Quantum Information and the Foundations of Quantum Physics

Renato Renner
ETH Zurich

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

tested to high precision

tested to low accuracy

?

Black Holes and the Information Paradox

What happens to the information in matter destroyed by a black hole? Searching for that answer, physicists are groping toward a quantum theory of gravity

by Leonard Susskind

Somewhere in outer space, Professor Windbag's time capsule has been sabotaged by his arch rival, Professor Goulash. The capsule contains the only copy of a vital mathematical formula, to be used by future generations. But Goulash's diabolical scheme to plant a hydrogen bomb on board the capsule has succeeded. Bang! The formula is vaporized into a cloud of electrons, nucleons, photons and an occasional neutrino. Windbag is distraught. He has no record of the formula and cannot remember its derivation.

Later in court, Windbag shouts that he will be reassembled. That proves, beyond a shadow of a doubt, that I could never have destroyed your precious information." Goulash wins the case.

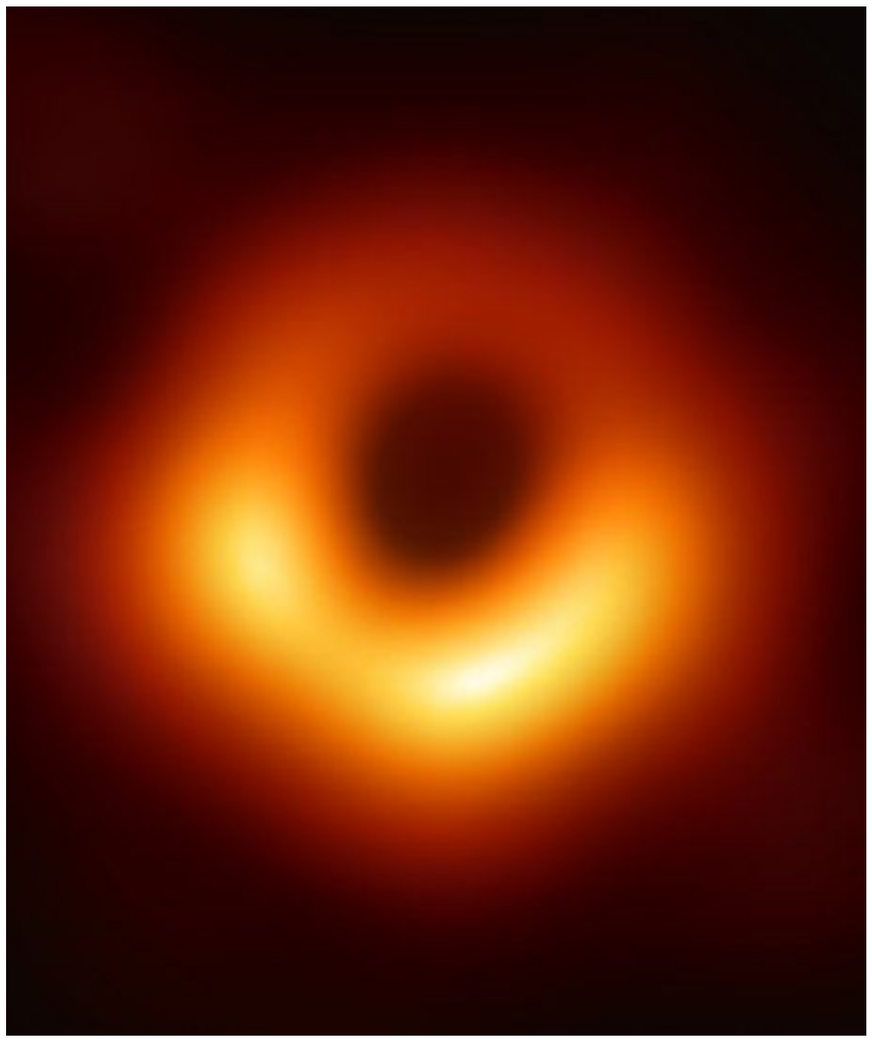
Windbag's revenge is equally diabolical. While Goulash is out of town, his computer is burglarized, along with all his files, including his culinary recipes. Just to make sure that Goulash will never again enjoy his famous Matelote d'anguilles with truffles, Windbag launches the computer into outer space and straight into a nearby black hole.

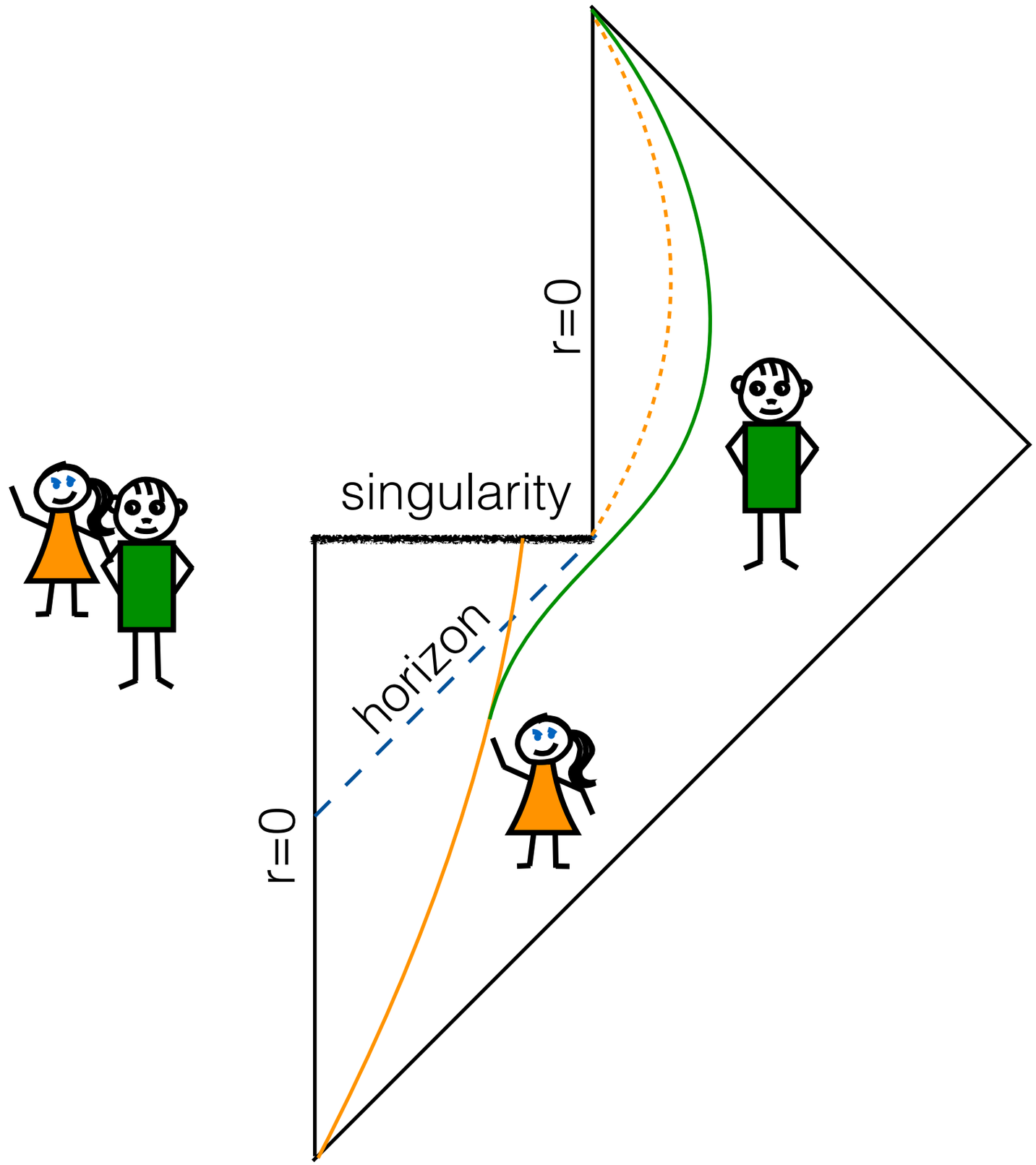
At Windbag's trial, Goulash is beside himself. "You've got to fix this up. Everyone knows that black holes eventually evaporate. Wait long enough, and the black hole will radiate away all its mass and turn into outgoing photons and other particles. True, it may take 10^{70} years, but it's the principle that counts. It's really no different from the bomb. All Goulash has to do is reverse the paths of the debris, and his computer will come flying back out of the black hole."

