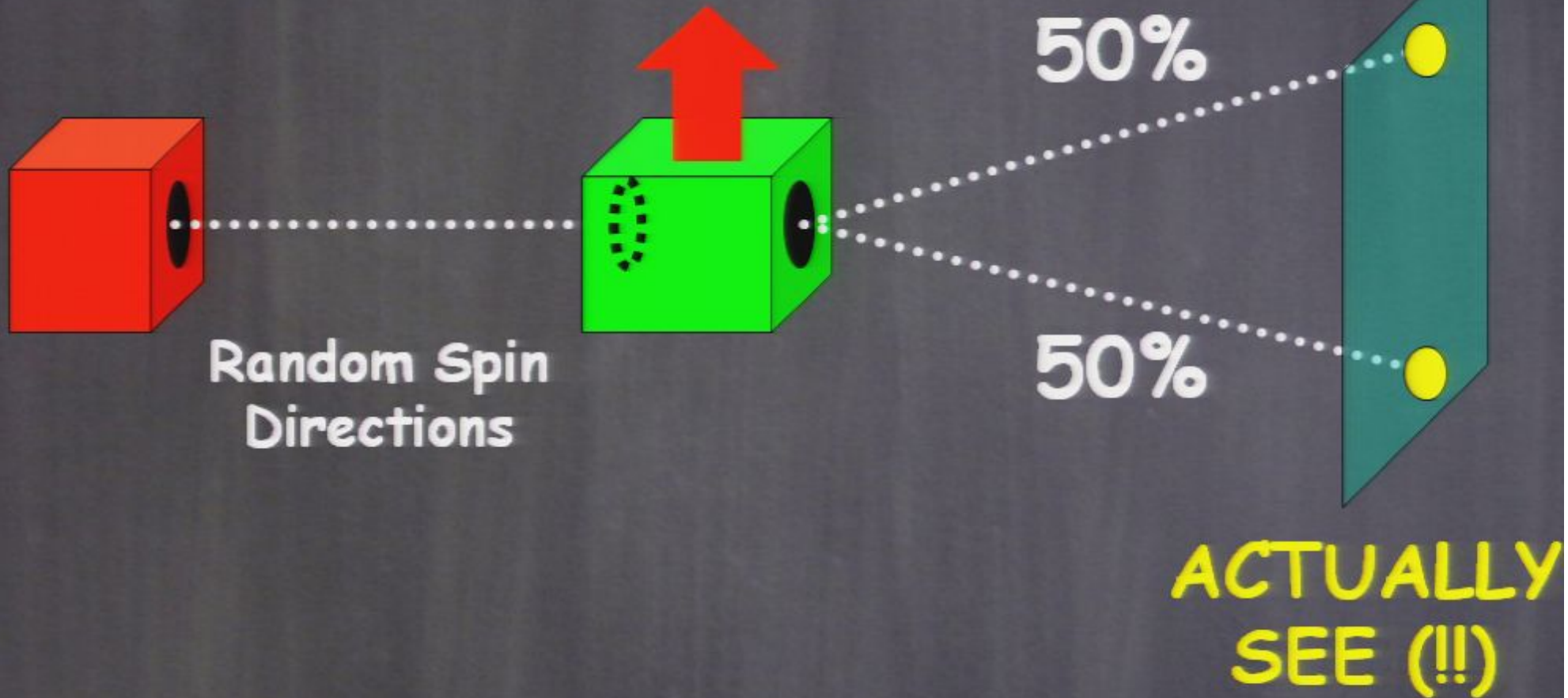
Experiment #1



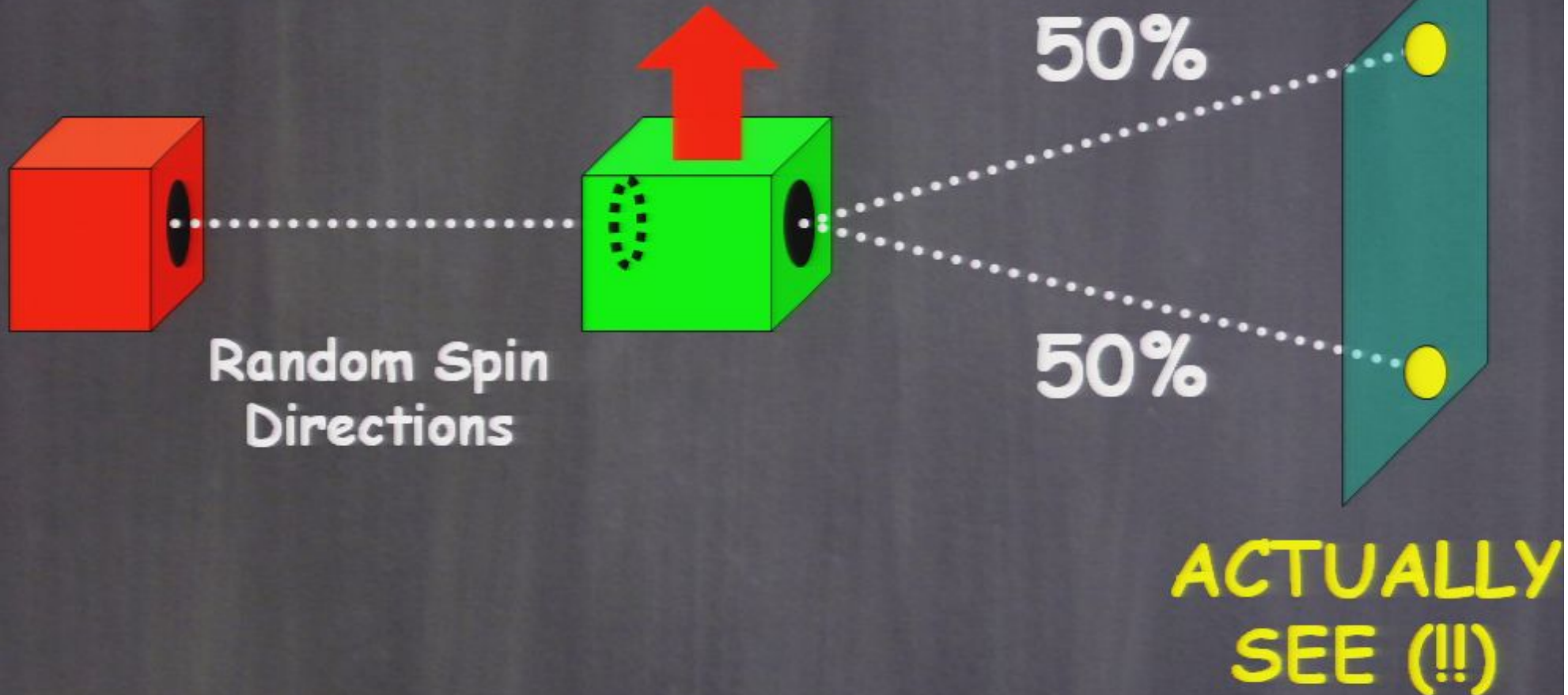
Experiment #1



Experiment #1



Experiment #1



This result has no "classical" or "commonsense" explanation

Experiment #2

Experiment #2



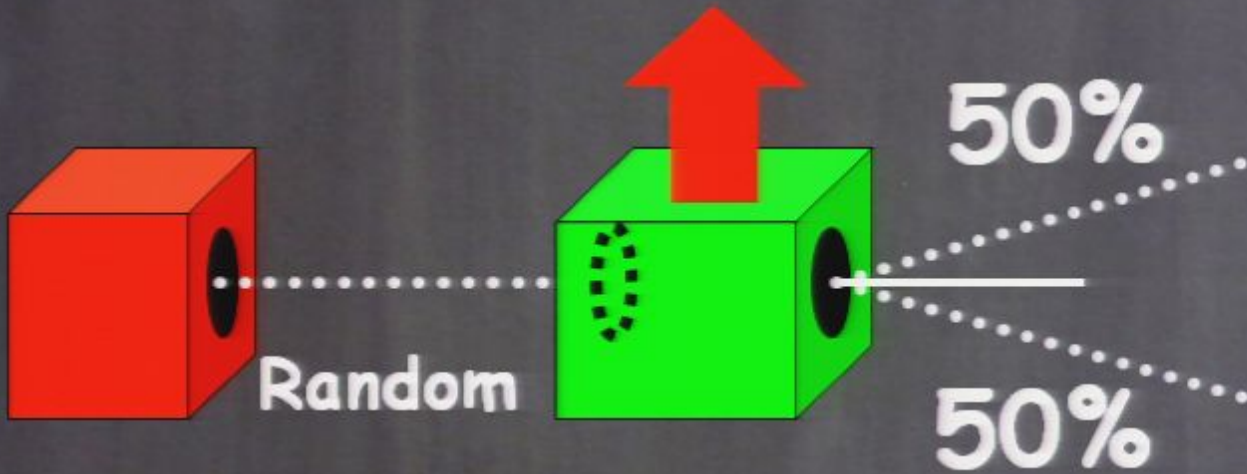
Experiment #2



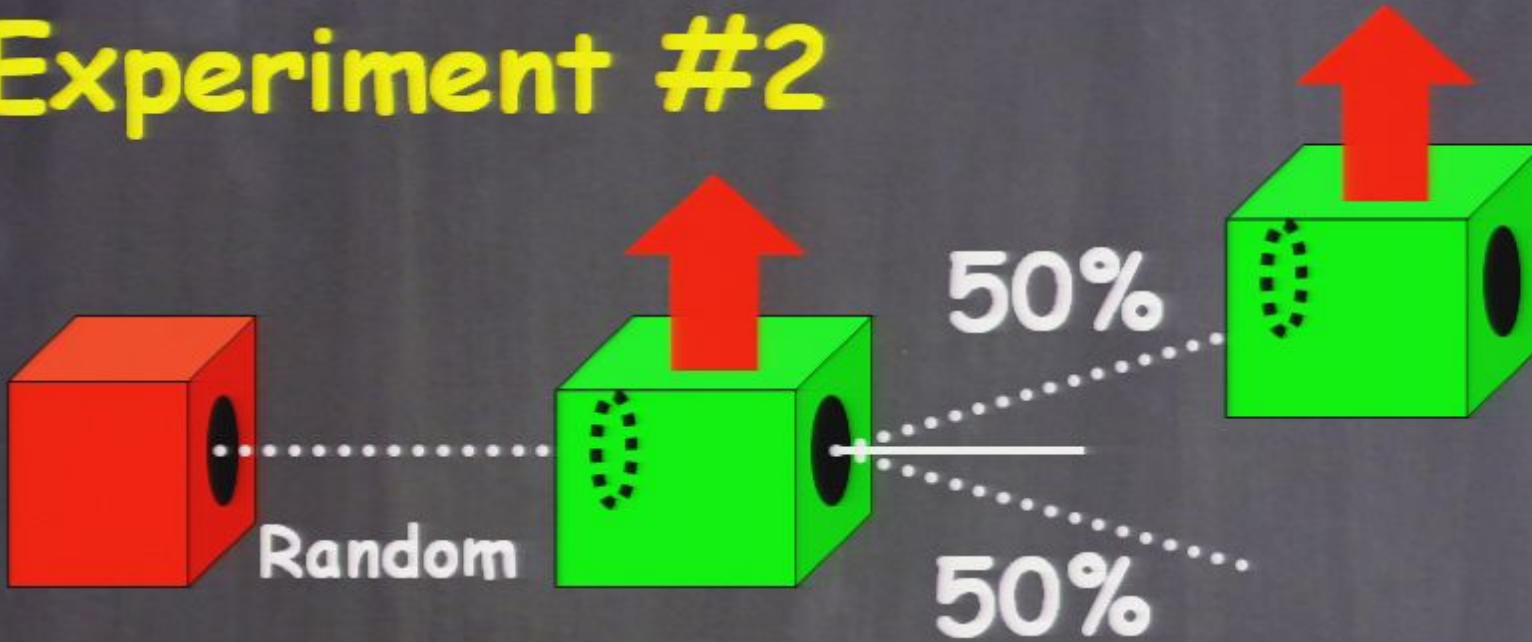
Experiment #2



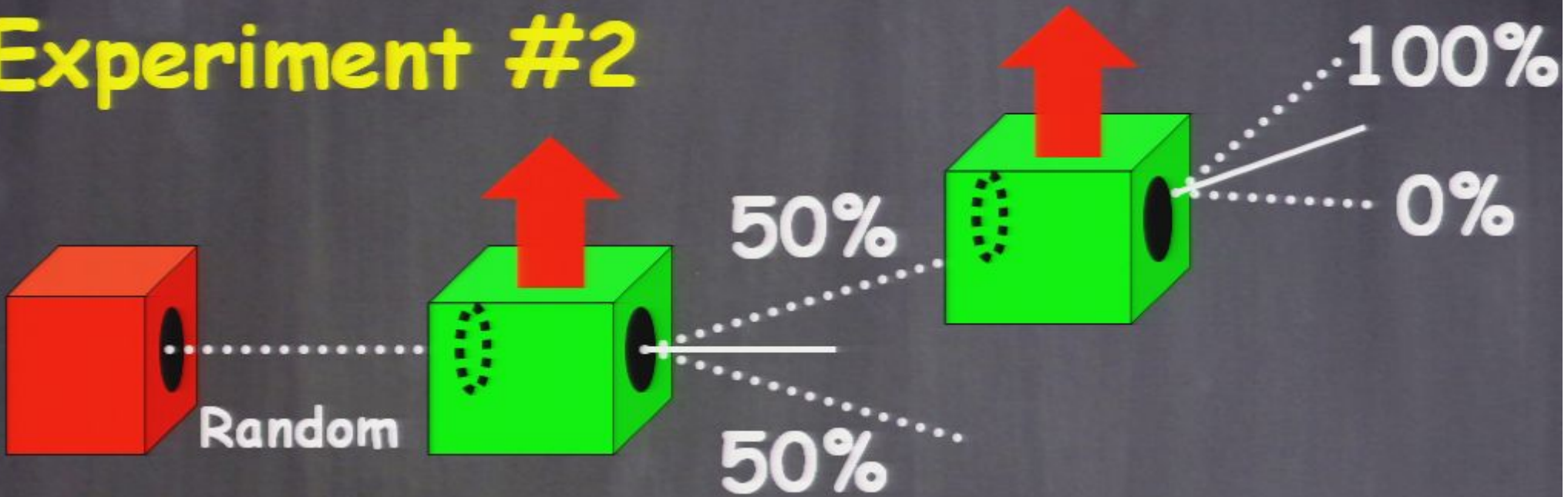
Experiment #2



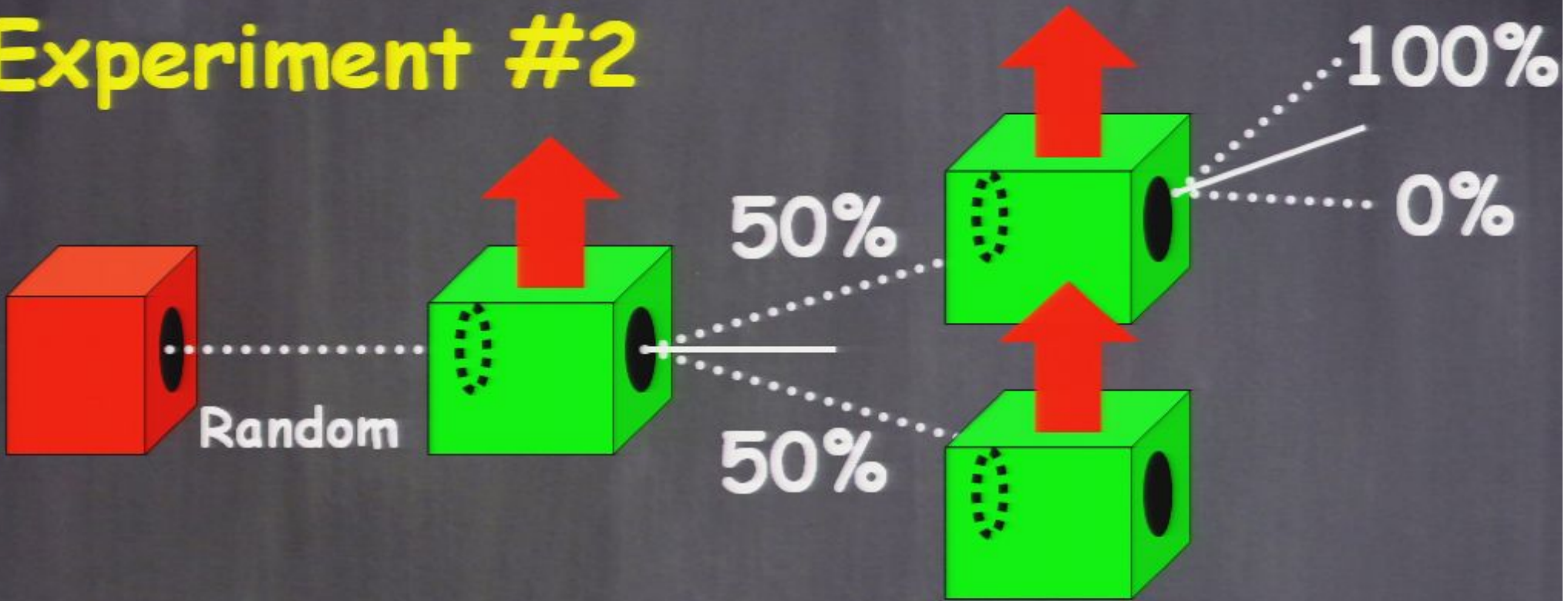
Experiment #2



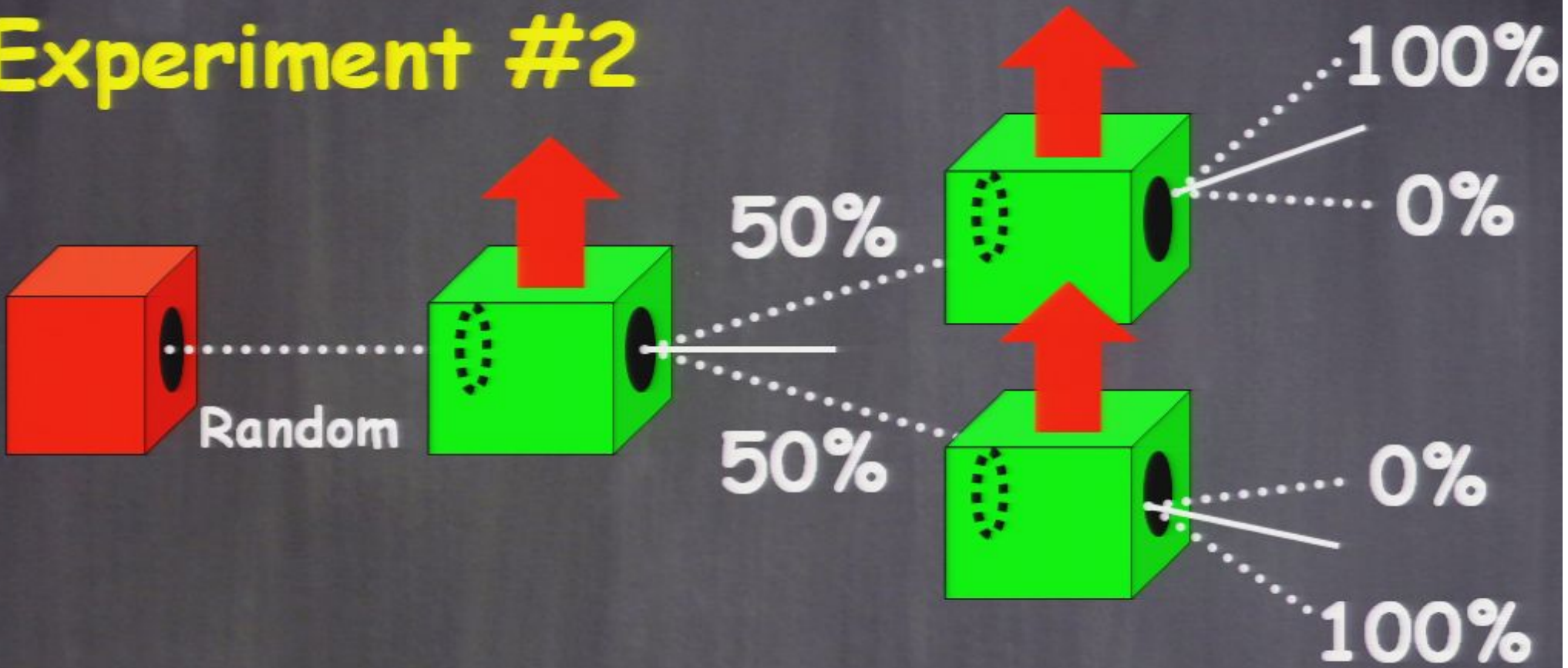
Experiment #2



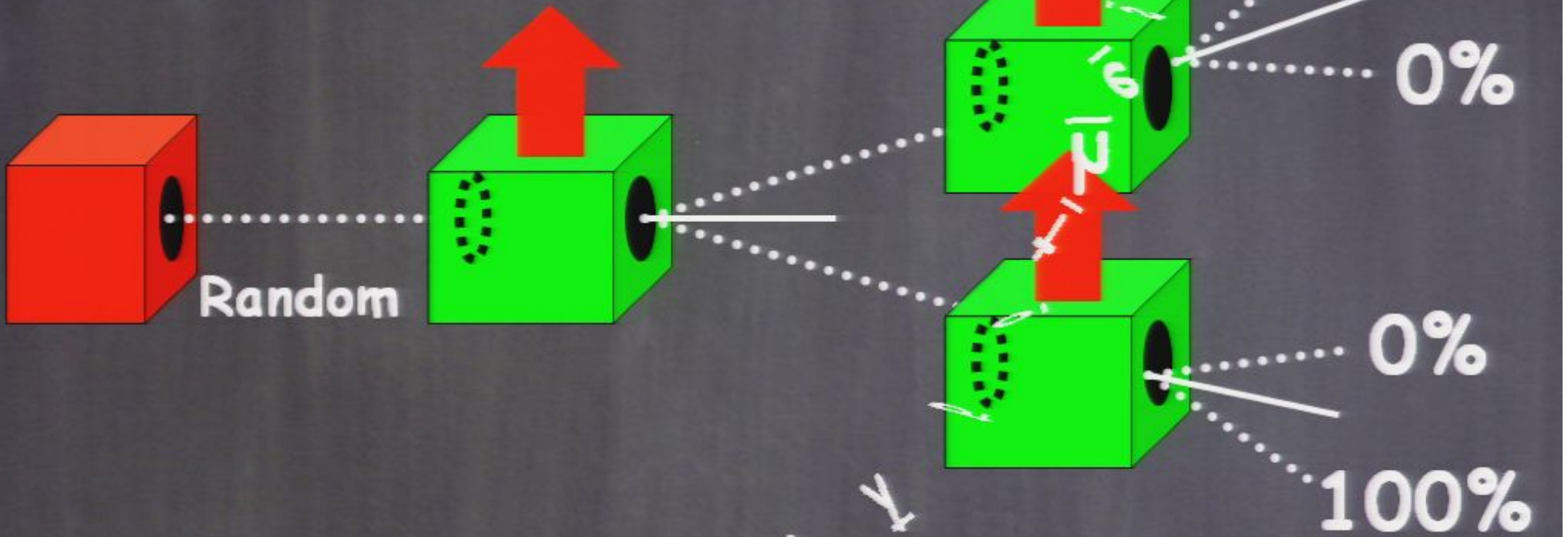
Experiment #2



Experiment #2

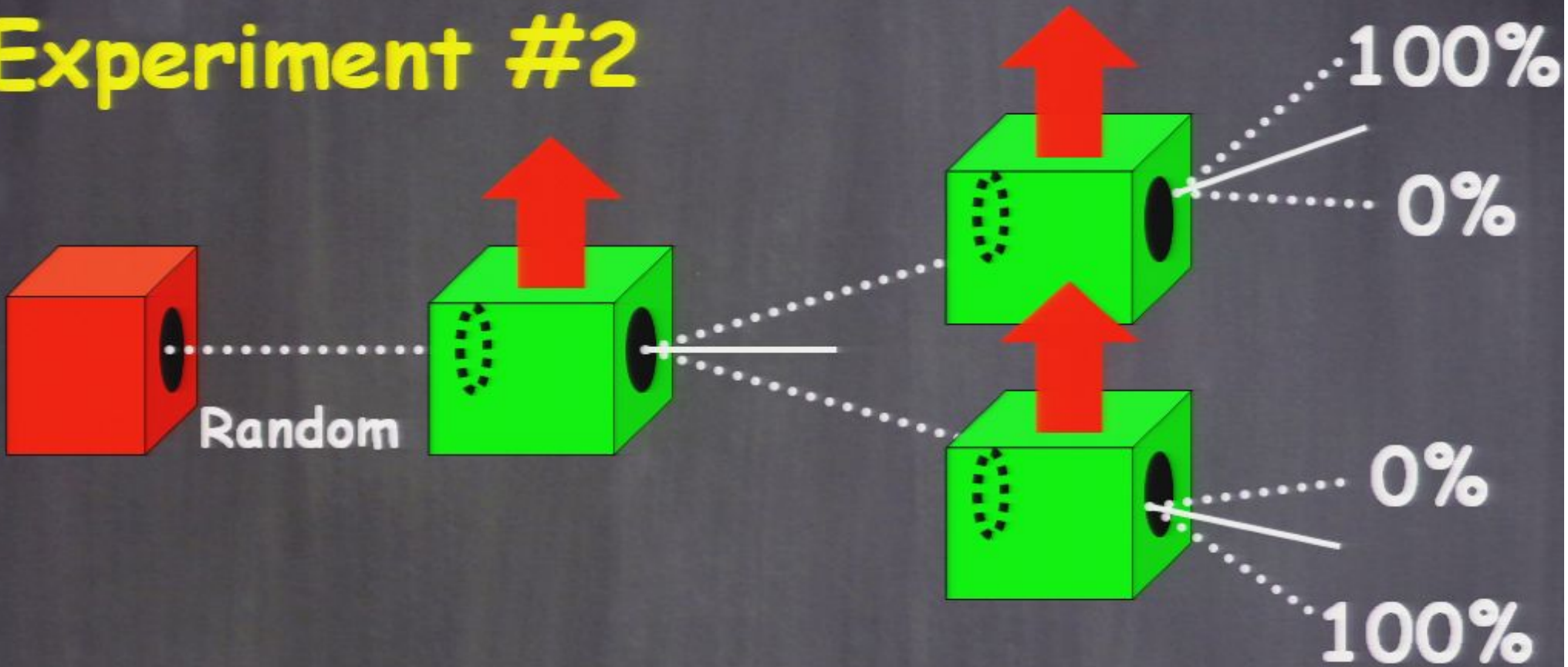


Experiment #2



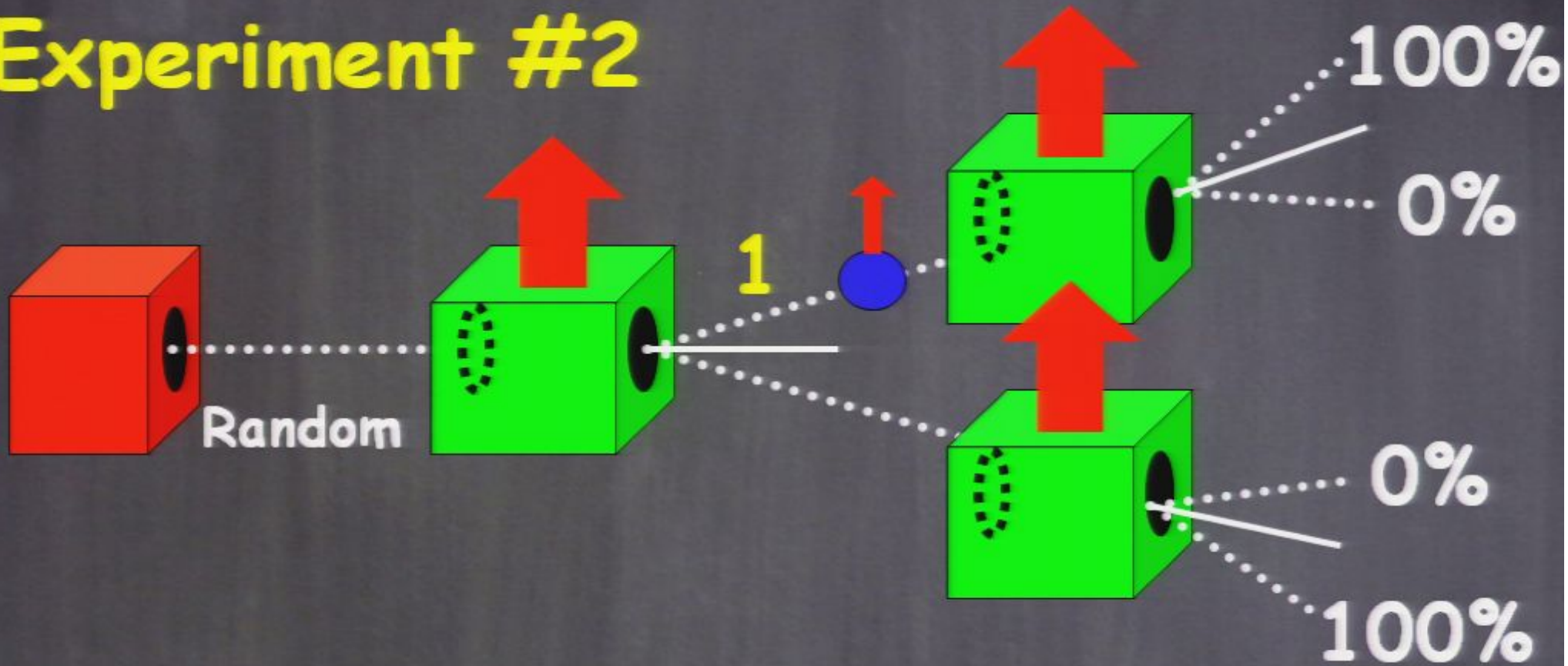
It is consistent to \hbar

Experiment #2




It is consistent to hypothesize:

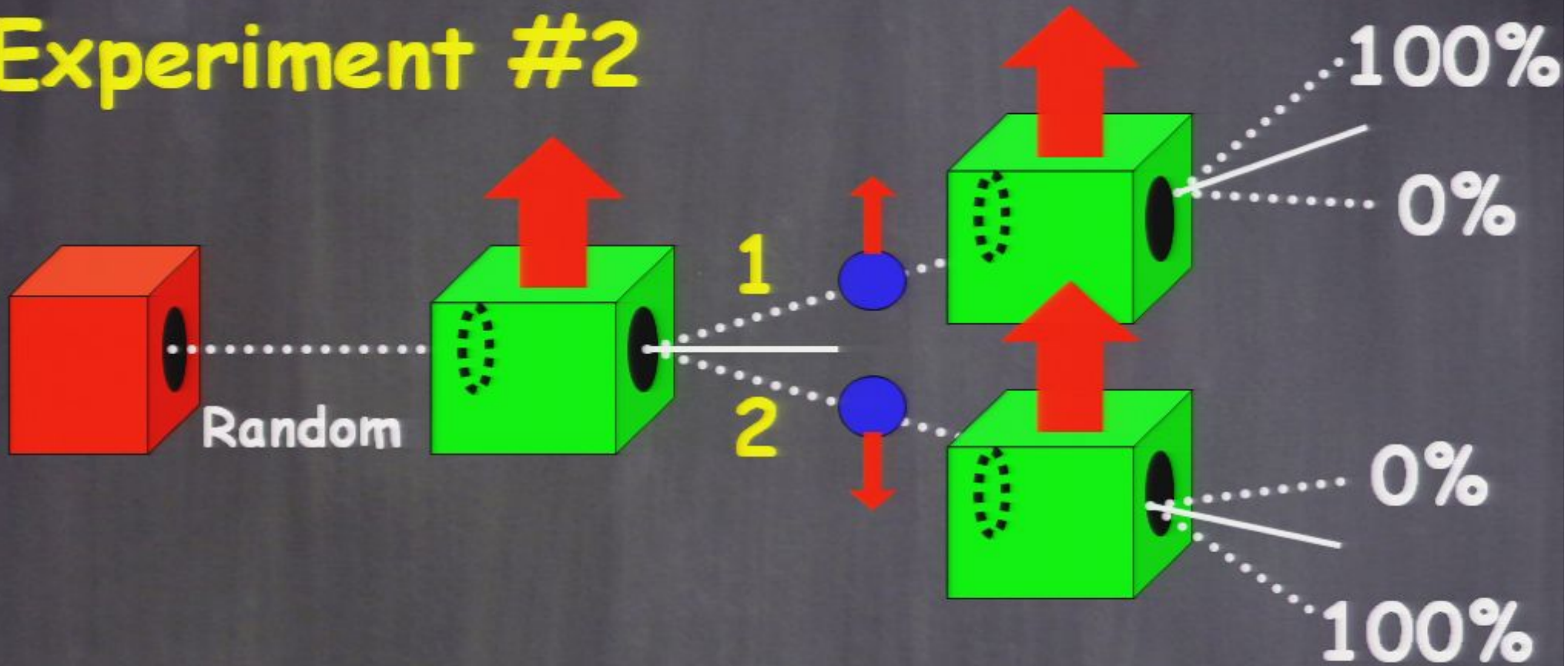
Experiment #2



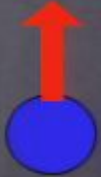
It is consistent to hypothesize:


Beam 1 atoms are all "spin up": 

Experiment #2

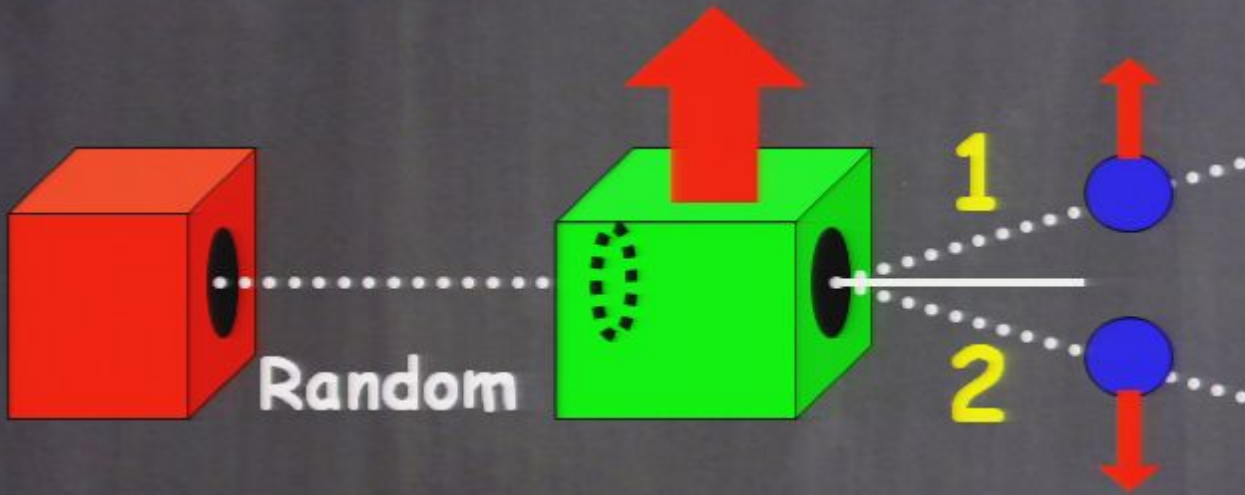


It is consistent to hypothesize:

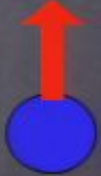
Beam 1 atoms are all "spin up": 


Beam 2 atoms are all "spin down": 

Experiment #2

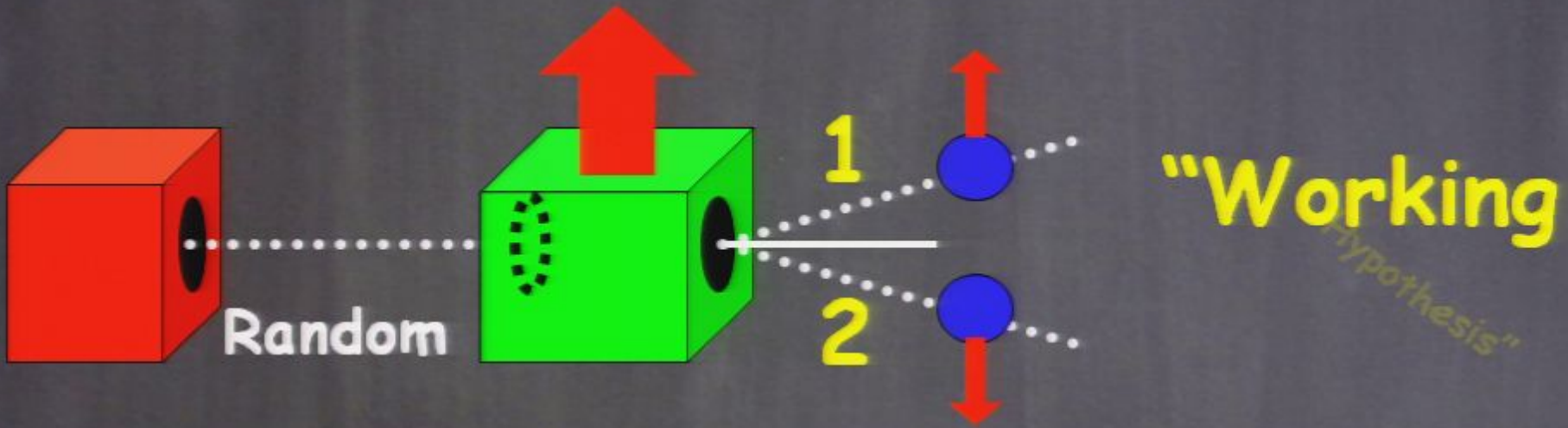


It is consistent to hypothesize:

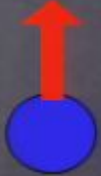
Beam 1 atoms are all "spin up": 


Beam 2 atoms are all "spin down": 

Experiment #2



It is consistent to hypothesize:

Beam 1 atoms are all "spin up": 

Beam 2 atoms are all "spin down": 

Experiment #3

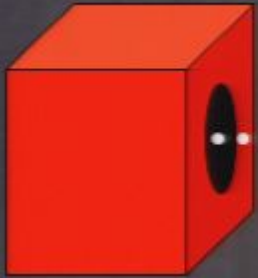
Experiment #3



Experiment #3



Experiment #3



Random



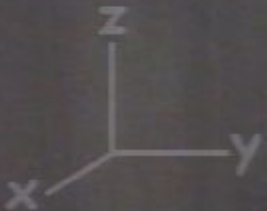
Experiment #3



Experiment #3



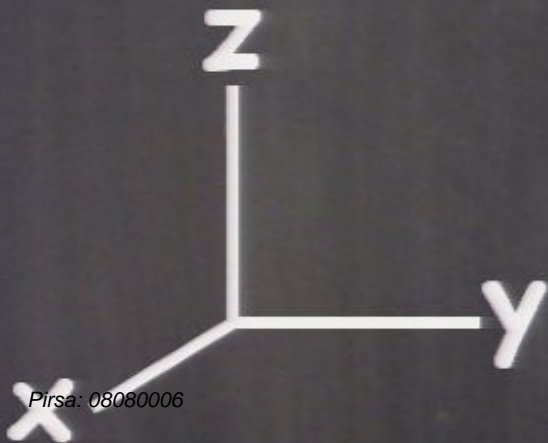
HORIZONTAL



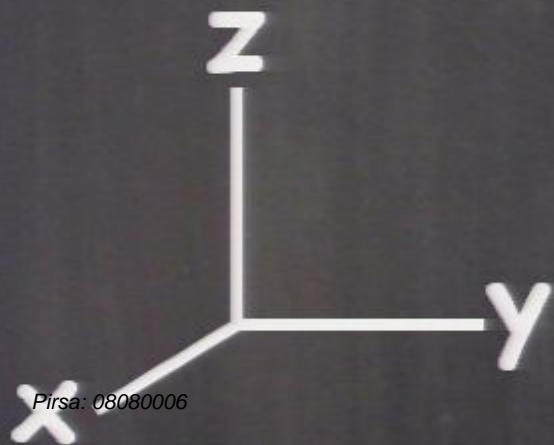
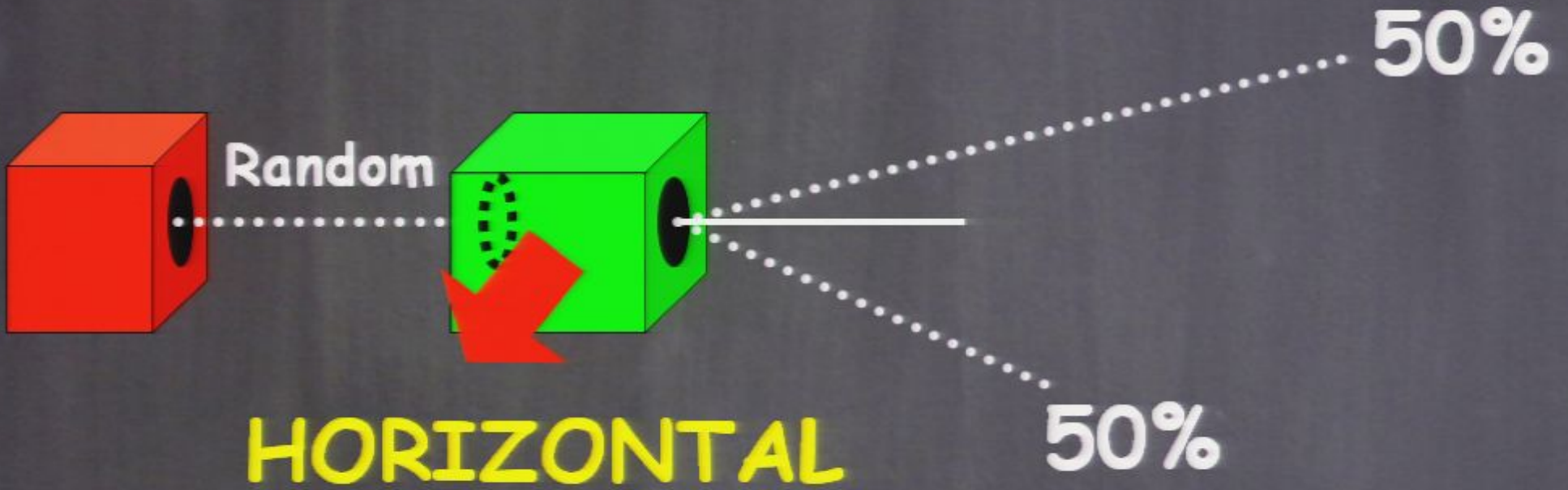
Experiment #3



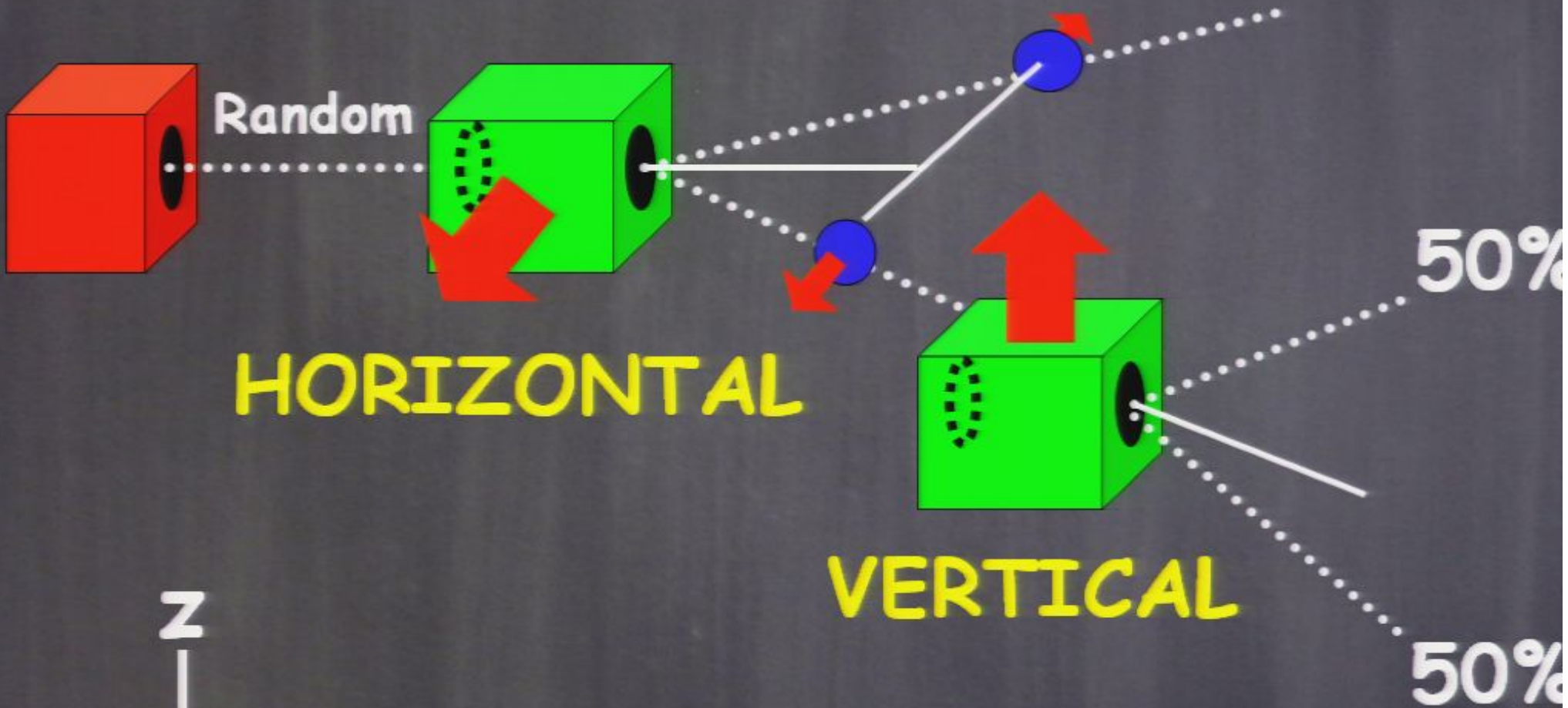
HORIZONTAL



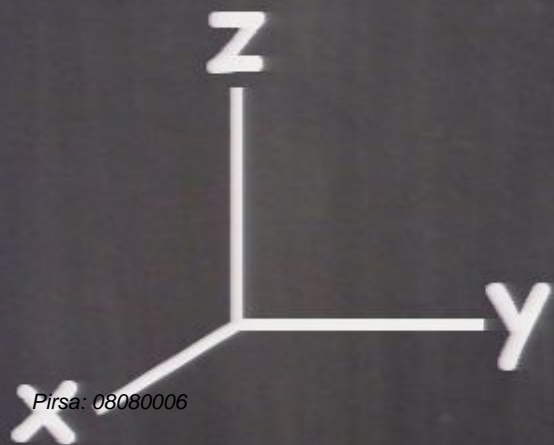
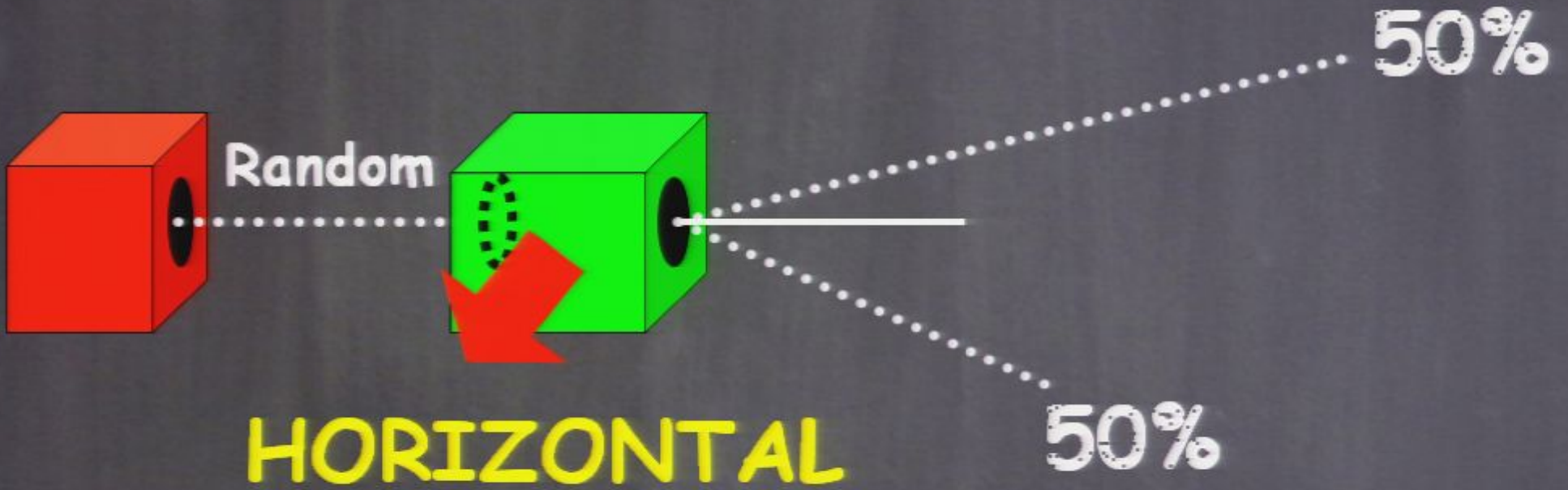
Experiment #3



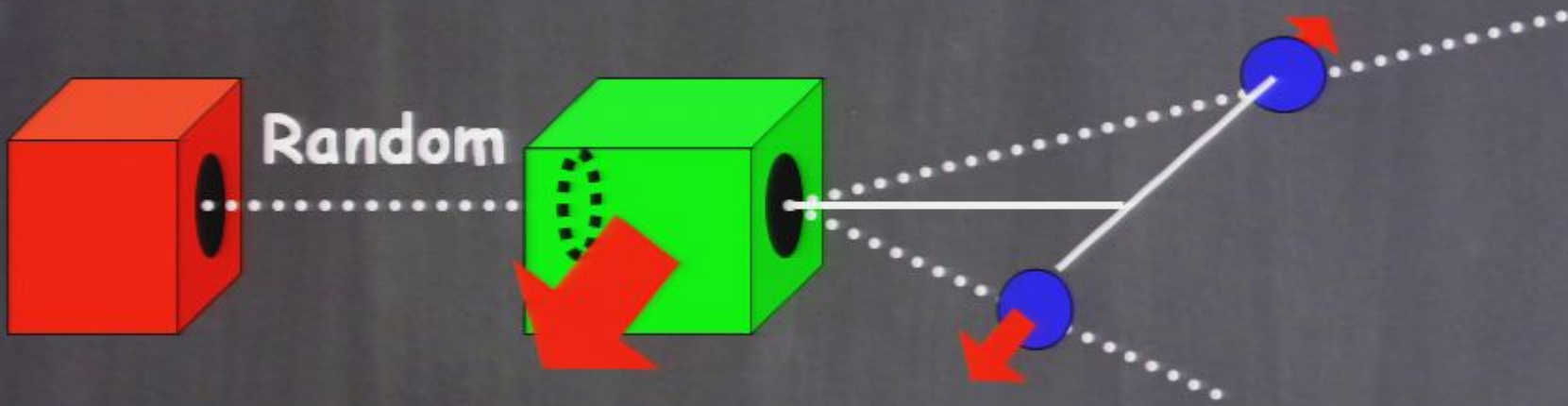
Experiment #3



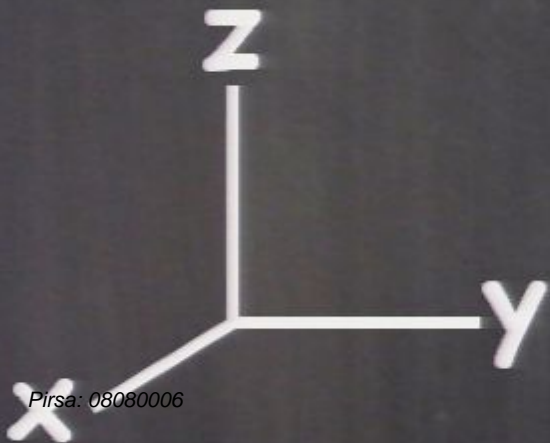
Experiment #3



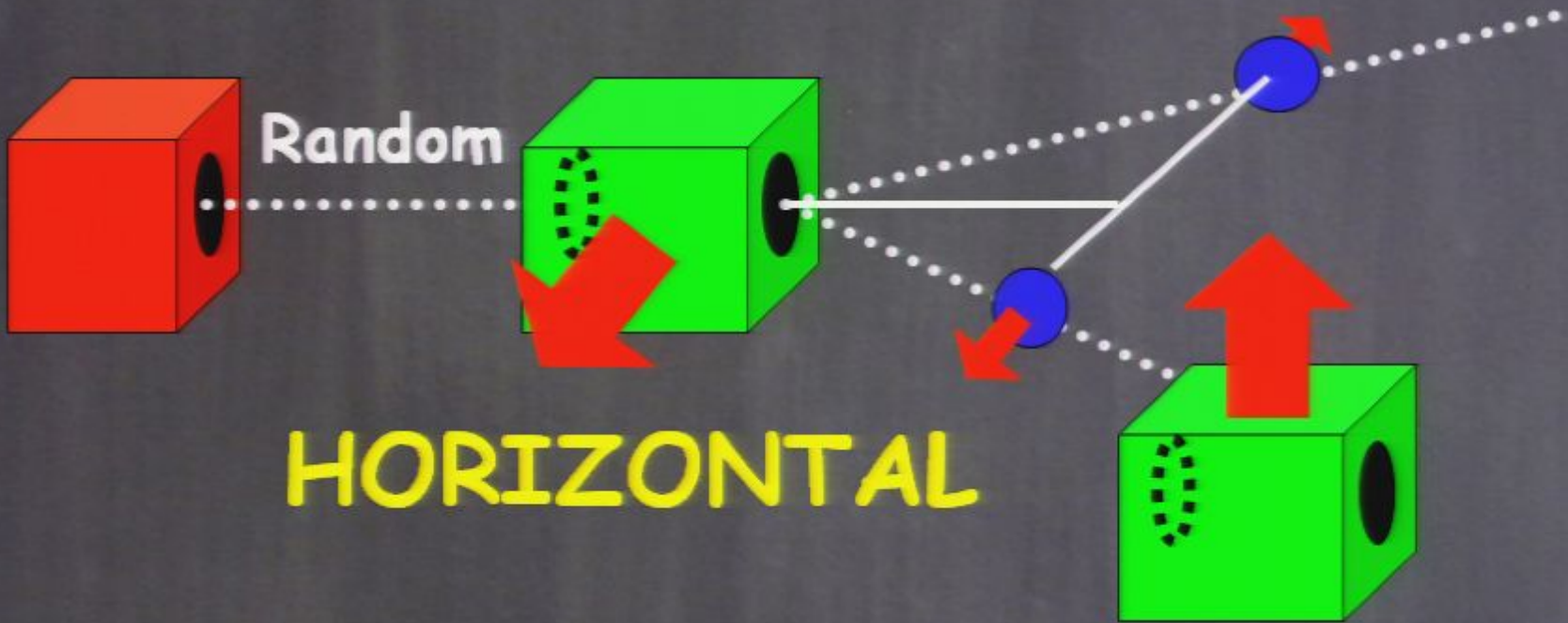
Experiment #3



HORIZONTAL

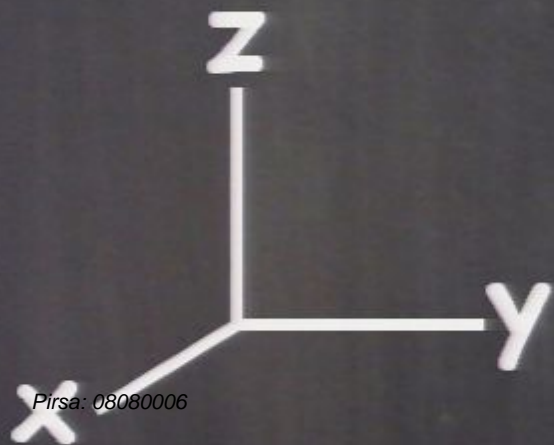


Experiment #3

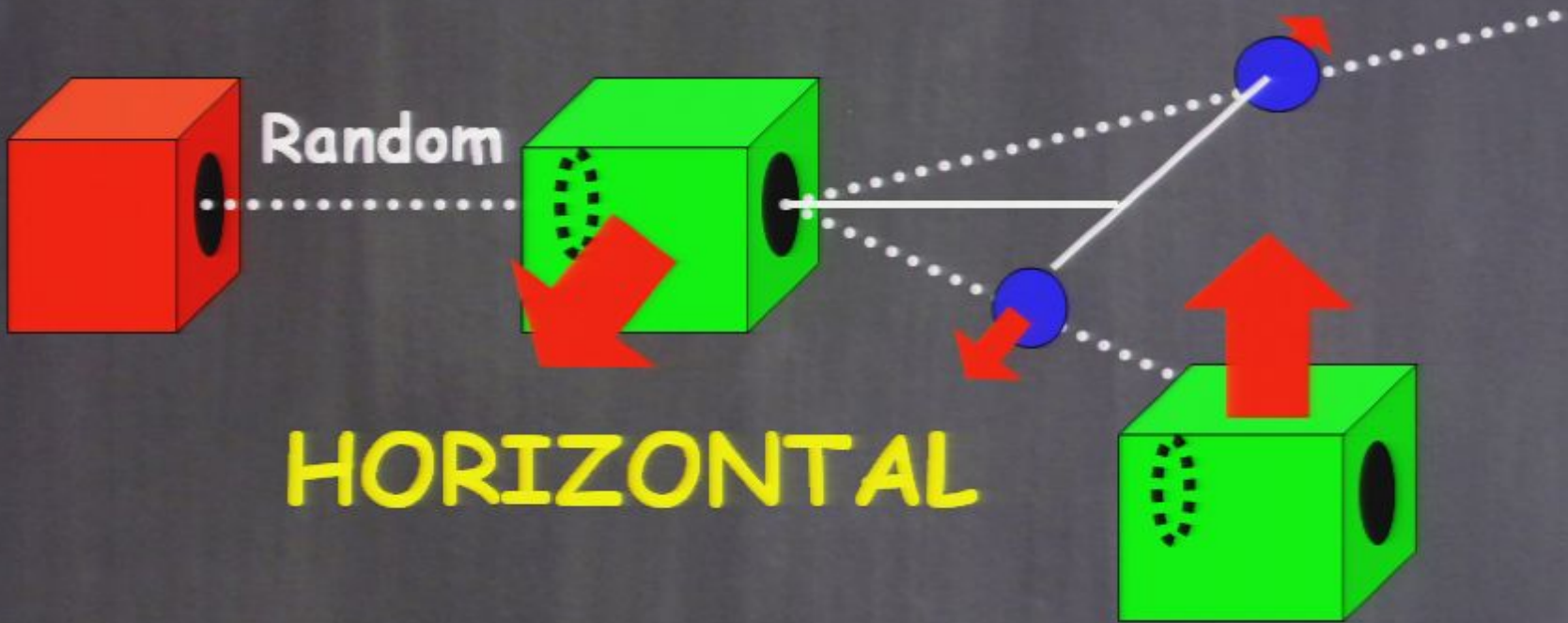


HORIZONTAL

VE

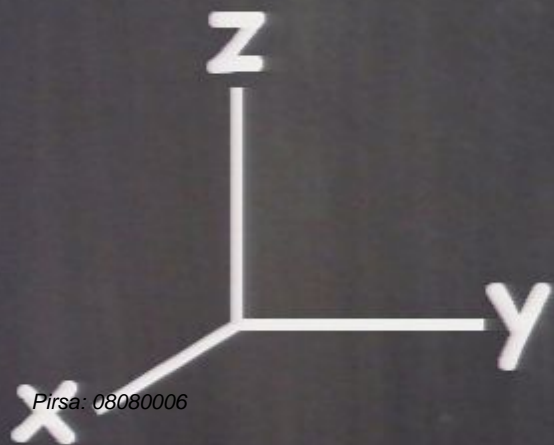


Experiment #3

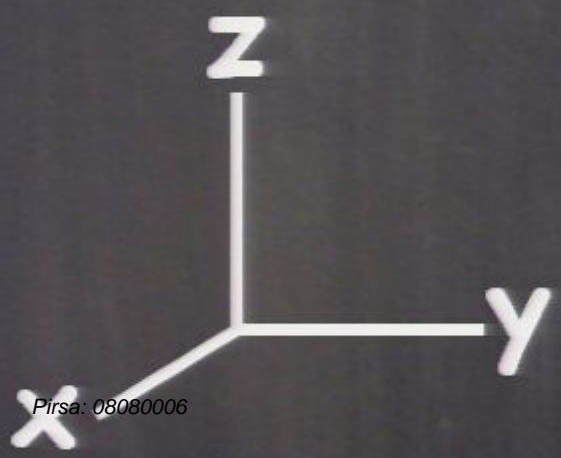
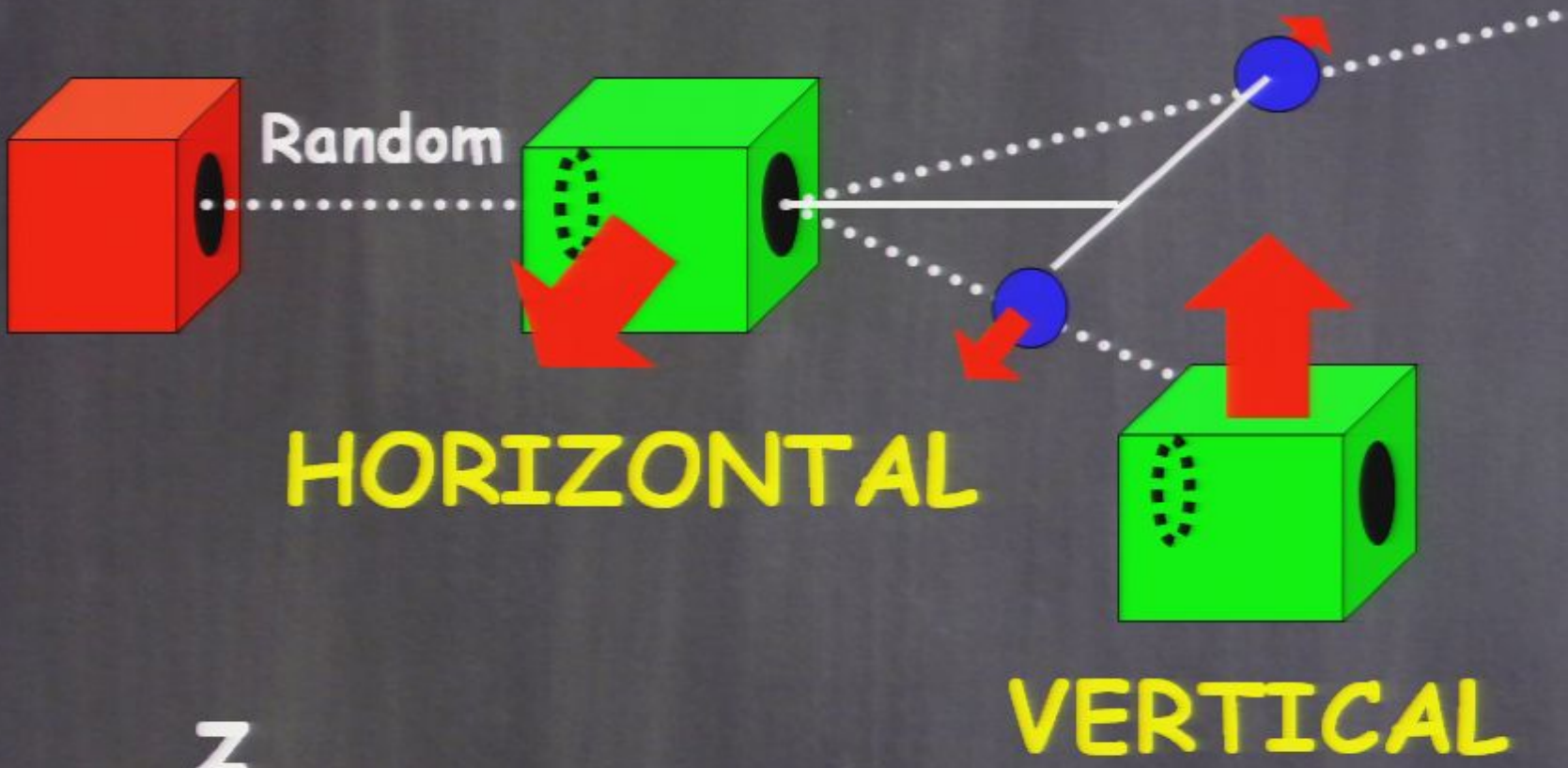


