How to test Quantum Theory with thought experiments

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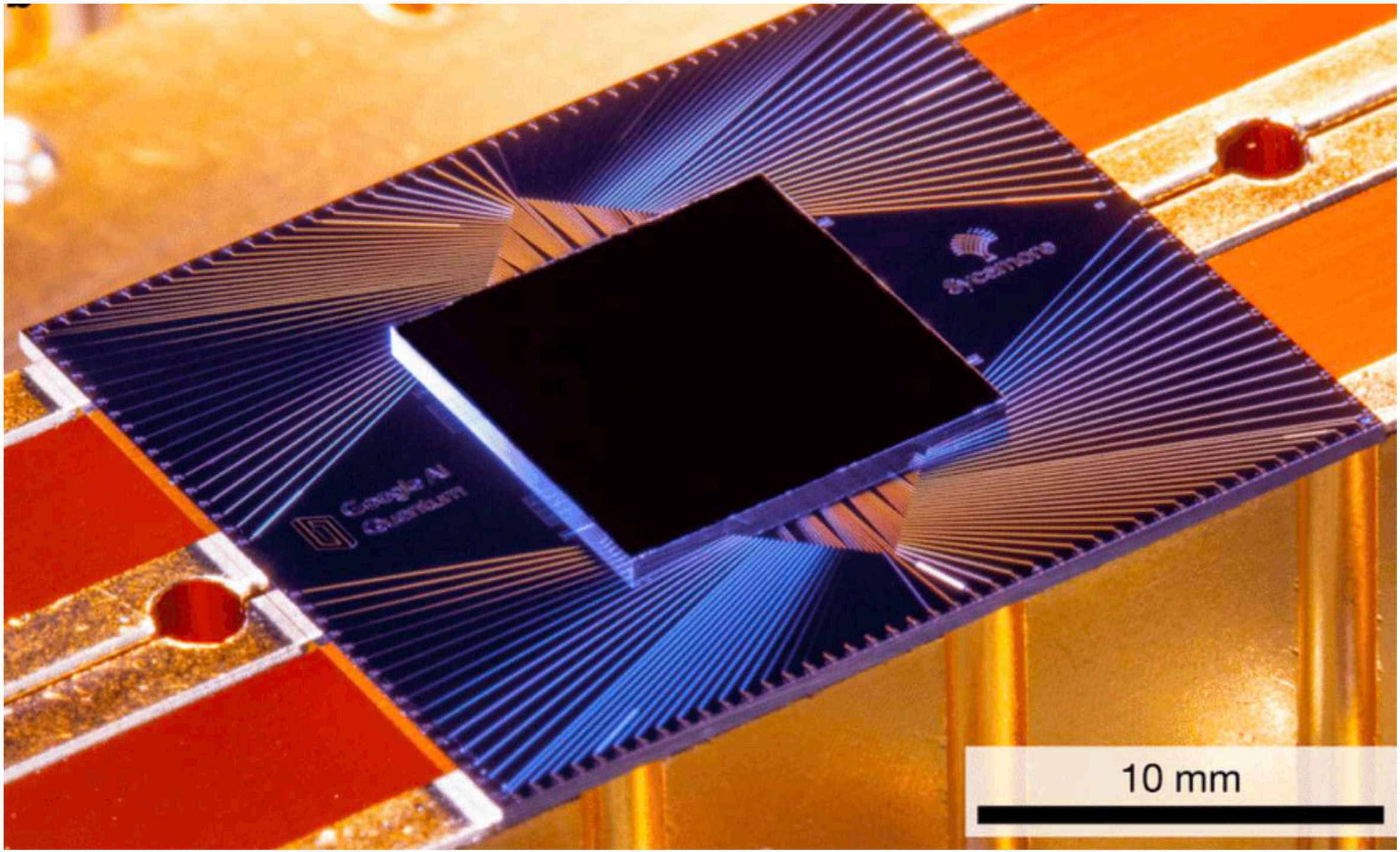
GGI Seminar — Firenze, 14.4.2021

The World Quantum Day is an initiative from quantum scientists from 65+ countries, launched on 14 April 2021 as the countdown towards the first global celebration on 14 April 2022.

Is it correctly described by quantum theory?

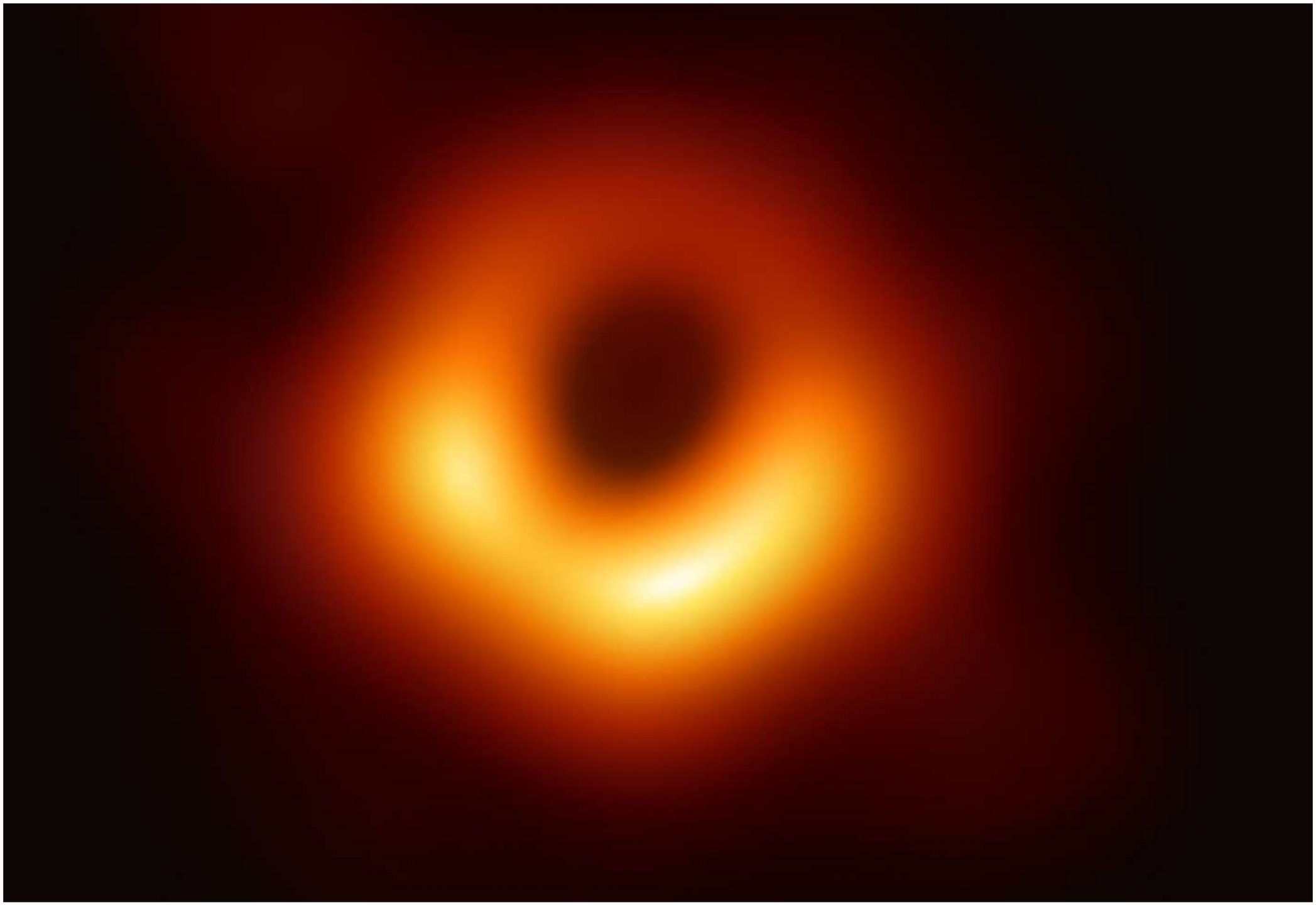


Google's Sycamore processor (from nature.com)

Is it correctly described by quantum theory?

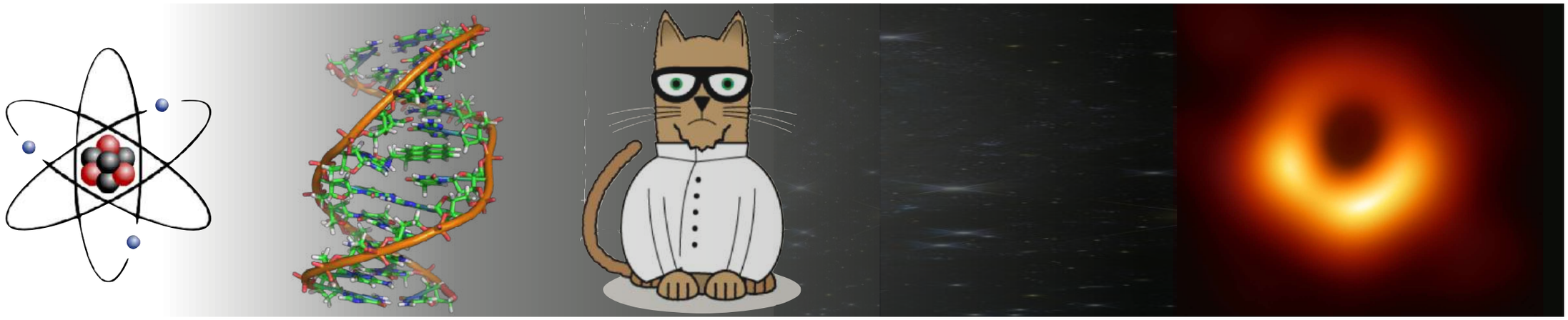
Erwin Schrödinger's cat (at his house in Huttenstrasse 9, Zurich)

Is it correctly described by quantum theory?



Black hole at the center of galaxy M87

Question:
What's the range of validity of quantum theory?

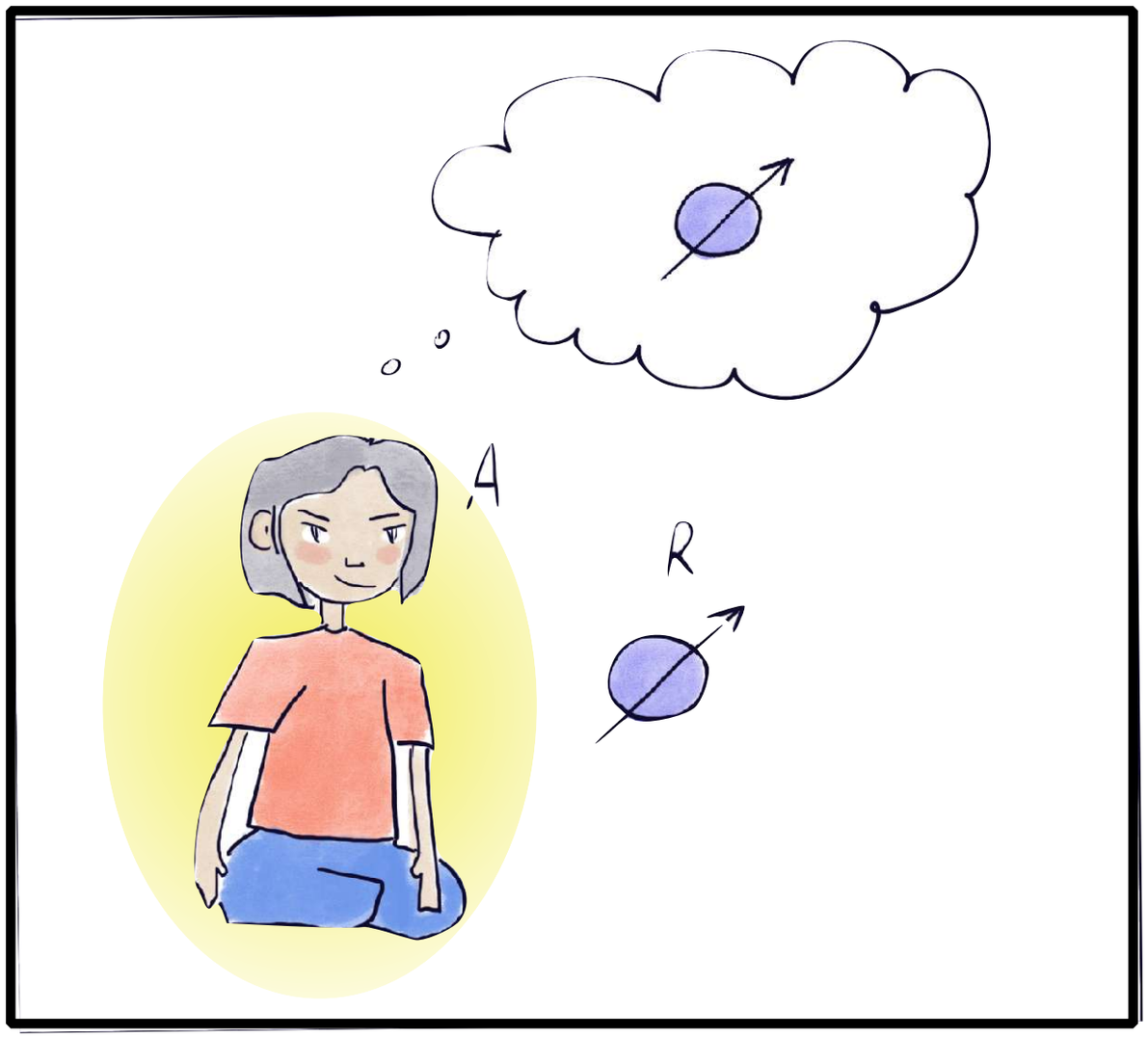


tested to high precision

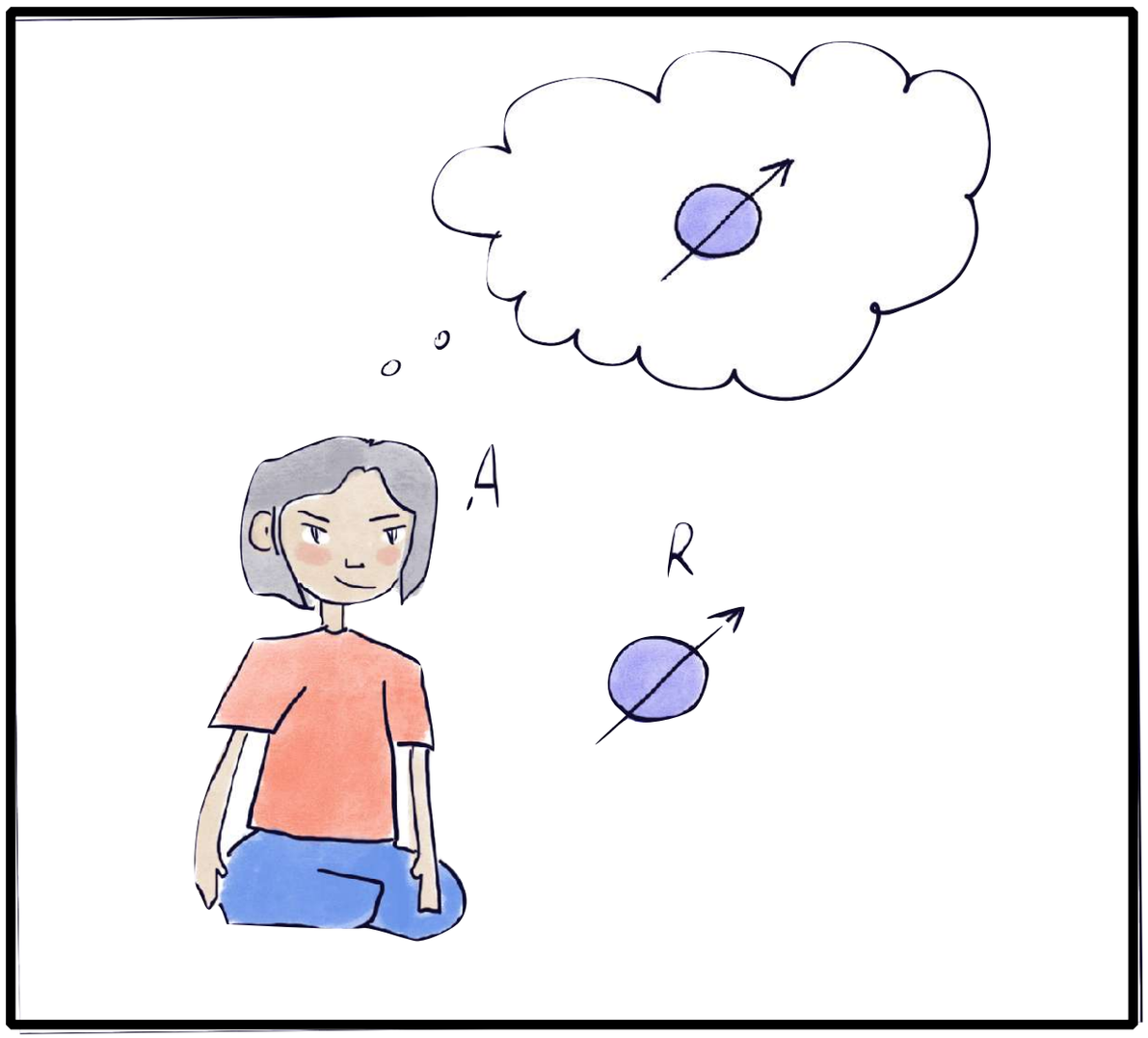
tested to low accuracy

?

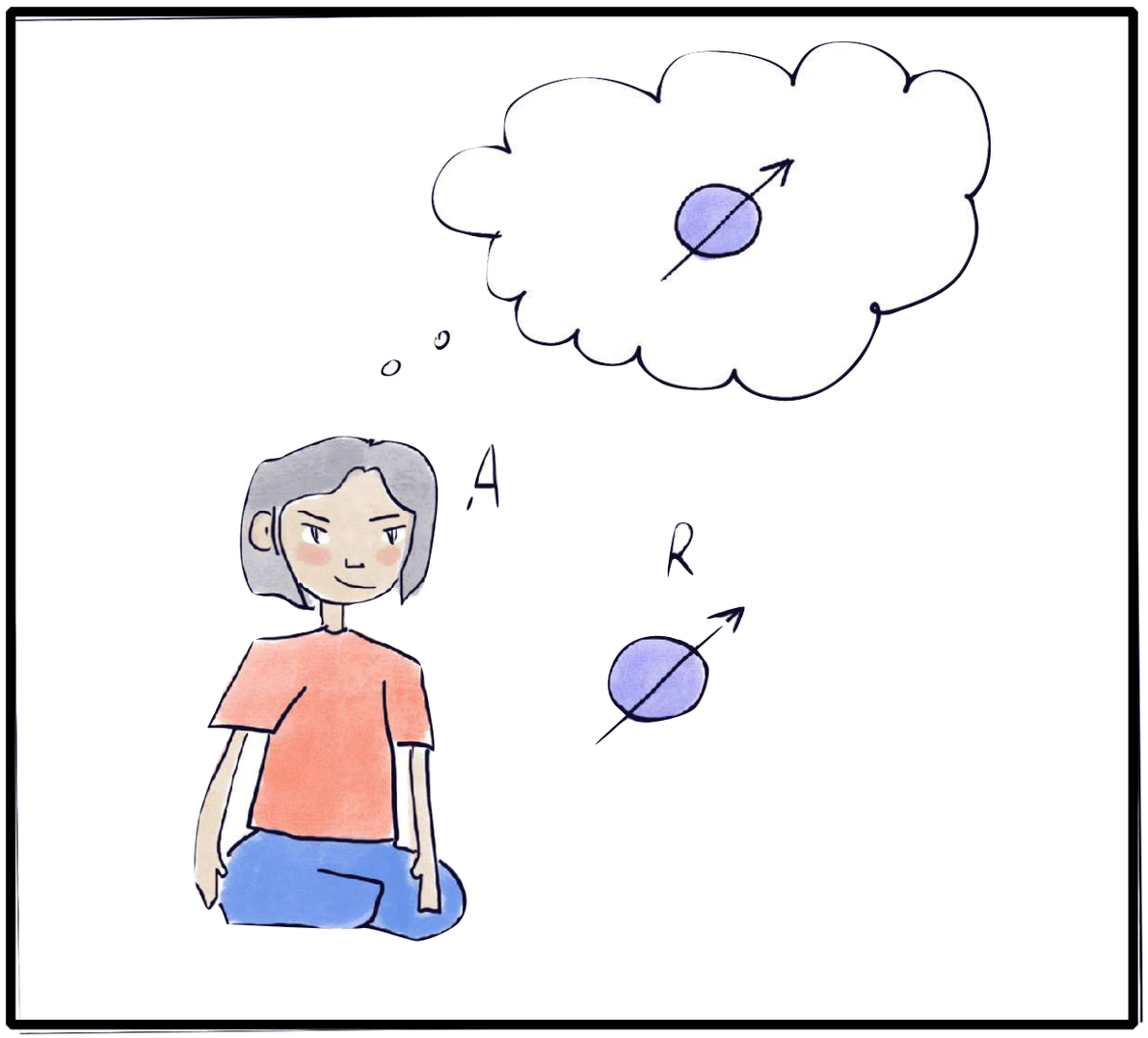
Information-theoretic approach



Information-theoretic approach



Information-theoretic approach



Idea: Use quantum theory to describe systems that can themselves be users of the theory.