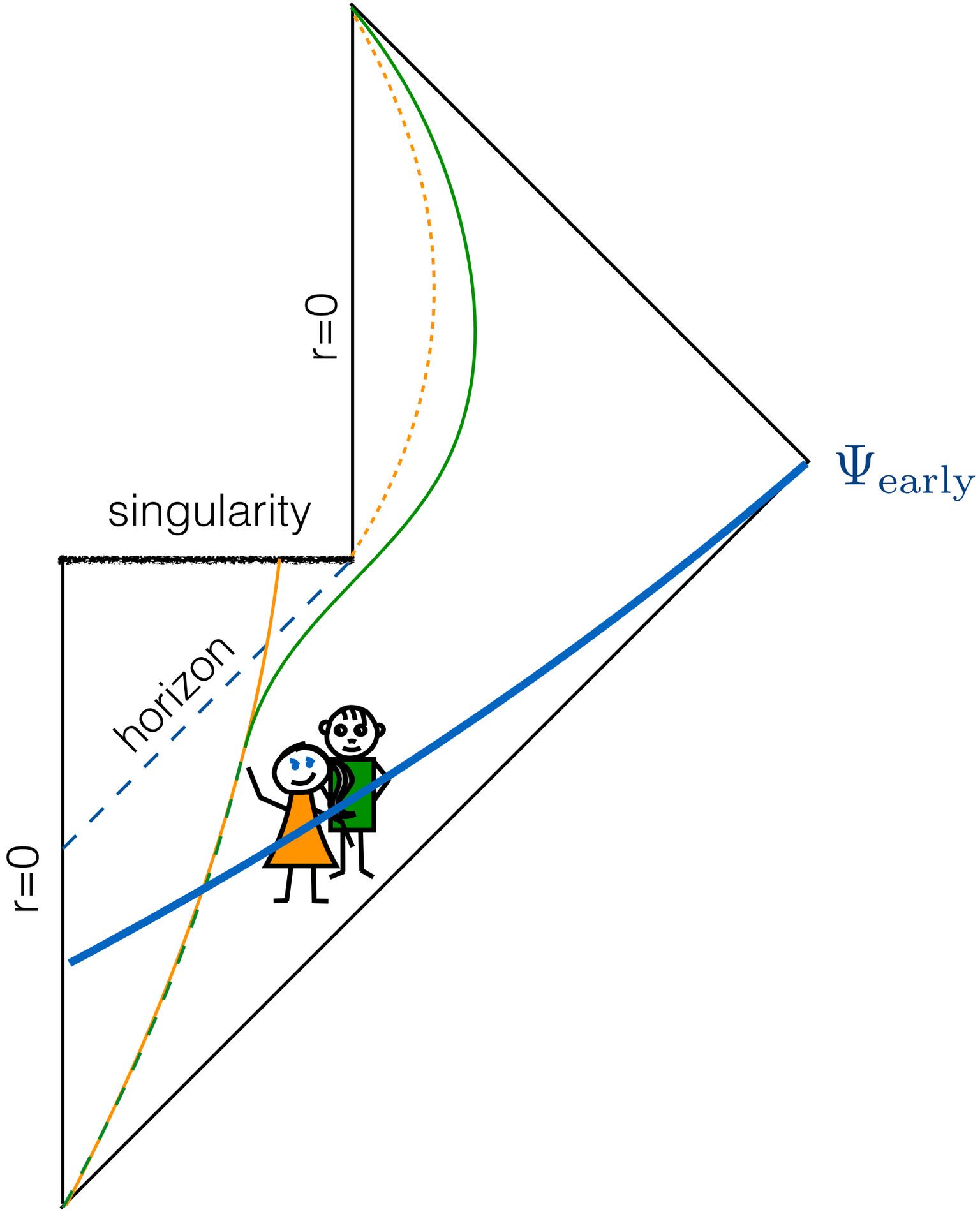
"Not so!" cries Goulash.