HORIZONTAL

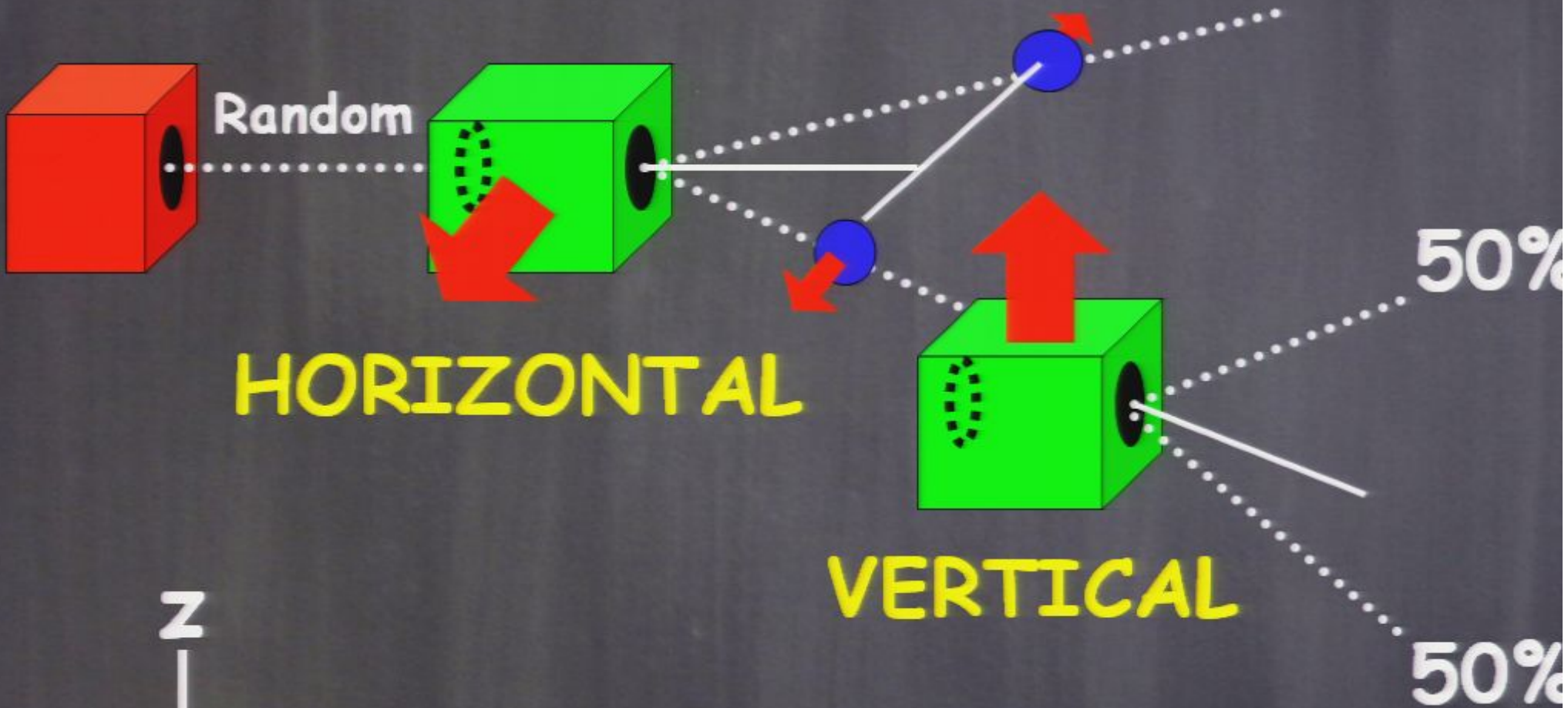
VERTICAL



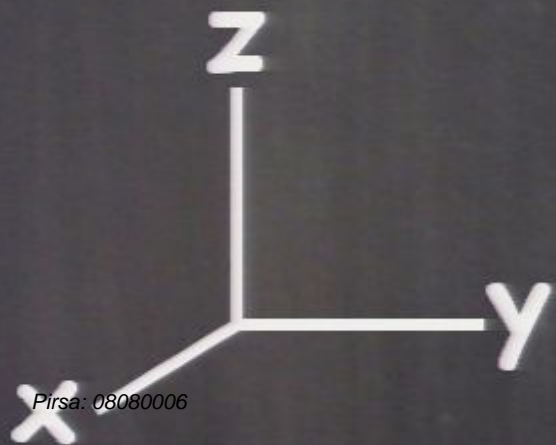
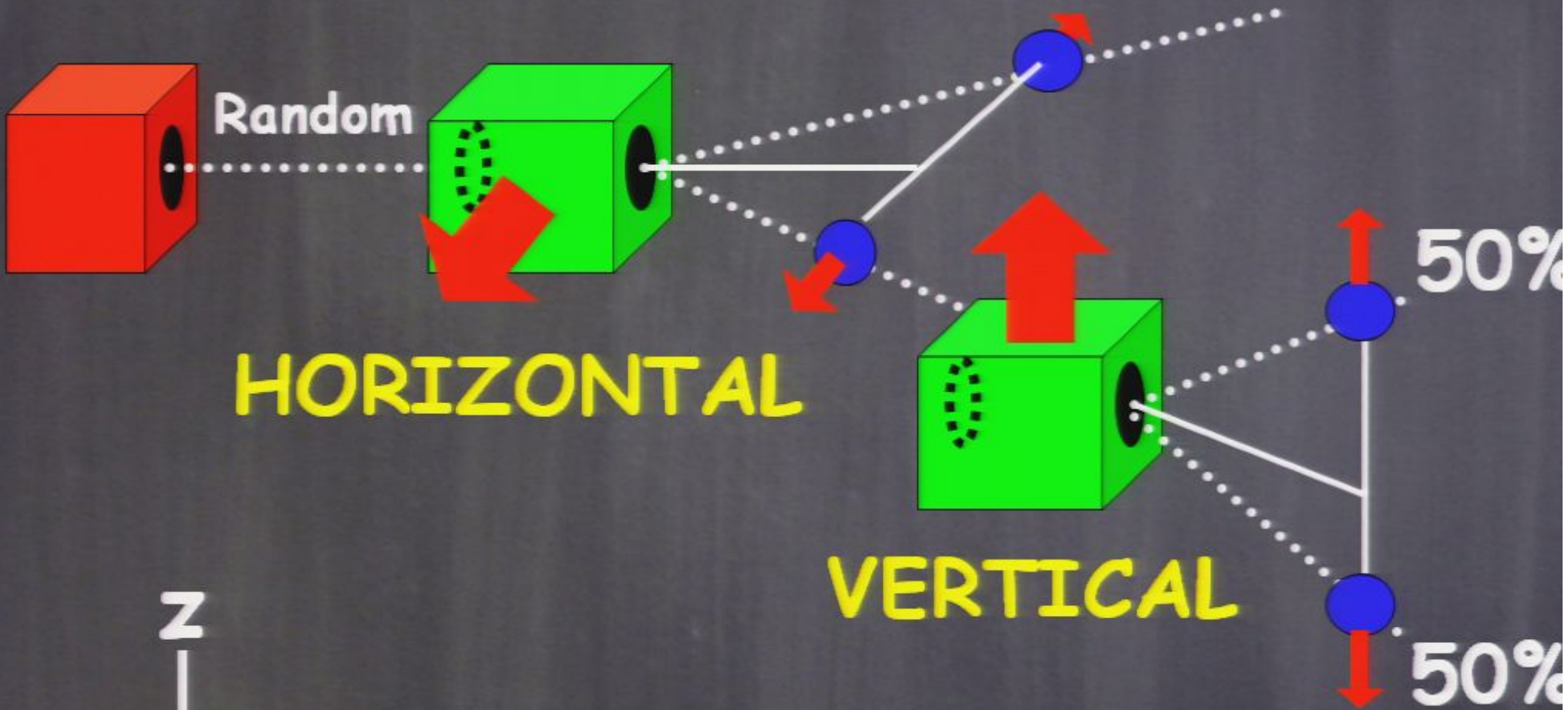
Experiment #3



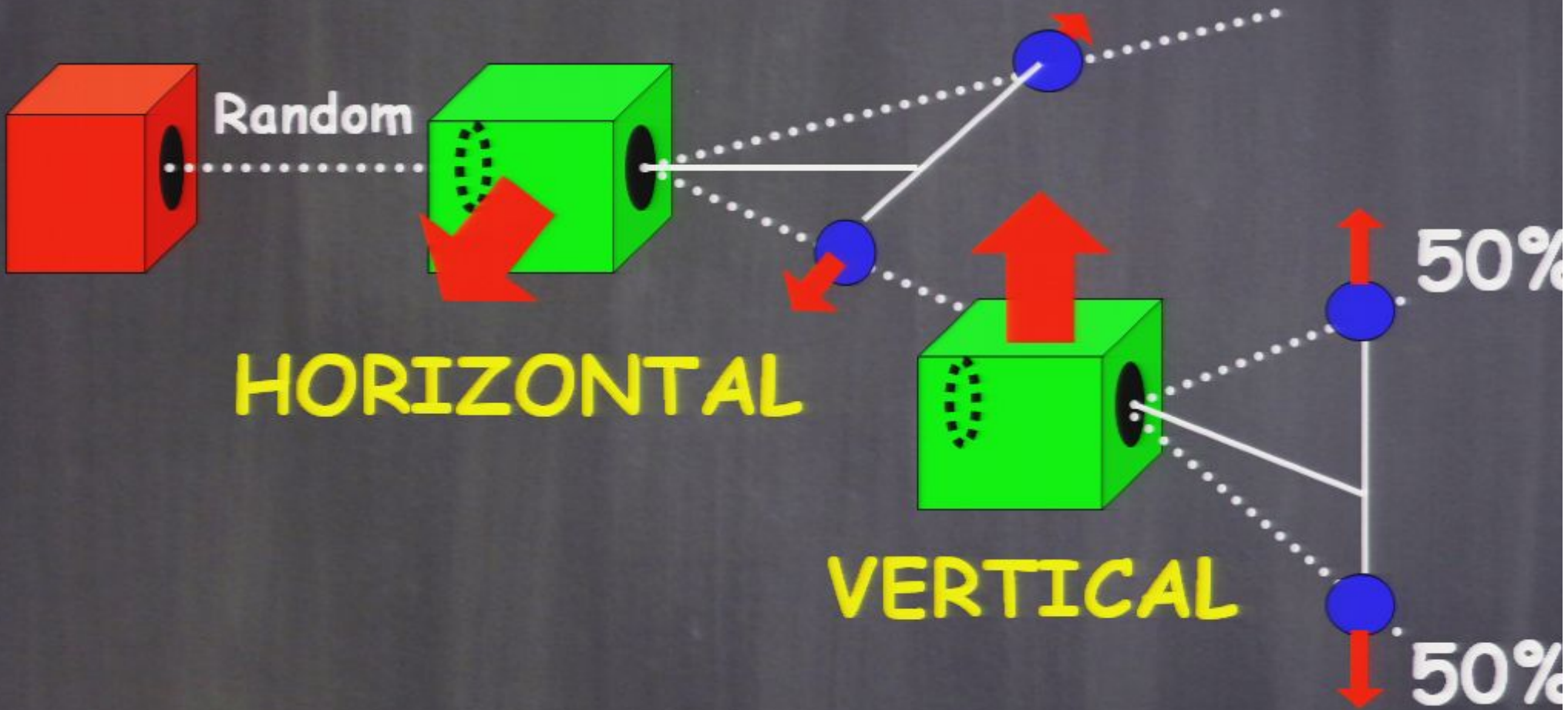
Experiment #3



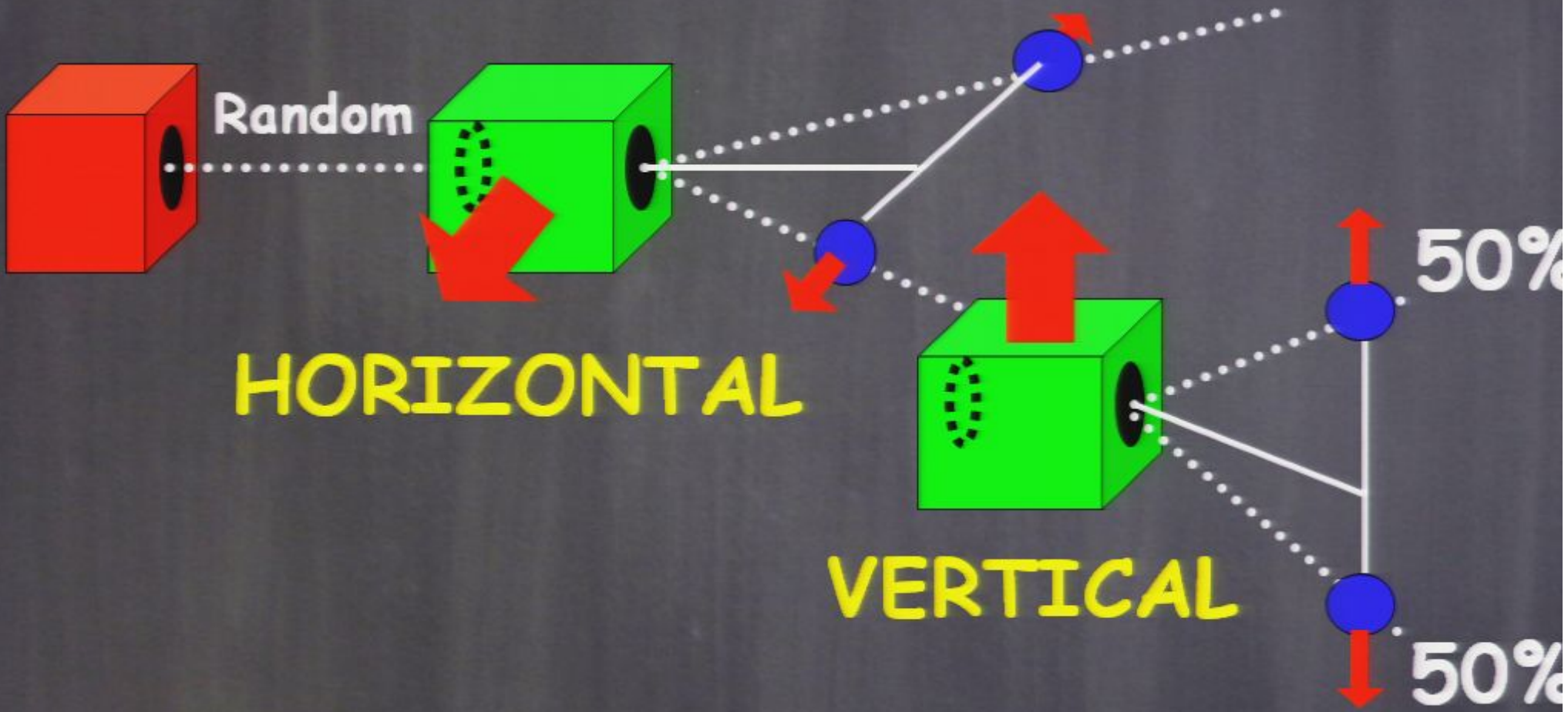
Experiment #3



Experiment #3



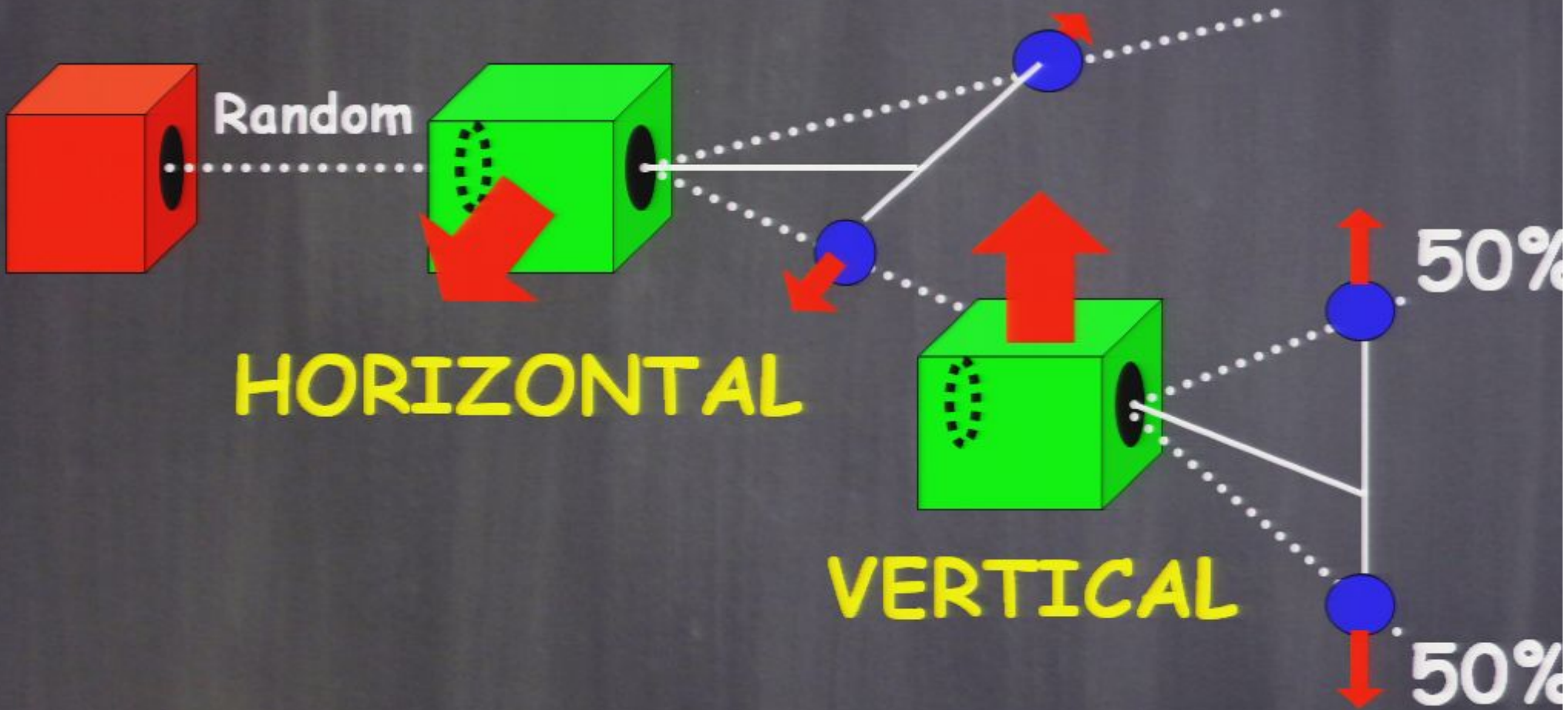
Experiment #3



HORIZONTAL atom has 50/50 CHANCE of emerging "spin up" or "spin down"

Summary of Experiments

Experiment #3



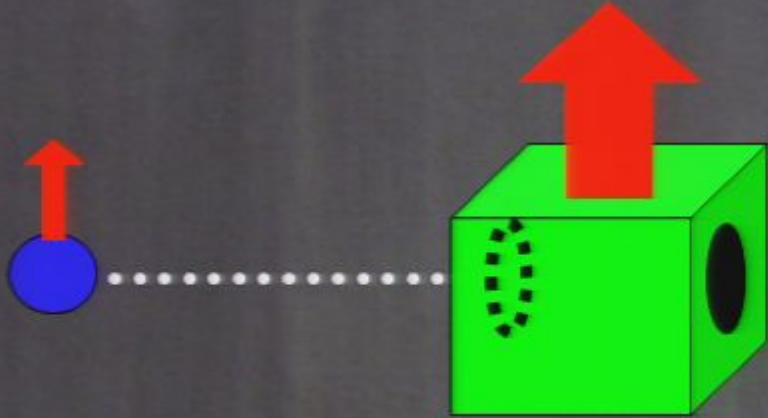
HORIZONTAL atom has 50/50 **CHANCE** of emerging "spin up" or "spin down"