A conceptual separation

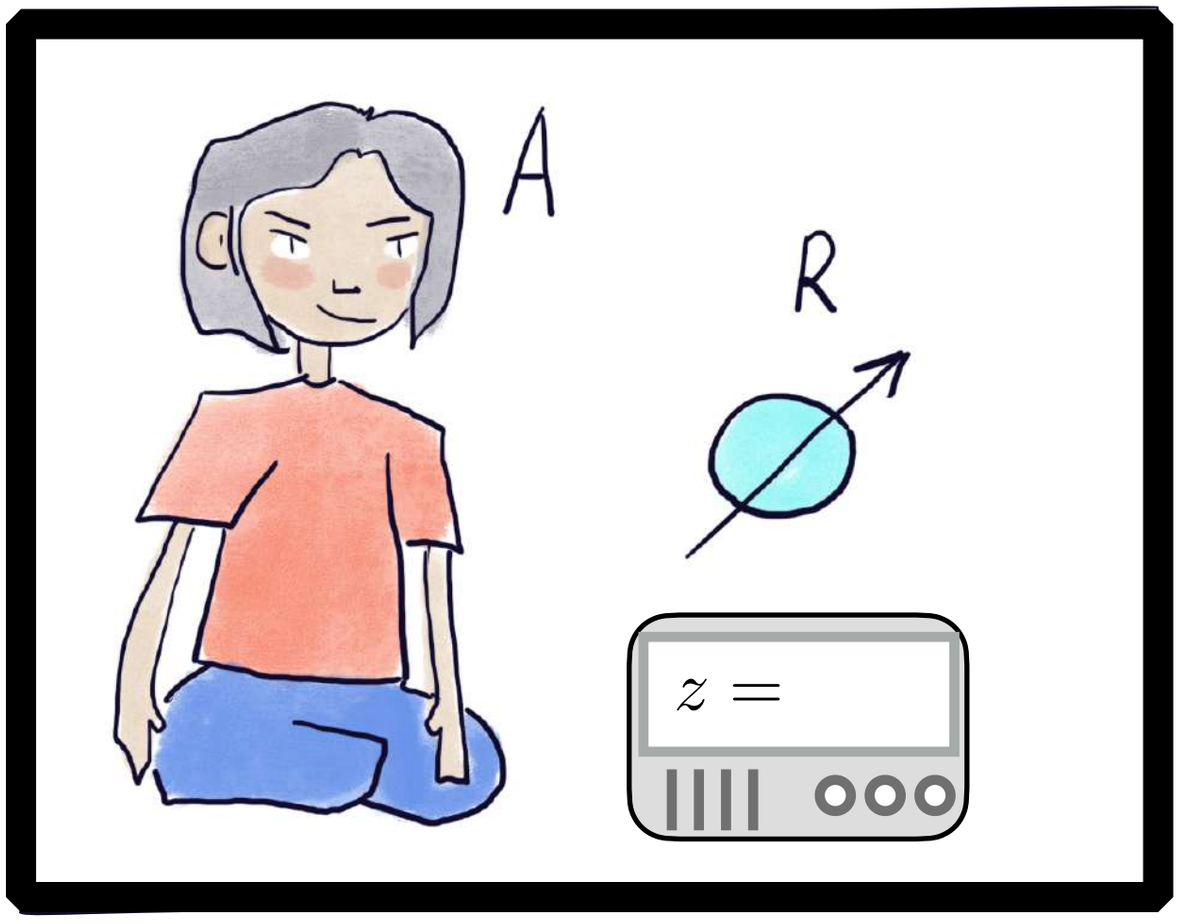
cannot be users of quantum theory

can be users of quantum theory

quantum theory valid

quantum theory invalid?

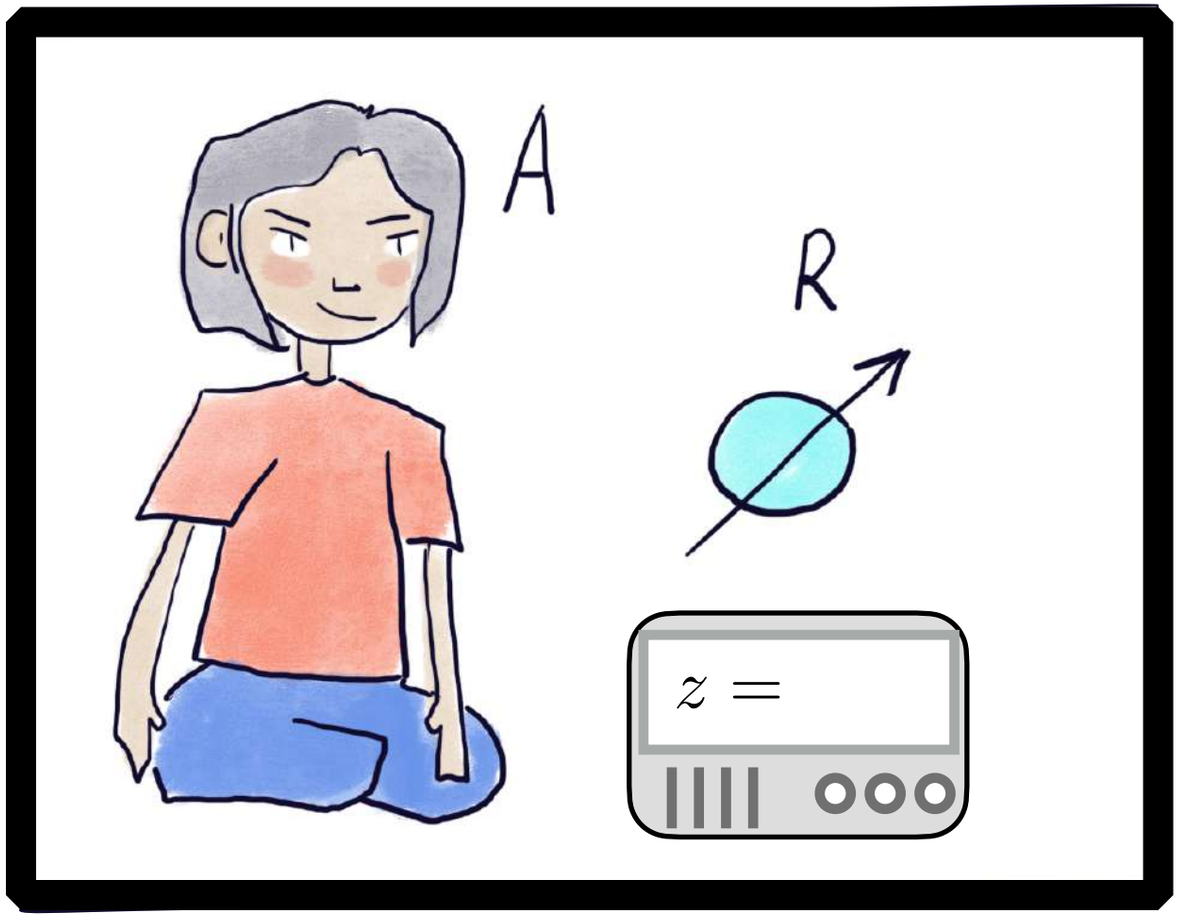
Wigner's friend thought experiment



$$|\uparrow\rangle_R \otimes |\text{ready}\rangle_A \quad \mapsto \quad |\uparrow\rangle_R \otimes |\text{I observed } z = \text{up}\rangle_A$$

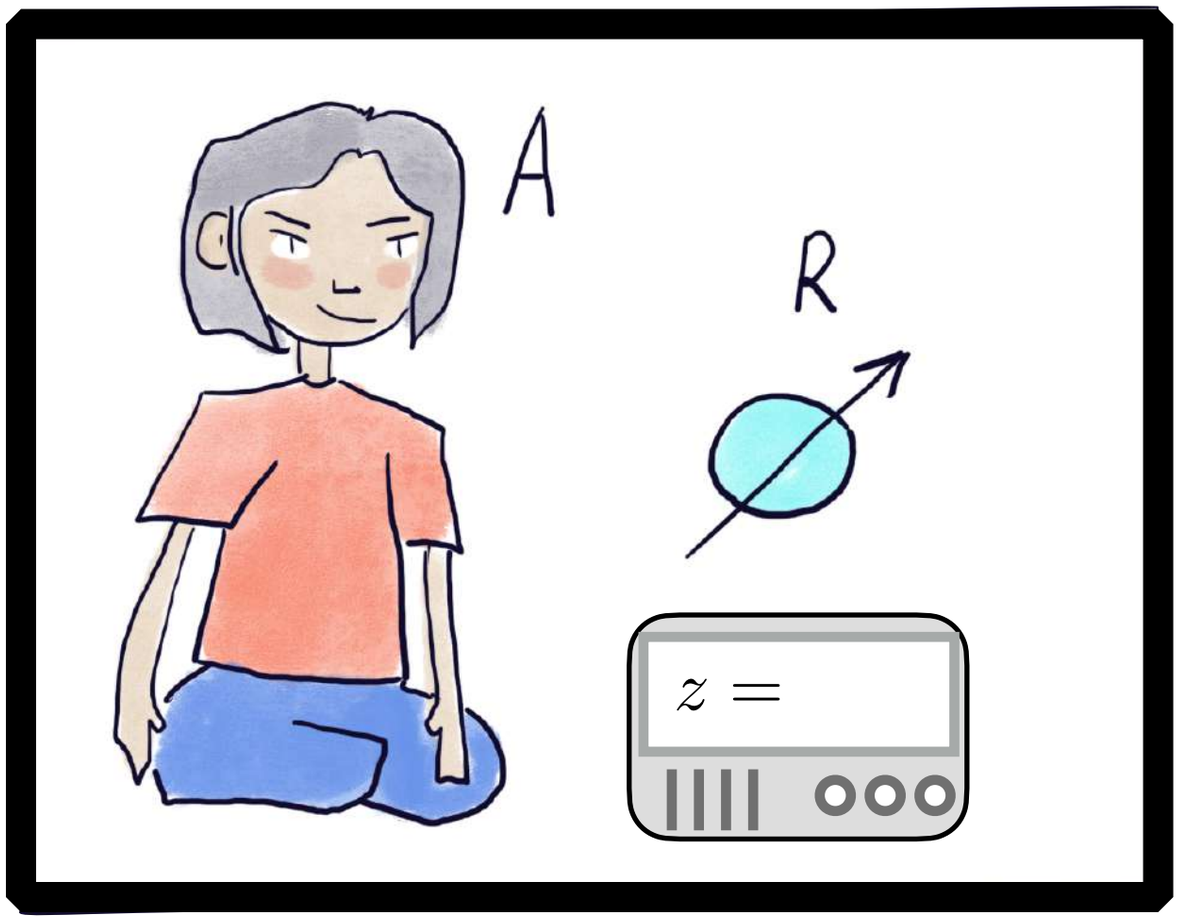
$$|\downarrow\rangle_R \otimes |\text{ready}\rangle_A \quad \mapsto \quad |\downarrow\rangle_R \otimes |\text{I observed } z = \text{down}\rangle_A$$

Wigner's friend thought experiment



$$|\rightarrow\rangle_R = \frac{|\uparrow\rangle_R + |\downarrow\rangle_R}{\sqrt{2}}$$

Wigner's friend thought experiment

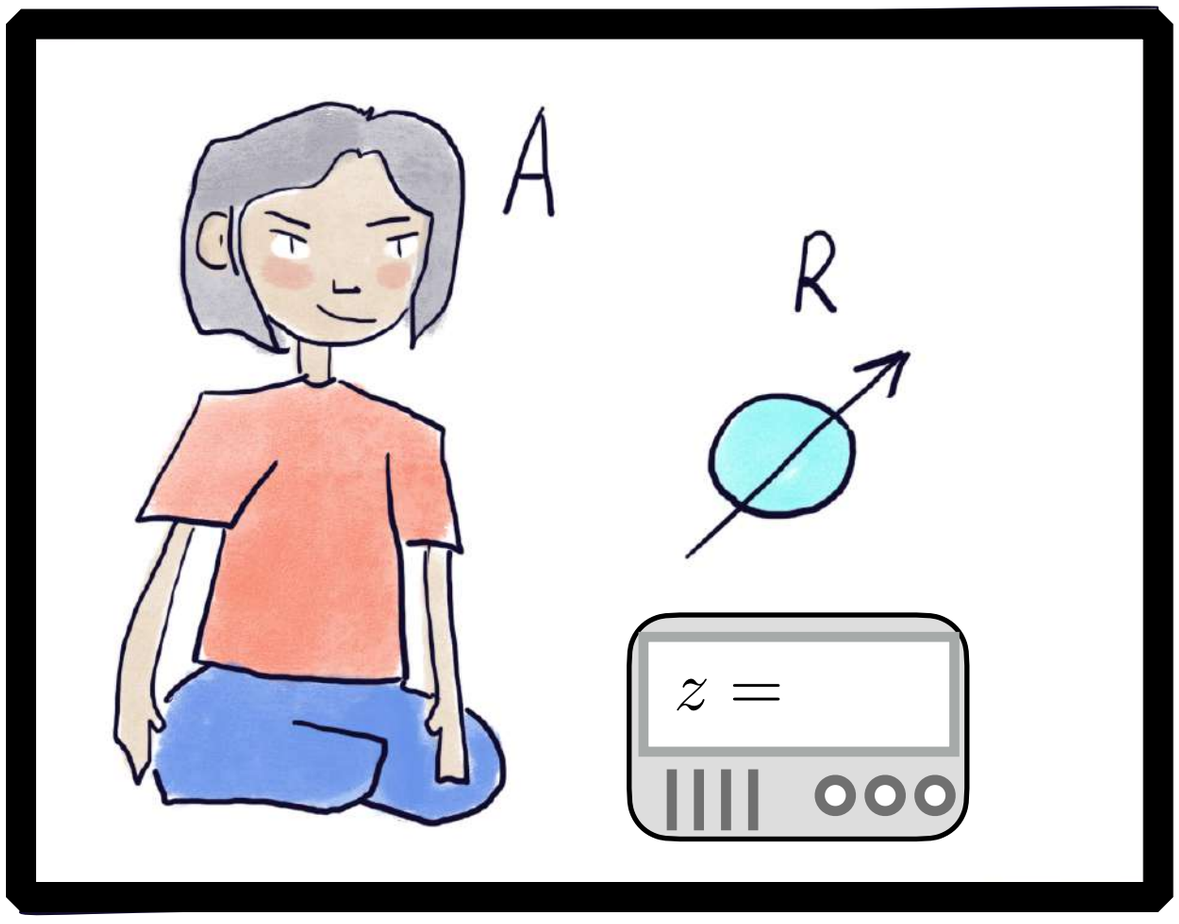


$$(|\uparrow\rangle_R + |\downarrow\rangle_R) \otimes |\text{ready}\rangle_A$$

$$\mapsto$$

?

Wigner's friend thought experiment

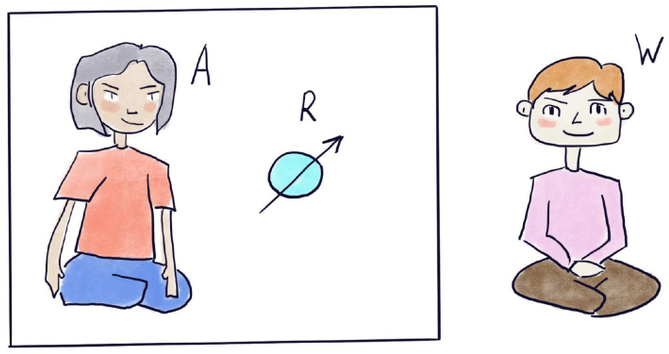


$$(|\uparrow\rangle_R + |\downarrow\rangle_R) \otimes |\text{ready}\rangle_A$$

$$\mapsto$$

$$|\uparrow\rangle_R \otimes |\text{I observed } z = \text{up}\rangle_A \; + \; |\downarrow\rangle_R \otimes |\text{I observed } z = \text{down}\rangle_A$$

Wigner's friend thought experiment



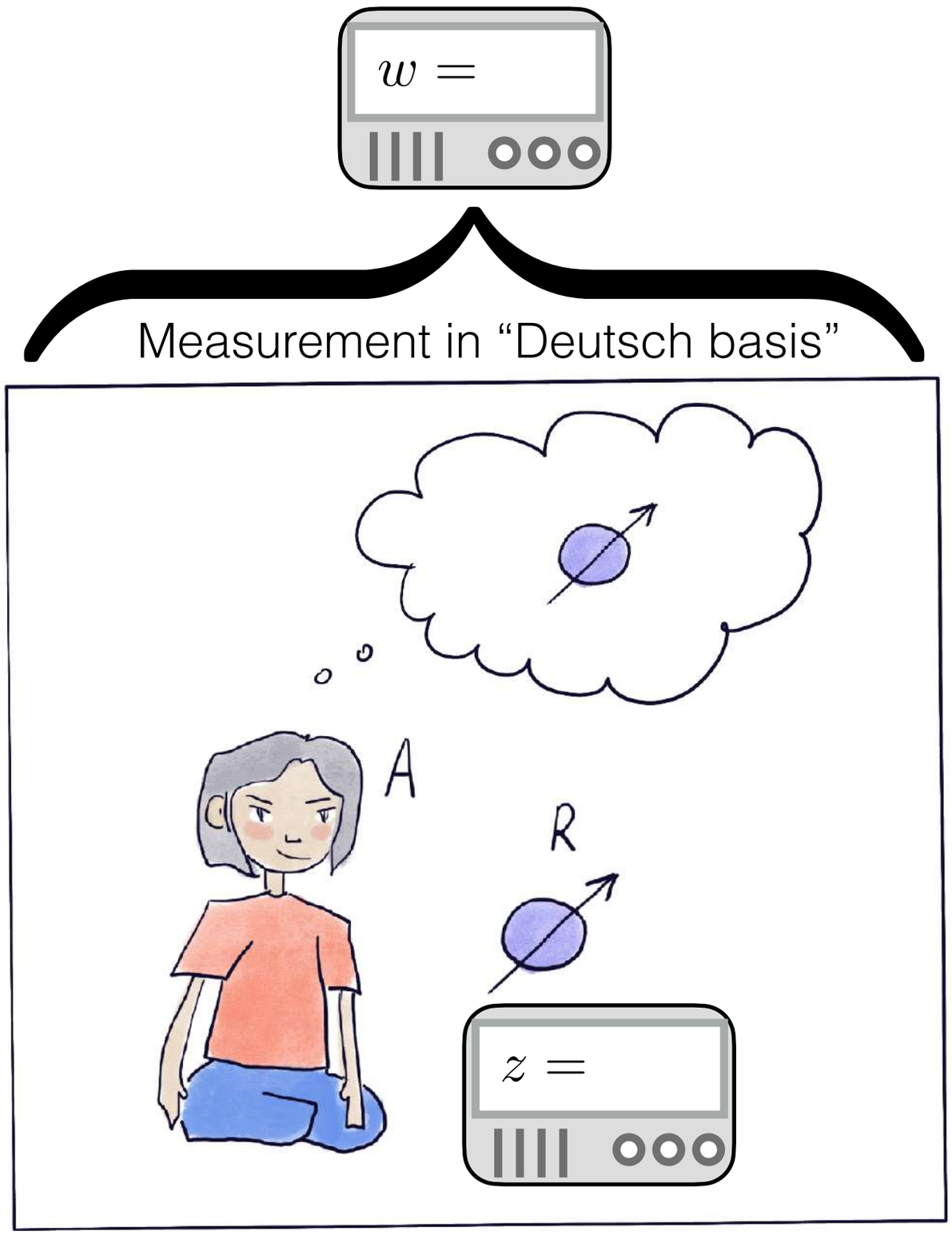
Alice's claim: *"I observed* $z = \text{up}$ *"*

or *"I observed* $z = \text{down}$*"*

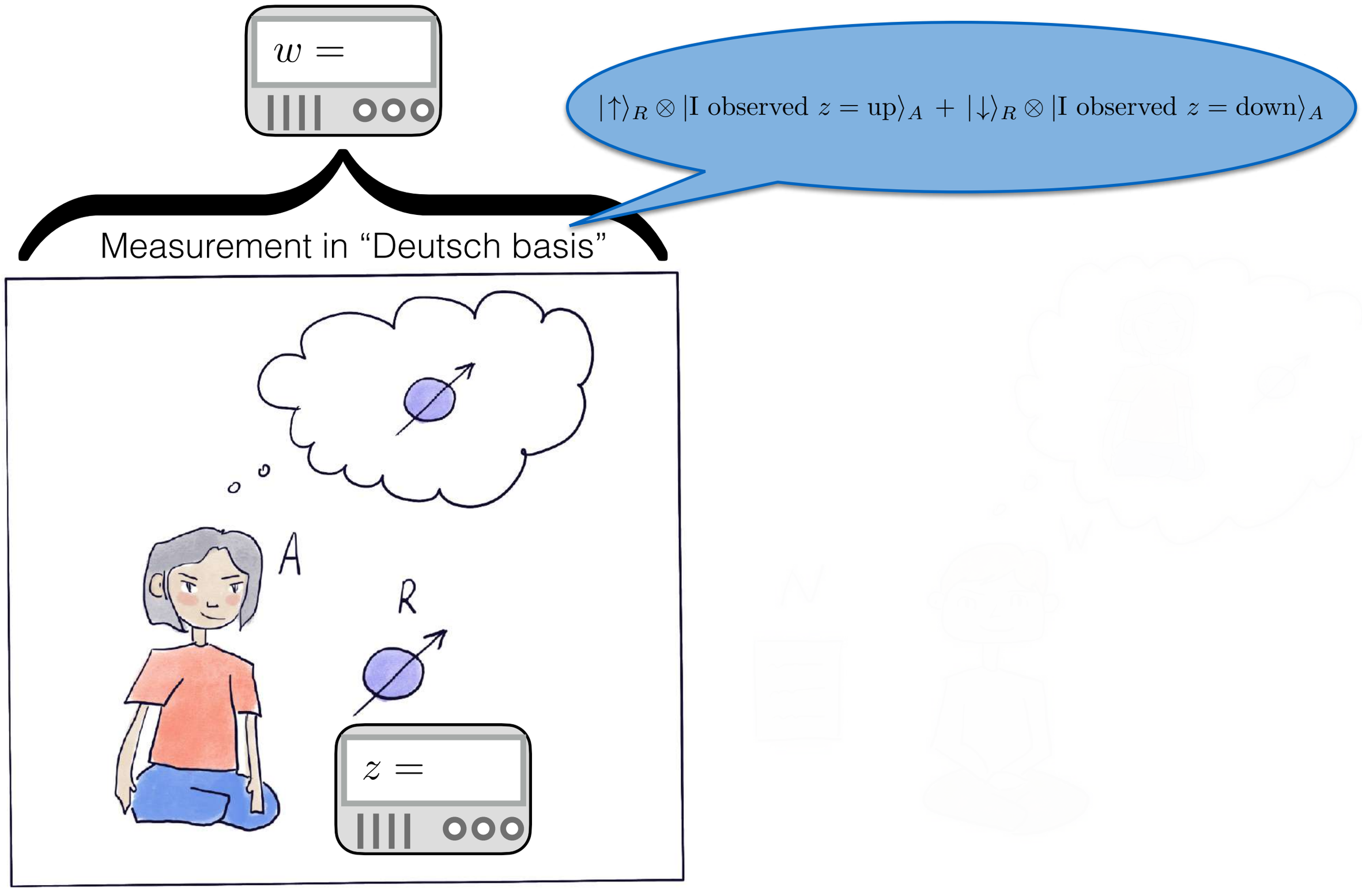
Wigner's claim: *"Alice is in a superposition between having observed* $z = \text{up}$ *and* $z = \text{down}$*."*