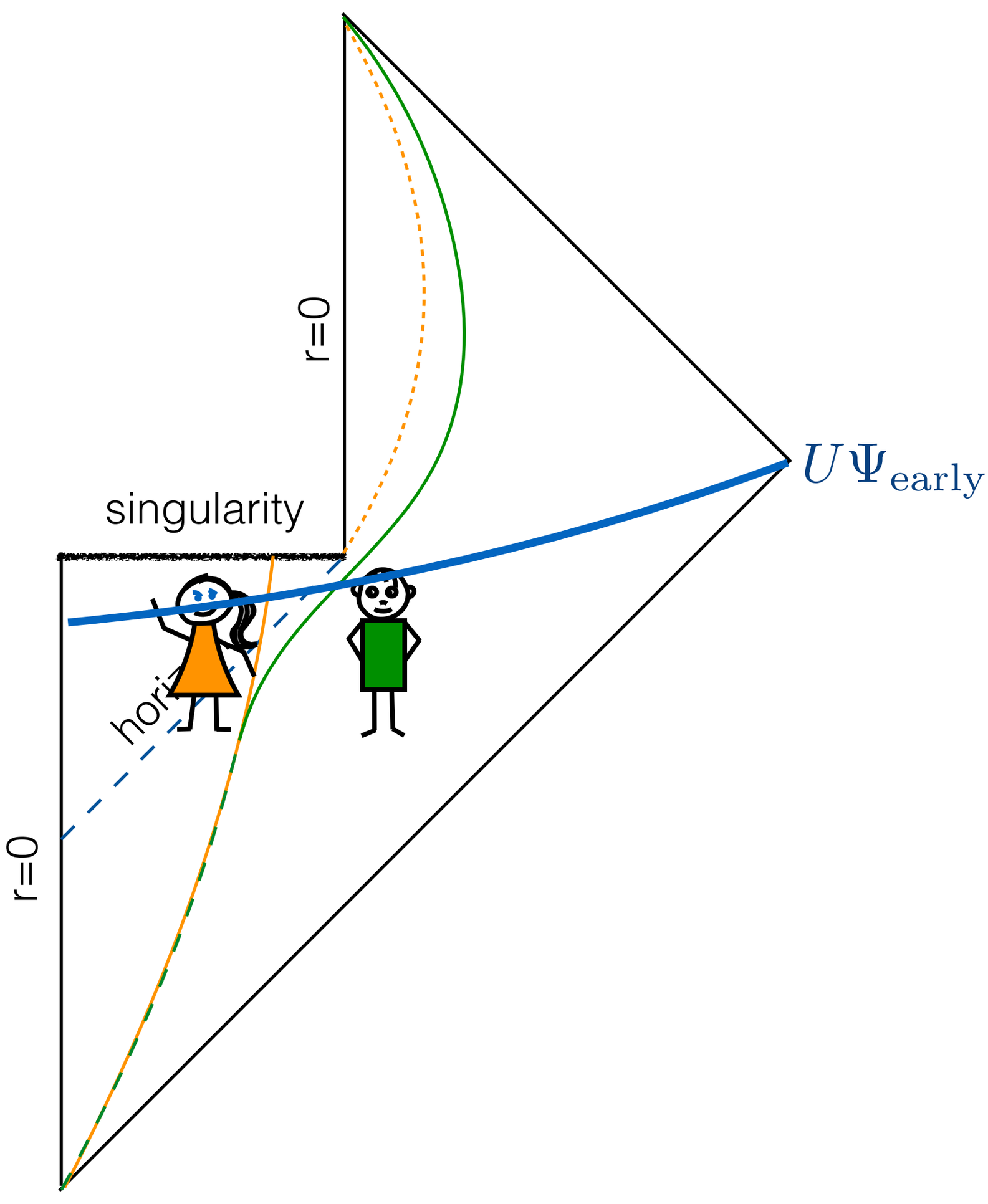
from *Scientific American* **276** (1997)