Summary of Experiments

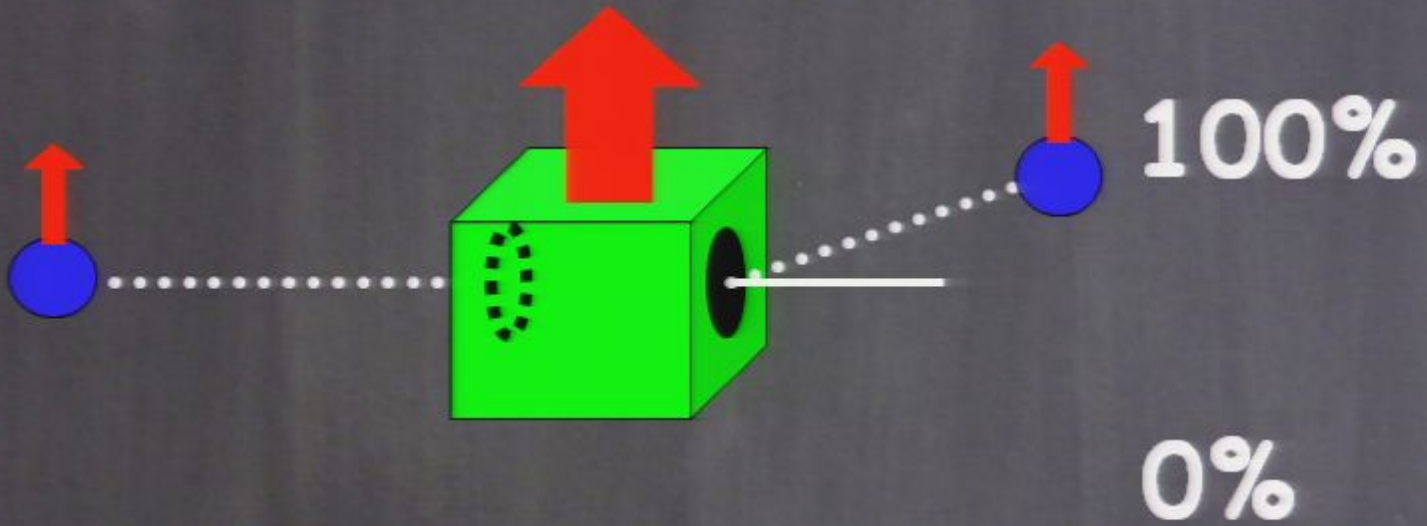
Summary of Experiments



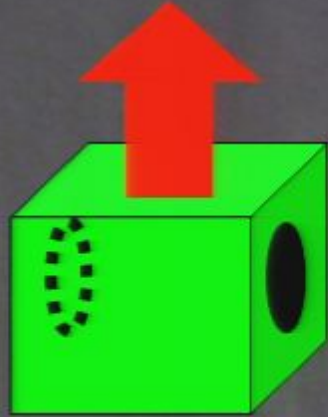
Summary of Experiments



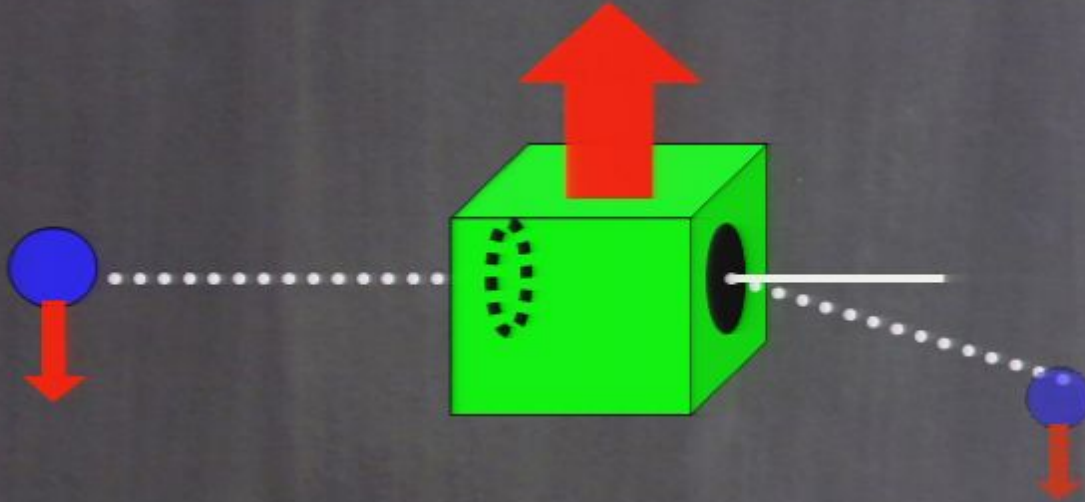
Summary of Experiments



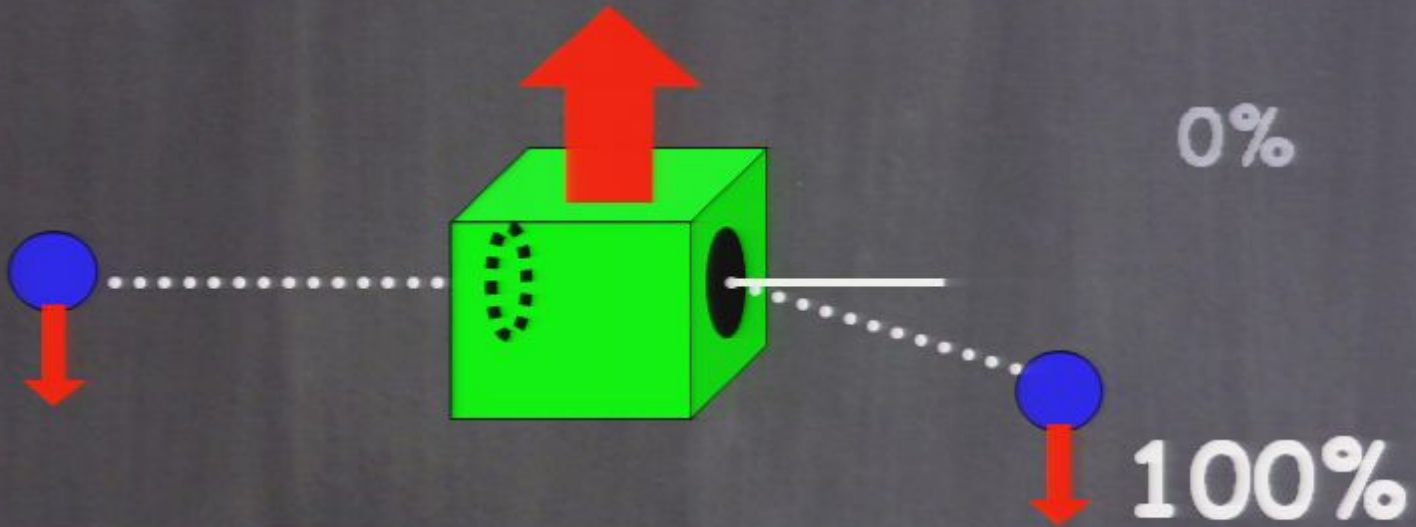
Summary of Experiments



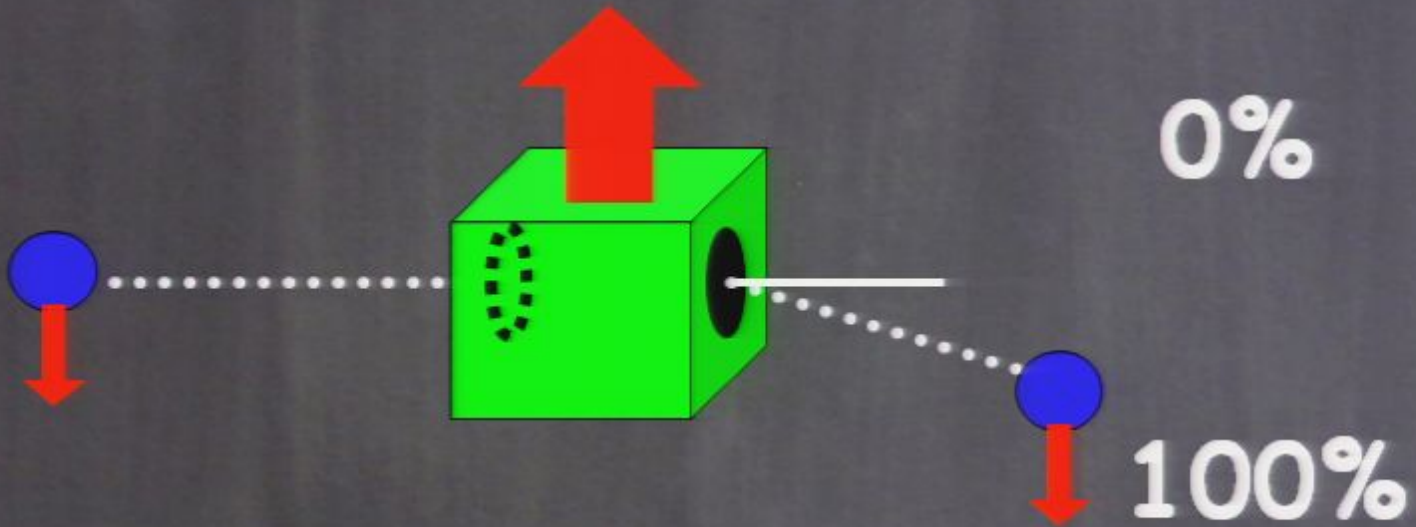
Summary of Experiments



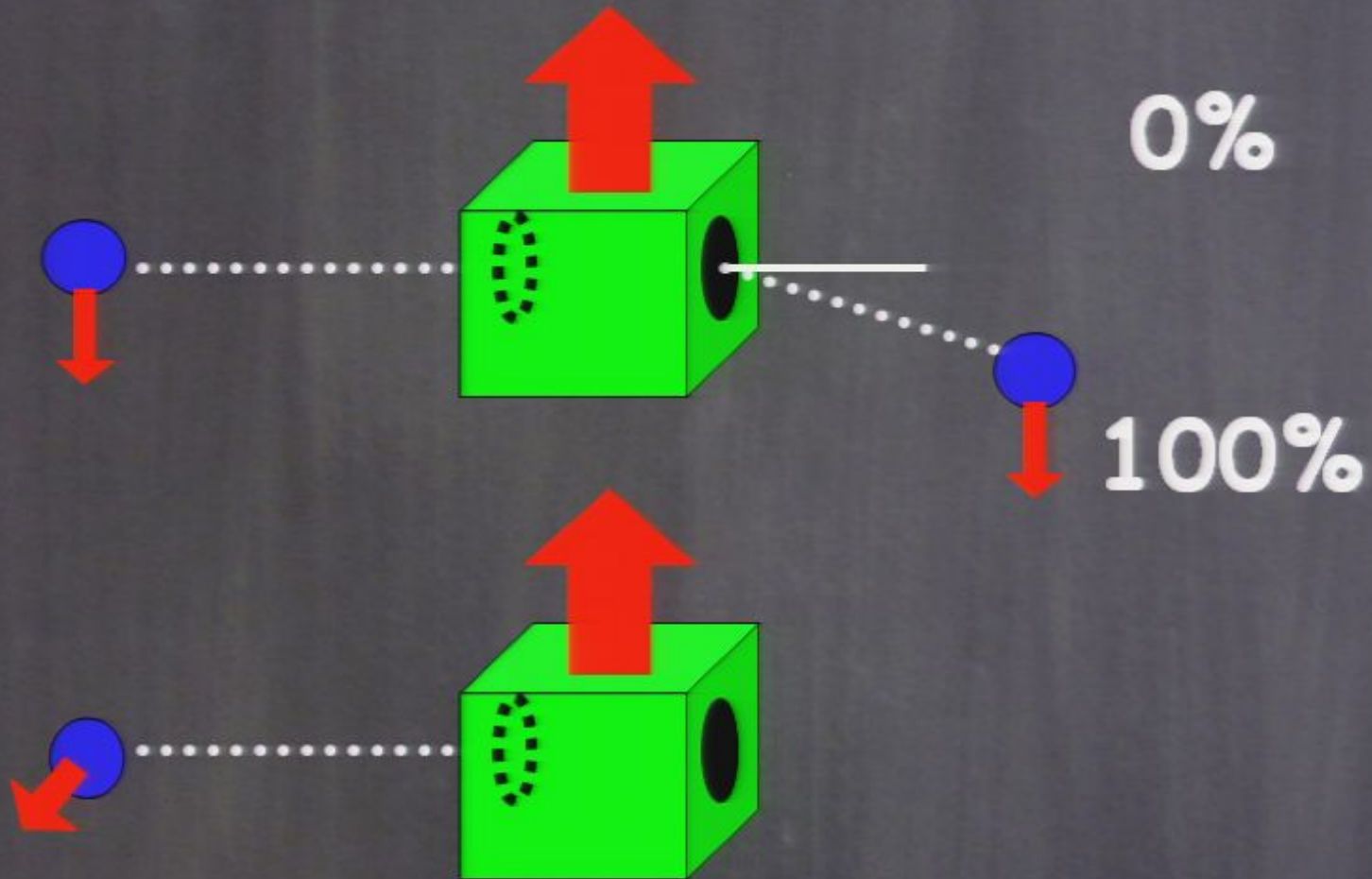
Summary of Experiments



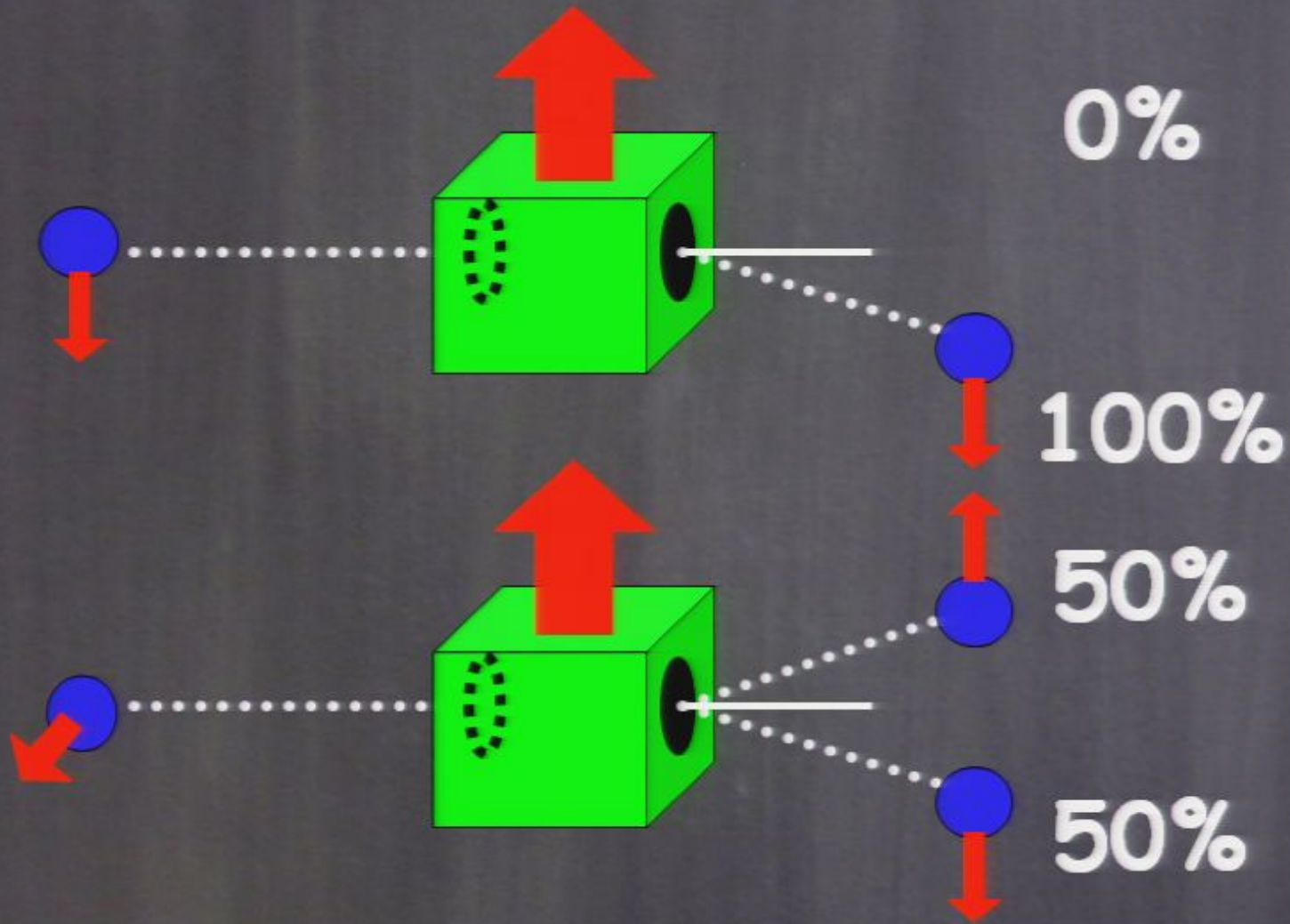
Summary of Experiments



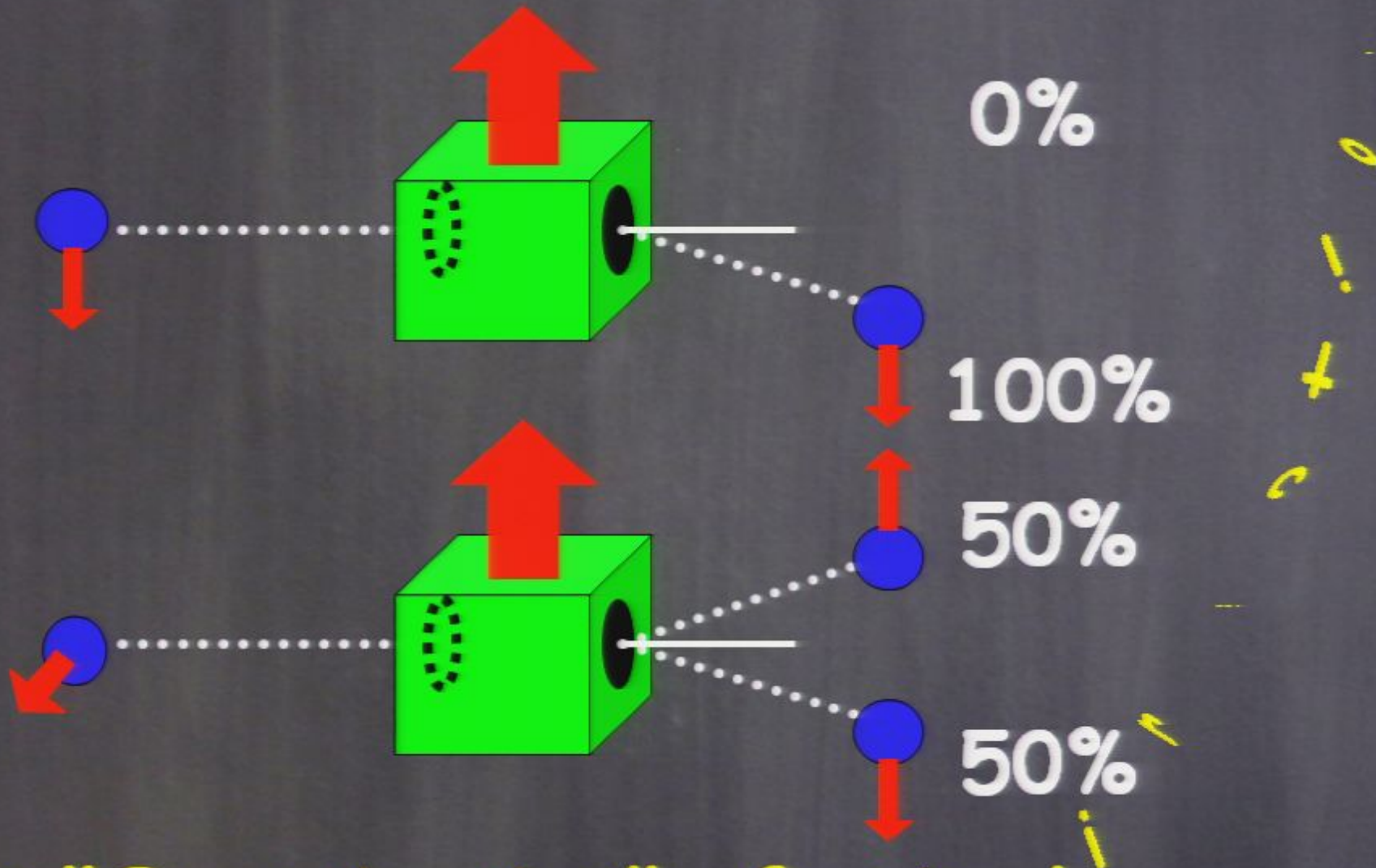
Summary of Experiments



Summary of Experiments

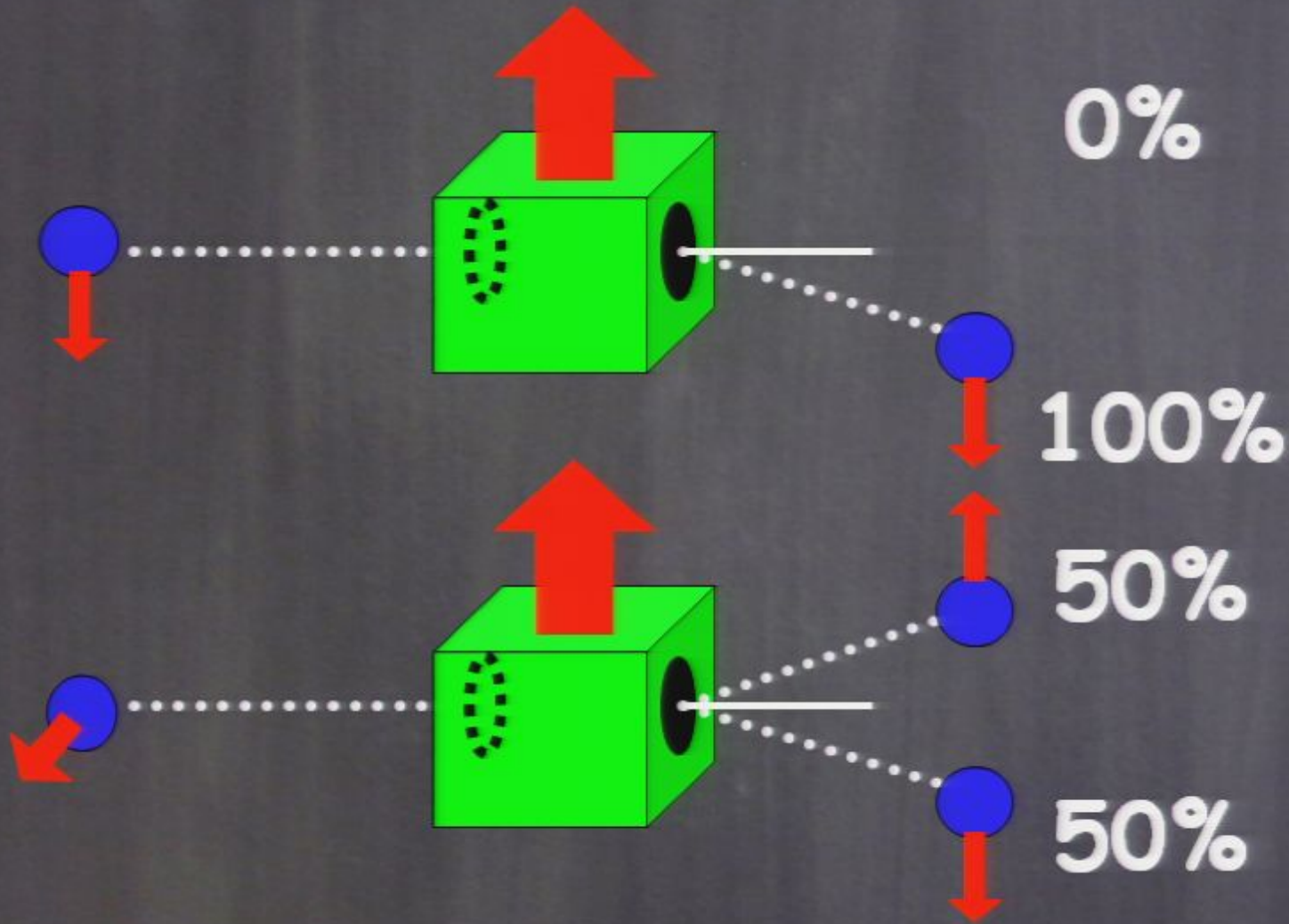


Summary of Experiments



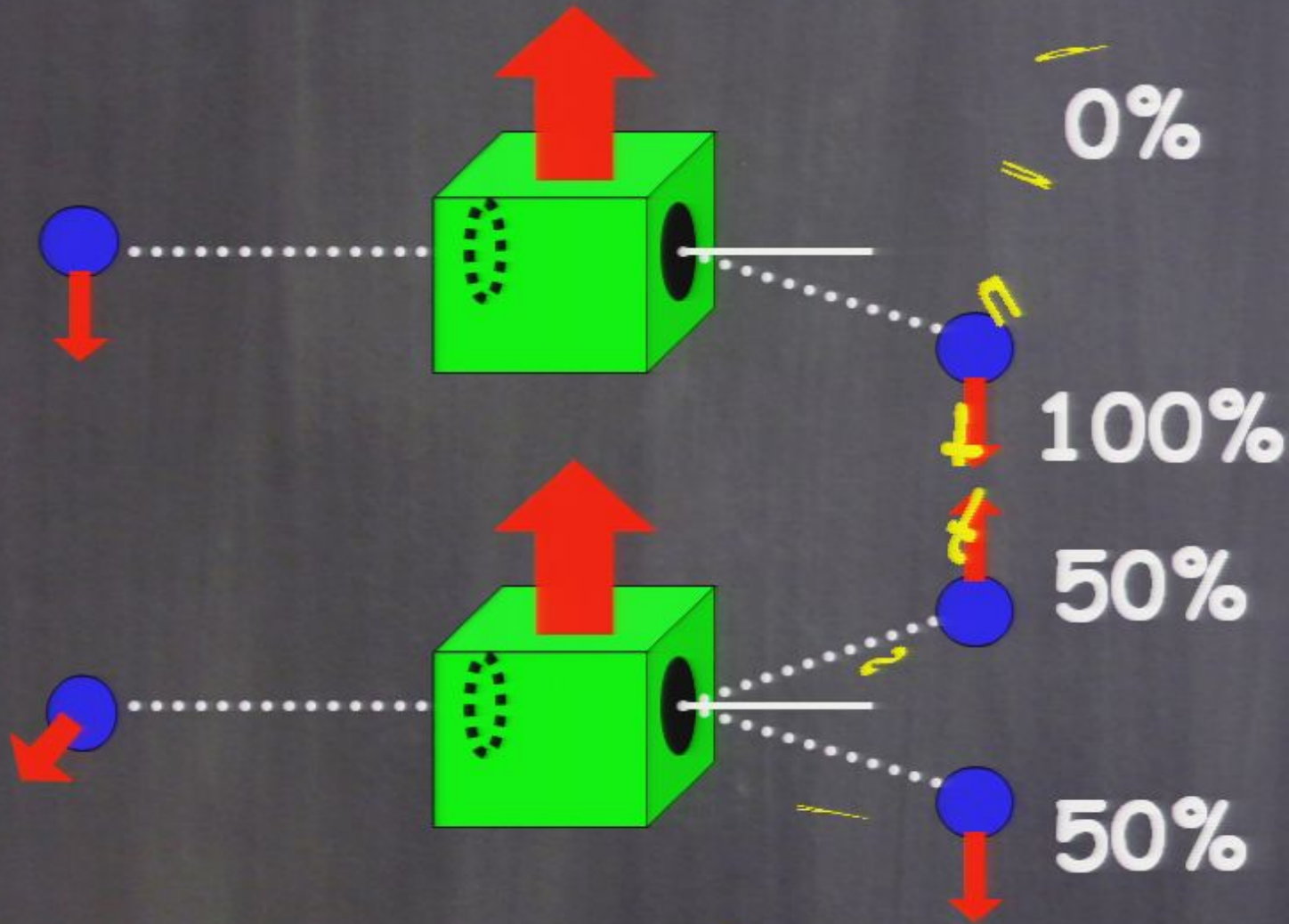
1: "Quantization" of spin d

Summary of Experiments



1: "Quantization" of spin direction

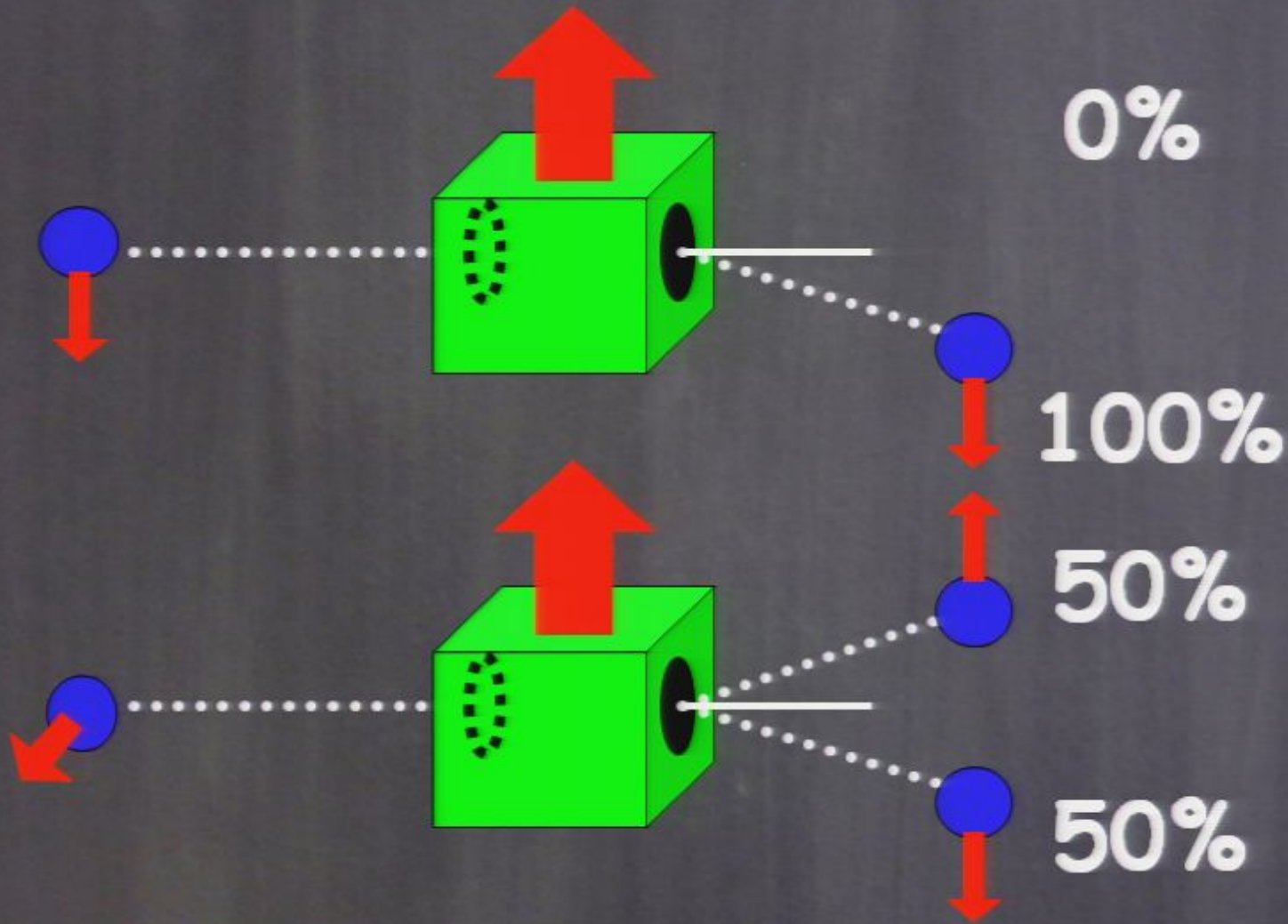
Summary of Experiments



1: "Quantization" of spin direction

2: Probability p

Summary of Experiments



1: "Quantization" of spin direction

2: Probability plays fundamental role

The Mathematics of Zing

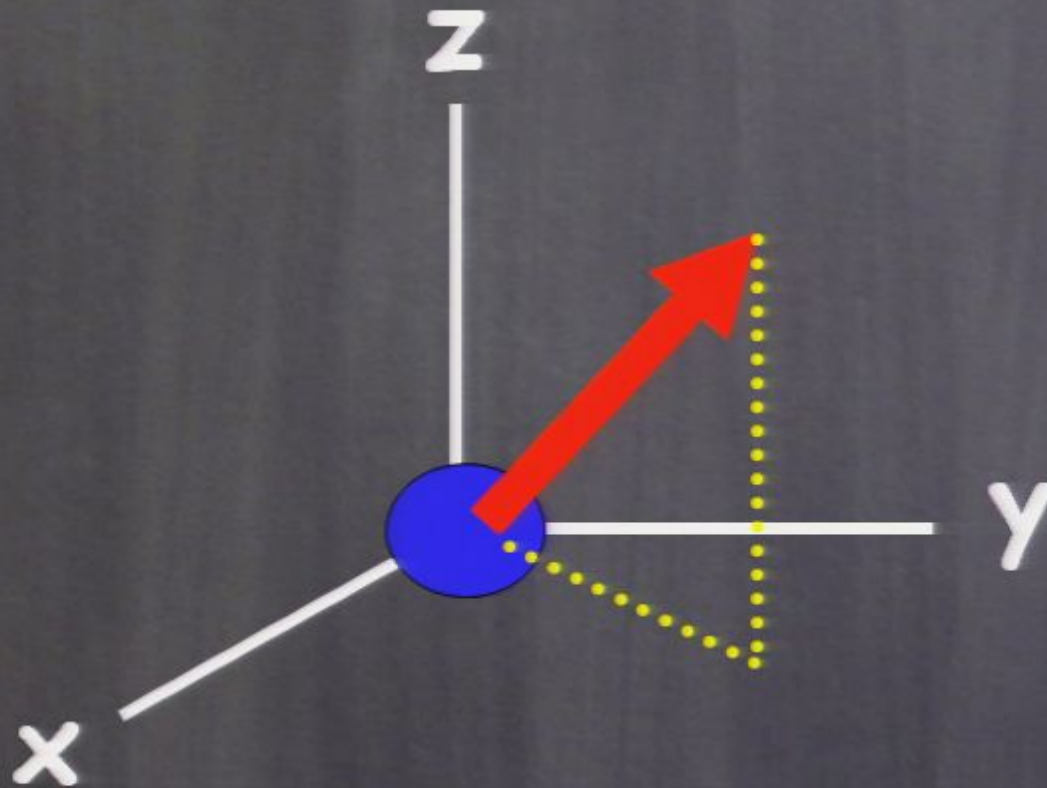
The Mathematics of Spin

The Mathematics of Spin

Spin seems to be a VECTOR:

The Mathematics of Spin

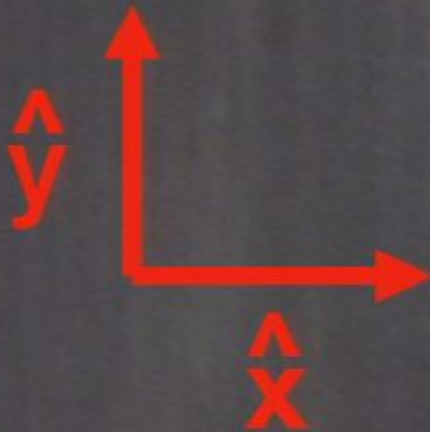
Spin seems to be a VECTOR:



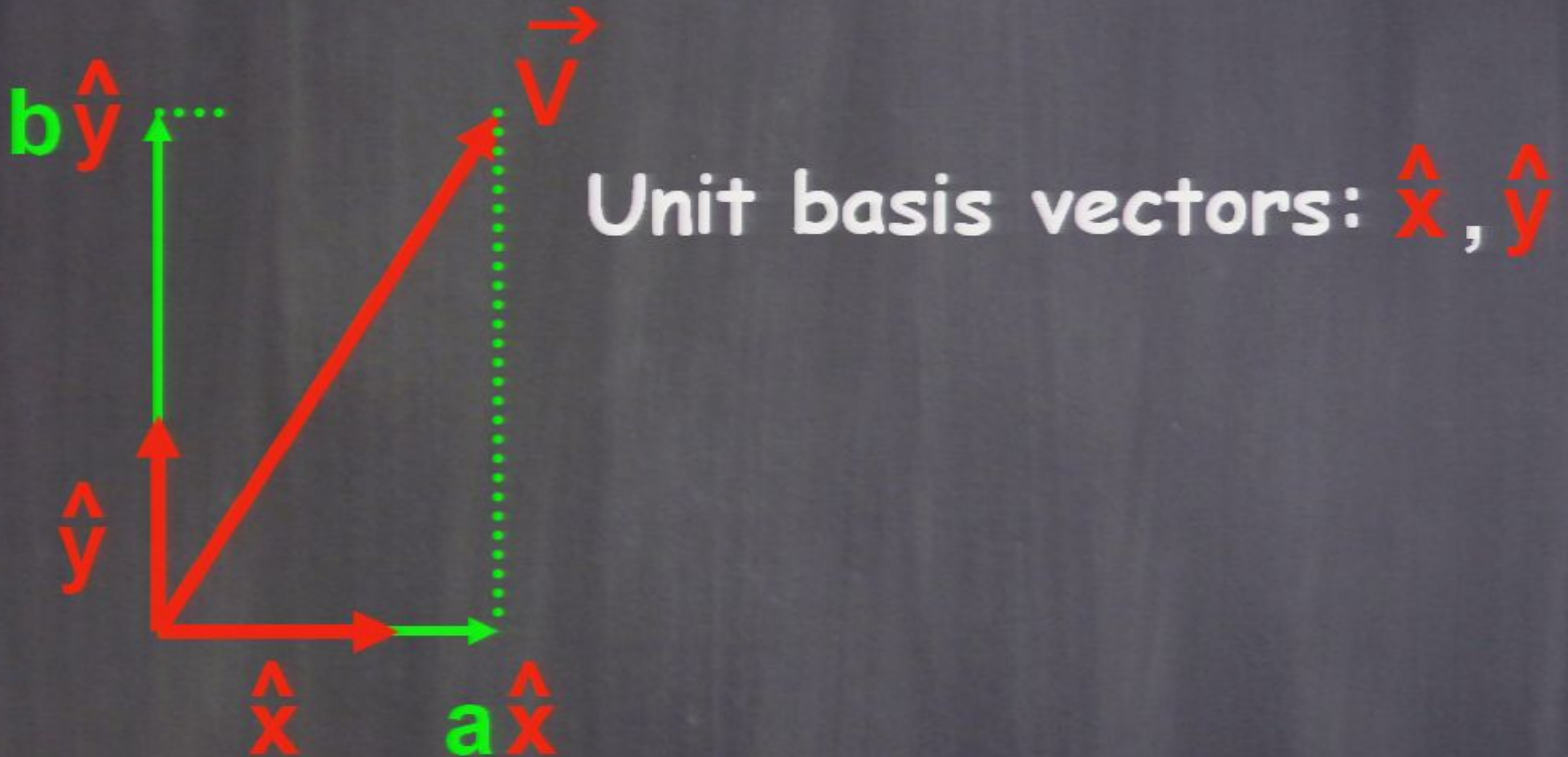
What do we know about VECTORS?