	Alice	Bob
Copenhagen	✔	✘
Collapse theories	✔	✘
QBism	✔	✔
Relational Quantum Mechanics	✔	✔
Bohmian Mechanics	✔	✔
Many-Worlds	✘	✔
…	…	…

Deutsch's extension of Wigner's experiment

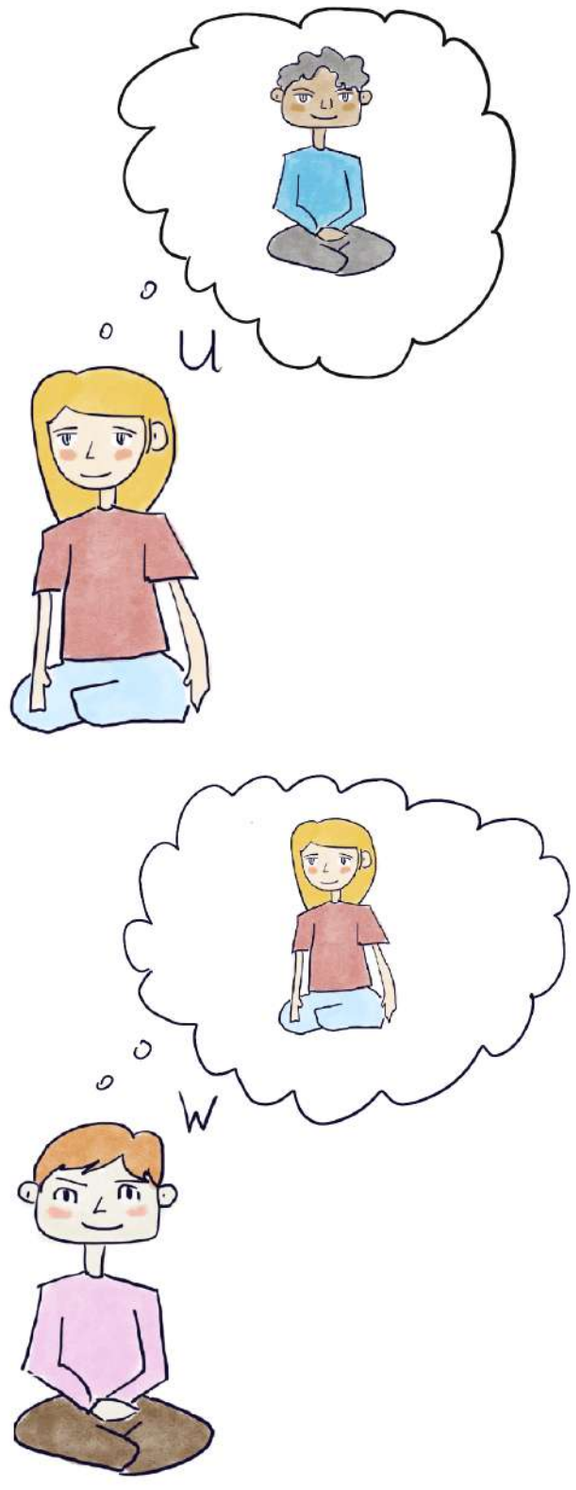


Deutsch's extension of Wigner's experiment



FR thought experiment

[D. Frauchiger and R. Renner, Quantum theory cannot consistently describe the use of itself *Nat. Comm*, **9**, 2018]



The most obvious fact that events occur is troubling to
purists due to their supposed cosmic spacetime 'block' of potted physics
history. Nature does not trouble to clutter the universe by absurdly conserving
its banal flux of activity (or even more absurdly, perversely producing for us an
illusion of activity in a potted Potemkin universe).
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Idea from "David Star" and
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8093 Zurich
Switzerland
Change: Every
defined change.
error is the law
in entropy in a
does not chan
If it's true th
suggested
GLOBAL USA FOREVER 2016
thanking you in advance
Tau-lepton ?
to 1,5 x 10^13 MHz
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Mateus Araújo Says:

Comment #294 December 7th, 2018 at 5:21 am

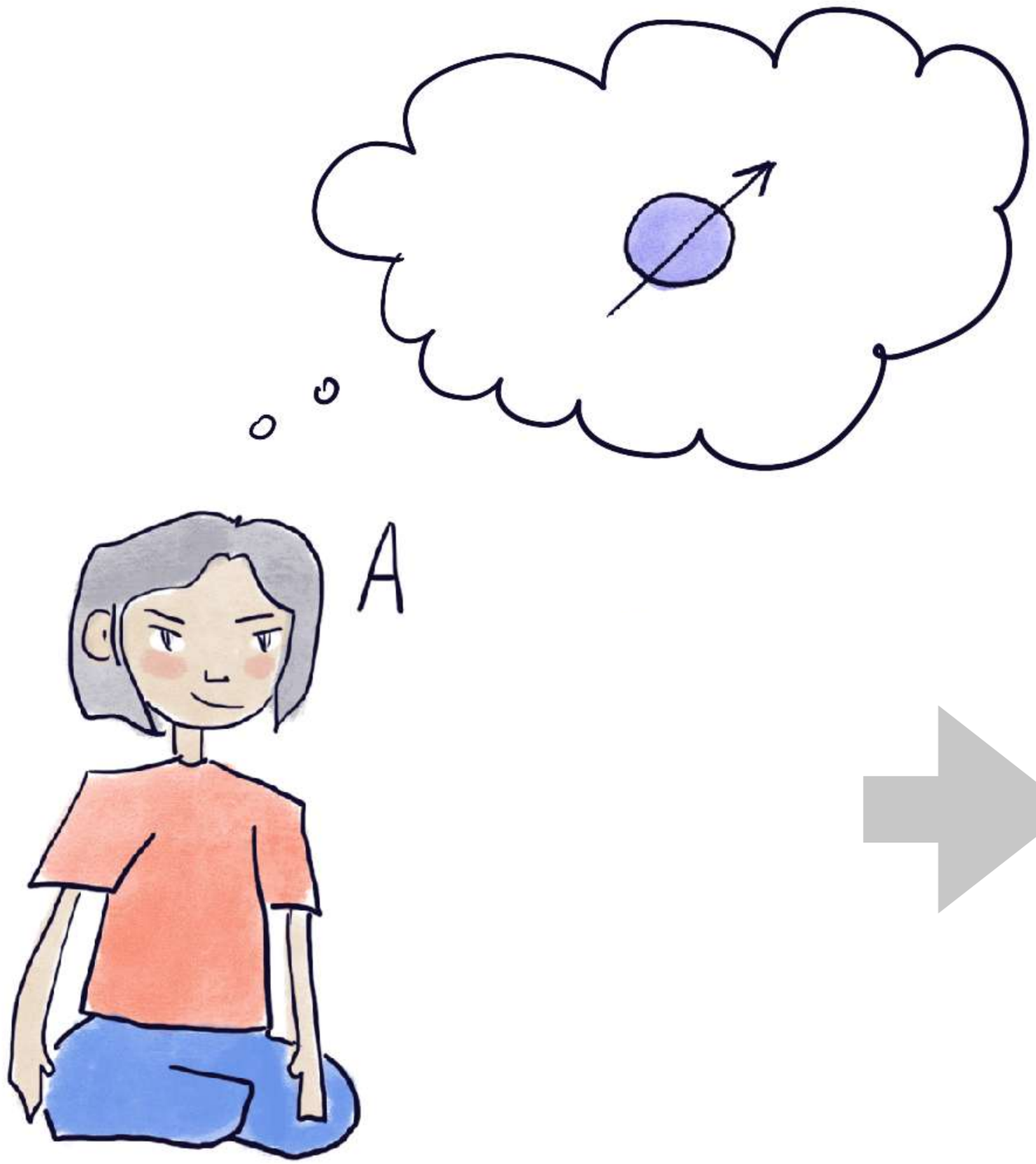
Renato #291:

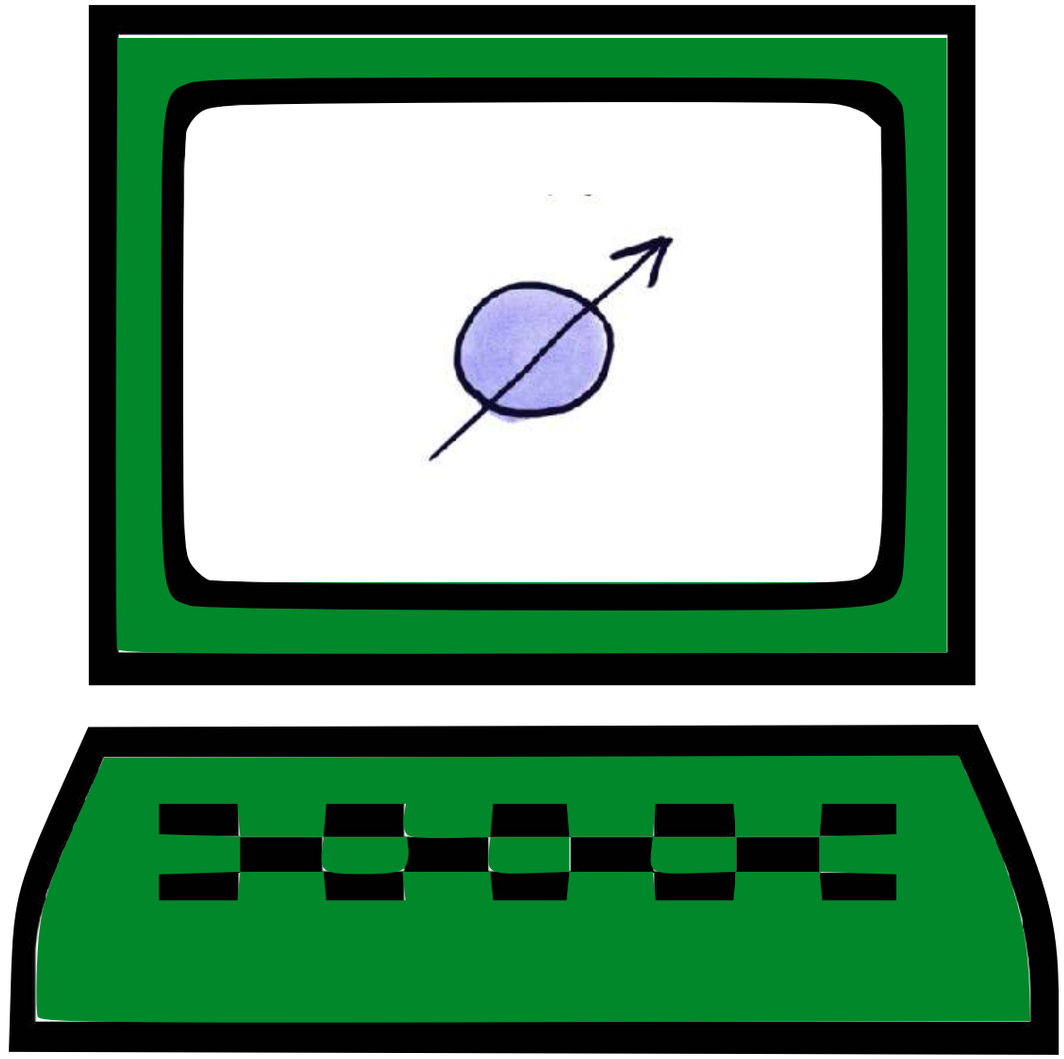
I would conclude instead that

"Users of quantum theory cannot consistently decide what quantum theory is."

Once we are clear about what quantum theory is, then deciding about its consistency is easy. For instance, I think we agreed here that QBism and RQM cannot consistently describe their own use.

Better get rid of human agents …





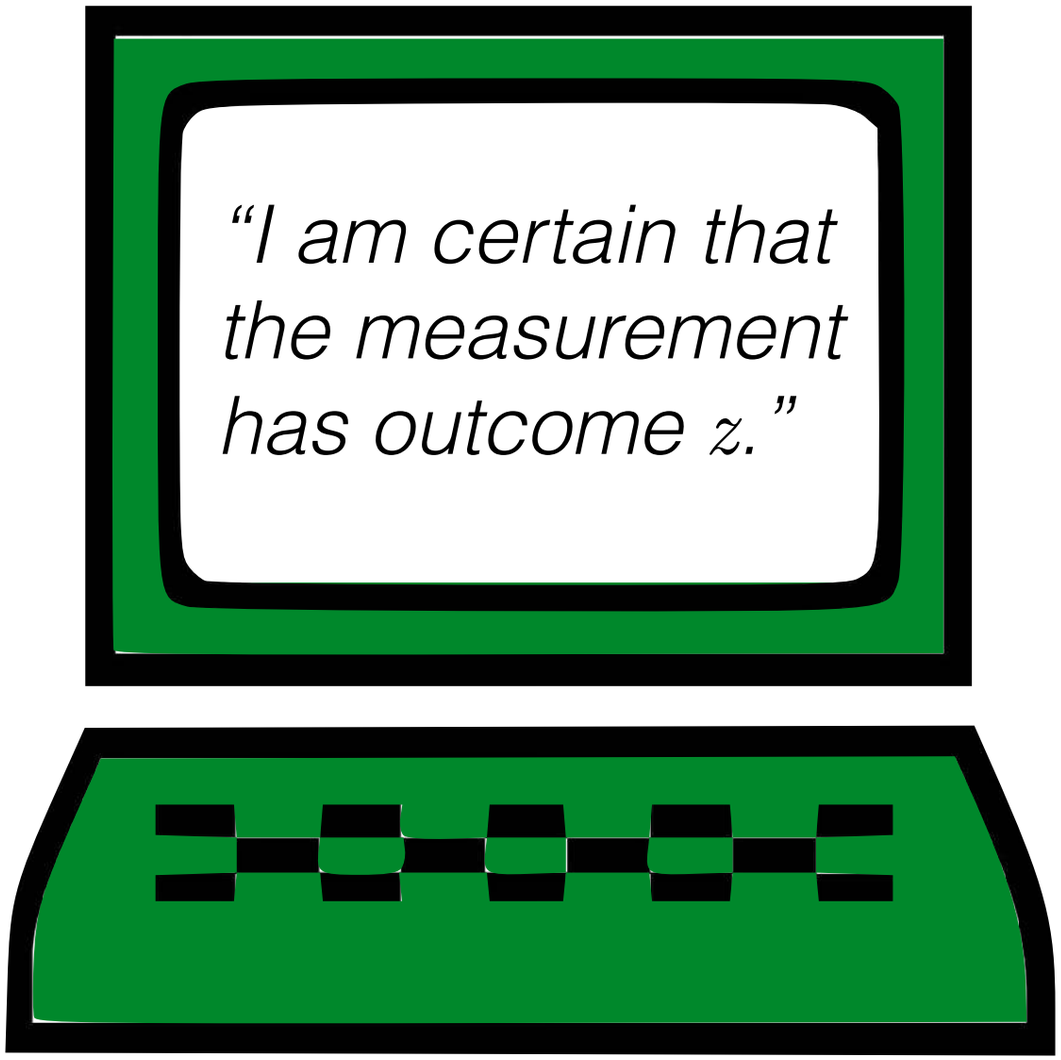
Computers as users of quantum theory

input

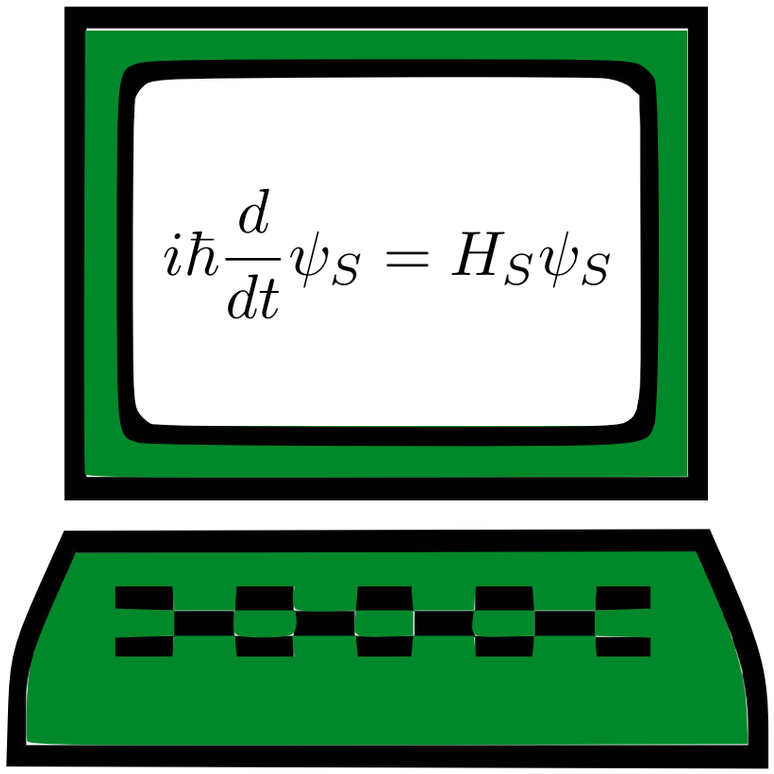
- Quantum formalism
- Description of experiment
- Observations

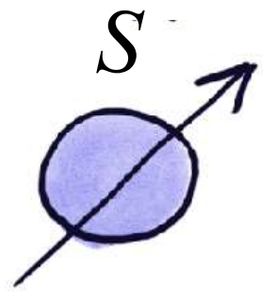
>>>

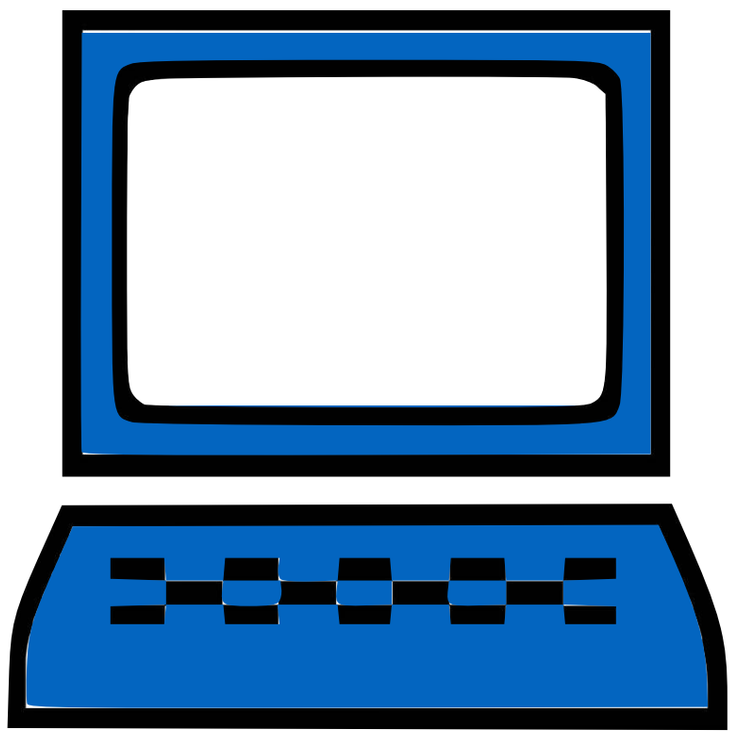
output



Role as subject:
Computer as agent that uses quantum theory.