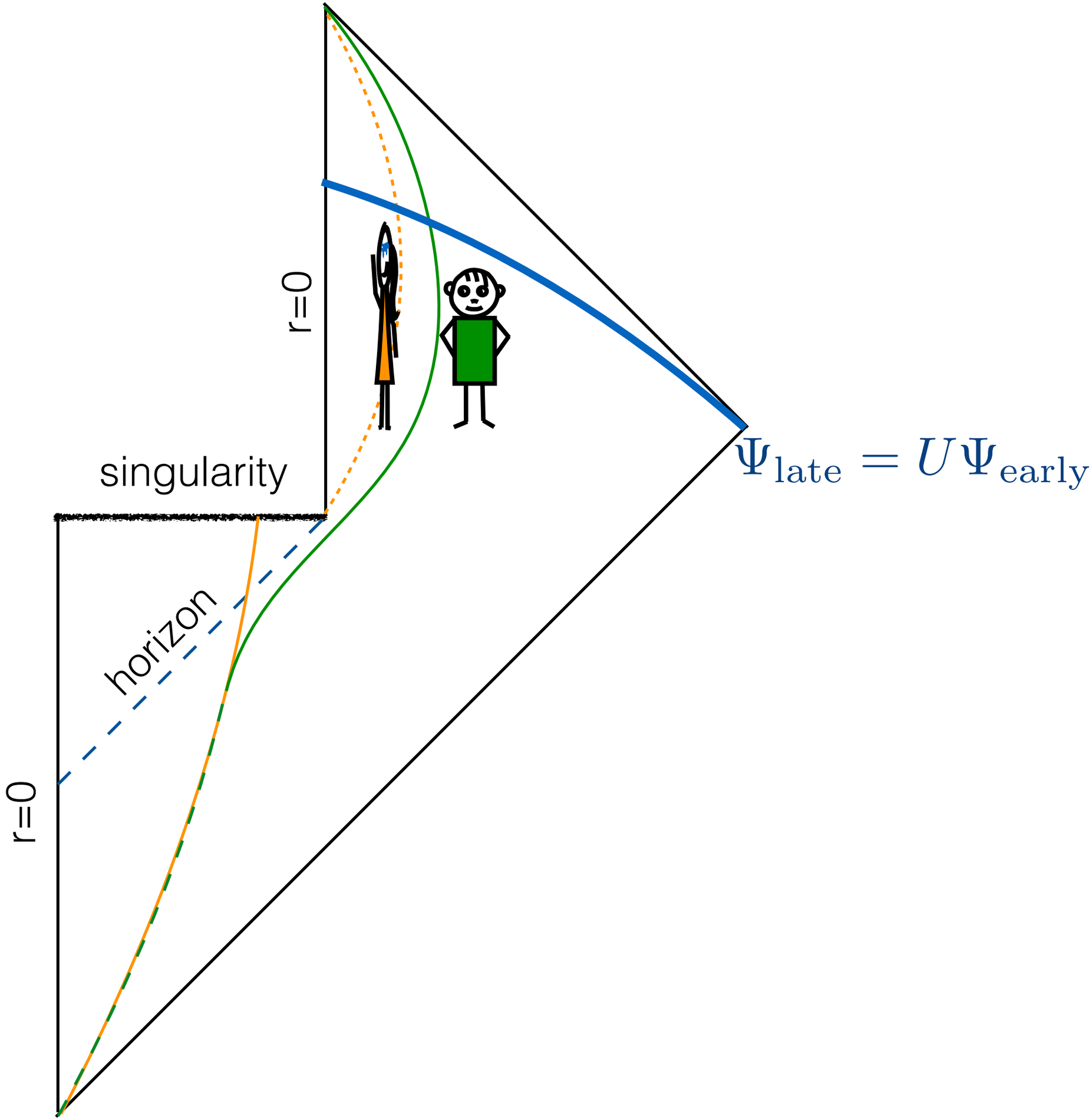
Black Hole Information Paradox






r=0
singularity
Ψ_{early}
horizon
r=0


r=0
singularity
$U\Psi_{\text{early}}$
horizon
r=0


r=0
singularity
horizon
r=0
$\Psi_{\text{late}} = U\Psi_{\text{early}}$

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

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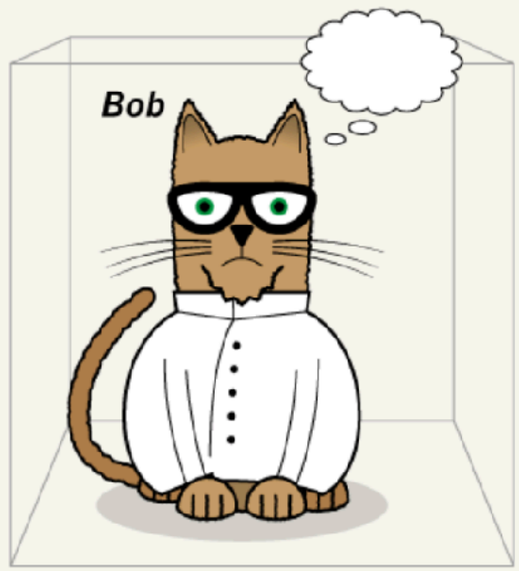
nature
International Journal of science

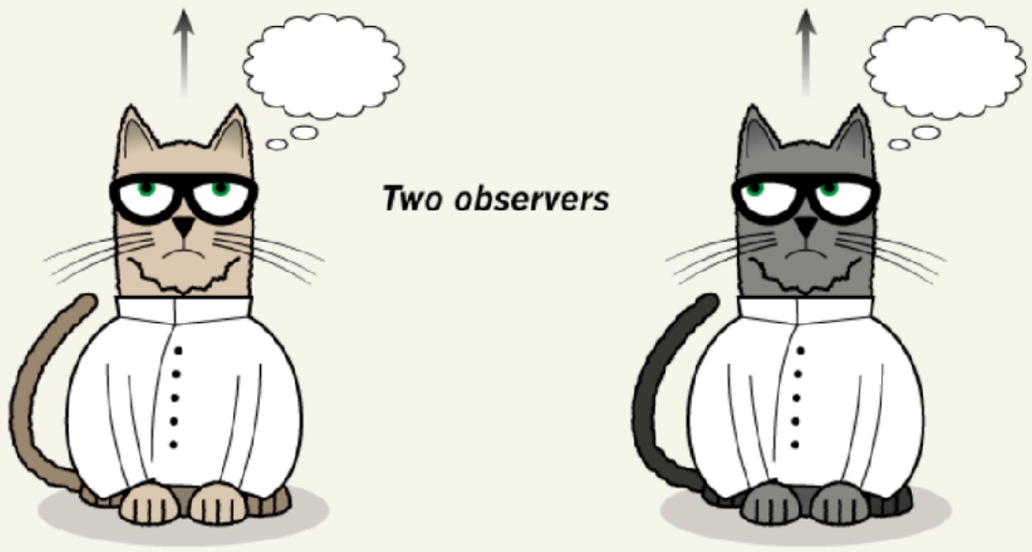
NEW CATS IN TOWN

Physicists have devised a variation of the iconic Schrödinger's cat thought experiment that involves several players who understand quantum theory. But surprisingly, using the standard interpretation of quantum mechanics, the observers sometimes seem to come to different conclusions about a particular event — suggesting that the interpretation contradicts itself for complex systems.

Alice tosses a coin and, using her knowledge of quantum physics, sends a quantum message to Bob.



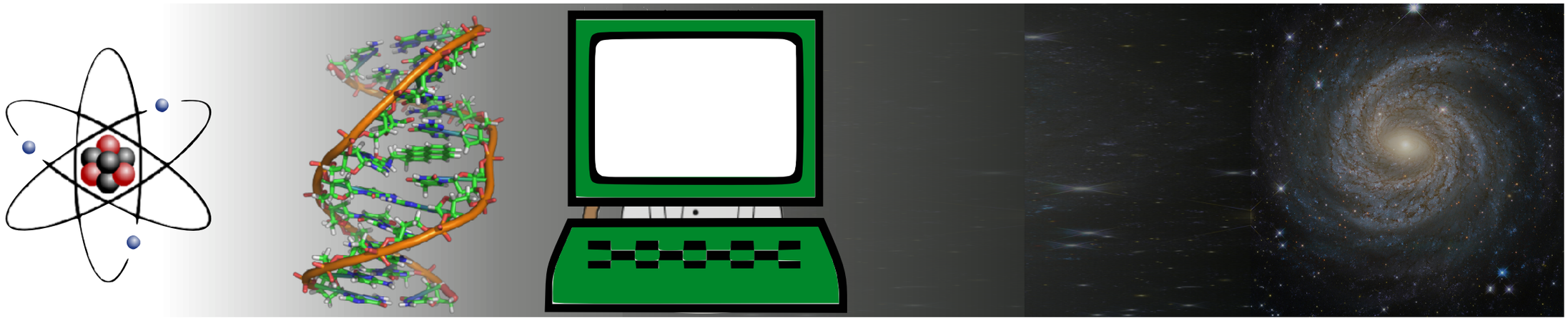
Using his knowledge of quantum theory, Bob can detect Alice's message and guess the result of her coin toss.



When the two observers open their boxes, in some situations they can conclude with certainty how the coin landed — but their conclusions are different. This means that the standard interpretation of quantum theory gives an inconsistent description of reality.