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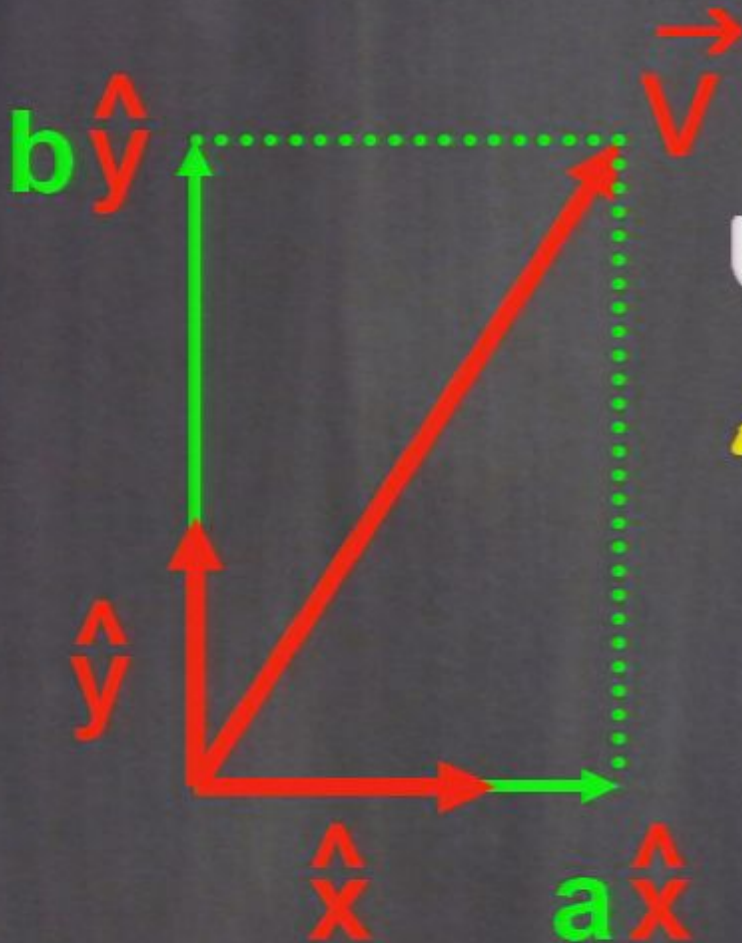
Unit basis vectors: \hat{x} , \hat{y}



What do we know about VECTORS?



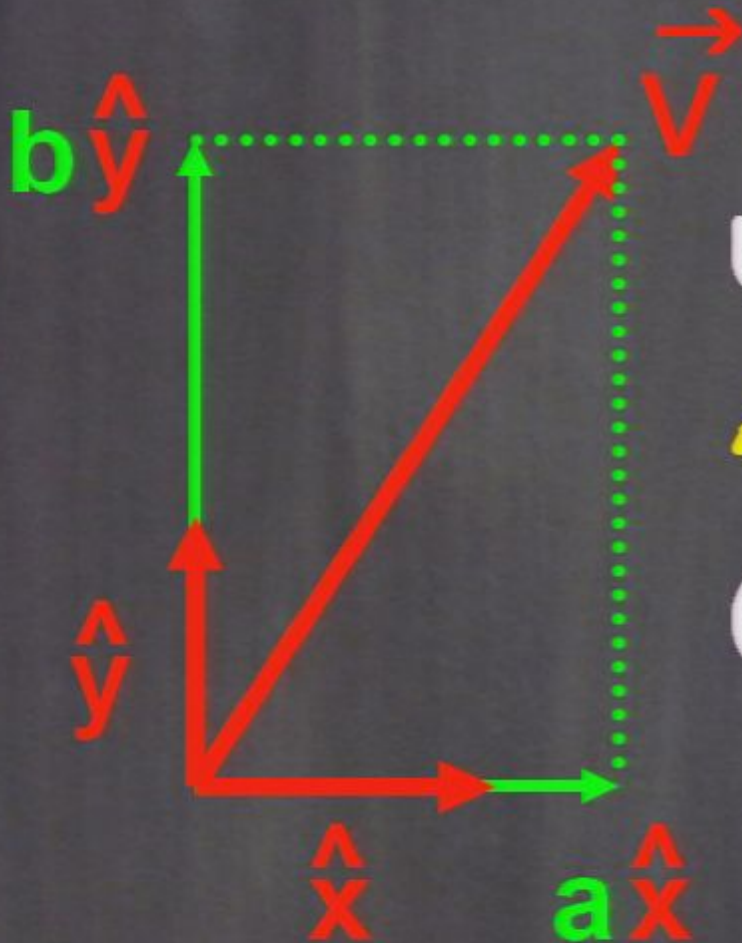
What do we know about VECTORS?



Unit basis vectors: \hat{x}, \hat{y}

Any vector: $\vec{v} = a\hat{x} + b\hat{y}$

What do we know about VECTORS?

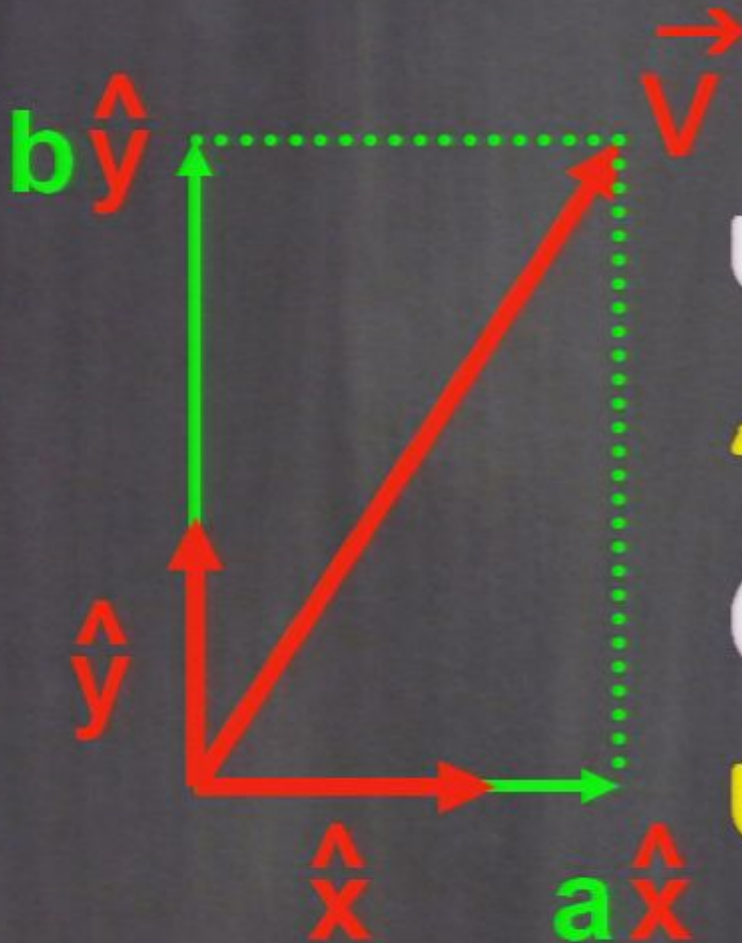


Unit basis vectors: \hat{x}, \hat{y}

Any vector: $\vec{v} = a\hat{x} + b\hat{y}$

(Length)²: $|\vec{v}|^2 = a^2 + b^2$

What do we know about VECTORS?



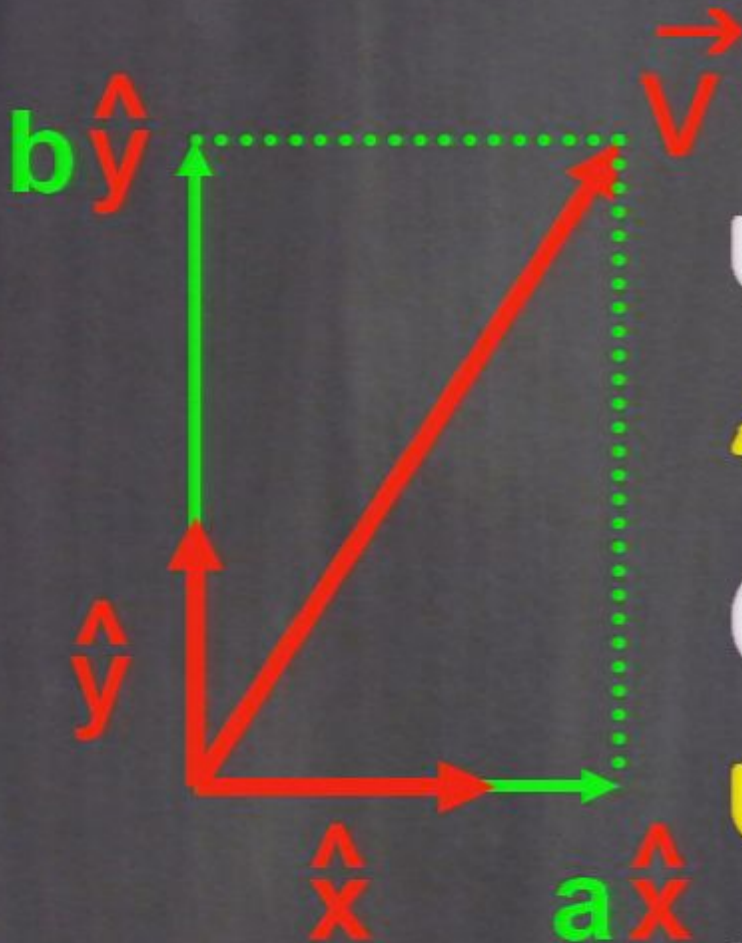
Unit basis vectors: \hat{x}, \hat{y}

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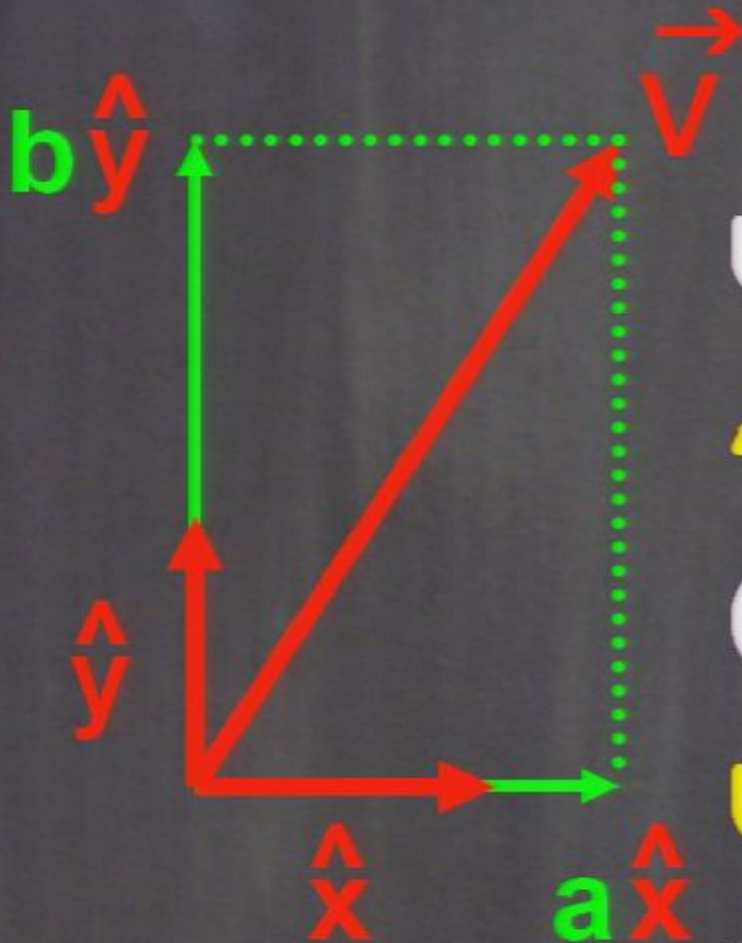
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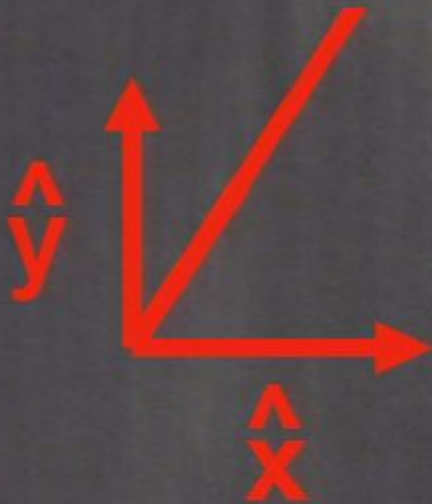
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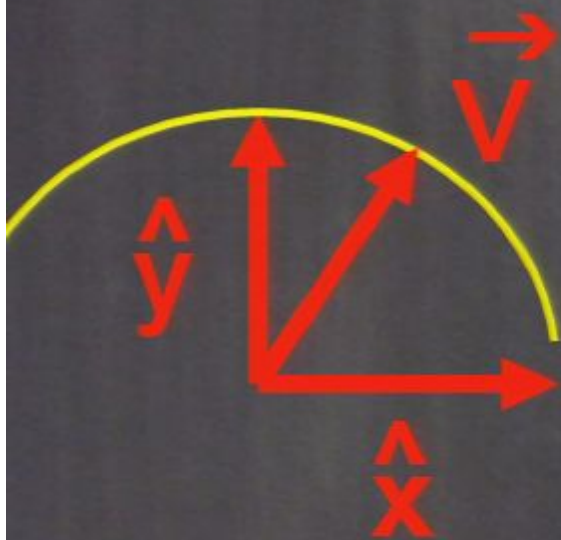
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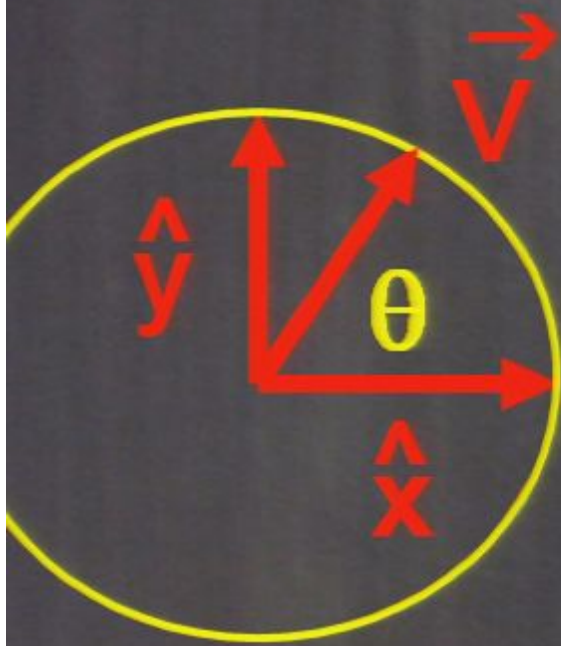
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Examples of: $\vec{V} = \cos \theta \hat{x} + \sin \theta \hat{y}$

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$\theta = 0:$



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$$\vec{V} = \hat{x}$$



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$$\vec{V} = \hat{x}$$



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$$\vec{V} = \frac{1}{\sqrt{2}} \hat{x} + \frac{1}{\sqrt{2}} \hat{y}$$

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$$\vec{V} = \hat{x}$$



$$\vec{V} = \hat{y}$$



$$\vec{V} = \frac{1}{\sqrt{2}} \hat{x} + \frac{1}{\sqrt{2}} \hat{y}$$

$$a^2 + b^2 = \left(\frac{1}{\sqrt{2}}\right)^2 + \left(\frac{1}{\sqrt{2}}\right)^2 = 1$$

Application to Spin:

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Analogue of unit basis vectors: \hat{x}, \hat{y} ?

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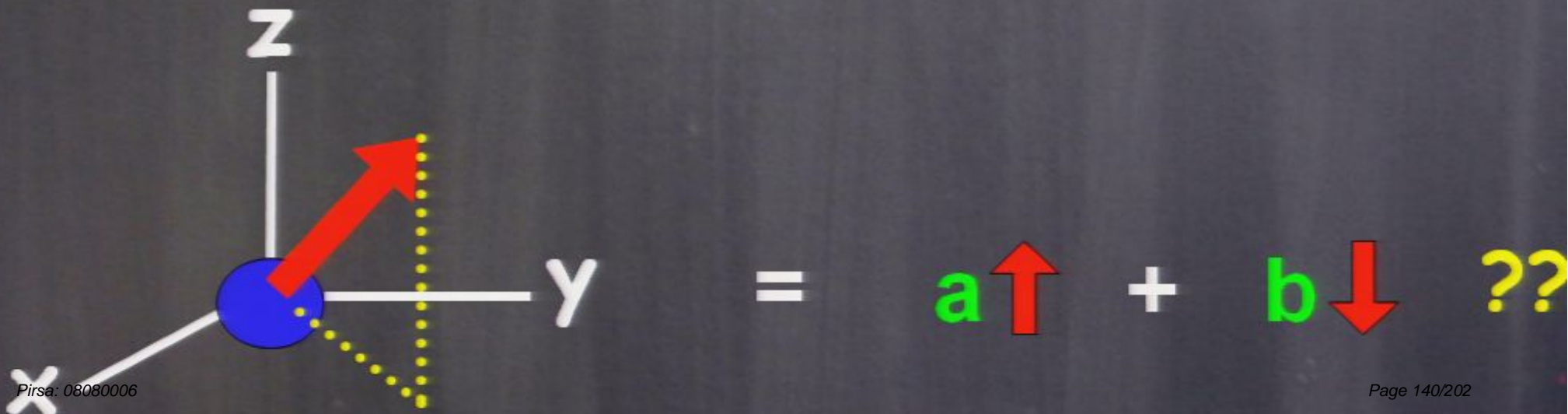
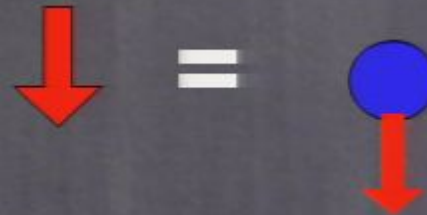
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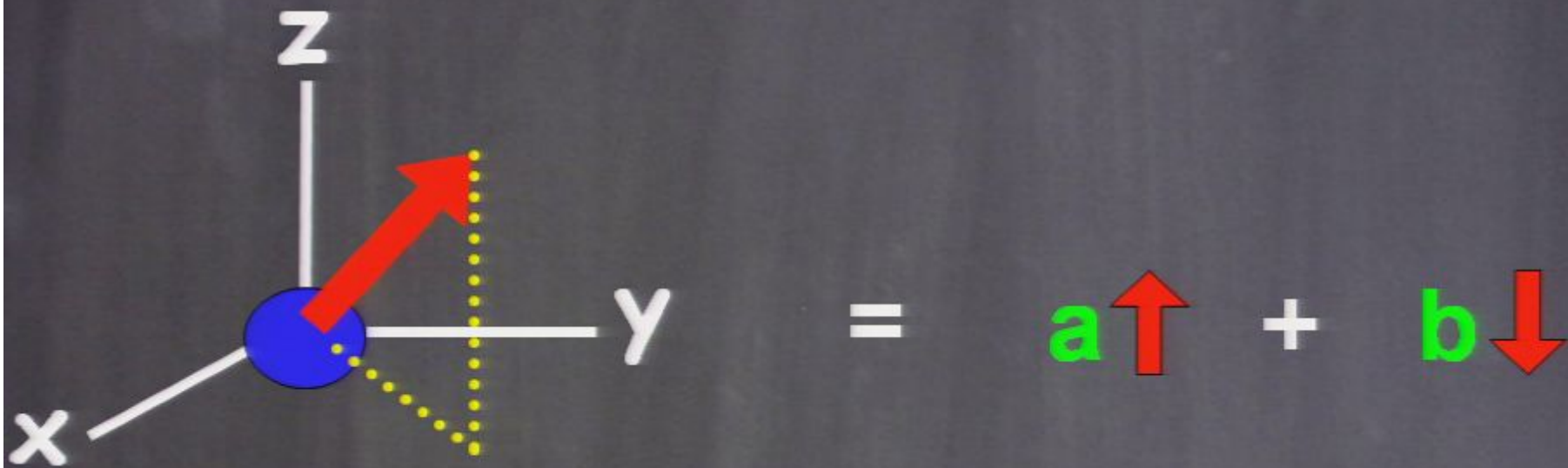


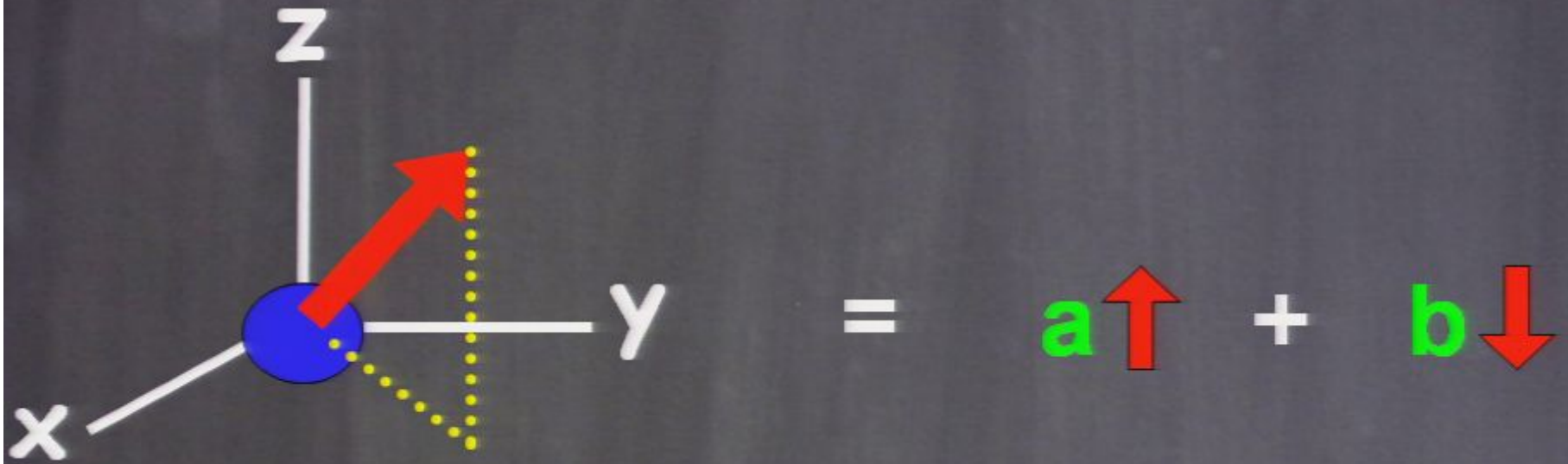
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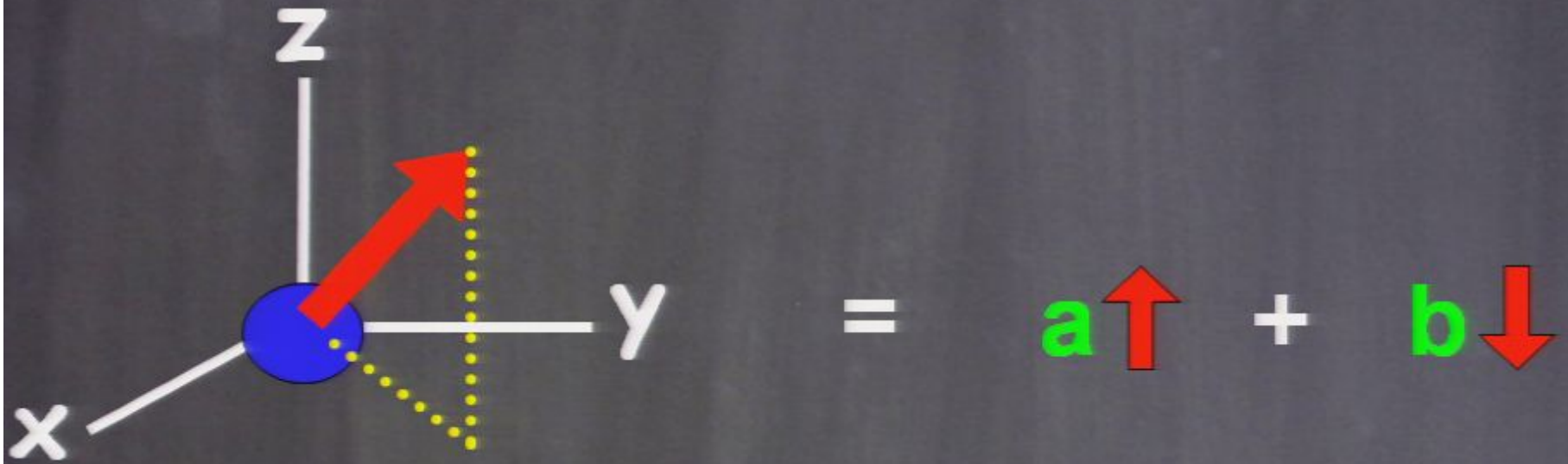
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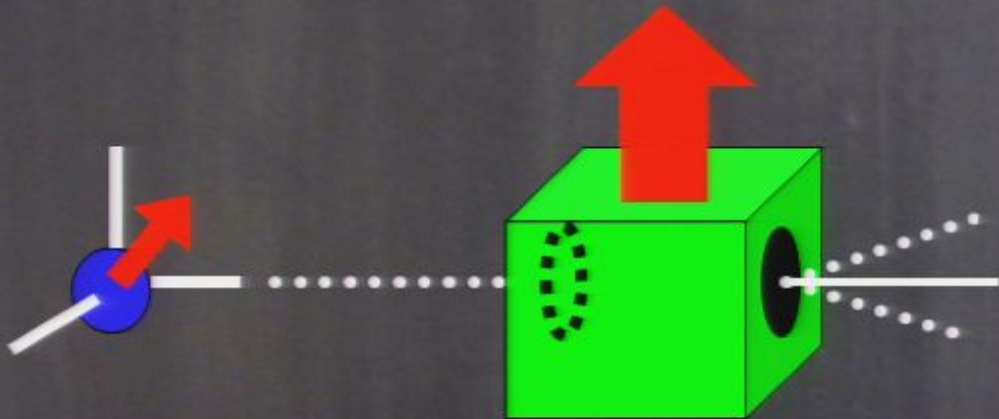