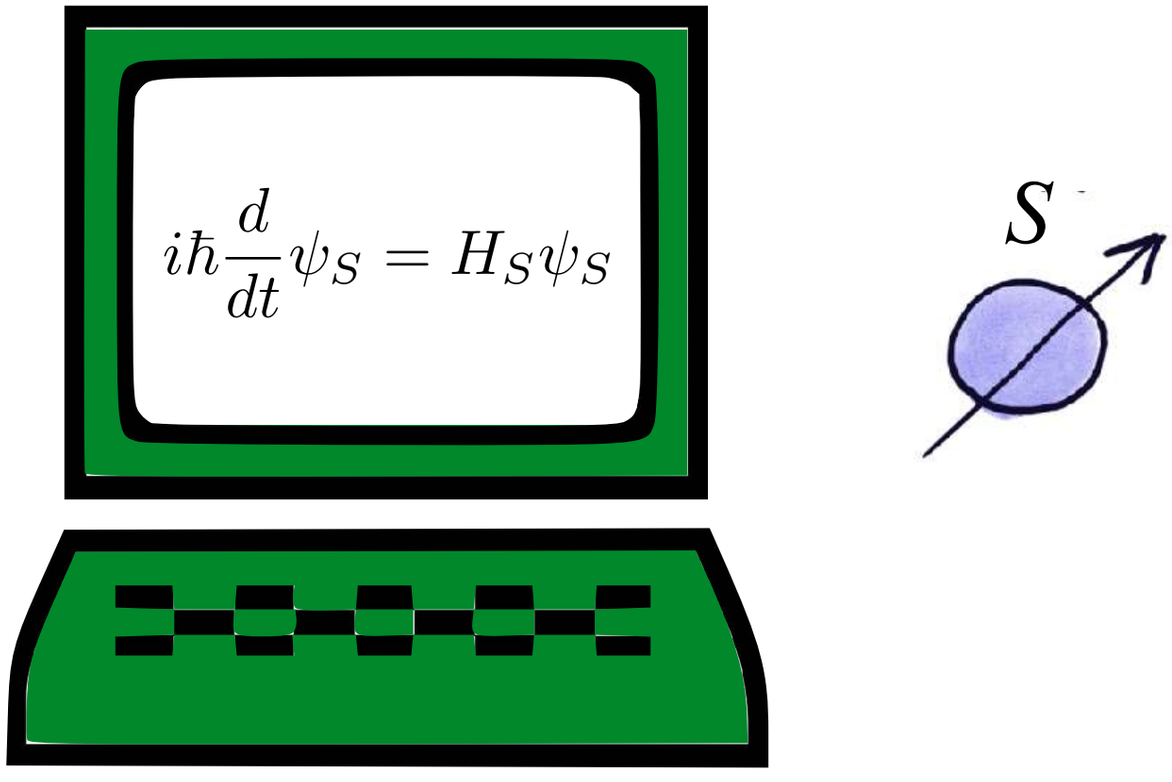




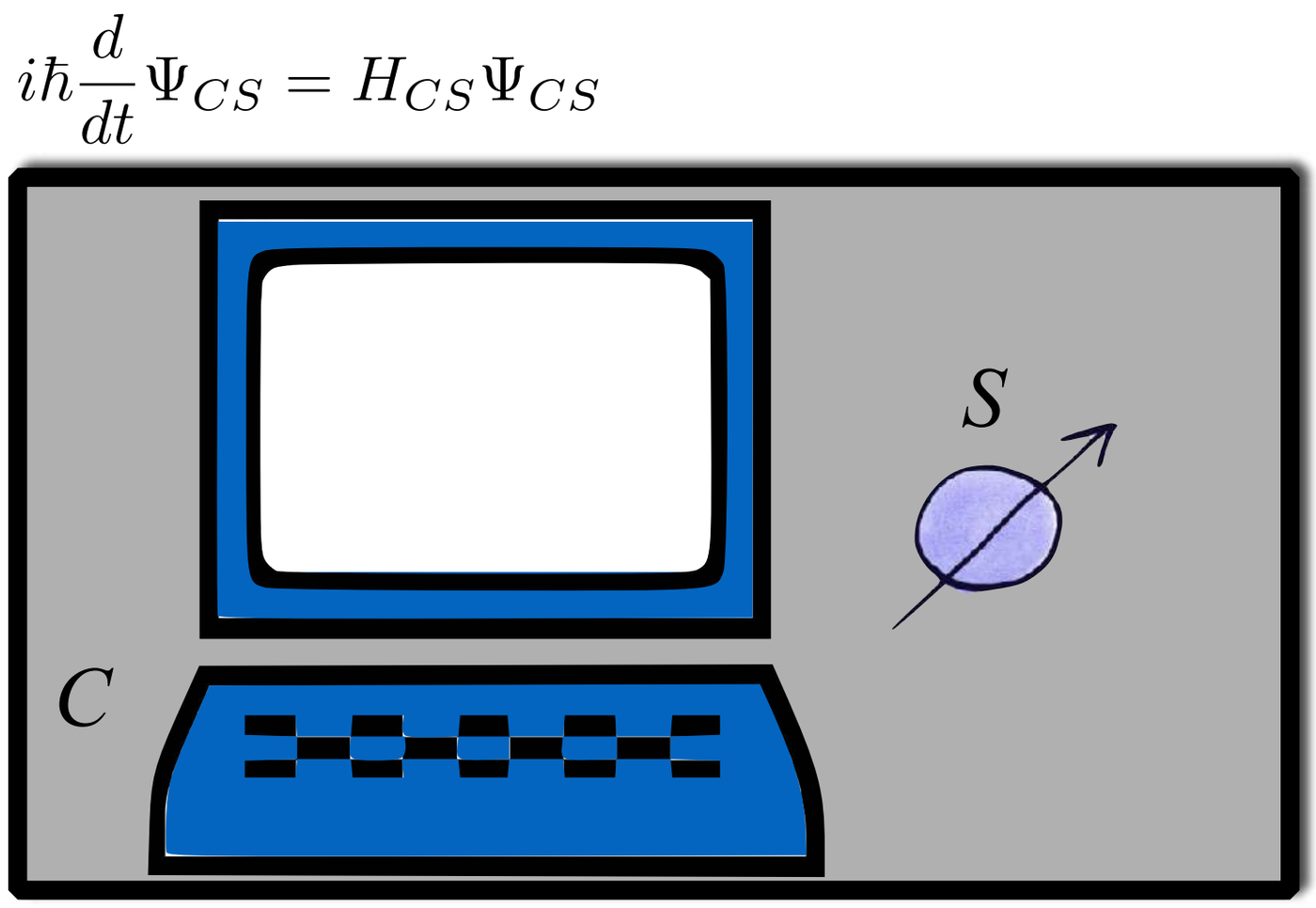


S

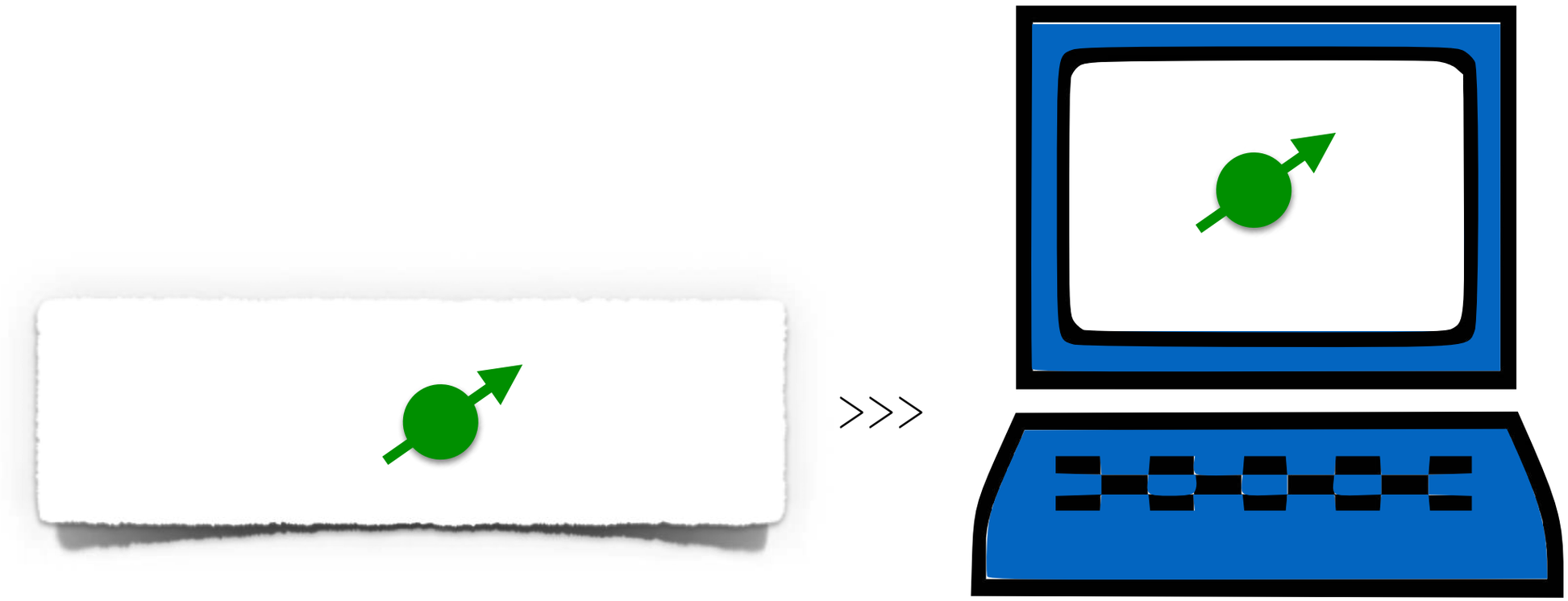
Role as subject:
Computer as agent that uses quantum theory.



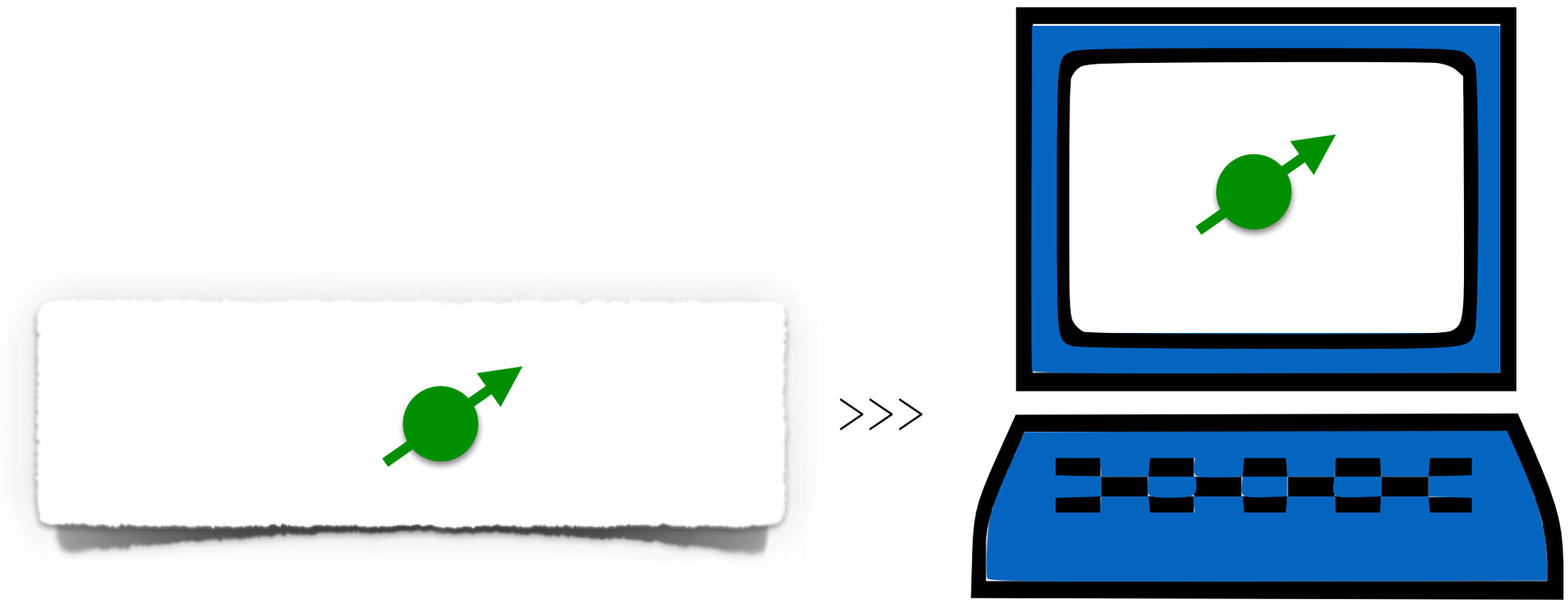
Role as object:
Computer as object described by quantum theory.