News article by Castelvecchi, *Nature* **561** (2018)

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

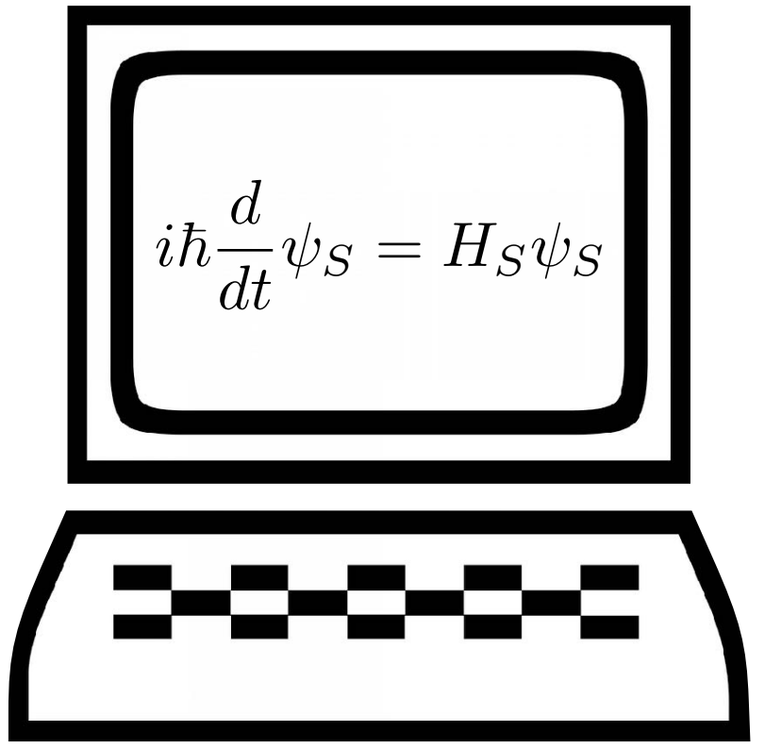


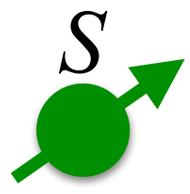
tested to high precision

tested to low accuracy

?

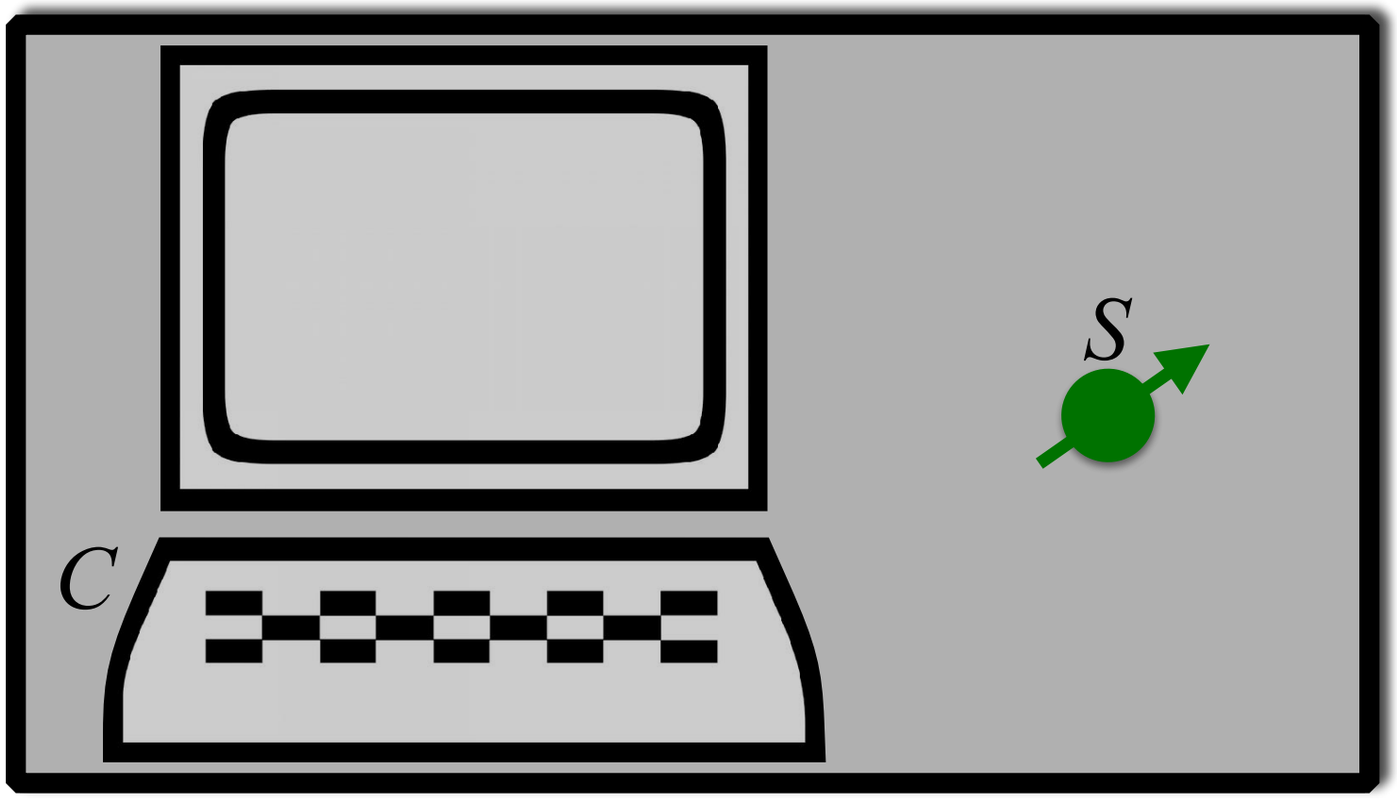
Role as subject:
Computer as agent that uses quantum theory.



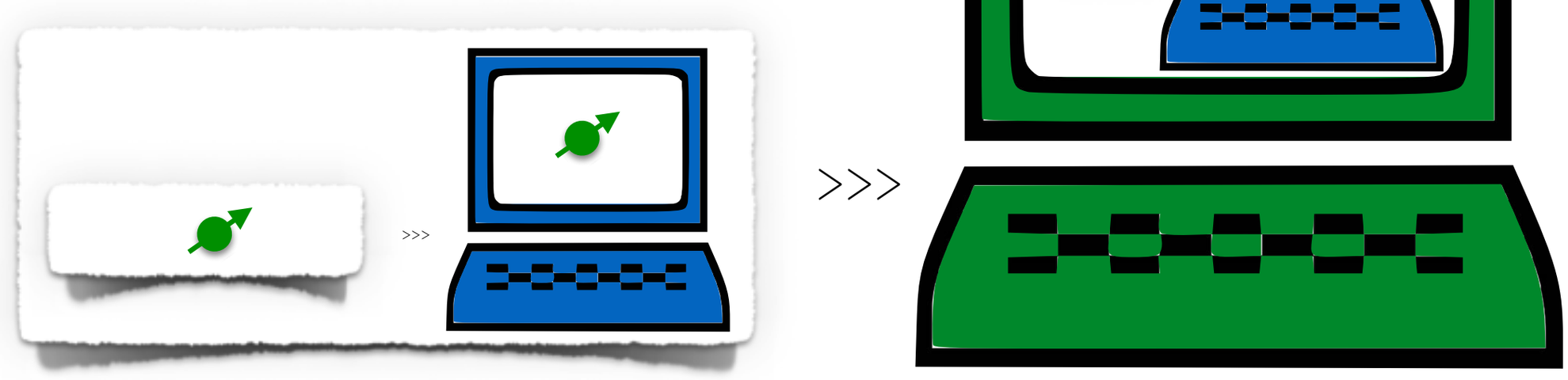


Role as object:
Computer as object described by quantum theory.