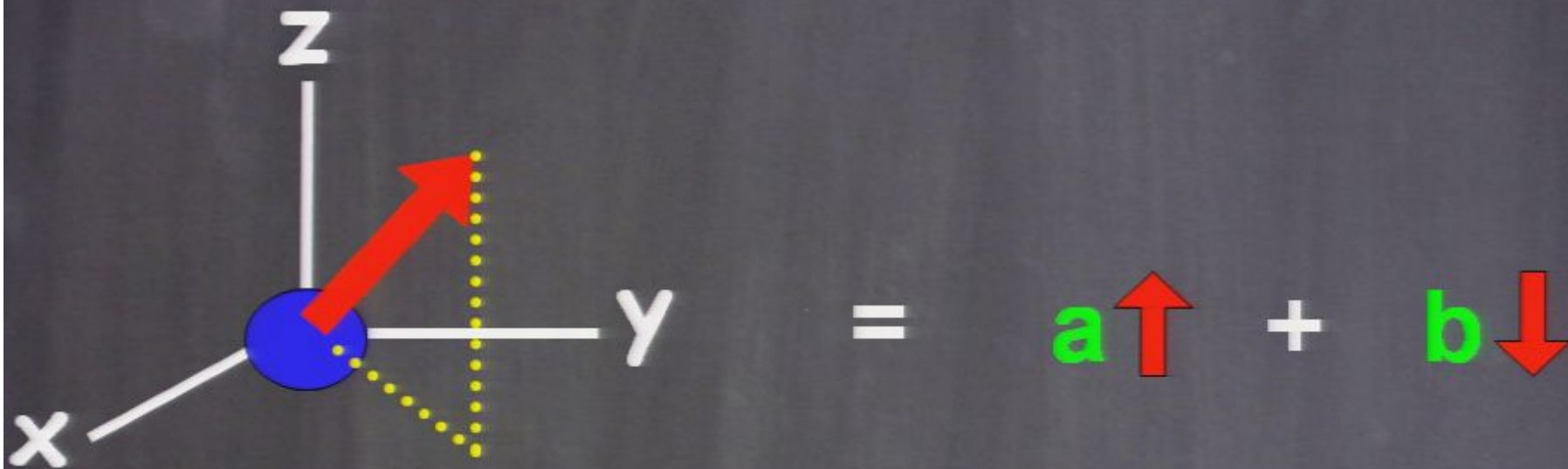


2: Probability suggests a natural interpretation for: $1 = a^2 + b^2$

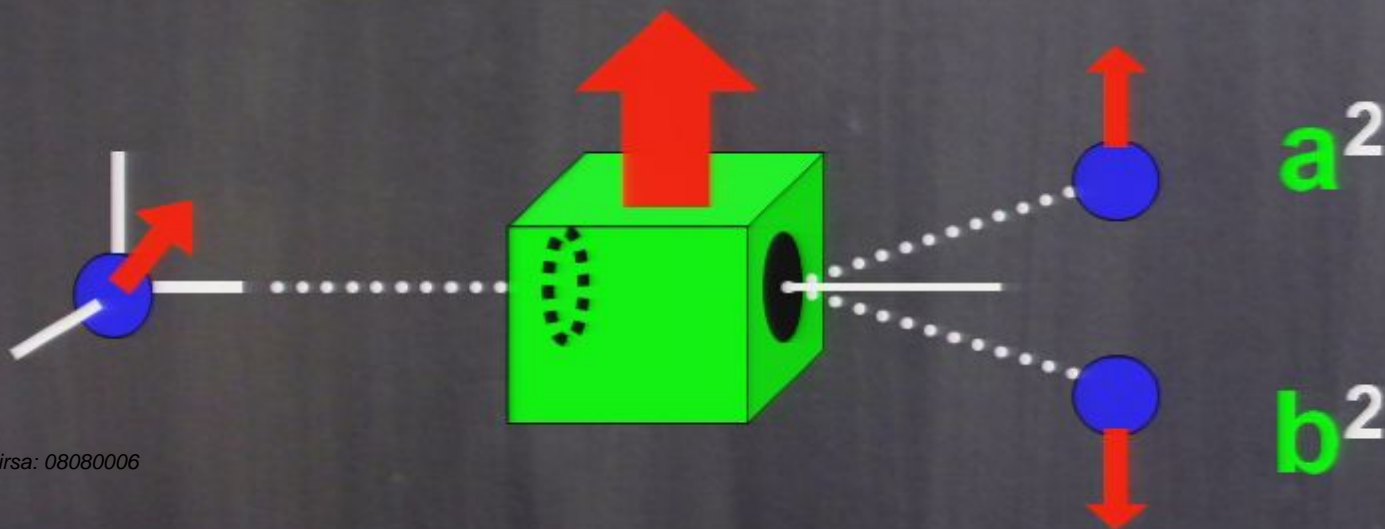


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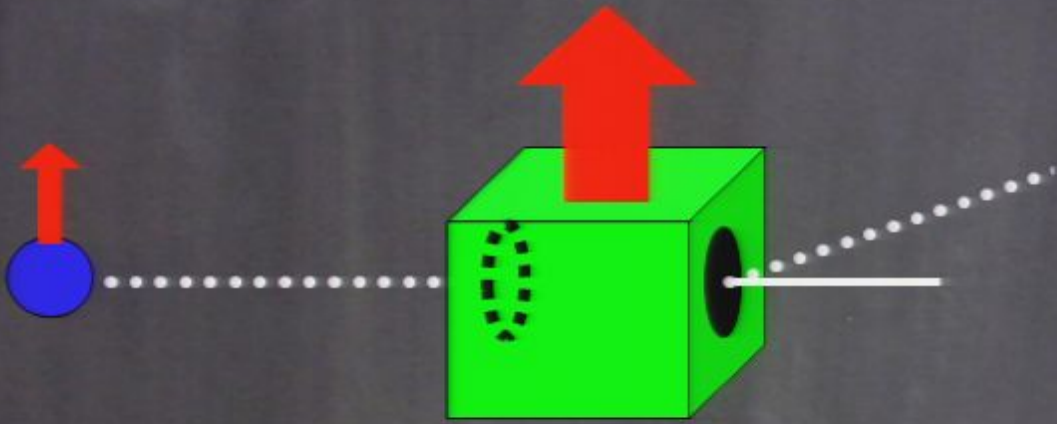


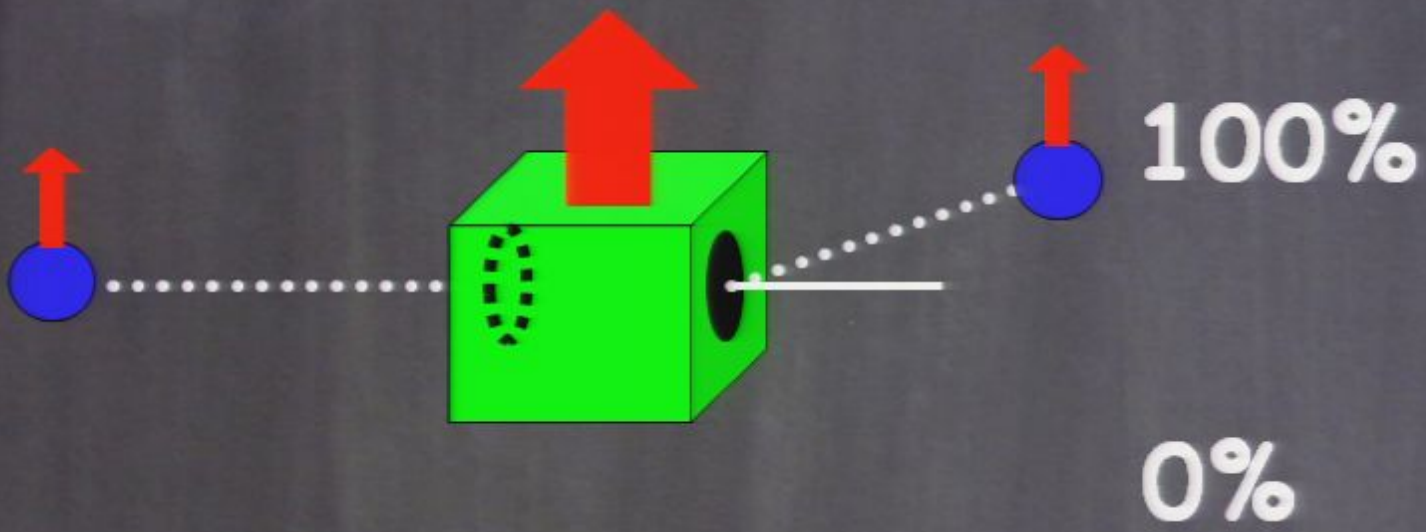


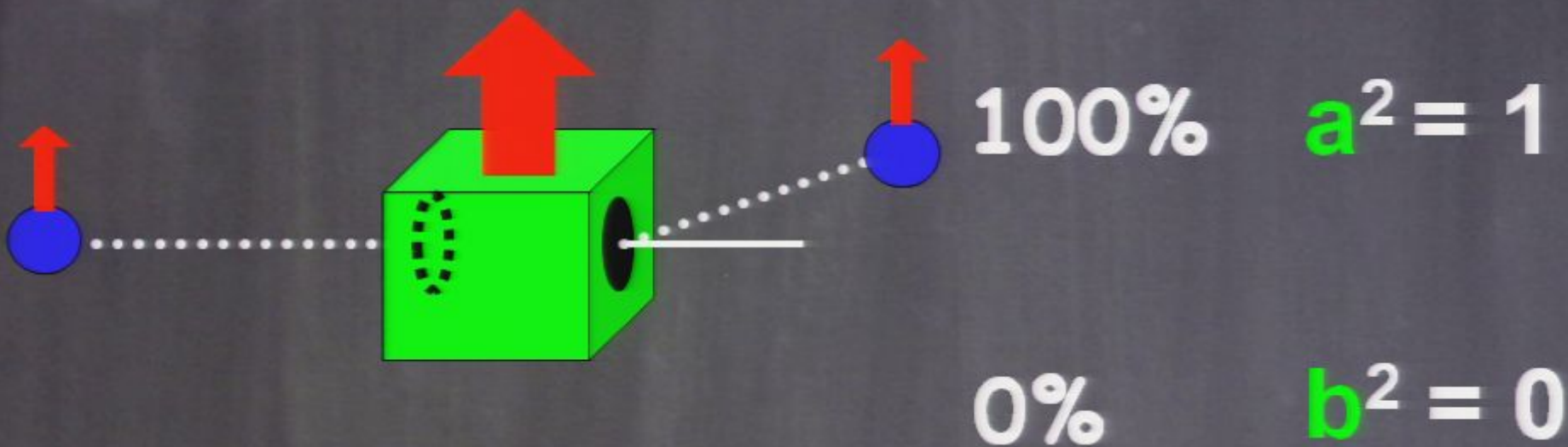
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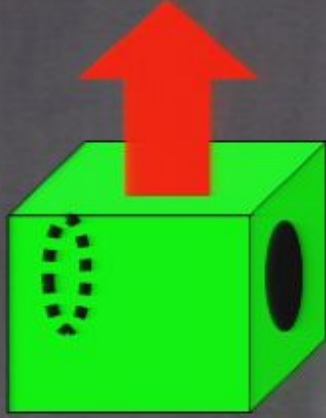


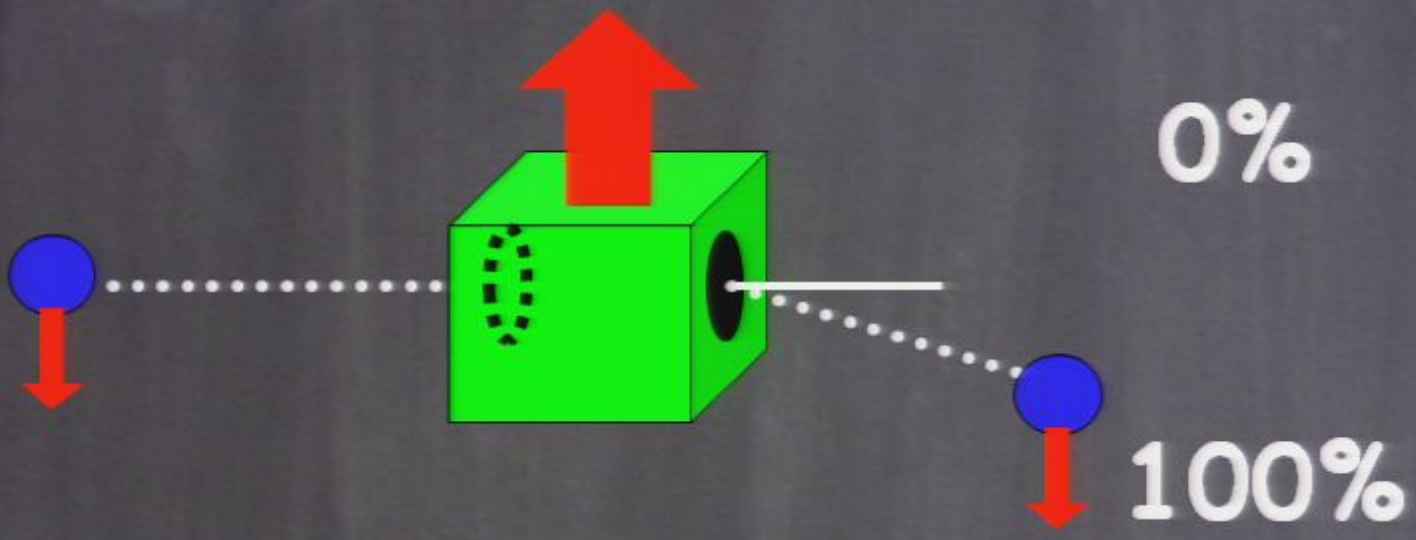


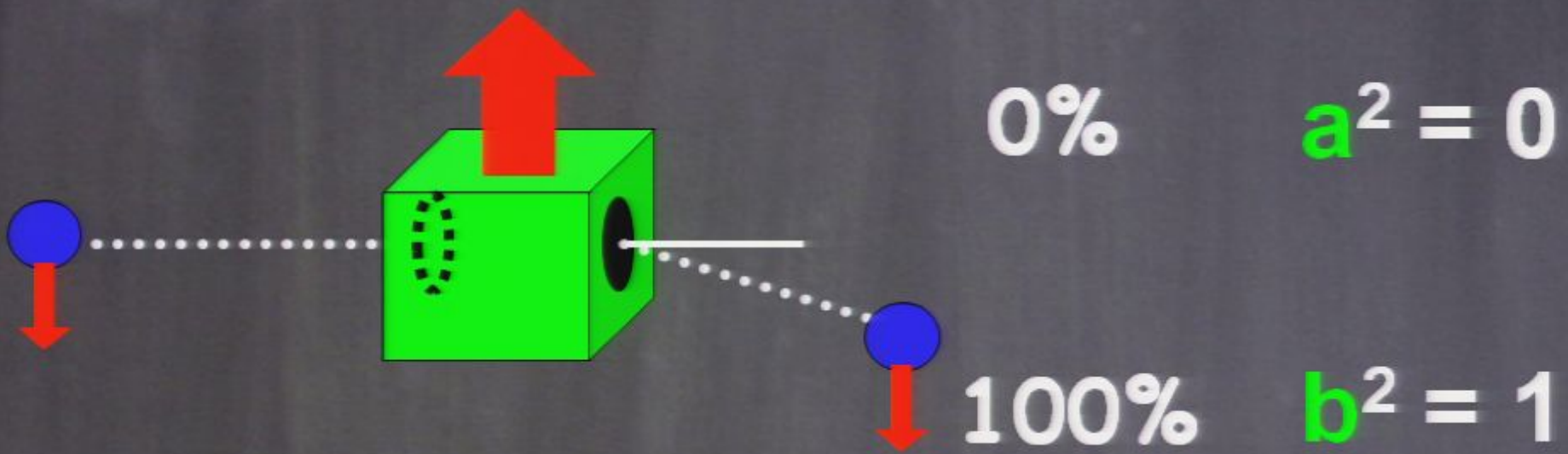


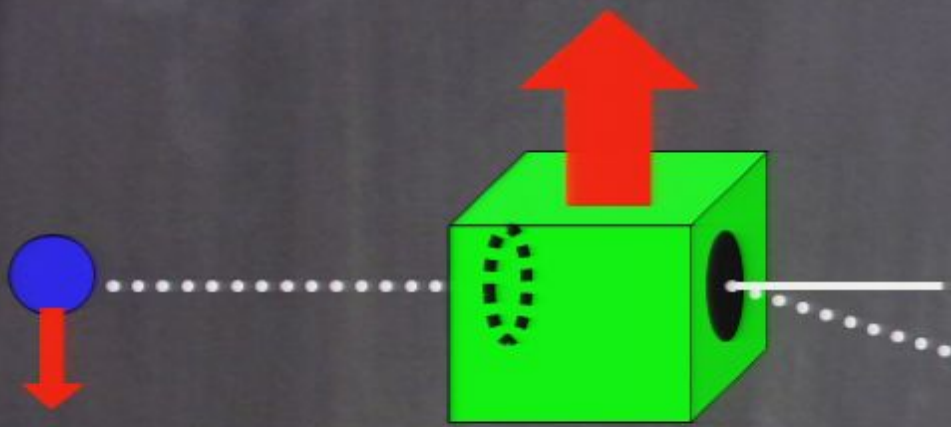






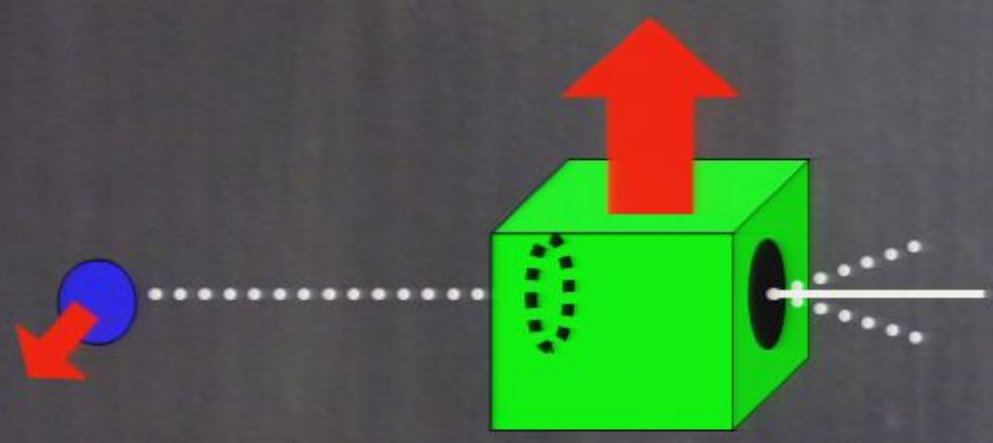


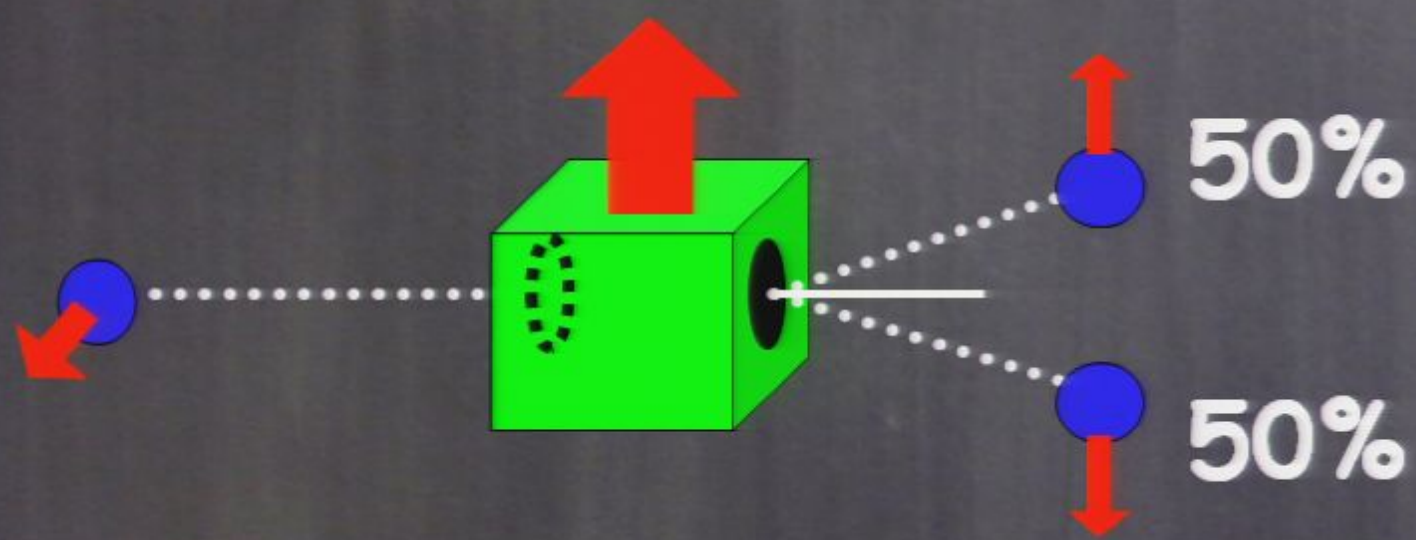
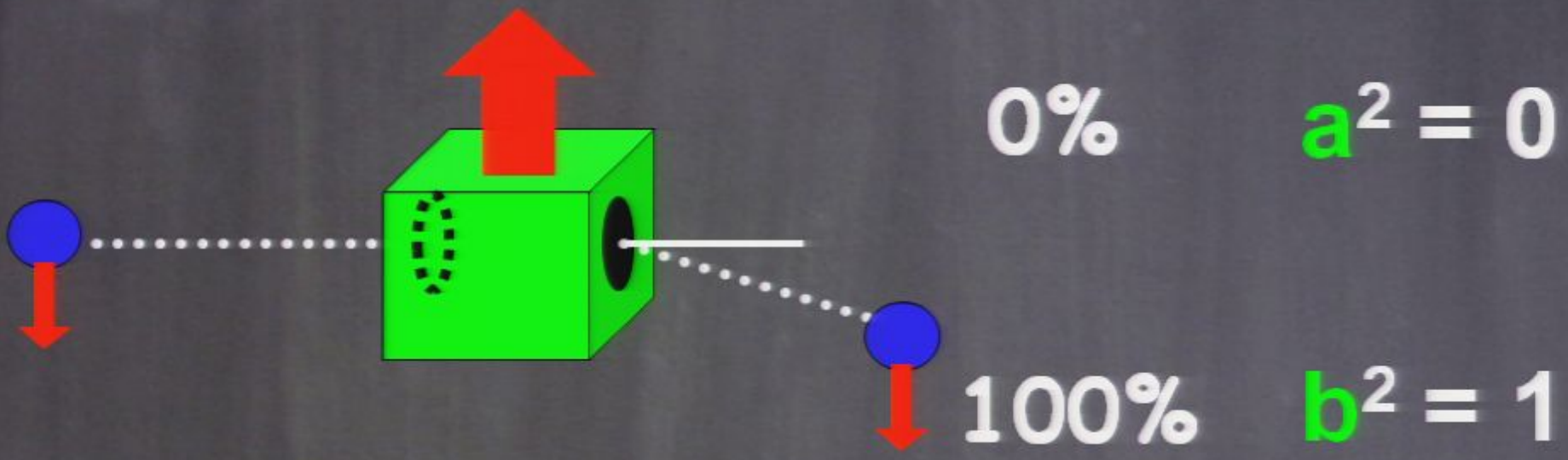




0% $a^2 = 0$

100% $b^2 = 1$

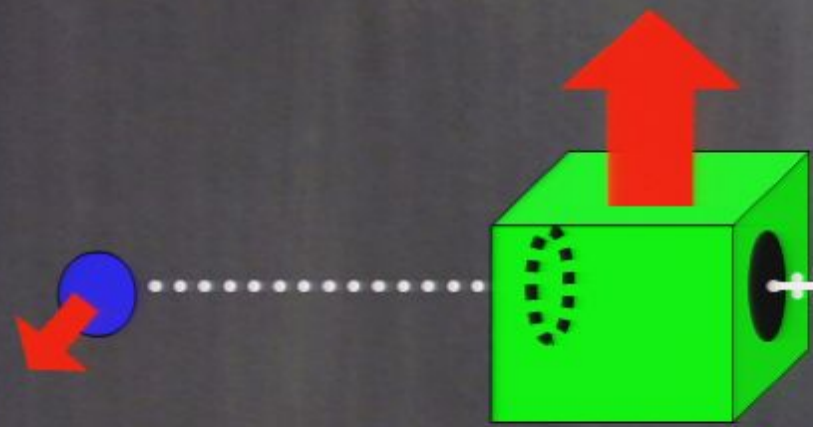






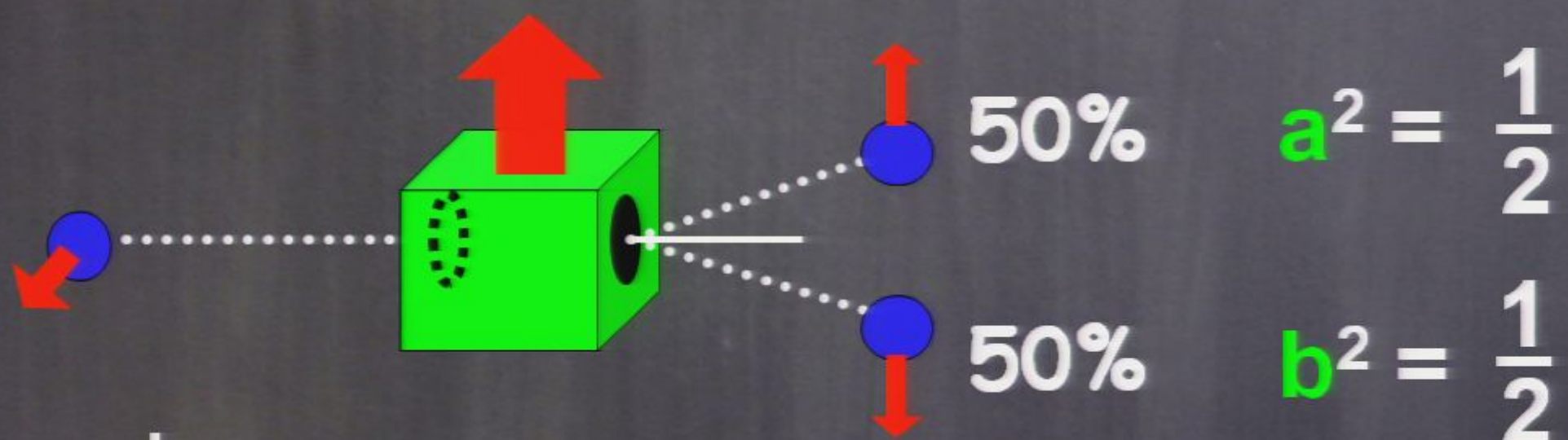
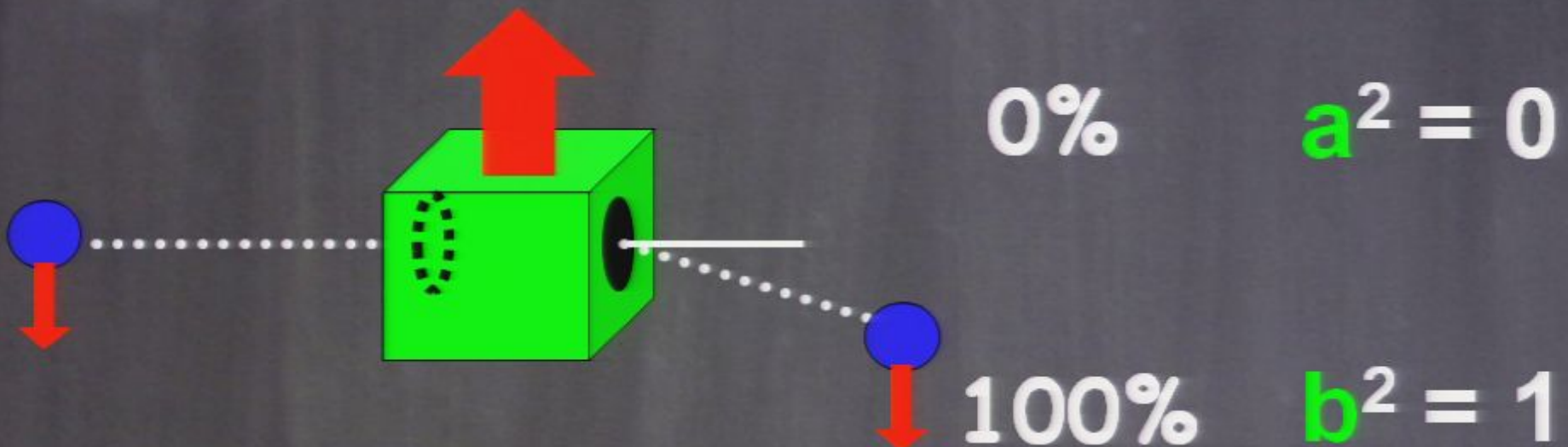
0% $a^2 = 0$

100% $b^2 = 1$



50% $a^2 = \frac{1}{2}$

50% $b^2 = \frac{1}{2}$



$$= \frac{1}{2} \uparrow + \frac{1}{2} \downarrow$$

Summary:

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$$= 1 \uparrow + 0 \downarrow$$

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$$\begin{array}{c} \uparrow \\ \bullet \\ \swarrow \end{array} = 1 \uparrow + 0 \downarrow$$

$$\begin{array}{c} \uparrow \\ \bullet \\ \swarrow \end{array} = \frac{1}{\sqrt{2}} \uparrow + \frac{1}{\sqrt{2}} \downarrow$$

Summary:

$$\begin{array}{c} \uparrow \\ \bullet \\ \swarrow \end{array} = 1 \uparrow + 0 \downarrow$$

$$\begin{array}{c} \uparrow \\ \bullet \\ \swarrow \downarrow \end{array} = \frac{1}{\sqrt{2}} \uparrow + \frac{1}{\sqrt{2}} \downarrow$$

$$\begin{array}{c} \uparrow \\ \bullet \\ \downarrow \end{array} = 0 \uparrow + 1 \downarrow$$

Summary:

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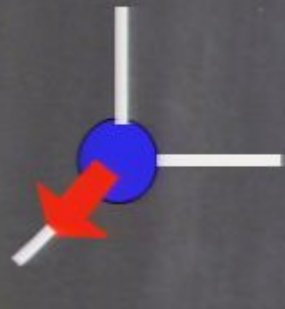
$$\begin{array}{c} \uparrow \\ \bullet \\ \swarrow \downarrow \end{array} = \frac{1}{\sqrt{2}} \uparrow + \frac{1}{\sqrt{2}} \downarrow$$

$$\begin{array}{c} \uparrow \\ \bullet \\ \downarrow \end{array} = 0 \uparrow + 1 \downarrow$$

Question:

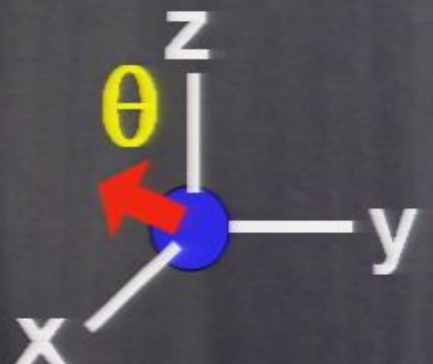
Summary:


$$= 1 \uparrow + 0 \downarrow$$


$$= \frac{1}{\sqrt{2}} \uparrow + \frac{1}{\sqrt{2}} \downarrow$$


$$= 0 \uparrow + 1 \downarrow$$

Question:


$$= (?) \uparrow + (?) \downarrow$$

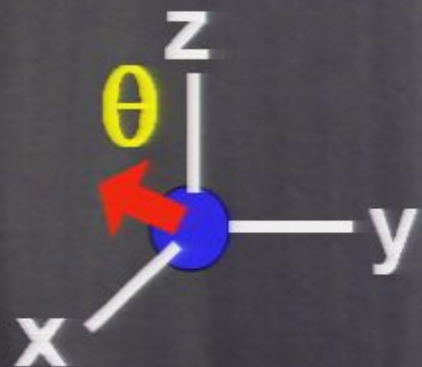
Summary:


$$= 1 \uparrow + 0 \downarrow$$


$$= \frac{1}{\sqrt{2}} \uparrow + \frac{1}{\sqrt{2}} \downarrow$$


$$= 0 \uparrow + 1 \downarrow$$

Question:


$$= \cos \theta \uparrow + \sin \theta \downarrow$$

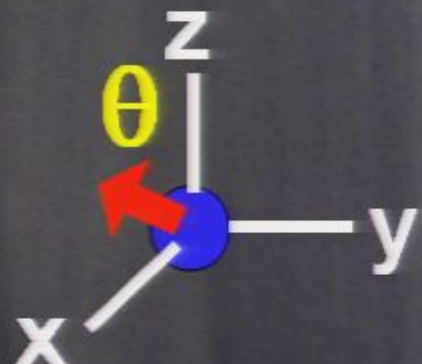
Summary:


$$= 1 \uparrow + 0 \downarrow$$

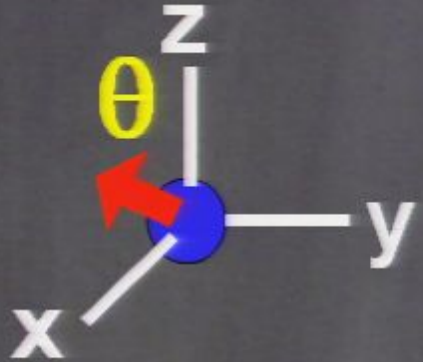

$$= \frac{1}{\sqrt{2}} \uparrow + \frac{1}{\sqrt{2}} \downarrow$$


$$= 0 \uparrow + 1 \downarrow$$

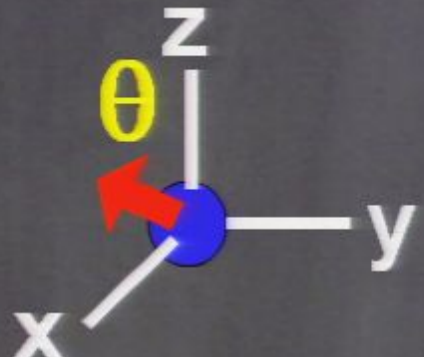
Question:


$$= \cos \frac{\theta}{2} \uparrow + \sin \frac{\theta}{2} \downarrow$$

Result:

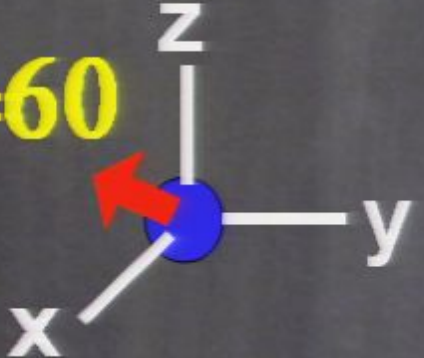

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Result:

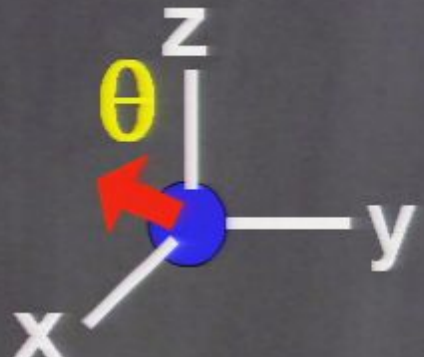

$$= \cos \frac{\theta}{2} \uparrow + \sin \frac{\theta}{2} \downarrow$$

E.g.:

$\theta = 60$

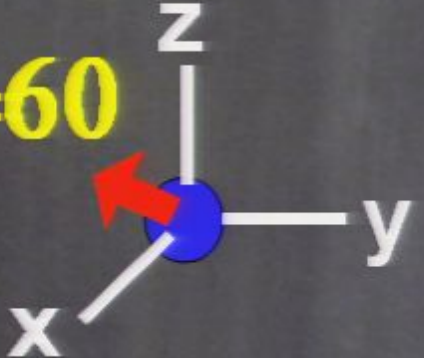

$$= \frac{\sqrt{3}}{2} \uparrow + \frac{1}{2} \downarrow$$

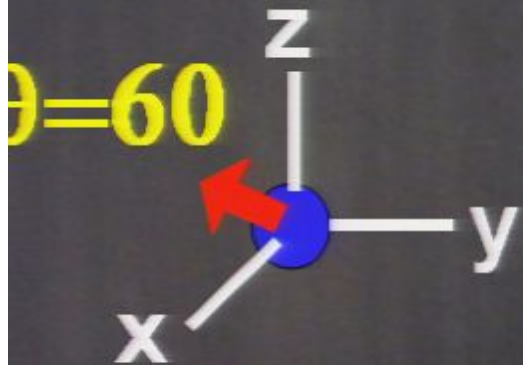
Result:


$$= \cos \frac{\theta}{2} \uparrow + \sin \frac{\theta}{2} \downarrow$$

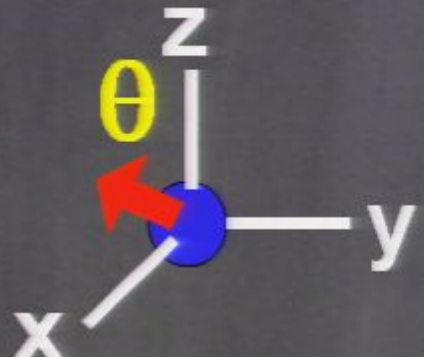
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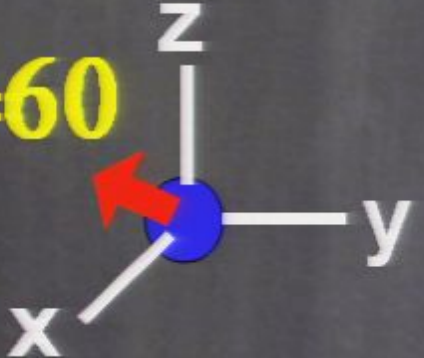


Result:

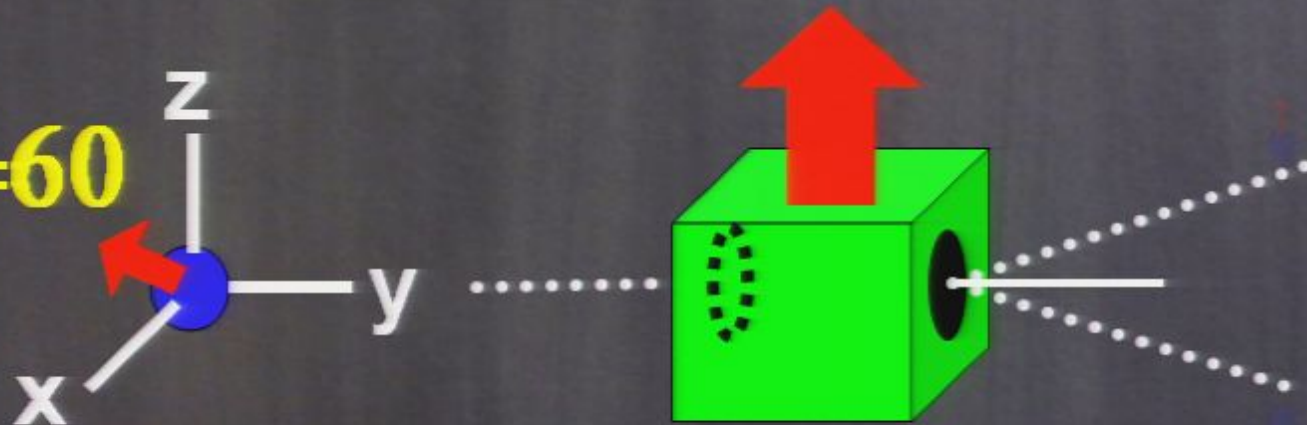

$$= \cos \frac{\theta}{2} \uparrow + \sin \frac{\theta}{2} \downarrow$$

E.g.:

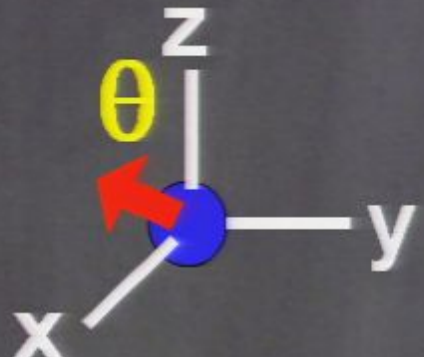
$\theta = 60$


$$= \frac{\sqrt{3}}{2} \uparrow + \frac{1}{2} \downarrow$$

$\theta = 60$

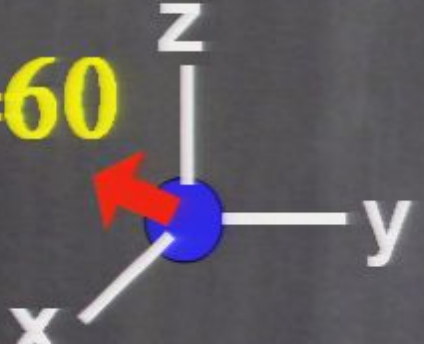


Result:

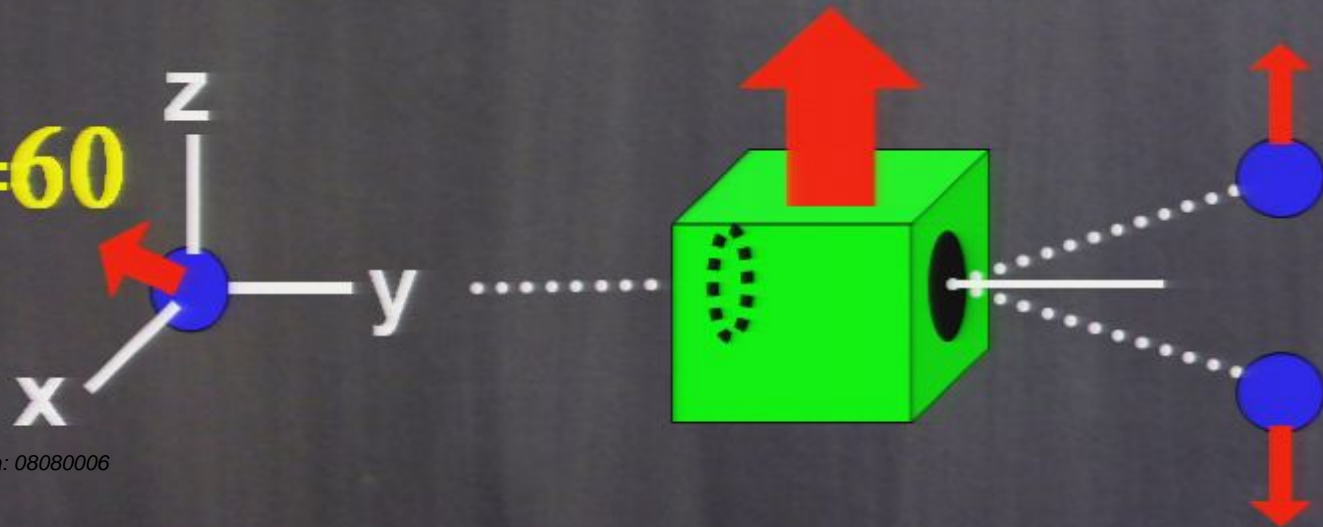

$$= \cos \frac{\theta}{2} \uparrow + \sin \frac{\theta}{2} \downarrow$$

E.g.:

$\theta = 60$


$$= \frac{\sqrt{3}}{2} \uparrow + \frac{1}{2} \downarrow$$

$\theta = 60$



$$\left(\frac{\sqrt{3}}{2} \right)^2 = 75\%$$

$$\left(\frac{1}{2} \right)^2 = 25\%$$

$$= \cos \frac{\theta}{2} \uparrow + \sin \frac{\theta}{2} \downarrow$$

We have constructed a successful
"mathematical model" of spin!

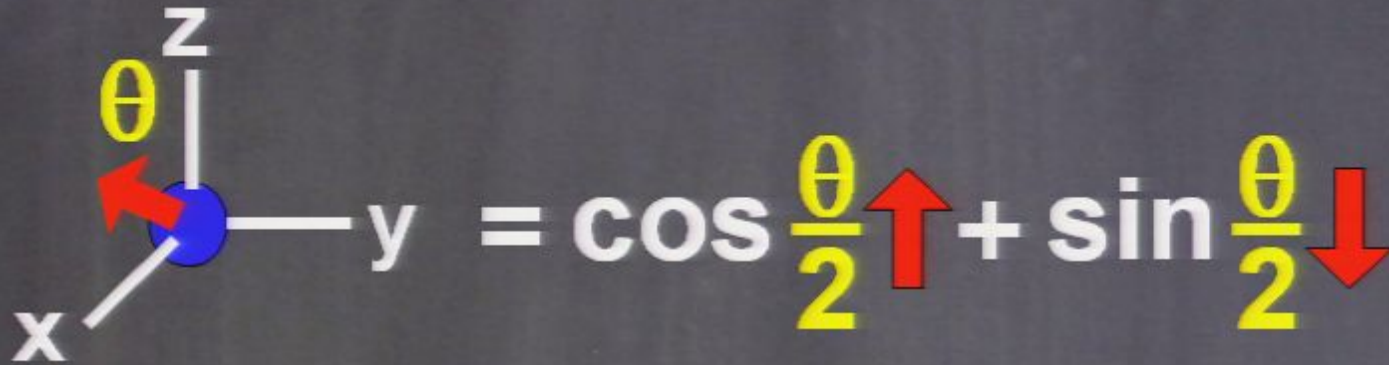
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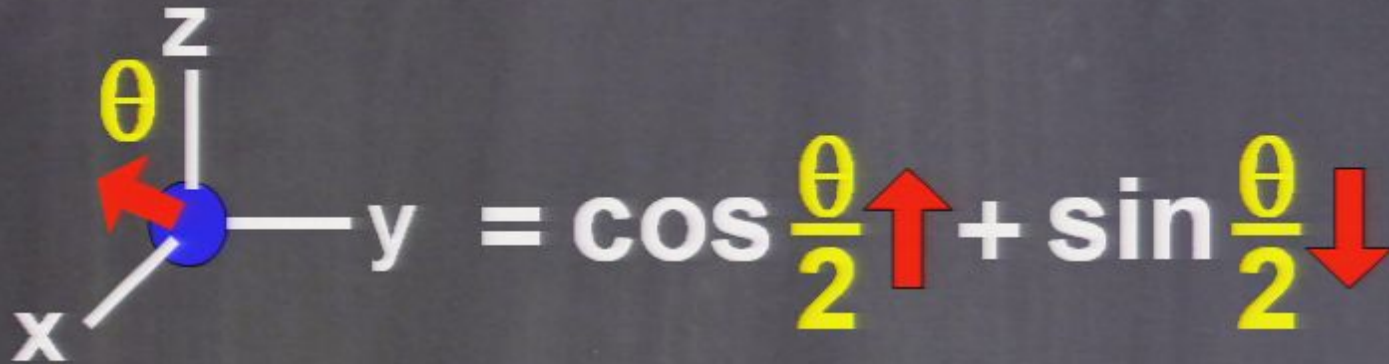
Does the mathematics predict anything
interesting we have not thought of yet?

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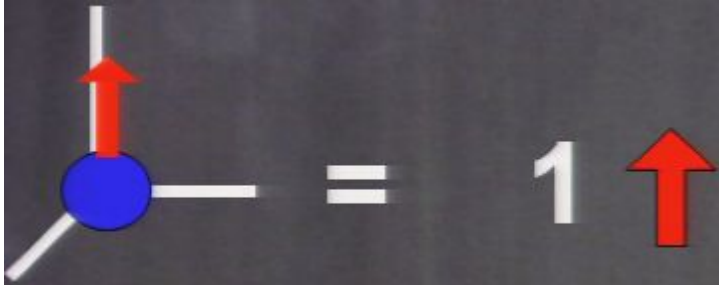
The power of mathematics in the

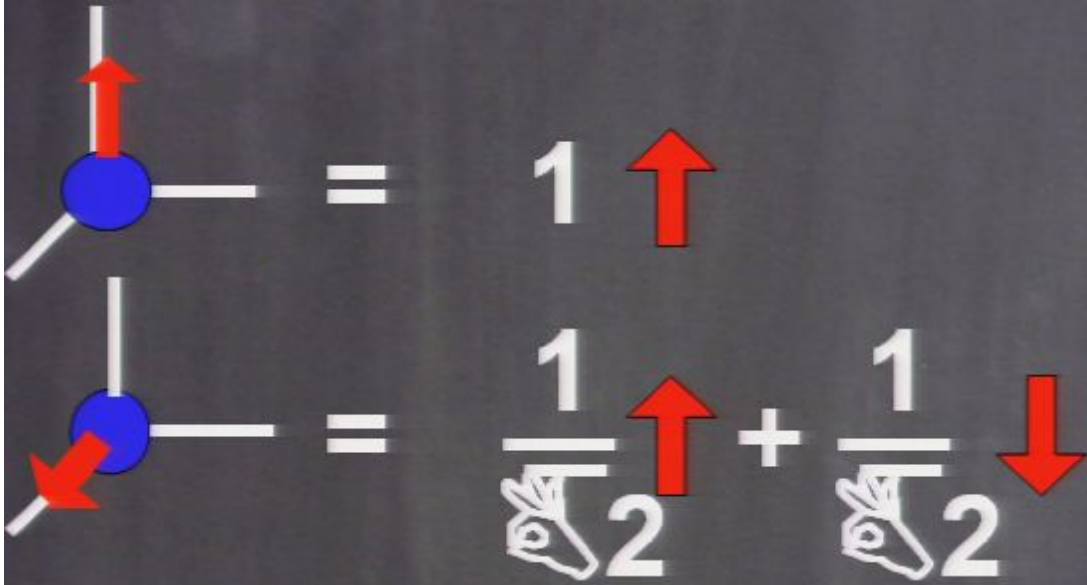

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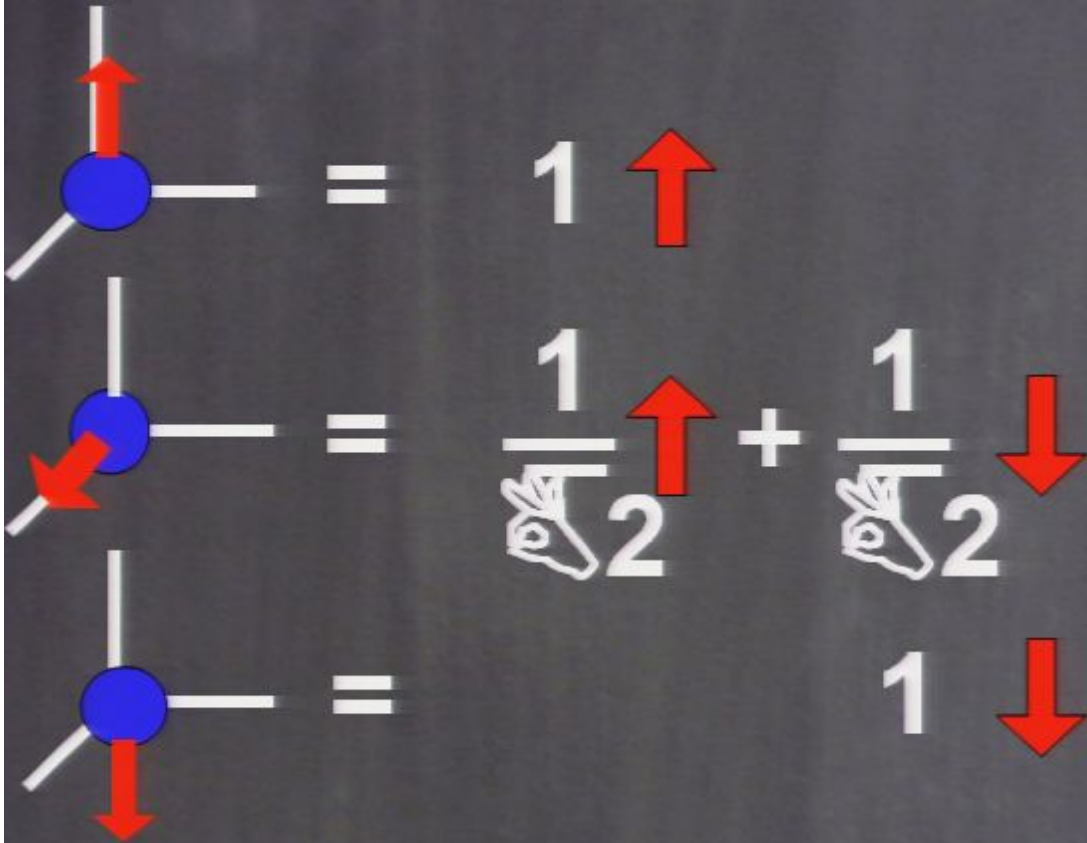
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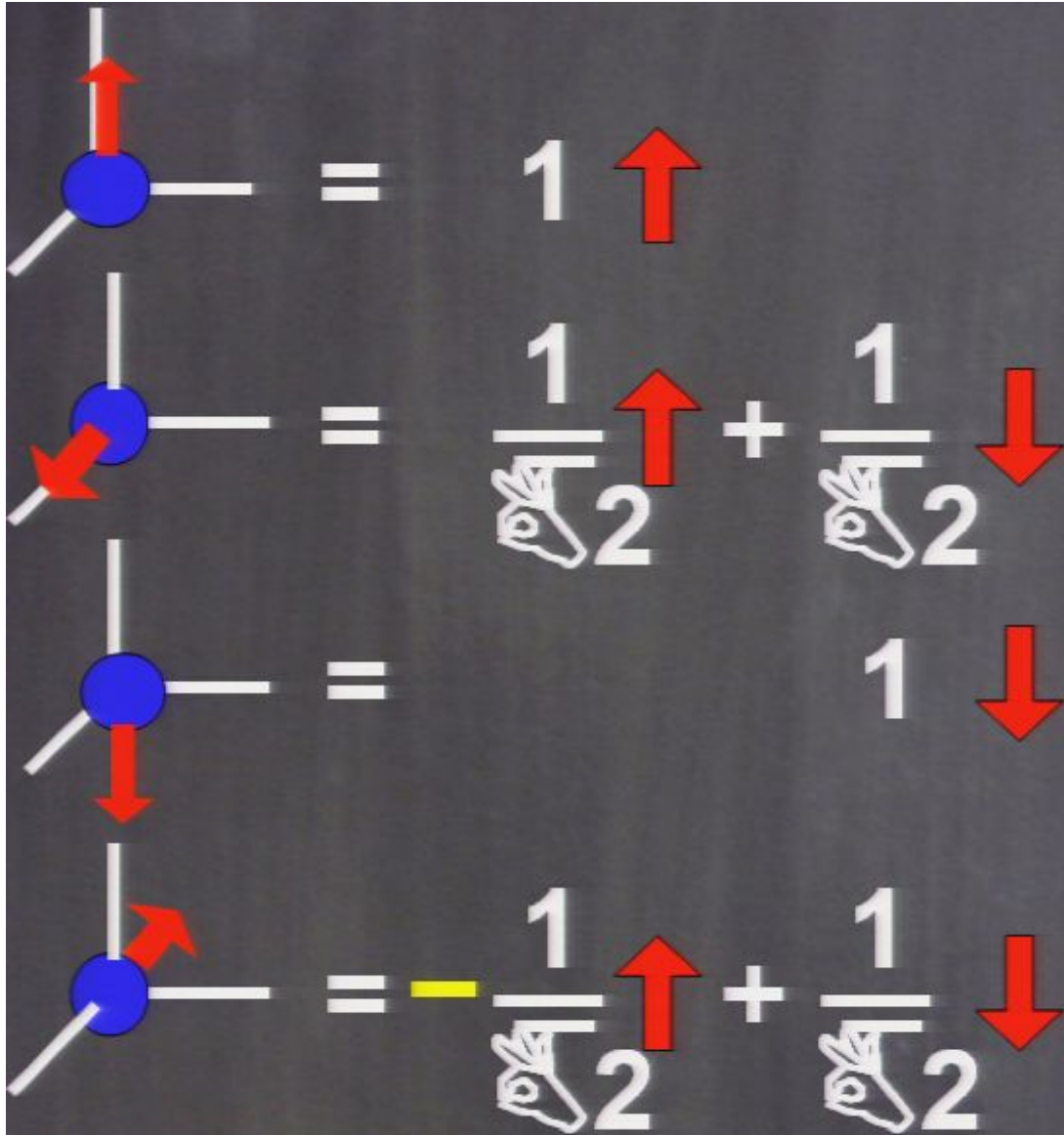
Does the mathematics predict anything
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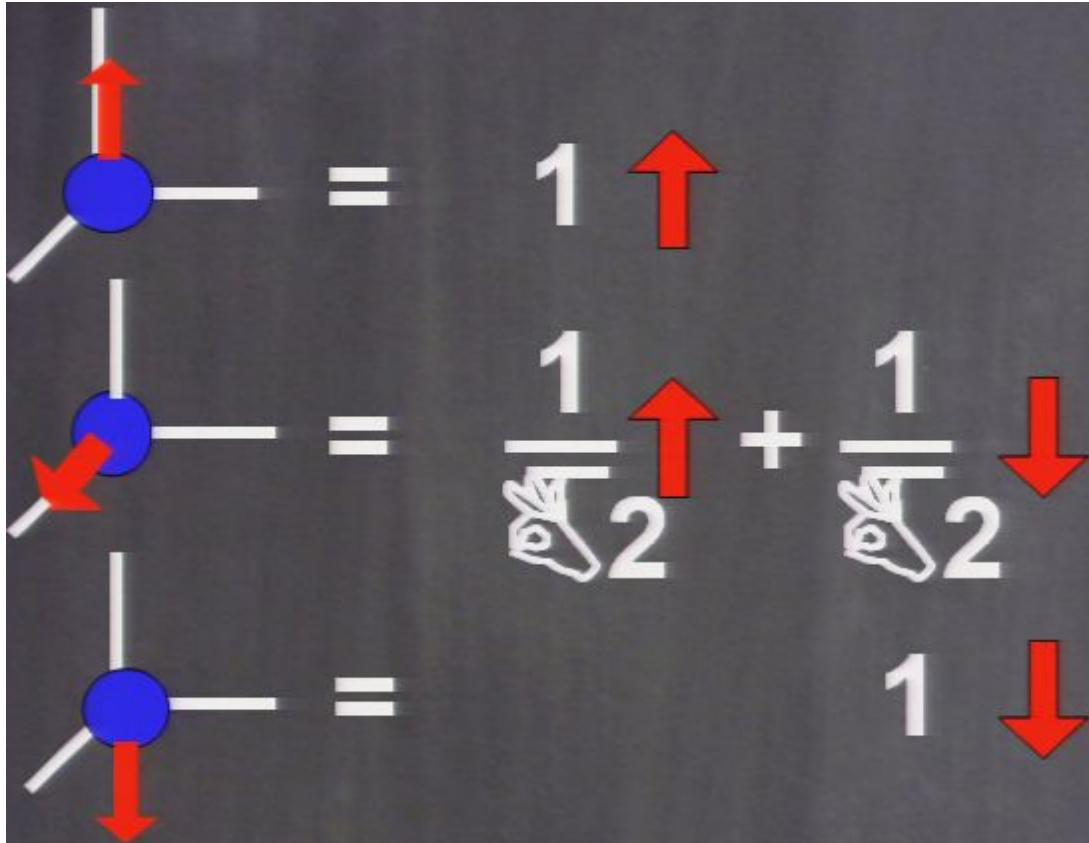
The power of mathematics in the
process of science