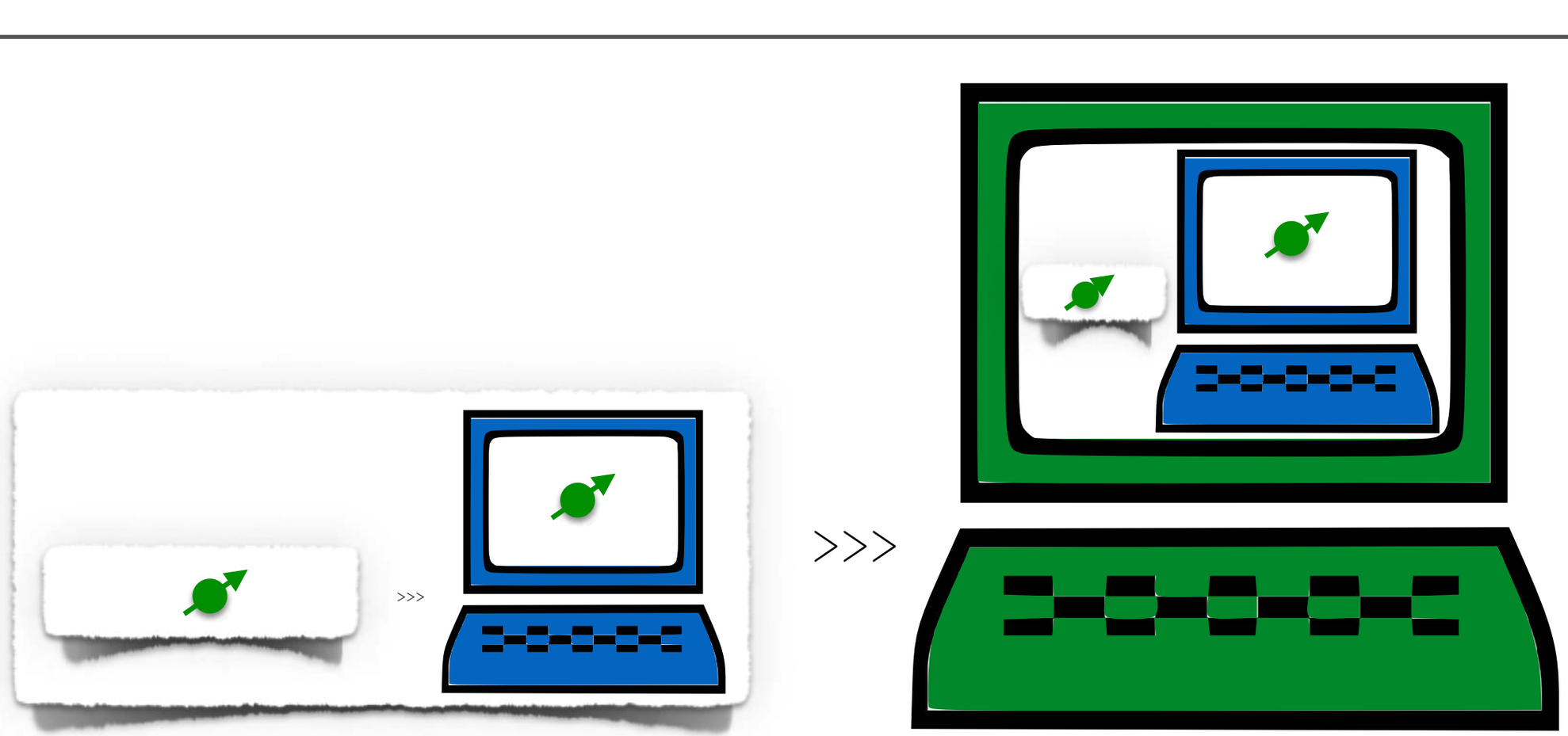


This enables nested use of quantum theory …



This enables nested use of quantum theory …





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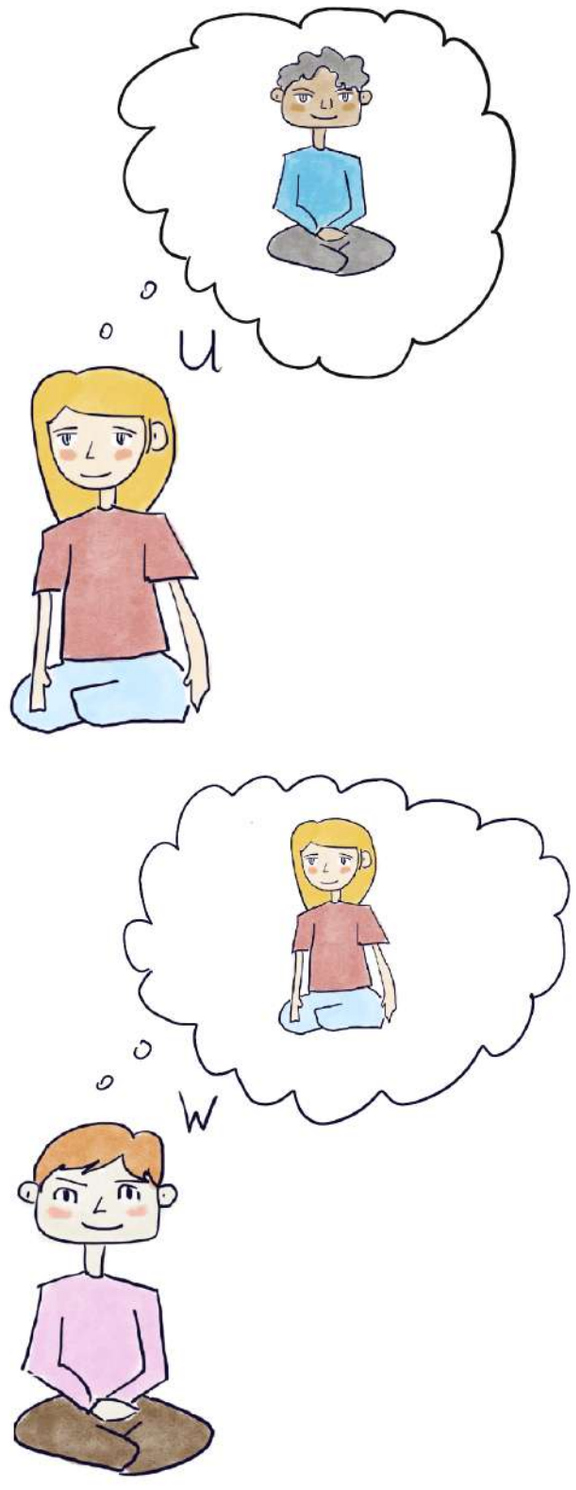
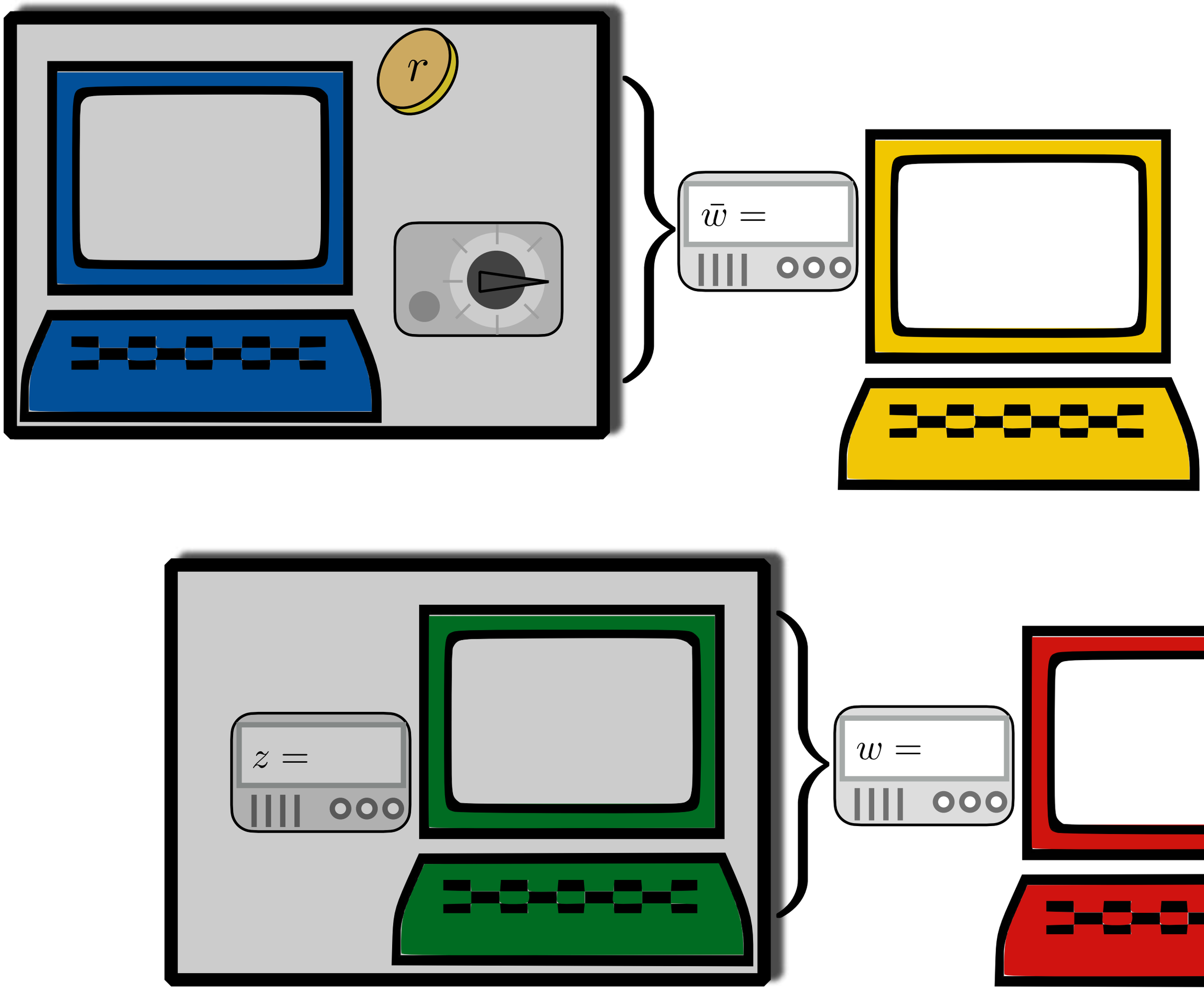
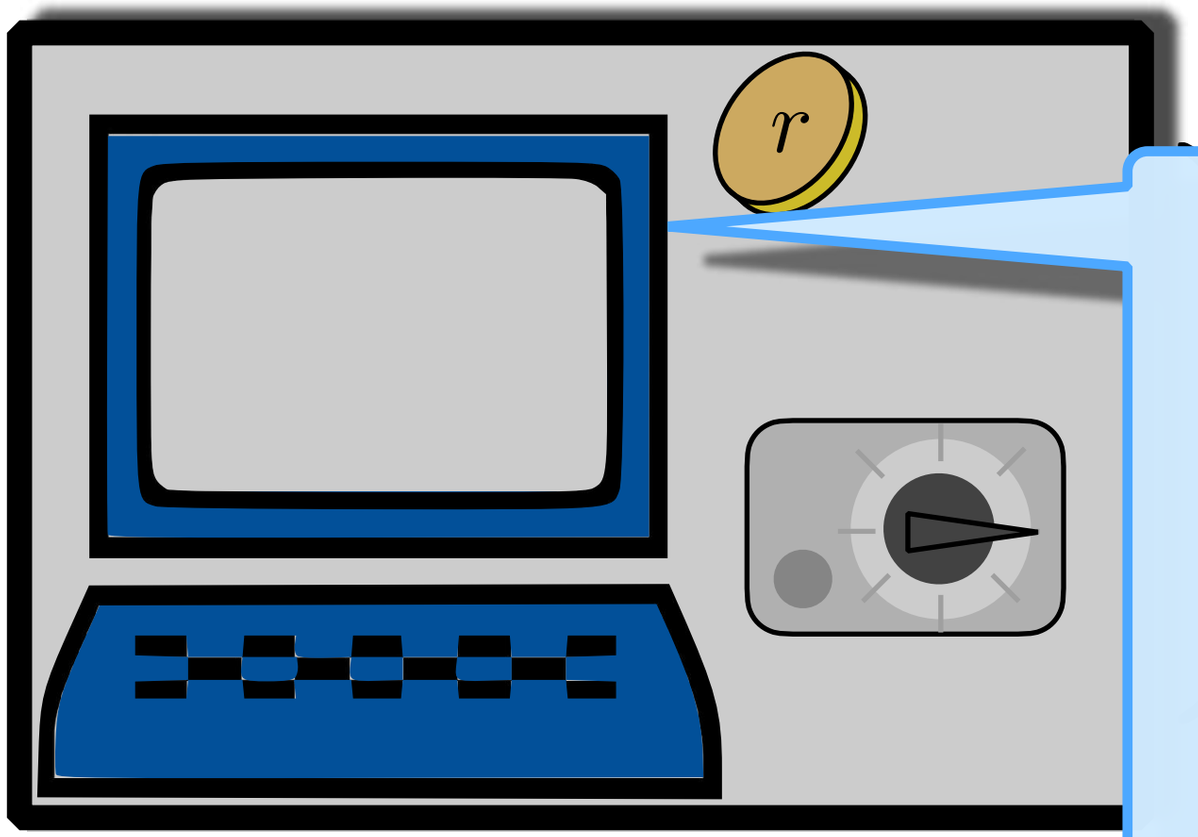
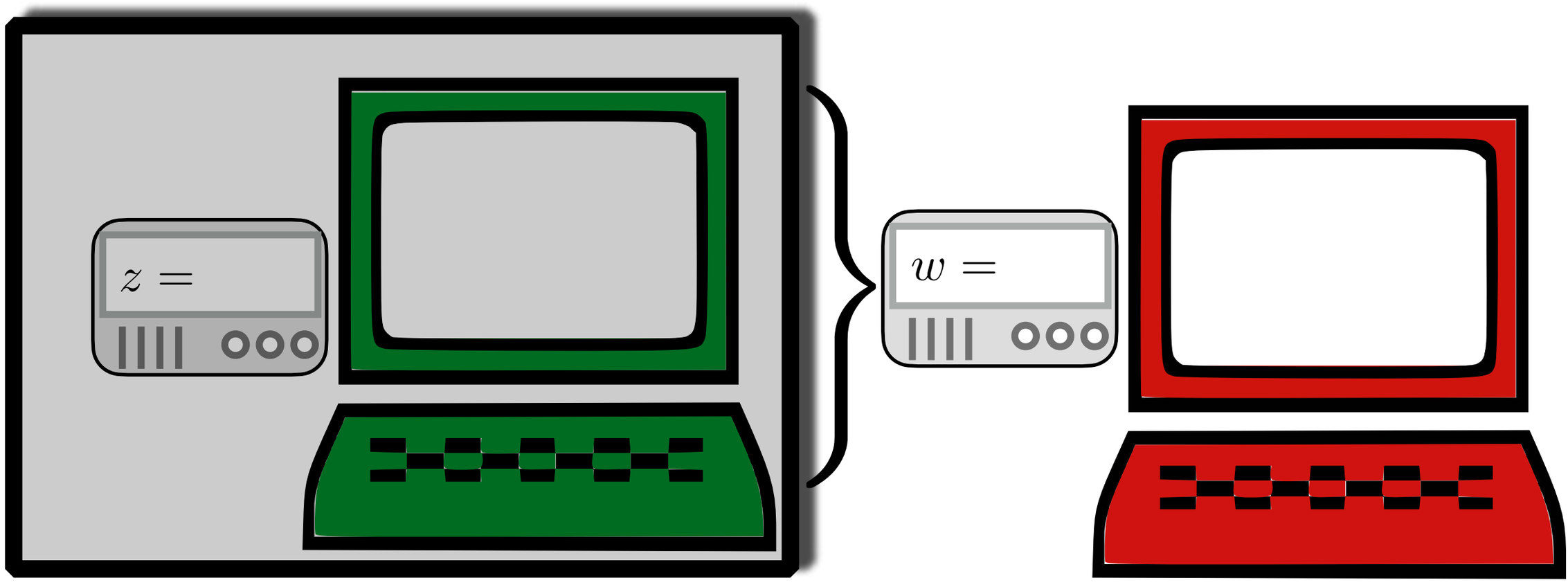


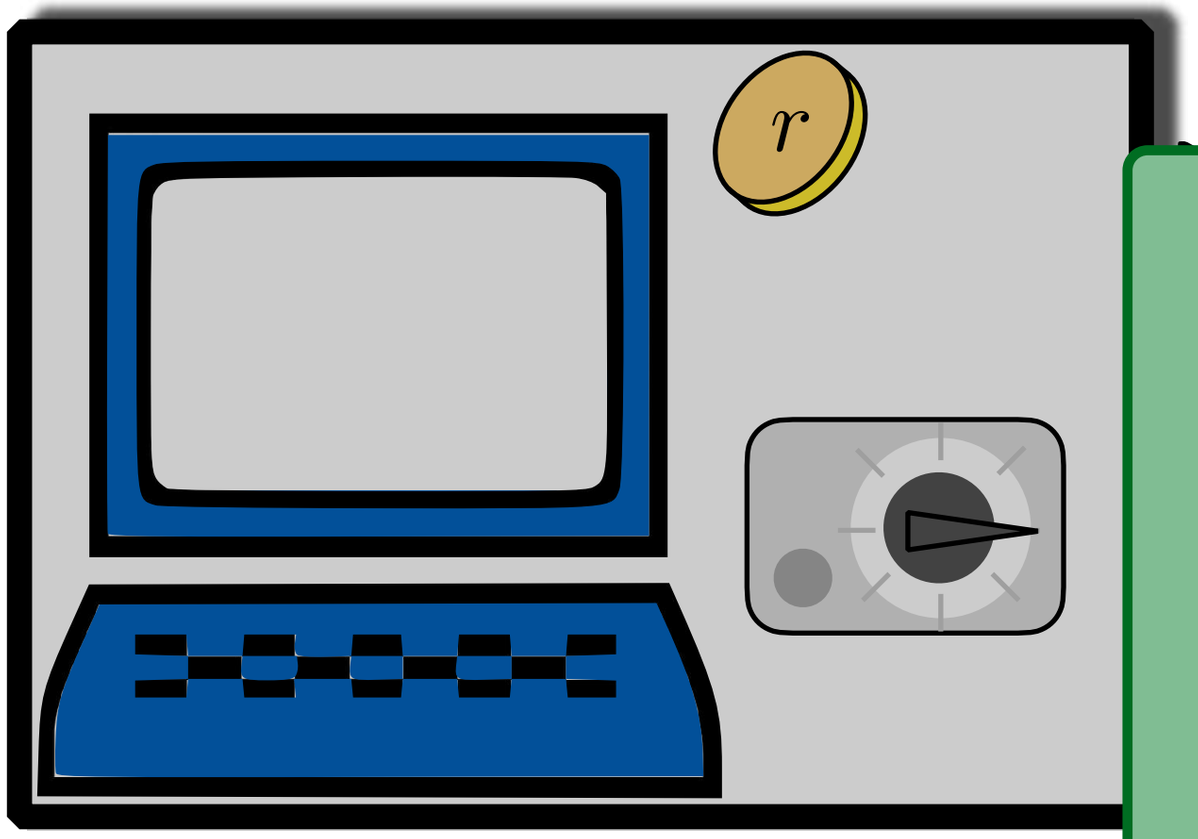

r
$\bar{w} =$
$z =$
$w =$



Protocol:

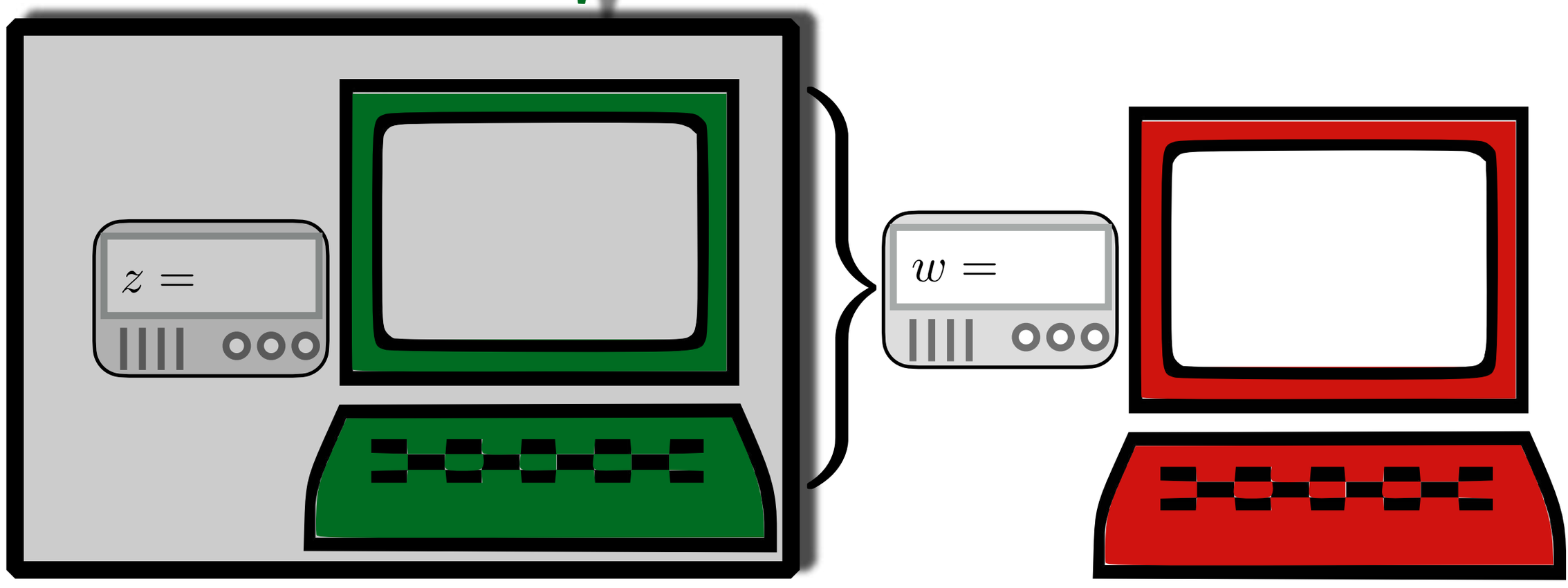
1) Generate a random bit r
2) Prepare spin S
   either spin down if r = heads
   or spin right if r = tails
3) Send S to Green
4) Make a prediction for w measured by Red.

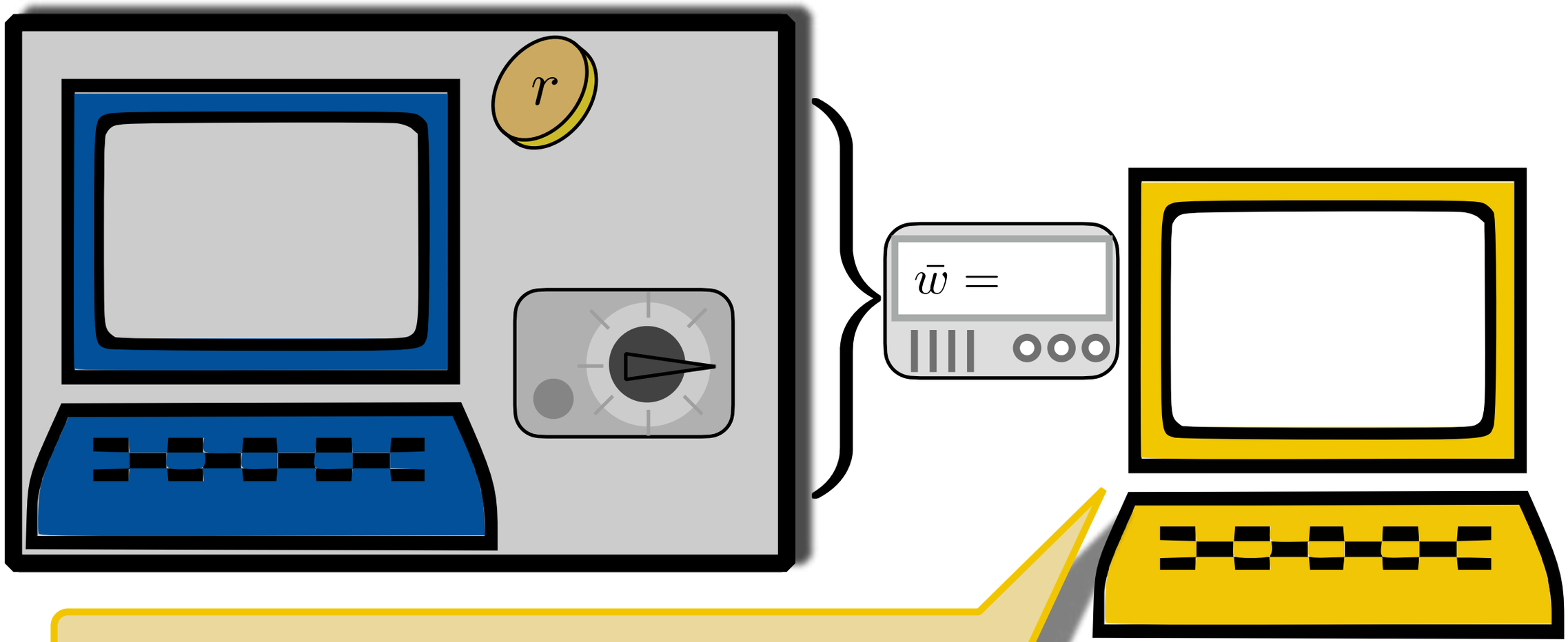




Protocol:

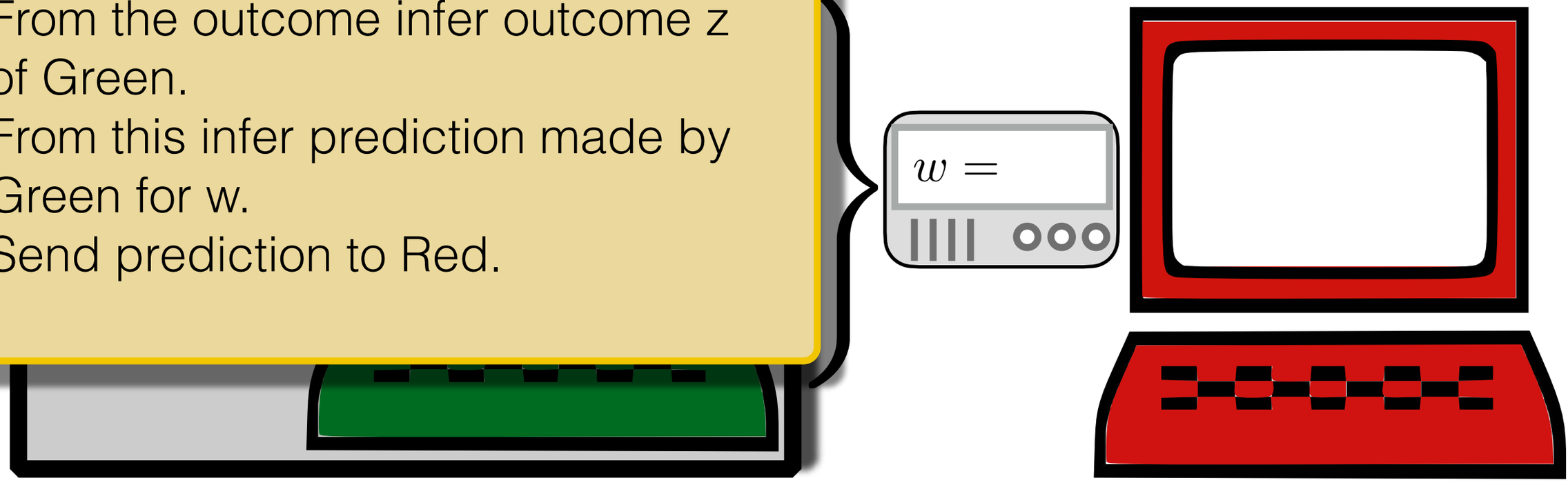
1) Receive S sent by Blue.
2) Measure S w.r.t. up/down basis.
3) From the outcome, infer the value r obtained by Blue.
4) From this infer the prediction made by Blue for w.