$$i\hbar\frac{d}{dt}\Psi_{CS} = H_{CS}\Psi_{CS}$$



The two roles …



A “multi-cat experiment”

nature
International Journal of science

NEW CATS IN TOWN

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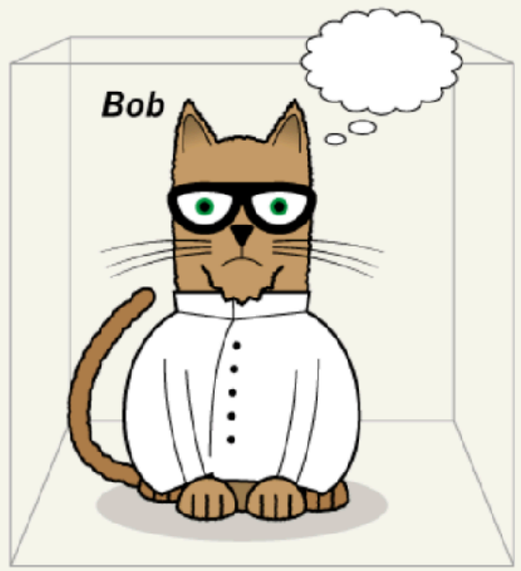

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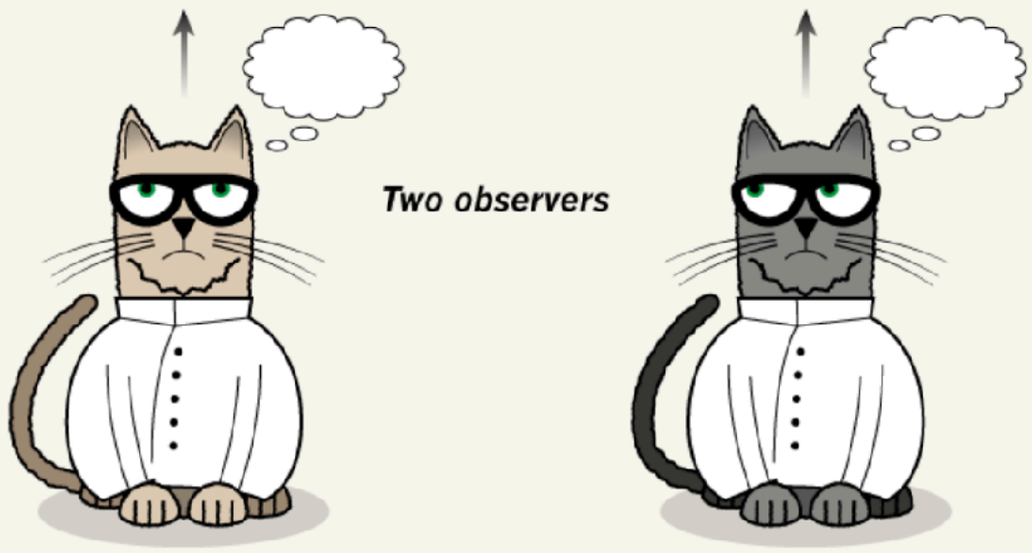

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News article by Castelvecchi, *Nature* **561** (2018)

A question of consistency

Can

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.

New Scientist

WEEKLY 23 March 2019

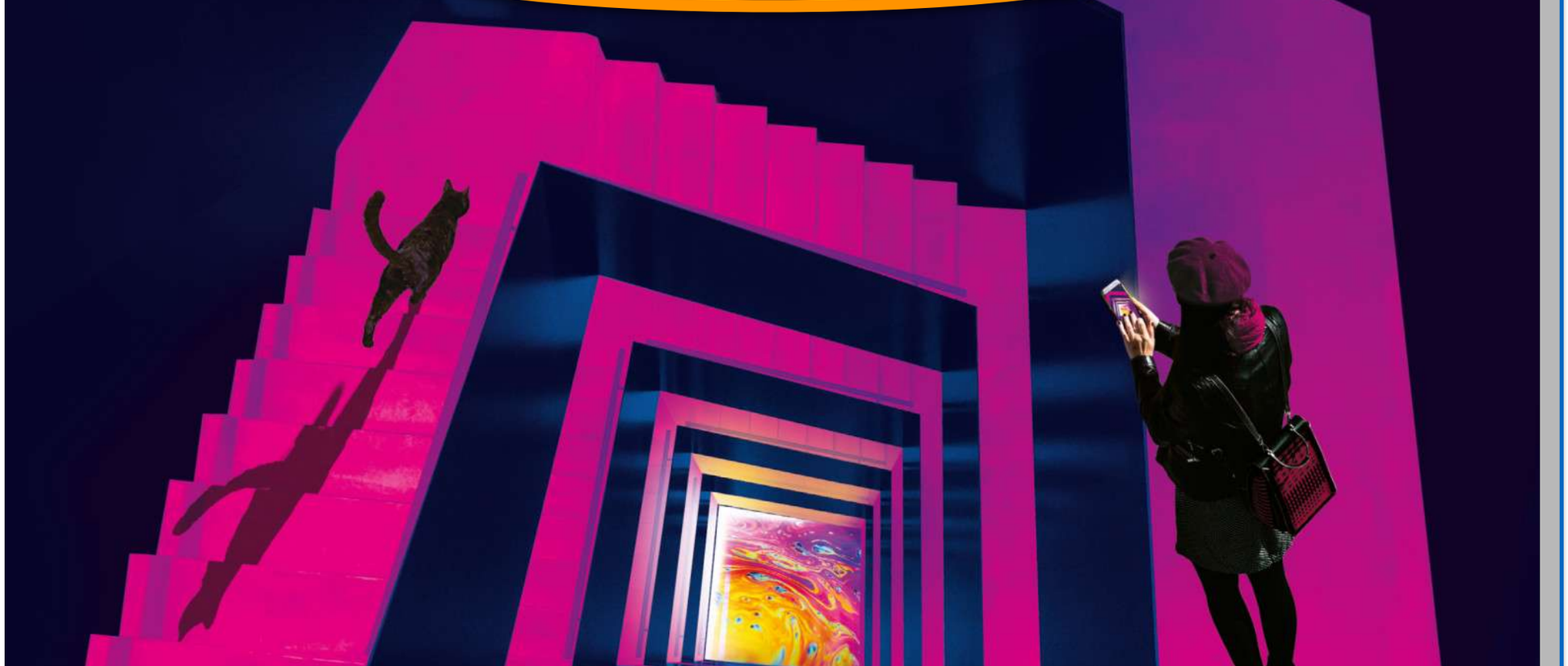
GAIA REBORN
The idea of Earth as one organism is back