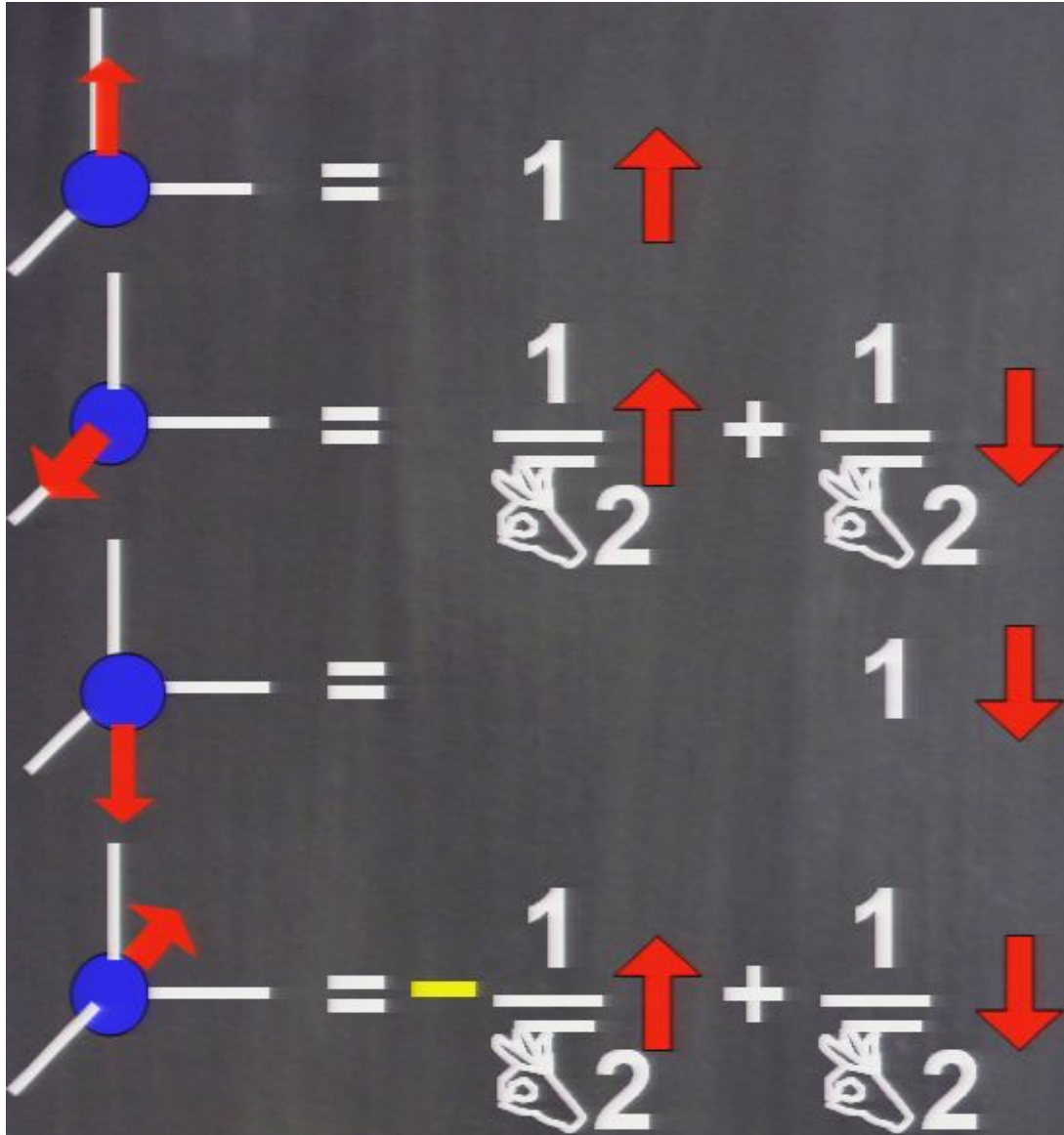


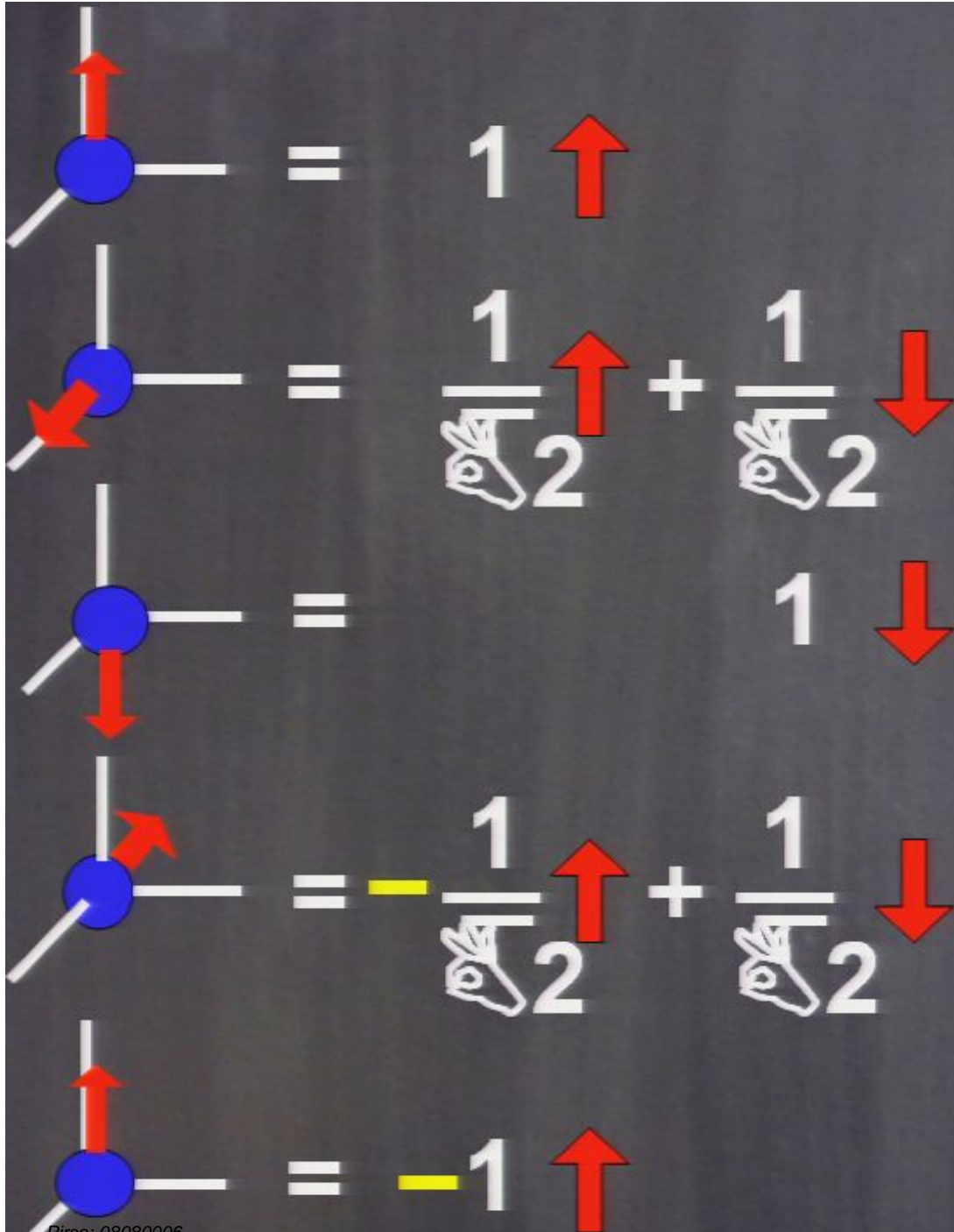


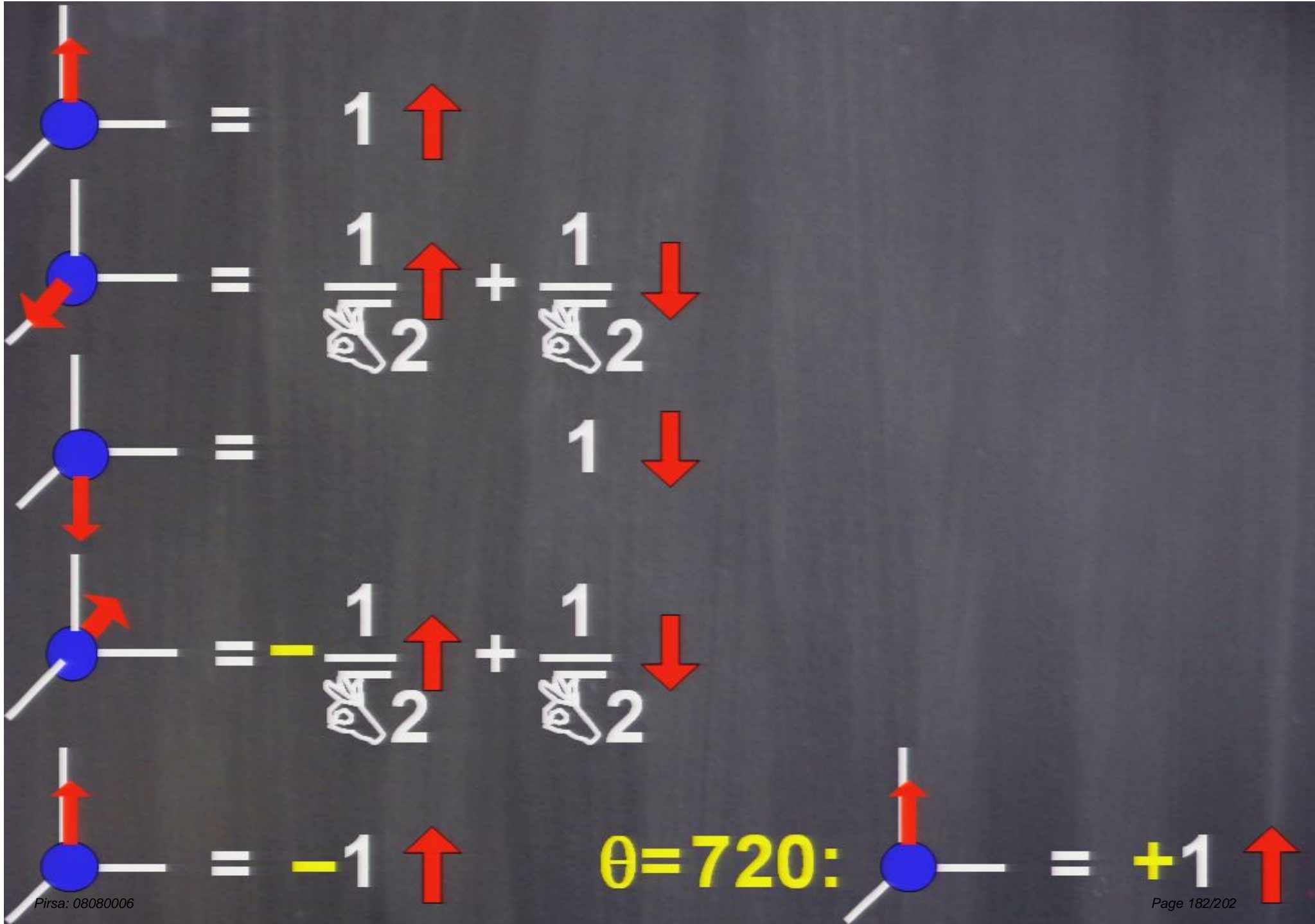












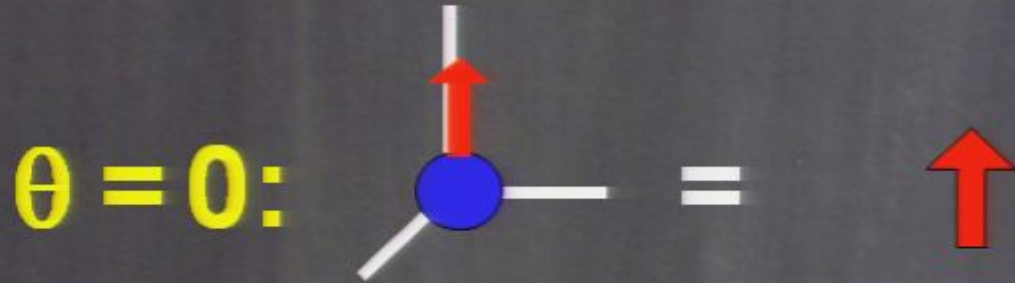
The Mys†

The Mystery

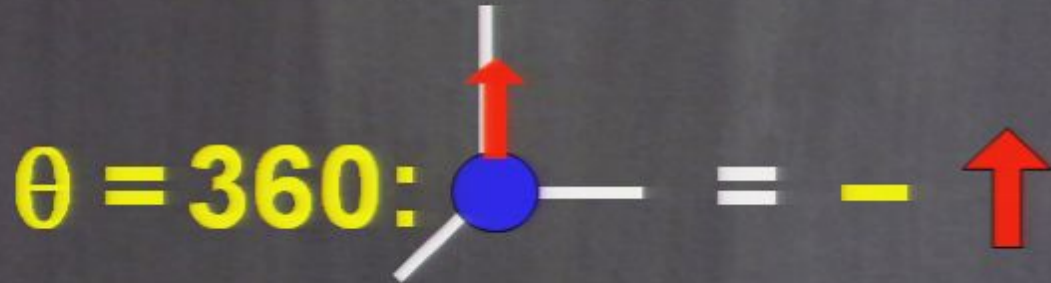
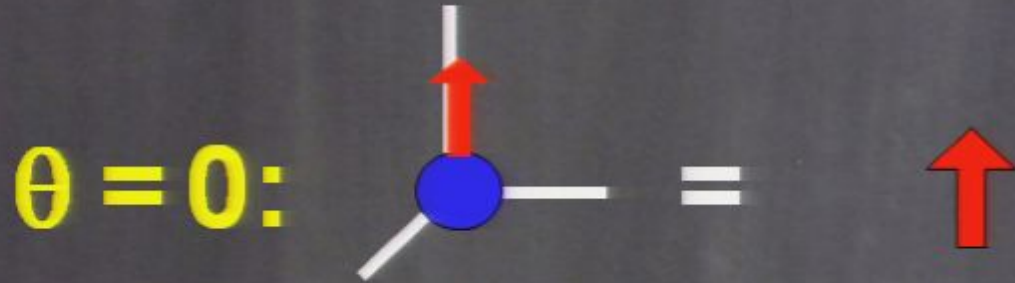
The Mysterious Min U S

The Mysterious Minus Sign:

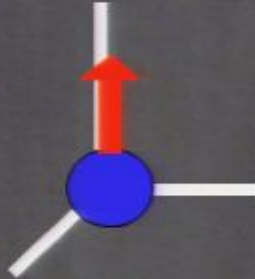

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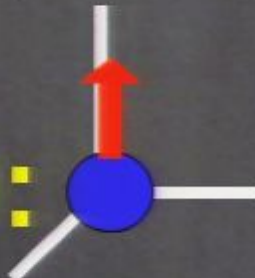





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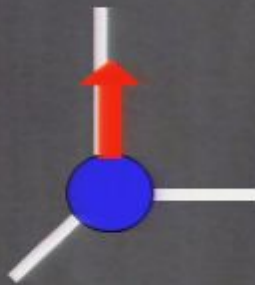

The Mysterious Minus Sign:



$\theta = 0:$  = 



$\theta = 360:$  = - 

$\theta = 720:$  = + 

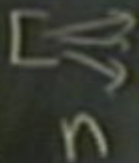
The Mysterious Minus Sign:

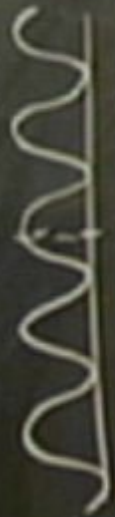
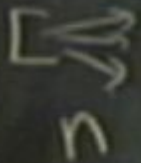
$\theta = 0:$  = 

$\theta = 360:$  = - 

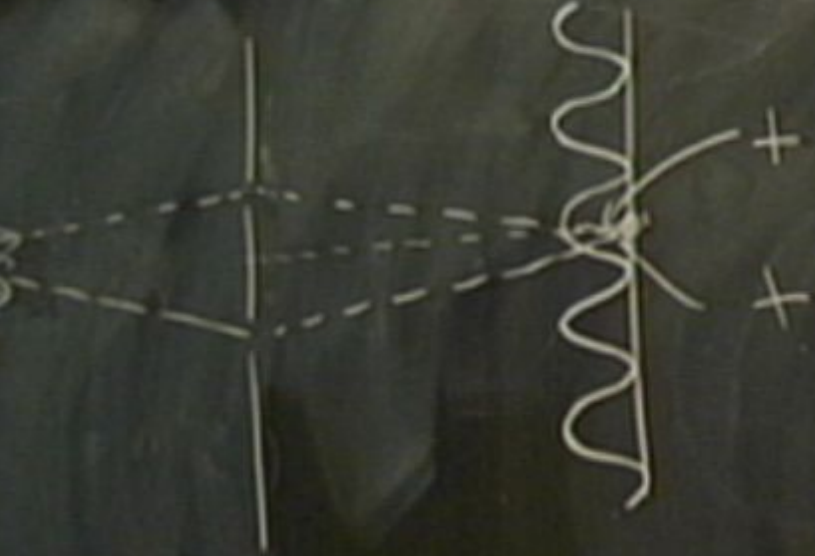
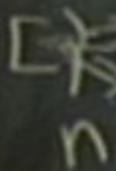
$\theta = 720:$  = + 

: Can be observed experimentally

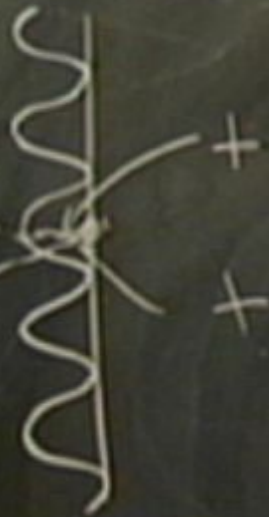
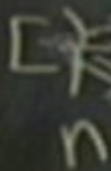




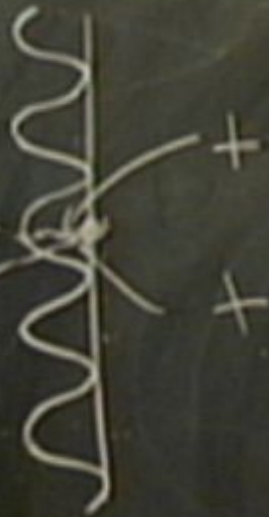
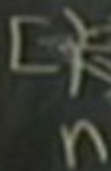
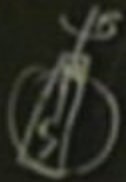
$$\lambda = 15$$



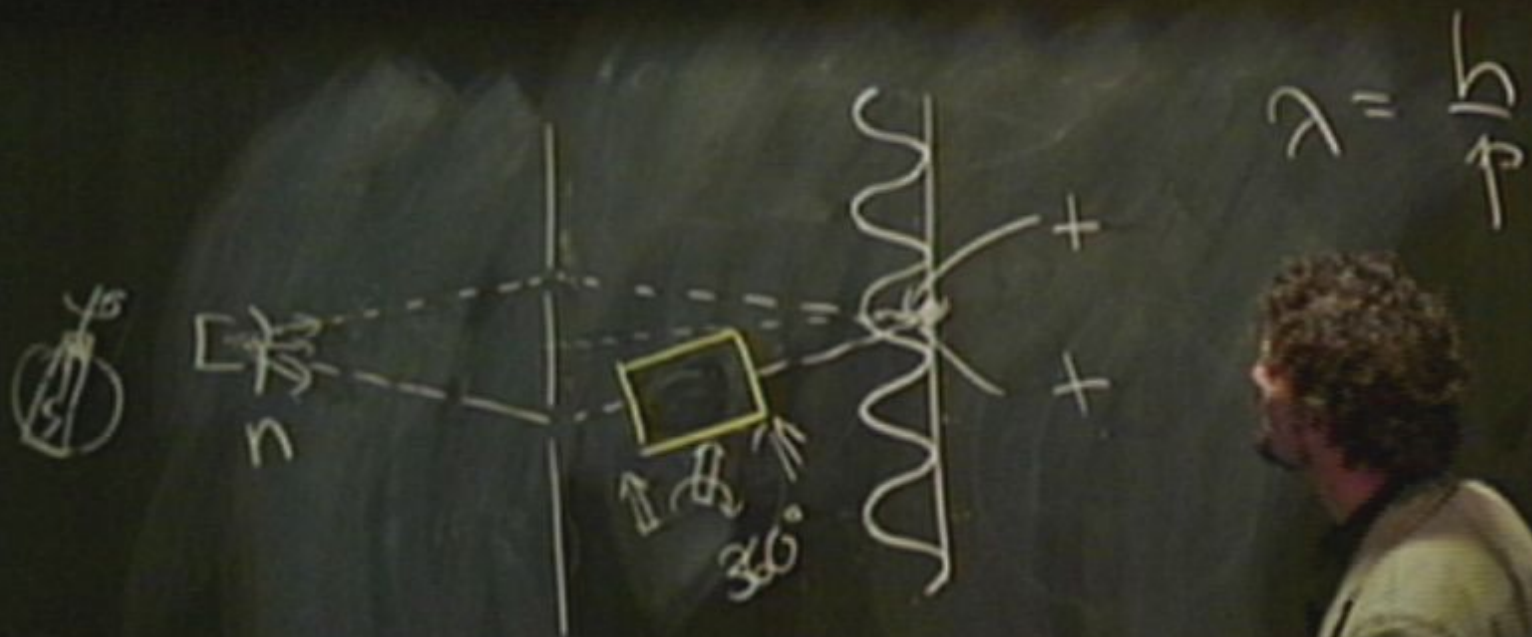
$\lambda = 514$

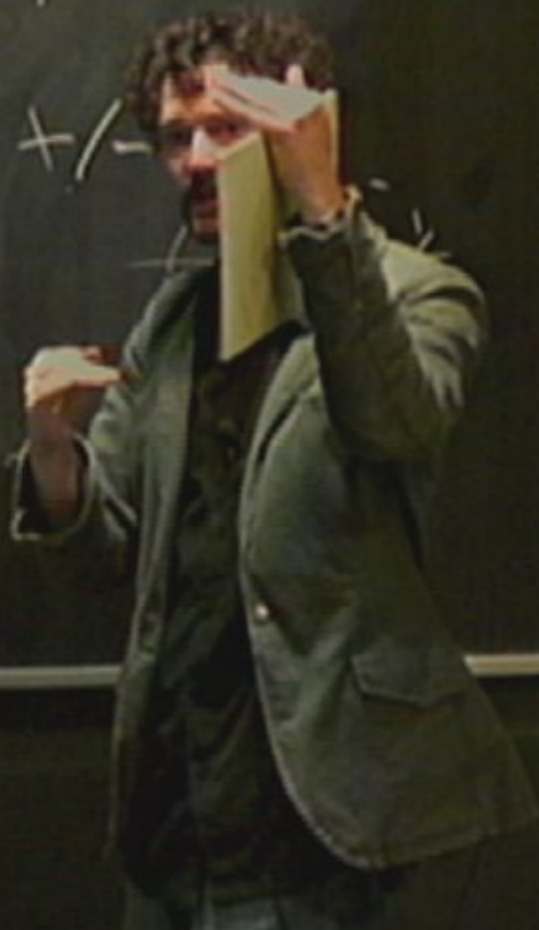
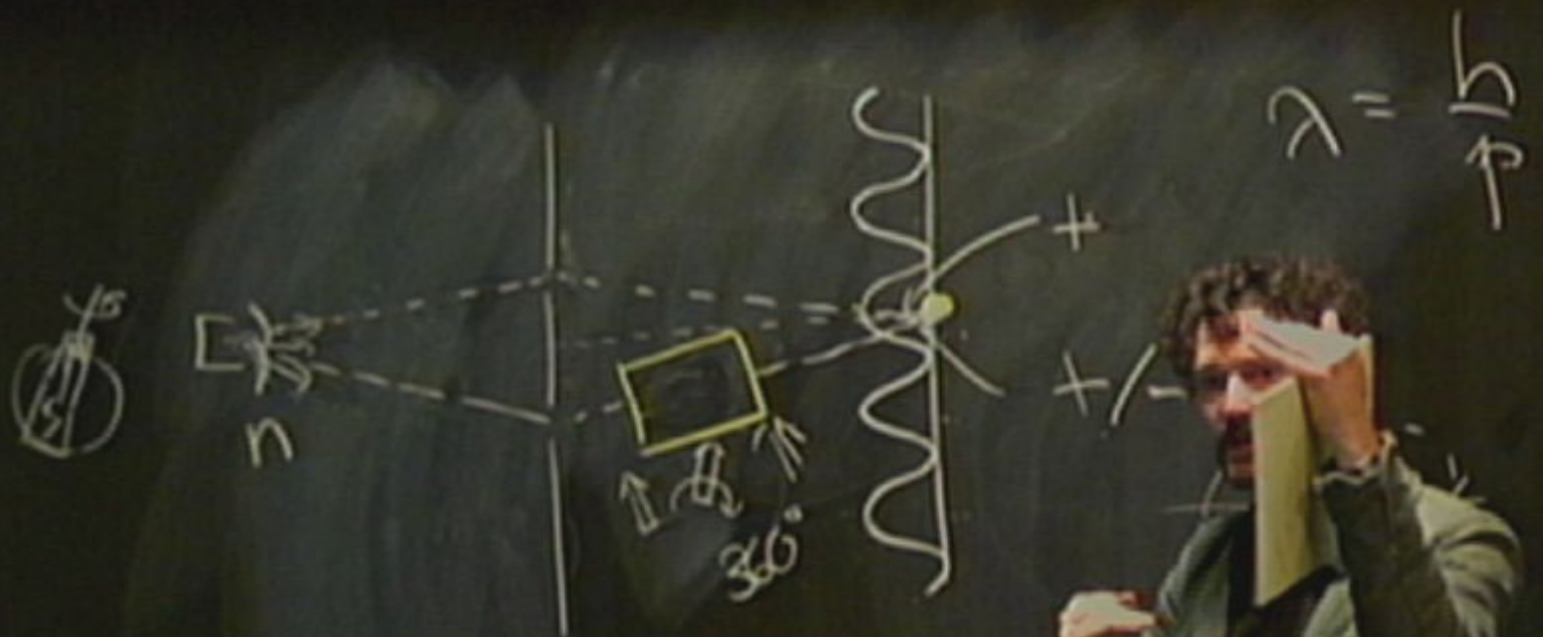


$\lambda = 515$

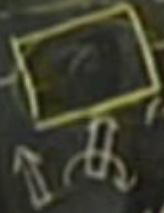
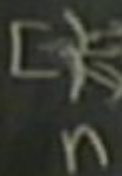
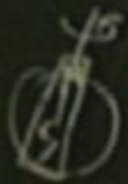


$$\lambda = 514$$









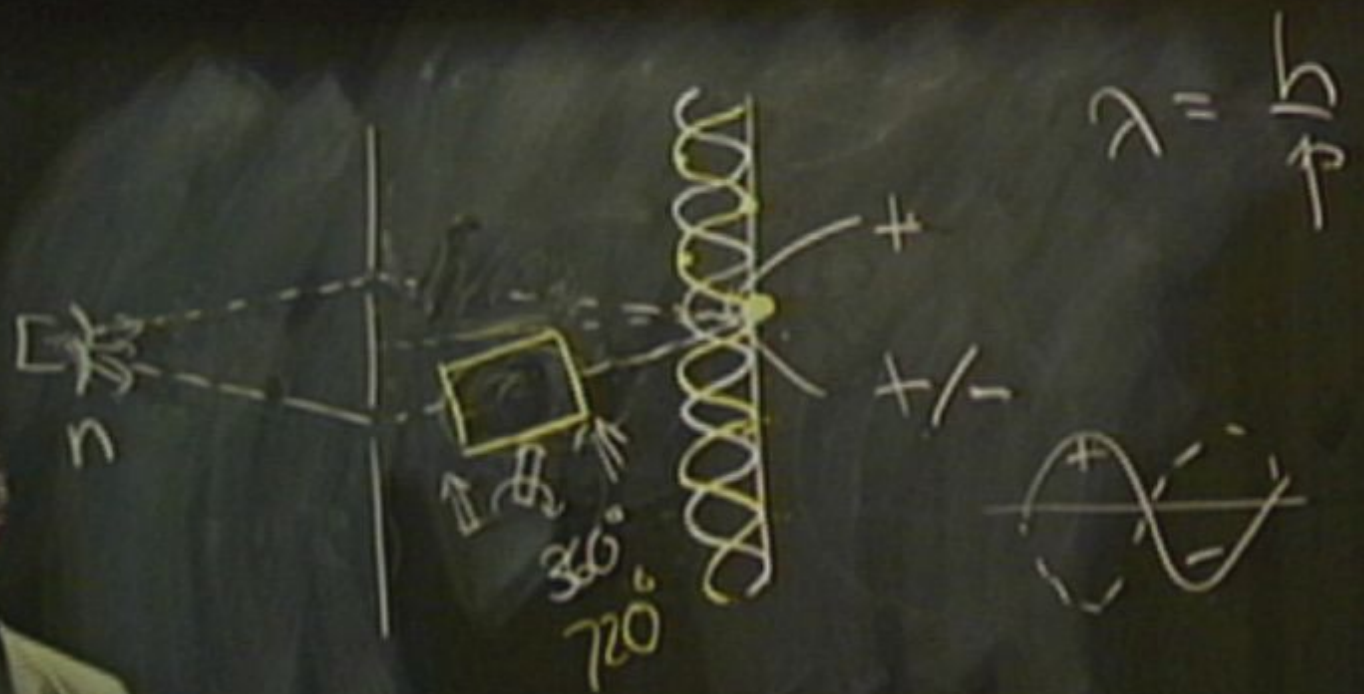
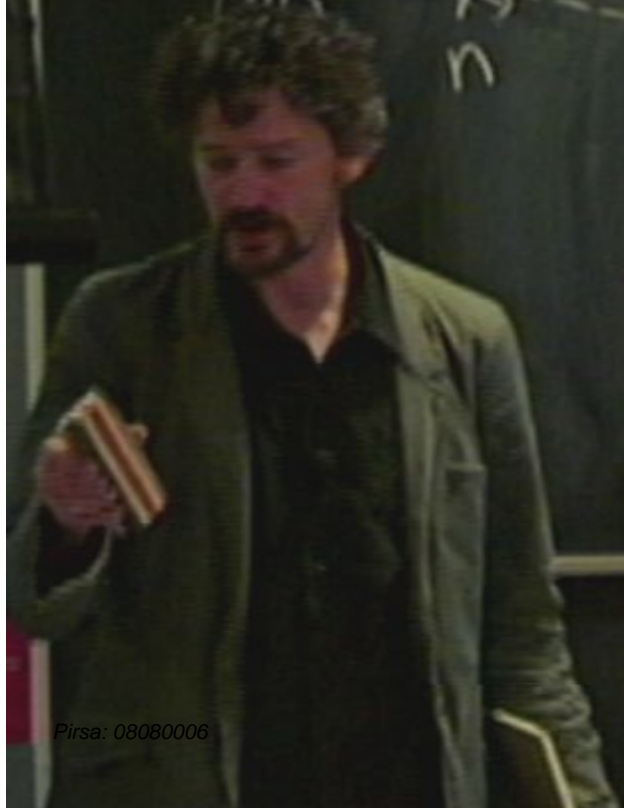
36°
 70°

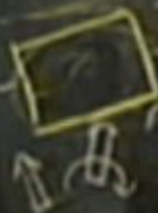
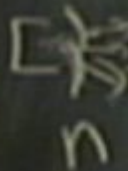
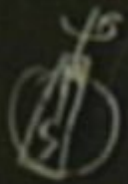


+

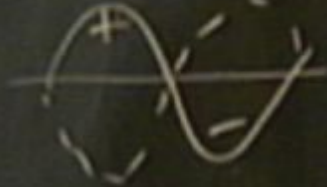
$\lambda = 15$







36°
20°



15
14