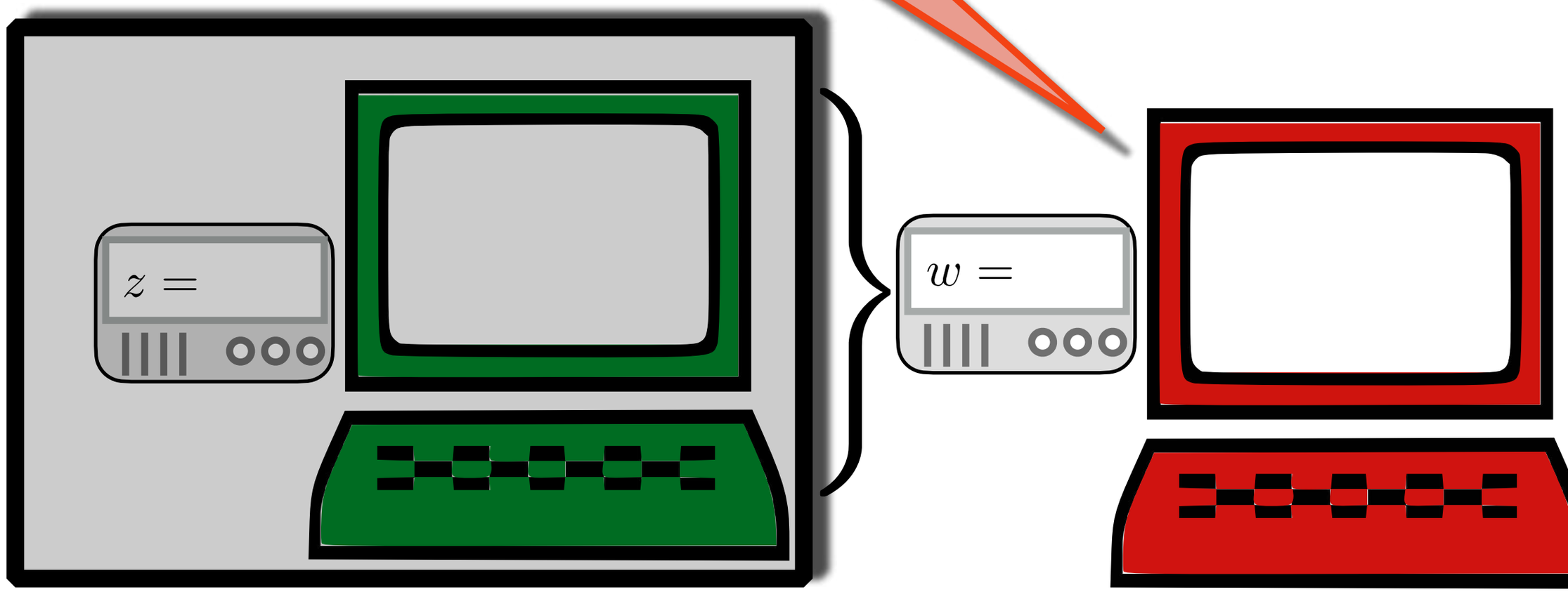
Protocol:

1) Measure Blue in Deutsch basis.
2) From the outcome infer outcome z of Green.
3) From this infer prediction made by Green for w.
4) Send prediction to Red.

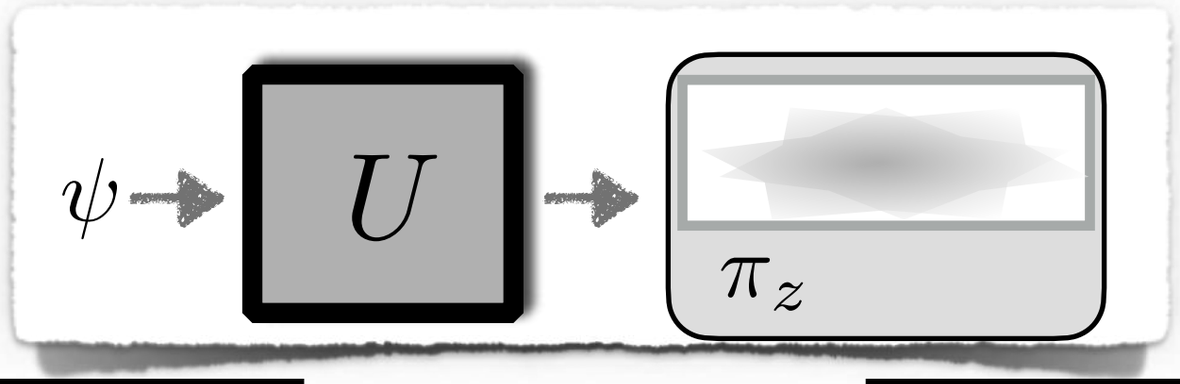


Protocol:

1) Read message sent from Yellow about the prediction for w.
2) Measure the lab of Green in Deutsch basis and compare the outcome w to the prediction.



Rule (Q): Quantum theory applicable to any subsystem



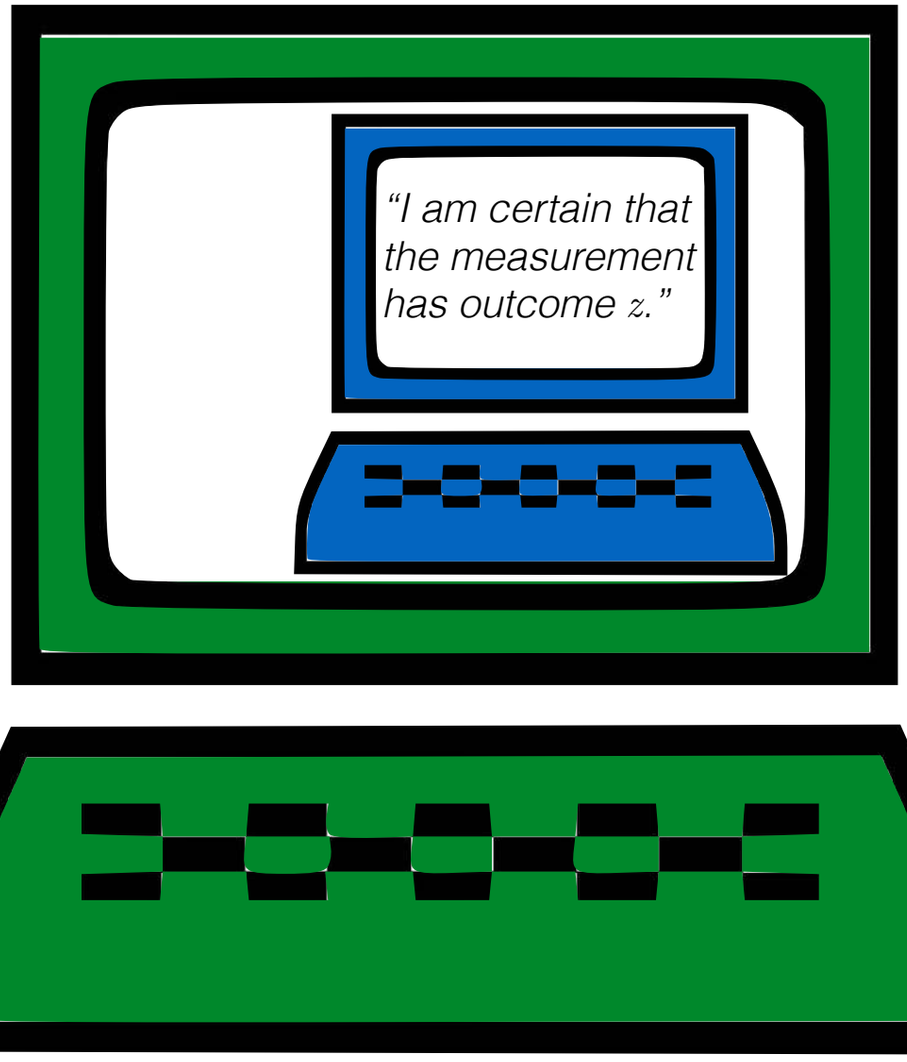
$$\|\pi_z U\psi\| = 1$$

(Q)

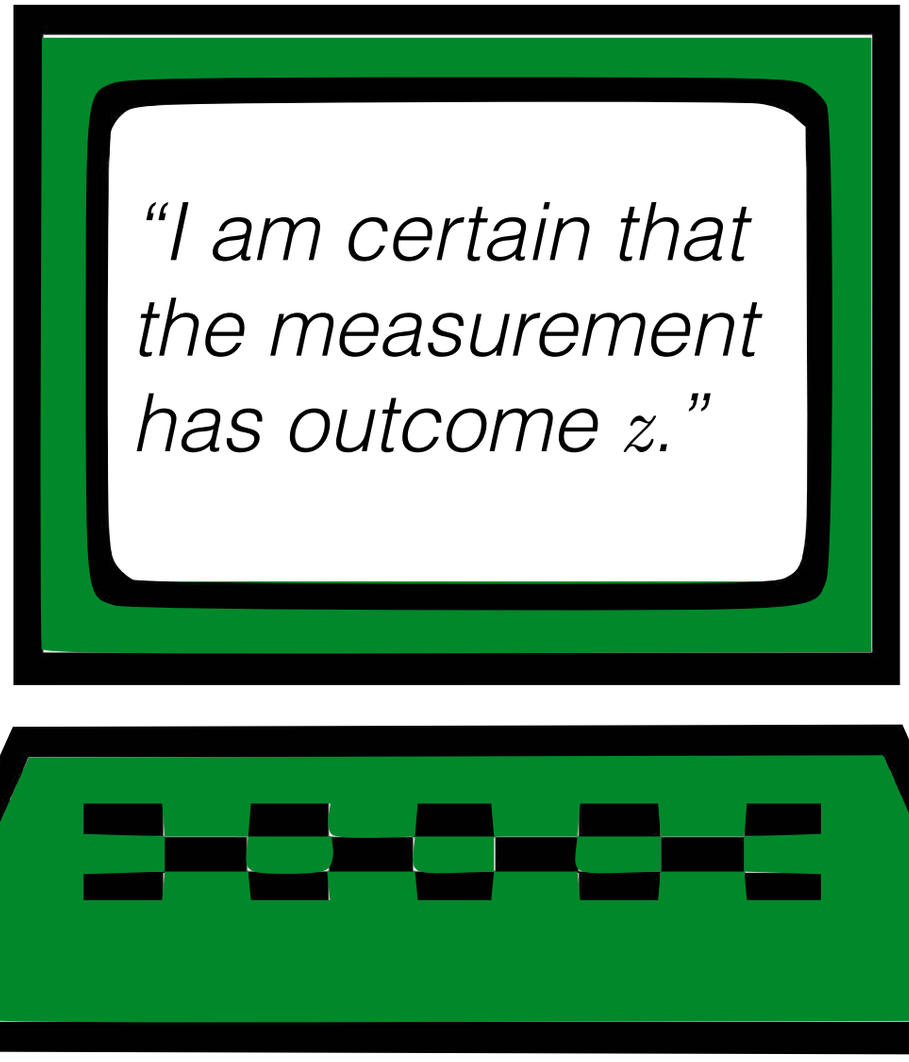
"I am certain that the measurement has outcome z."

Quantum-mechanical Born rule assigns probability 1 to outcome z.

Rule (C): Be consistent with conclusions of others

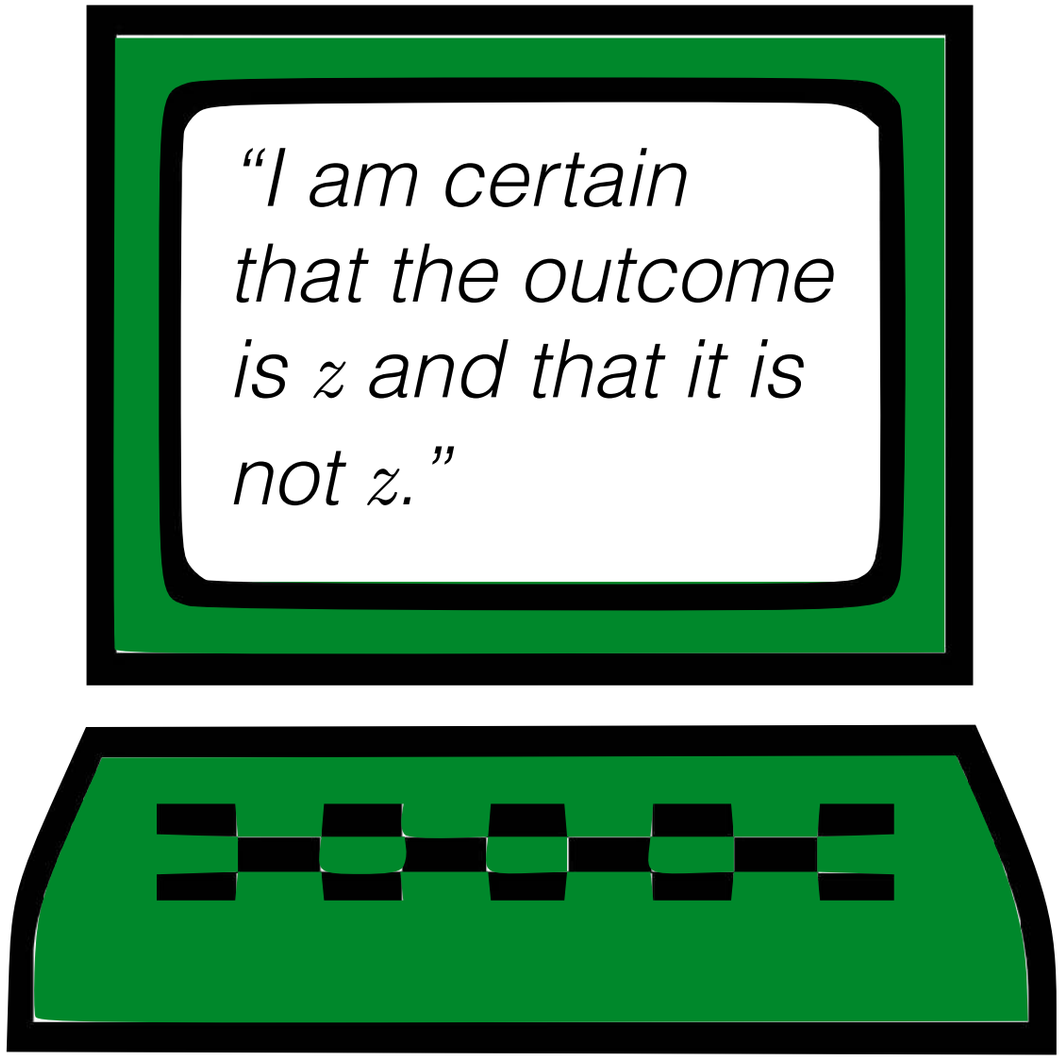


(C)



The green computer is certain that the blue computer is *at this moment* certain that the outcome is z.

Rule (S): Do not claim “alternative facts”



(S)

r

if $r =$ tails

if $r =$ heads

$\bar{w} =$

$z =$

$w =$

r

if $r = \text{tails}$

if $r = \text{heads}$

Spin right: $|\rightarrow\rangle = \dfrac{|\downarrow\rangle + |\uparrow\rangle}{\sqrt{2}}$

Spin down: $|\downarrow\rangle$

$z =$

$w =$

r

if $r =$ tails

if $r =$ heads

$\bar{w} =$

$z =$

$w =$

r

if $r =$ tails

if $r =$ heads

$\bar{w} =$

Value z obtained by measuring spin in vertical direction with possible outcomes

$z = +\frac{1}{2}$ and $z = -\frac{1}{2}$

$z =$

$w =$

$r = \text{tails}$

if $r = \text{tails}$

if $r = \text{heads}$

$\bar{w} =$

$z =$

$w = \text{fail}$

$r = \text{tails}$

if $r = \text{tails}$

if $r = \text{heads}$

irrelevant

U'

$z =$

U

$w = \text{fail}$

$r = \text{tails}$

if $r = \text{tails}$

if $r = \text{heads}$

Measurement designed such that

$$w = \text{fail}$$

whenever spin was prepared as

$$|{\rightarrow}\rangle = \frac{|{\downarrow}\rangle + |{\uparrow}\rangle}{\sqrt{2}}$$

(which is the case whenever $r = \text{tails}$)

$z =$

U

$w = \text{fail}$

$r = \text{tails}$

I am certain that will observe $w = \text{fail}$

if $r = \text{tails}$

if $r = \text{heads}$

Measurement designed such that

$$w = \text{fail}$$

whenever spin was prepared as

$$|{\rightarrow}\rangle = \frac{|{\downarrow}\rangle + |{\uparrow}\rangle}{\sqrt{2}}$$

(which is the case whenever $r = \text{tails}$)

U

$z =$

$w = \text{fail}$

$r = \text{tails}$

I am certain that [computer] will observe $w = \text{fail}$

if $r = \text{tails}$

if $r = \text{heads}$

$\bar{w} =$

$z = +\frac{1}{2}$

$w =$

$r = \text{tails}$

I am certain that will observe $w = \text{fail}$

if $r = \text{tails}$

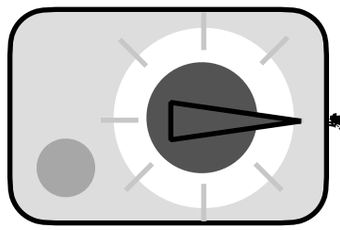
if $r = \text{heads}$

$z = +\frac{1}{2}$

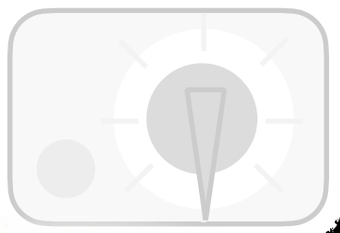
$r = \text{tails}$

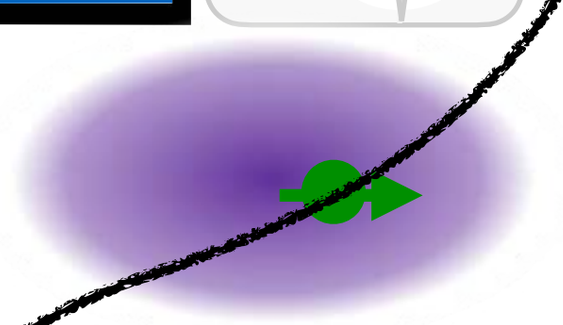
I am certain that 💻 will observe $w = \text{fail}$