OH MY COD!
Do you know what fish you're eating?

THE HUMAN COMPASS
How our brains detect magnetic fields

QUANTUM THEORY IS IN TROUBLE

And it looks like the problem is you



Computers as users of quantum theory

input

physical reasoning $\Longrightarrow$

output

- Laws of the theory
- Rules how to apply the theory (interpretation-dependent)
- Experimental protocol
- Observations

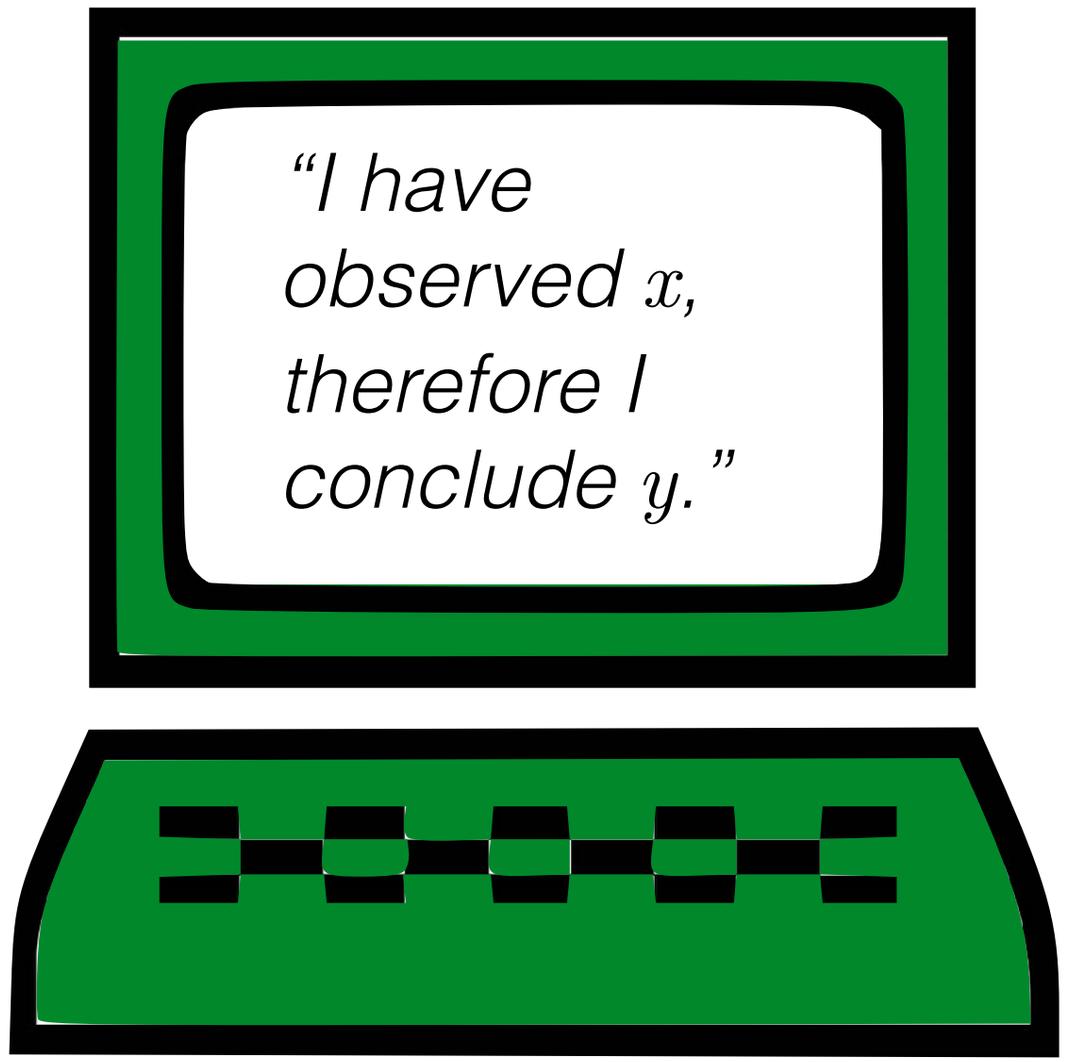
>>>

Programmed rules

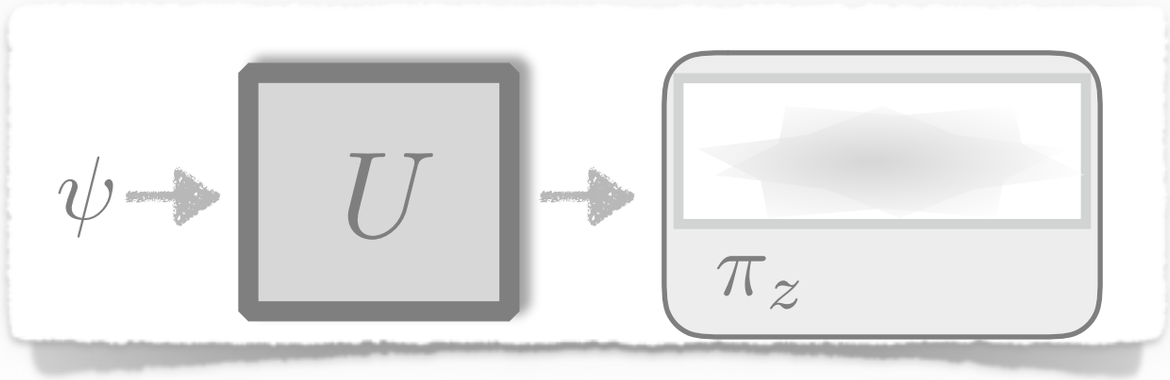
Rule (Q): Unitary evolution and Born rule (without an extra collapse mechanism)