if $r = \text{tails}$

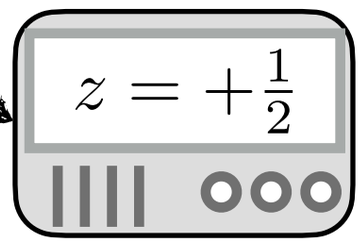


if $r = \text{heads}$

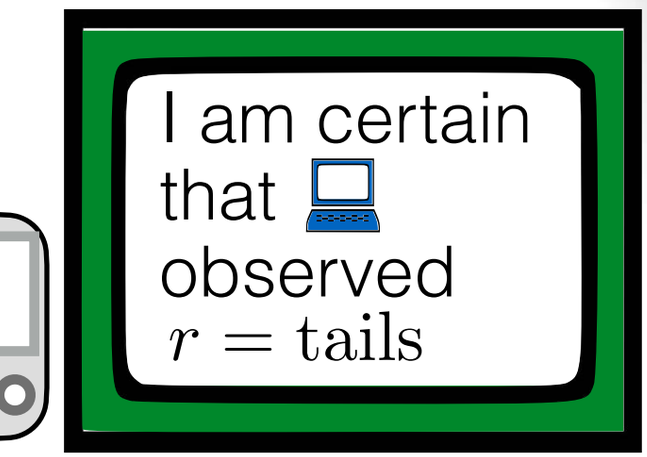




$z = +\frac{1}{2}$



I am certain that 💻 observed $r = \text{tails}$



I am certain that will observe $w = \text{fail}$

r

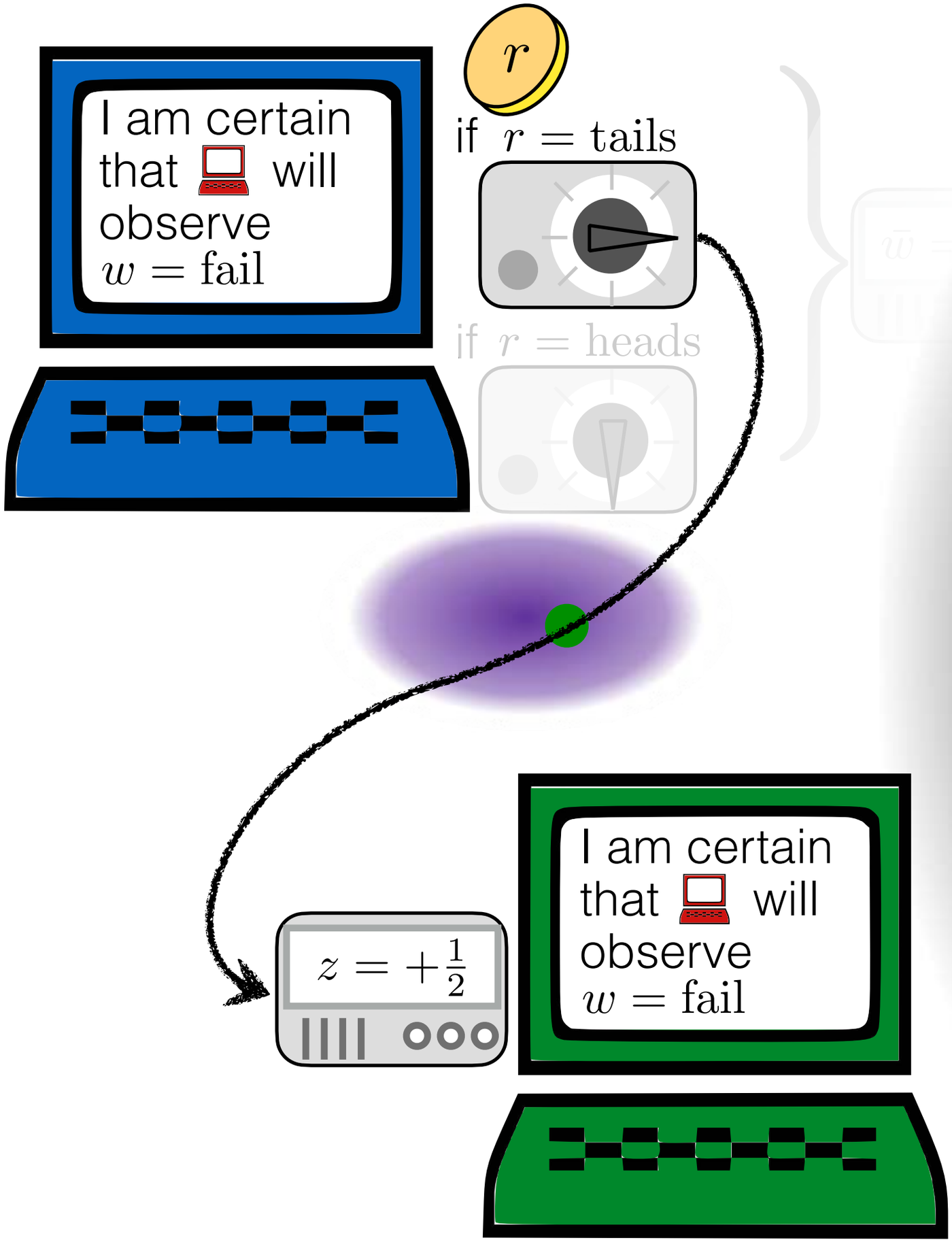
if $r = \text{tails}$

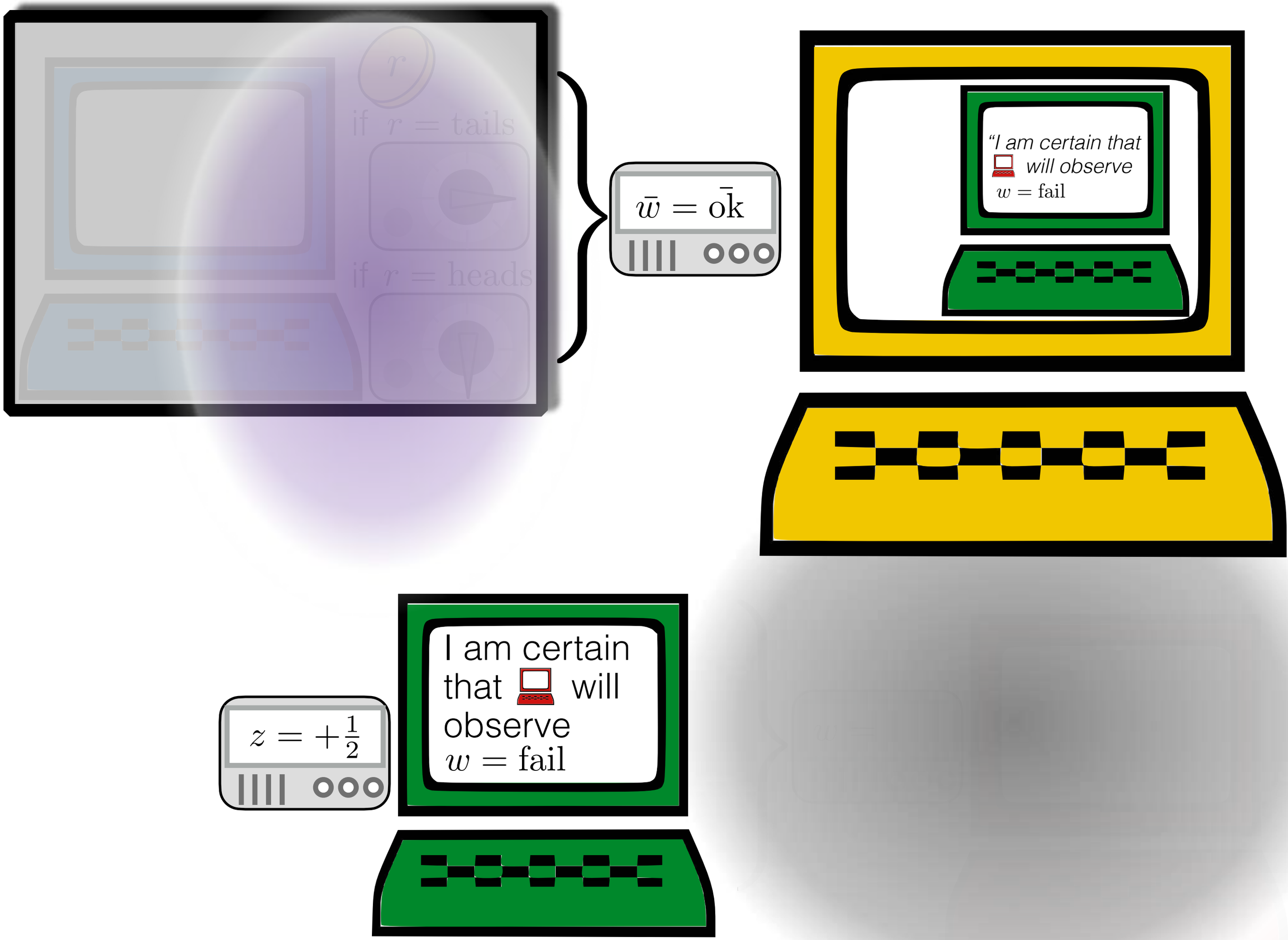
if $r = \text{heads}$

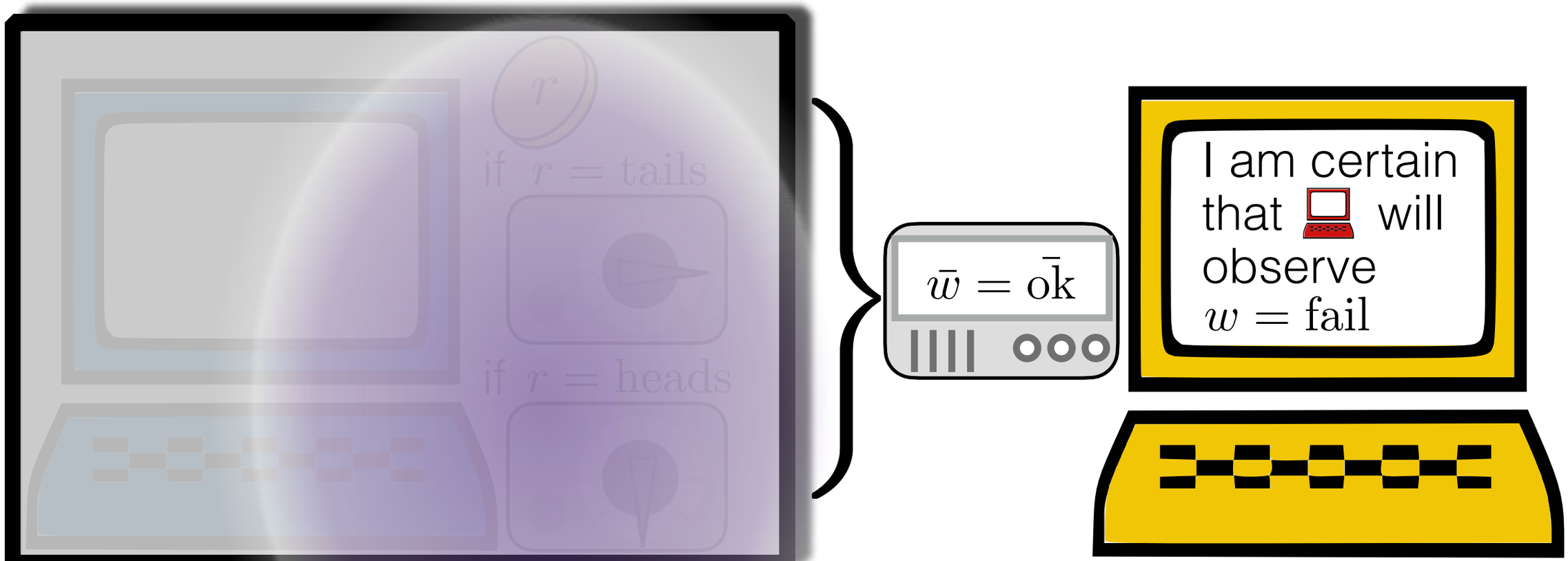
$\bar{w} =$

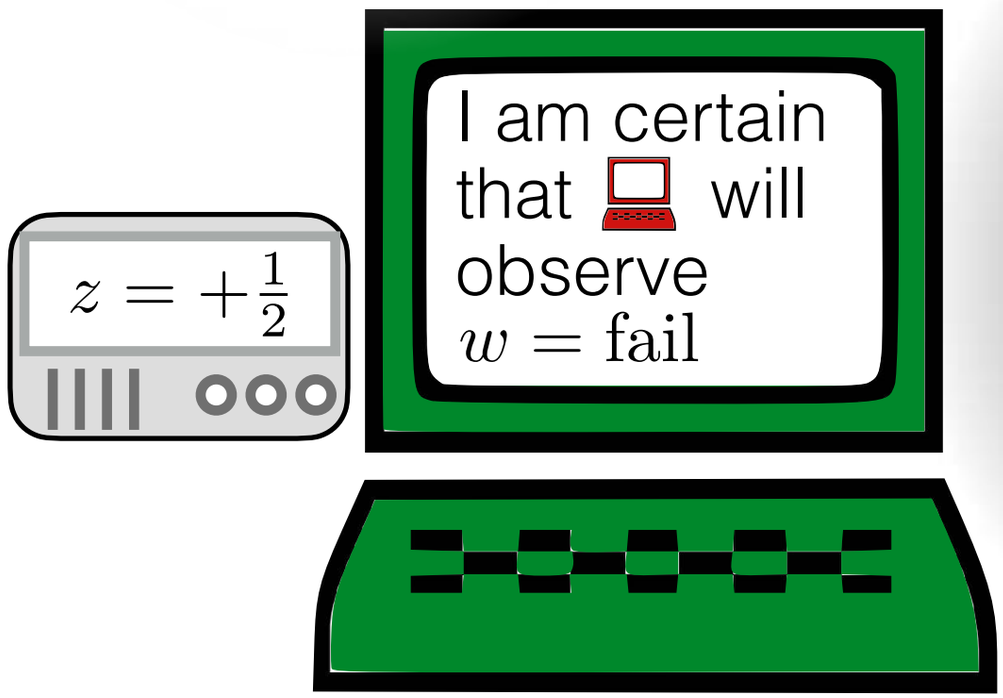
$z = +\frac{1}{2}$

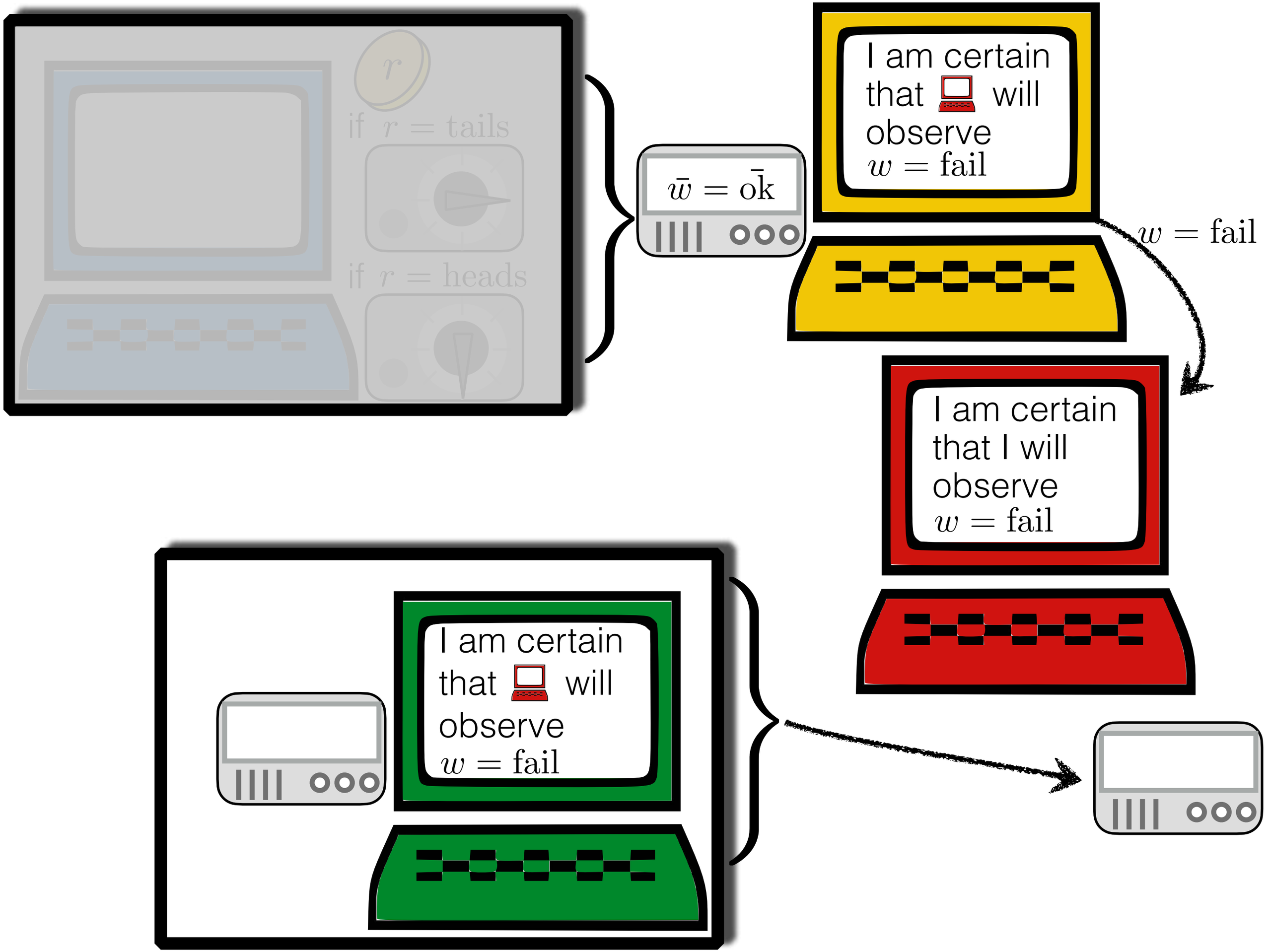
"I am certain that will observe $w = \text{fail}$


I am certain that will observe $w = \text{fail}$
r
if $r = \text{tails}$
if $r = \text{heads}$
$z = +\frac{1}{2}$
I am certain that will observe $w = \text{fail}$


r
if $r = \text{tails}$
if $r = \text{heads}$
$\bar{w} = \bar{\text{ok}}$
"I am certain that will observe $w = \text{fail}$
$z = +\frac{1}{2}$
I am certain that will observe $w = \text{fail}$


if $r = \text{tails}$
if $r = \text{heads}$
$\bar{w} = \bar{\text{ok}}$
I am certain that will observe $w = \text{fail}$


$z = +\frac{1}{2}$
I am certain that will observe $w = \text{fail}$


r
if $r = \text{tails}$
if $r = \text{heads}$
$\bar{w} = \bar{\text{ok}}$
I am certain that will observe $w = \text{fail}$
$w = \text{fail}$
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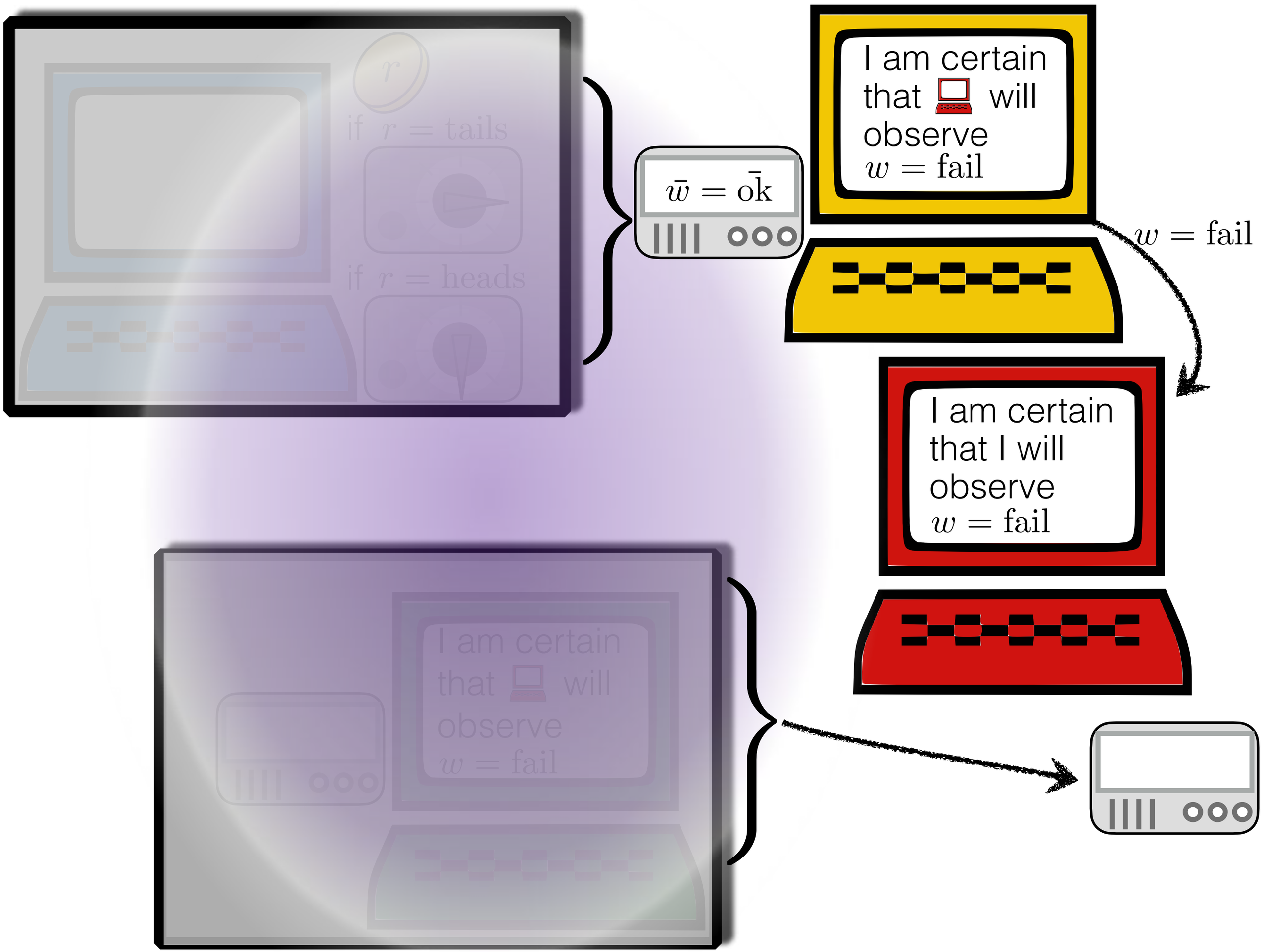
r
if $r = \text{tails}$
if $r = \text{heads}$
$\bar{w} = \bar{\text{ok}}$
I am certain that will observe $w = \text{fail}$
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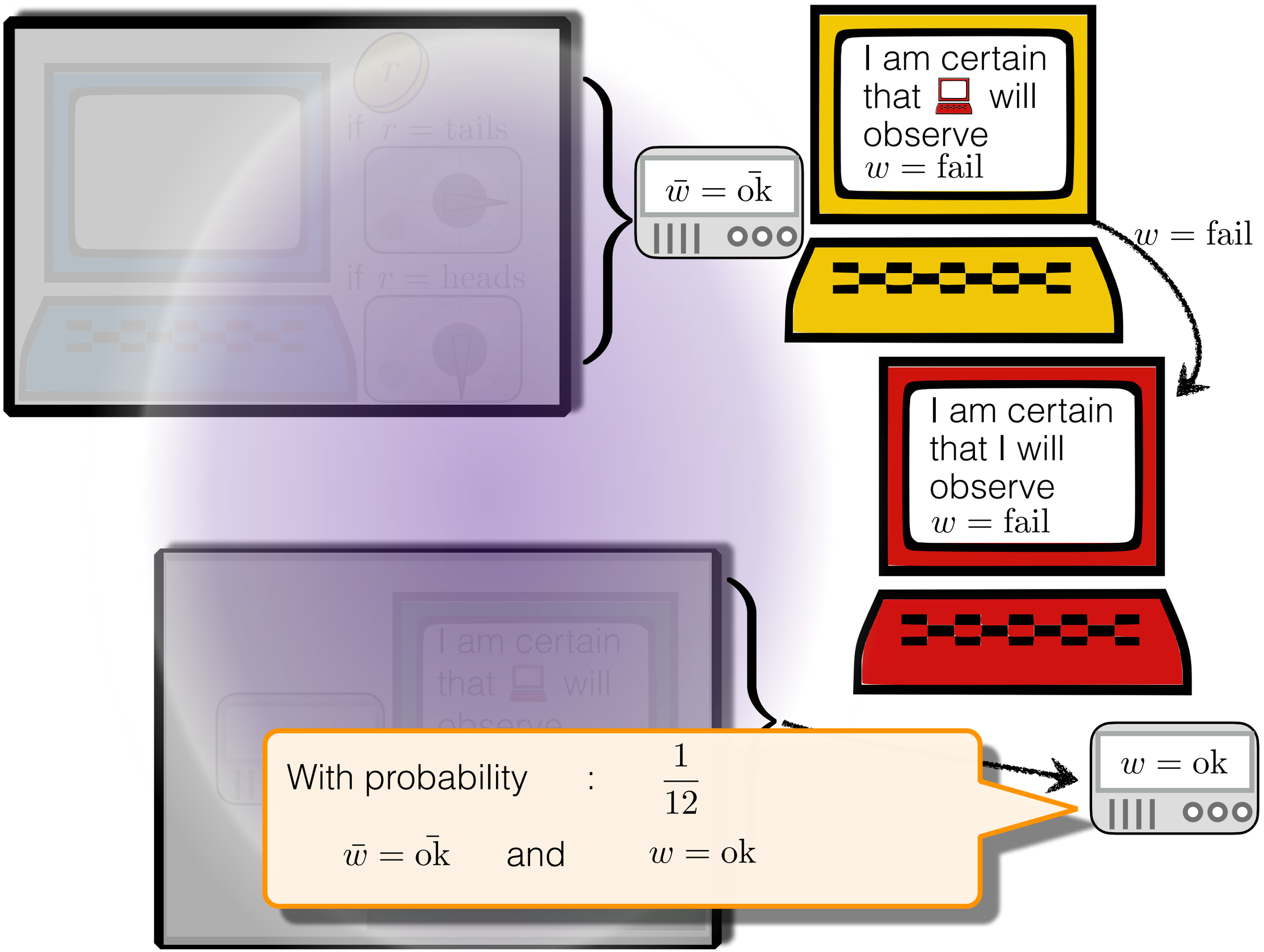
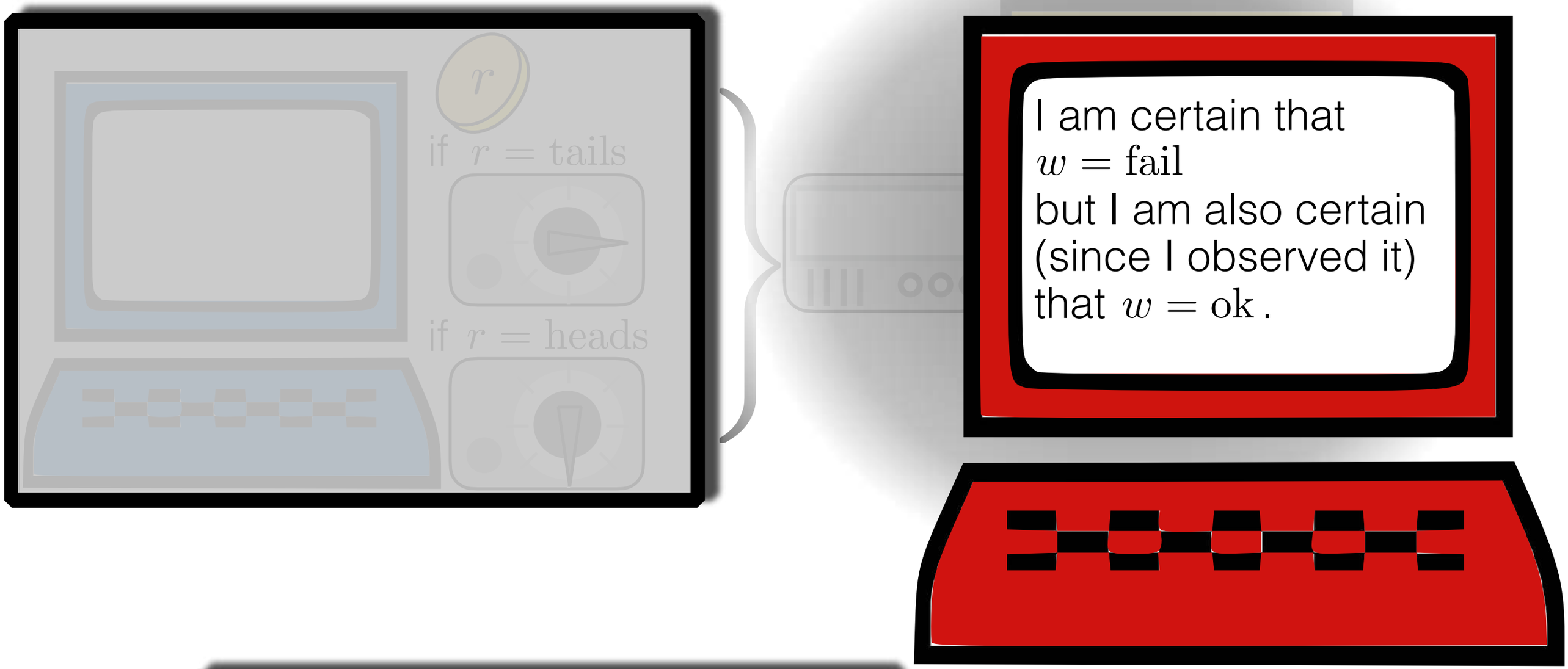
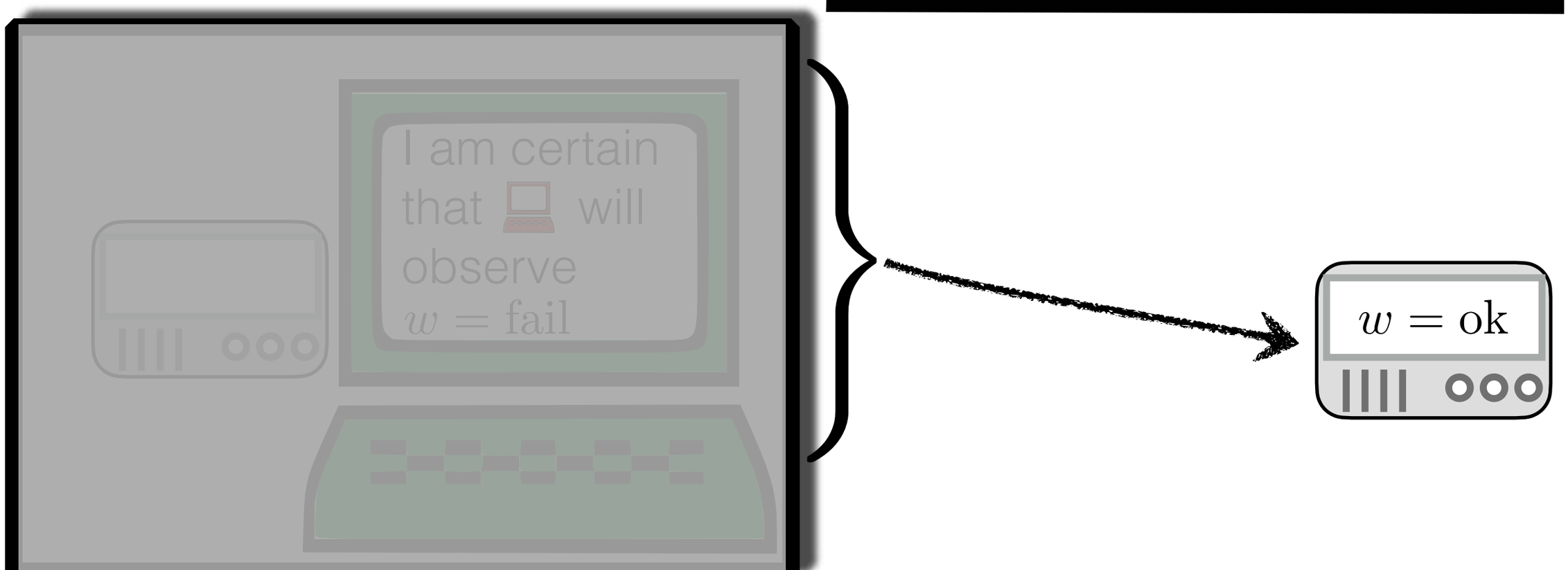
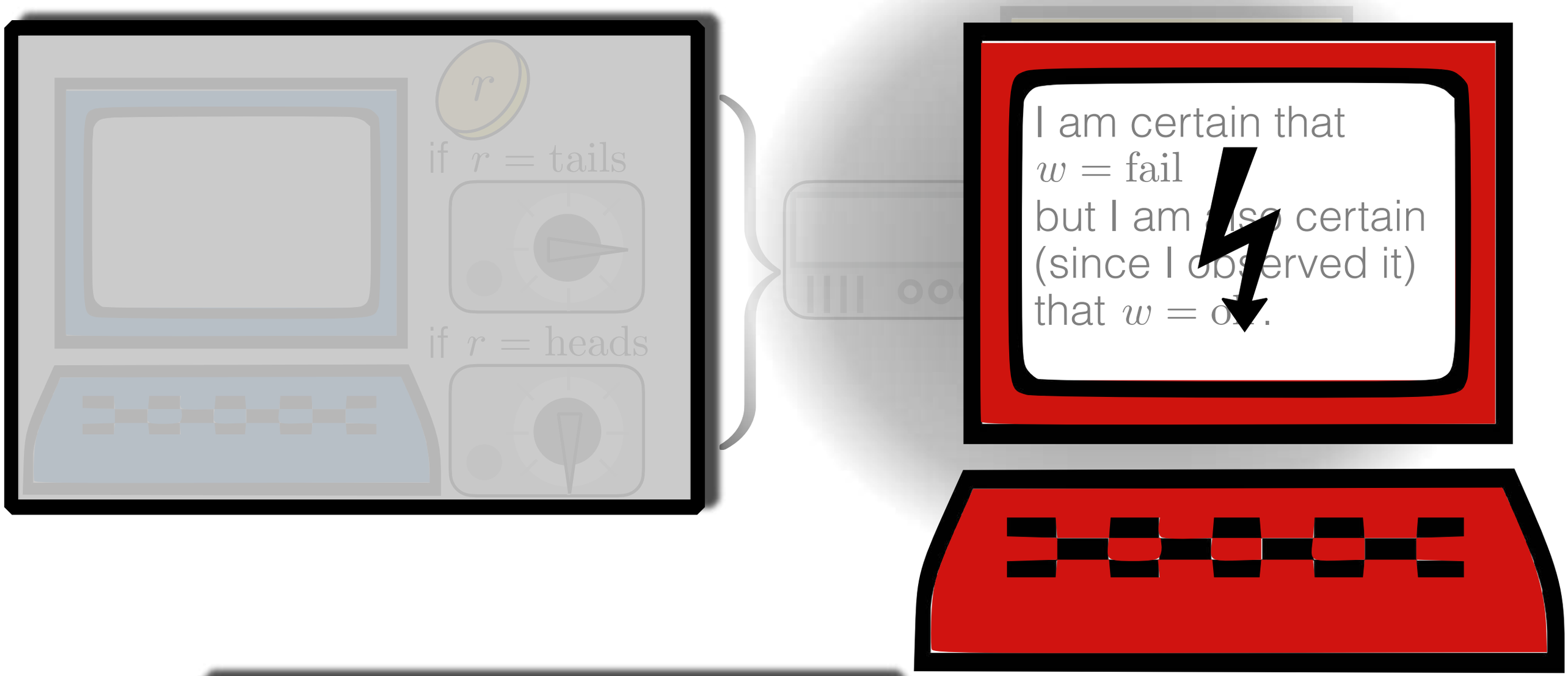

r
if $r = \text{tails}$
if $r = \text{heads}$
$\bar{w} = \bar{\text{ok}}$
I am certain that will observe $w = \text{fail}$
$w = \text{fail}$
I am certain that I will observe $w = \text{fail}$
With probability : $\frac{1}{12}$
$\bar{w} = \bar{\text{ok}}$ and $w = \text{ok}$
$w = \text{ok}$


r
if $r = \text{tails}$
if $r = \text{heads}$
I am certain that $w = \text{fail}$ but I am also certain (since I observed it) that $w = \text{ok}$.


I am certain that will observe $w = \text{fail}$
$w = \text{ok}$


r
if $r = \text{tails}$
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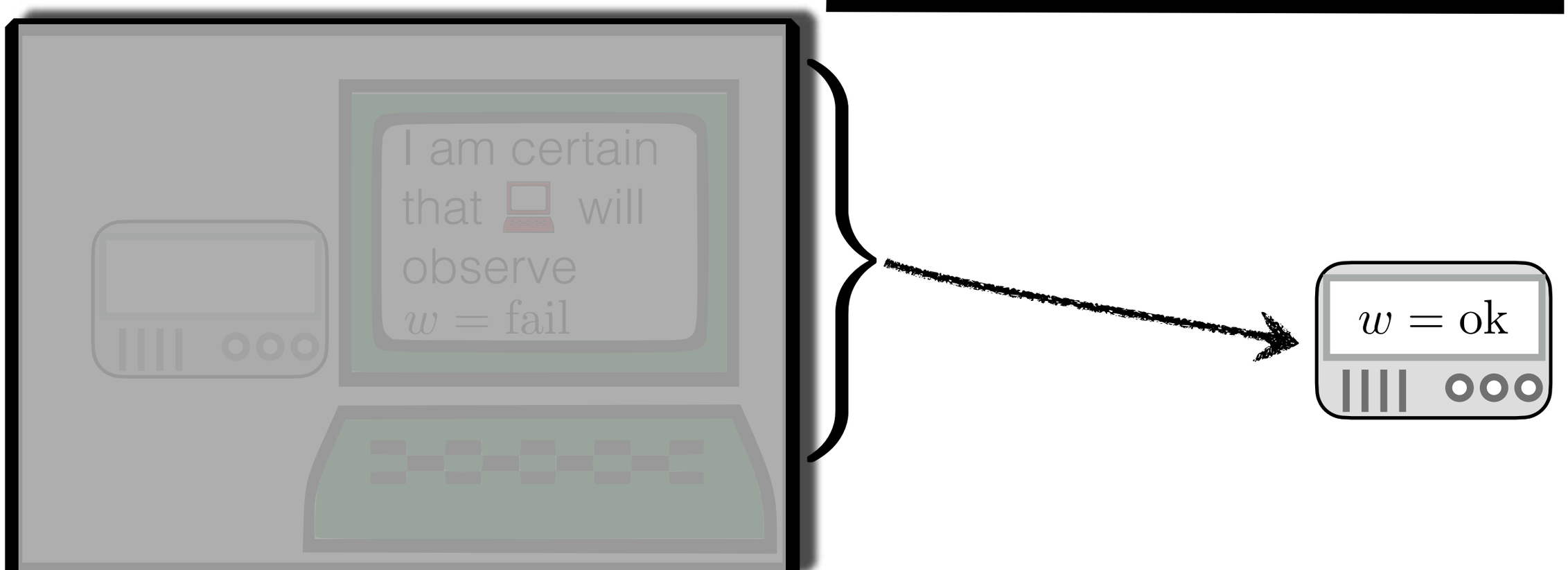

I am certain that will observe $w = \text{fail}$
$w = \text{ok}$

Programmed rules

Rule (Q): Unitary evolution and Born rule (without an extra collapse mechanism)

Rule (C): Be consistent with conclusions of others (programmed with the same rules)

Rule (S): Do not claim "alternative facts"

Programmed rules

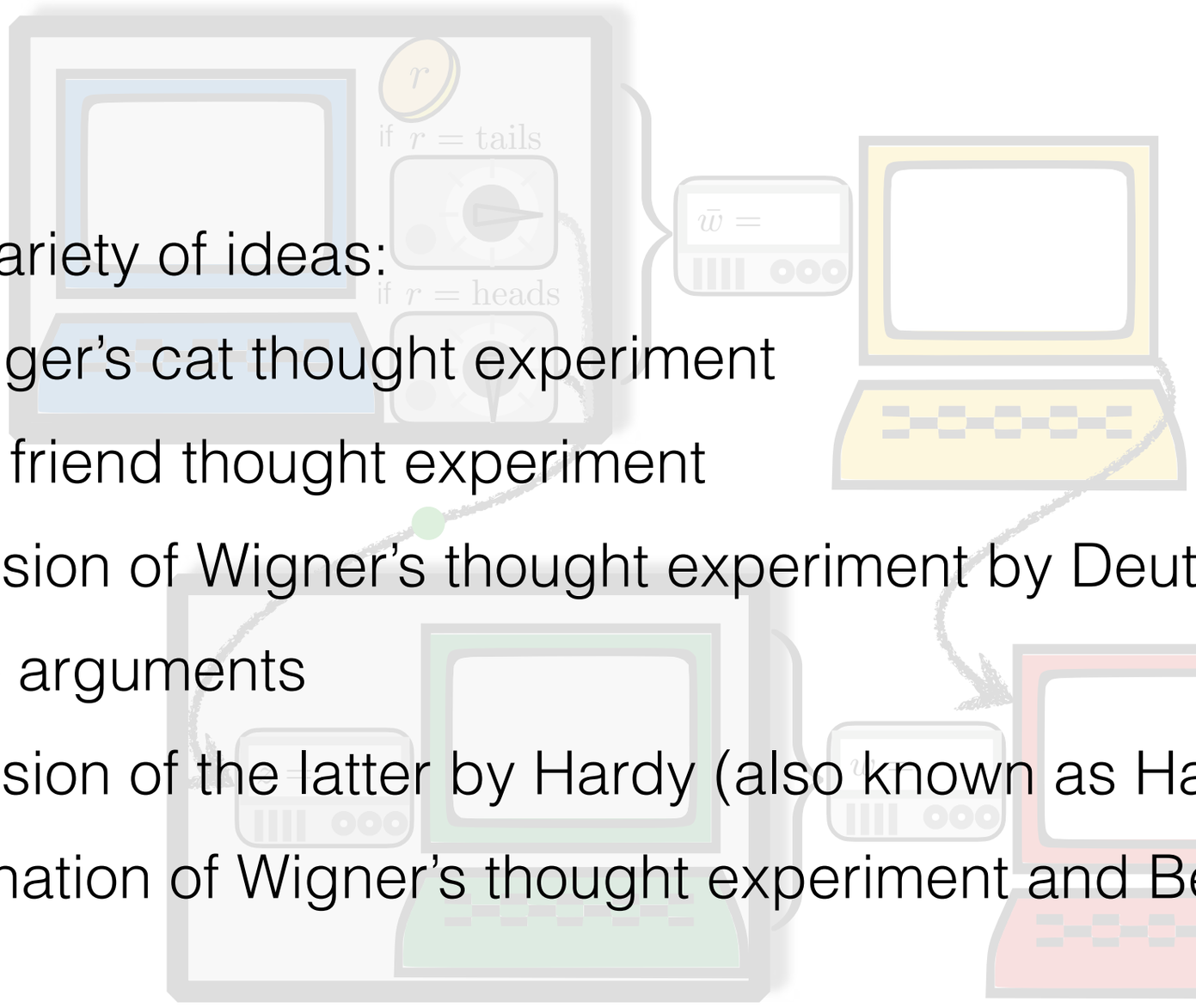
Rule (Q): Unitary evolution and Born rule (without an extra collapse mechanism)

Rule (C): Be consistent with conclusions of others (programmed with the same rules)

Rule (S): Do not claim "alternative facts"

Conclusion: Following these rules leads to a contradiction!

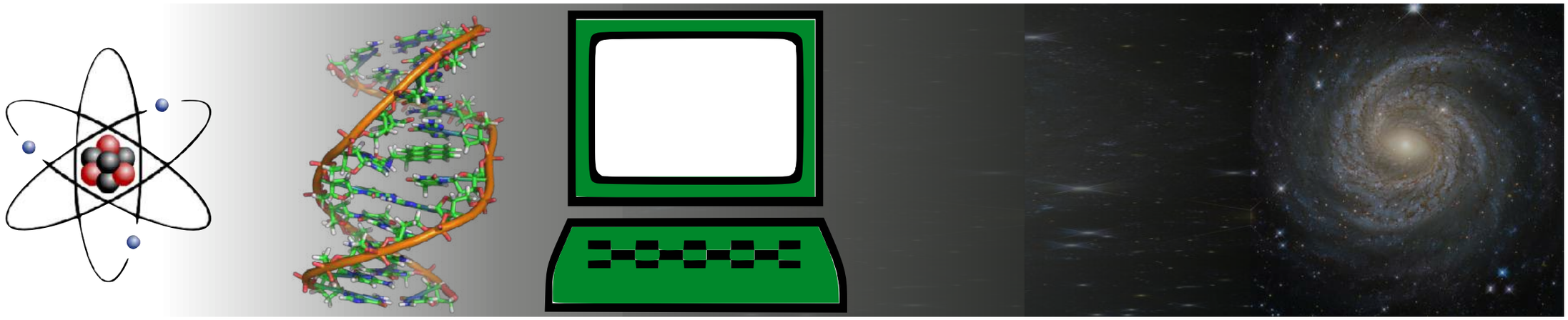
On the shoulders of giants



Based on a variety of ideas:

- Schrödinger's cat thought experiment
- Wigner's friend thought experiment
- An extension of Wigner's thought experiment by Deutsch
- Bell-type arguments
- An extension of the latter by Hardy (also known as Hardy's paradox)
- A combination of Wigner's thought experiment and Bell tests by Brukner

Conclusion



tested to high precision

tested to low accuracy

!

based on work with D. Frauchiger and N. Nurgalieva

Daniela Frauchiger

Nuriya Nurgalieva

Thank you for your attention

A description of the thought experiment can be found in

D. Frauchiger and RR,
"Quantum theory cannot consistently describe the use of itself"
Nat. Comm. **9**, 3711 (2018)

N Nurgalieva and RR,
"Testing quantum theory with thought experiments"
Contemporary Physics **61**, 193-216 (2021)

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