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

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



Rule (Q): Unitary evolution and Born rule



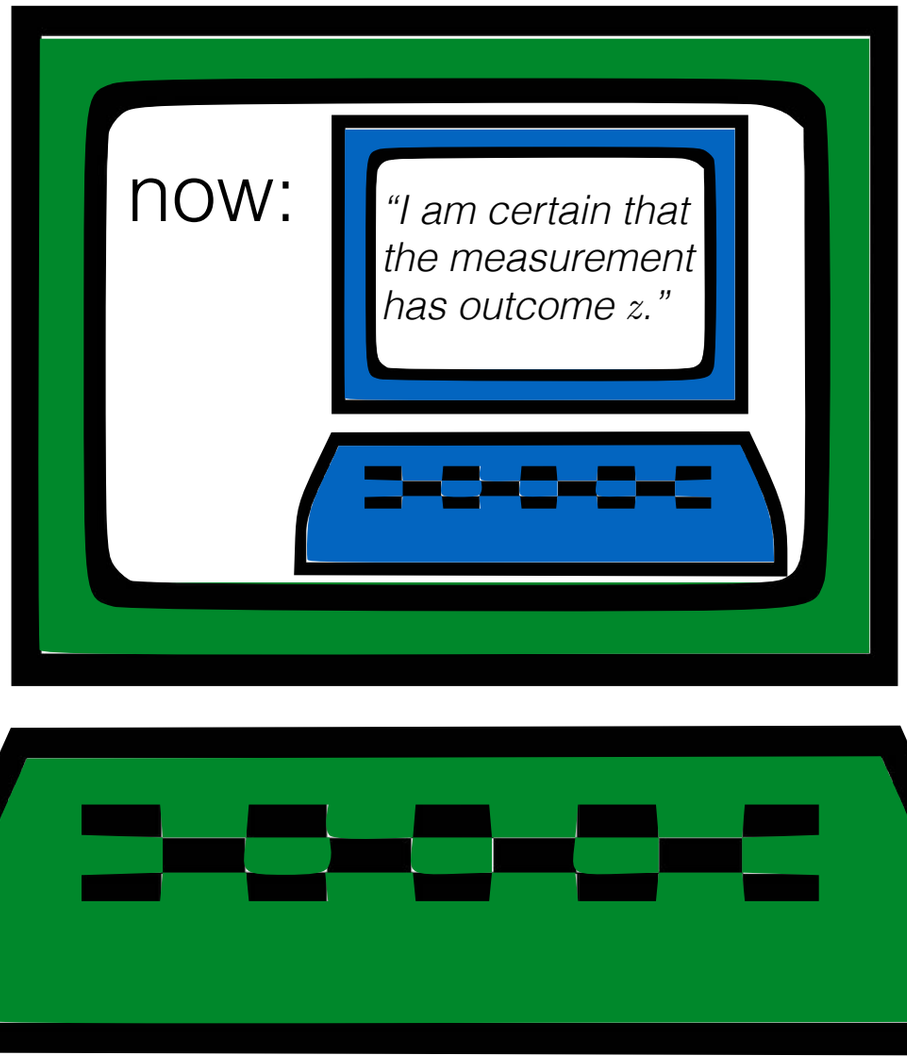
$$\|\pi_z U\psi\| = 1$$

(Q) $\Longrightarrow$

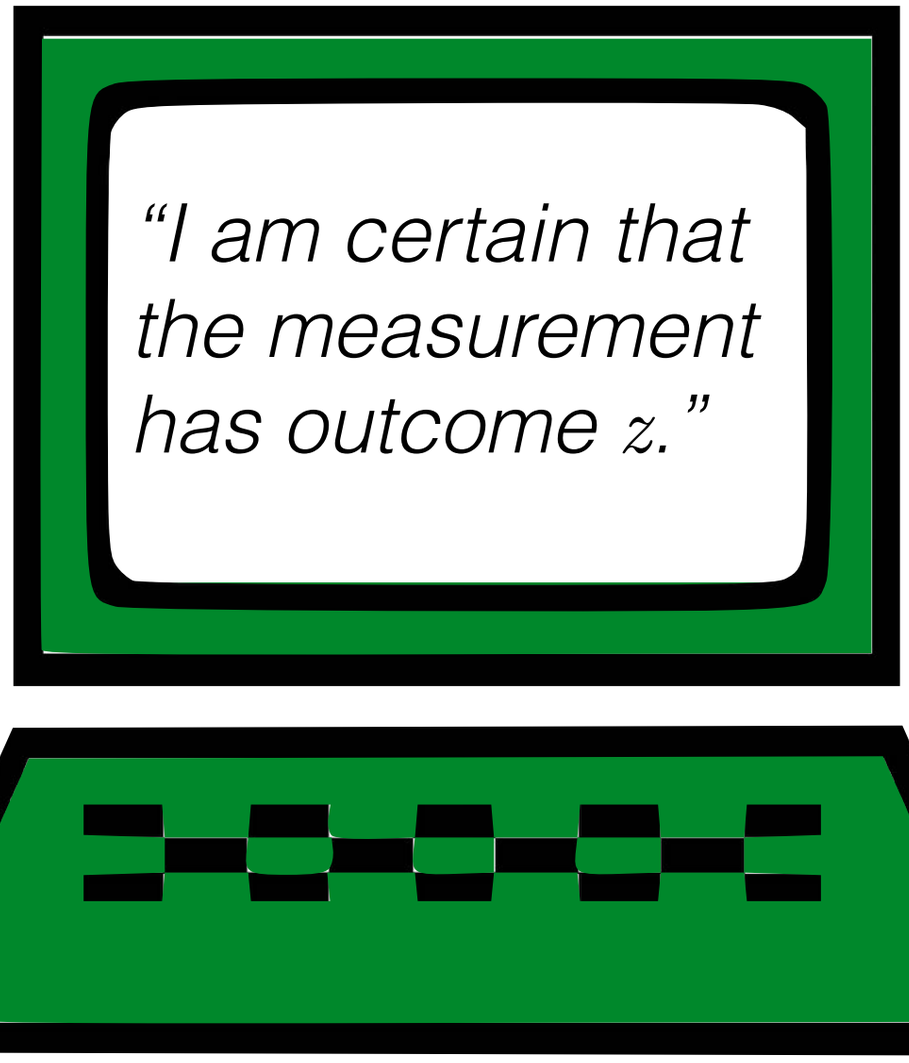
"I am certain that the measurement has outcome z."

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

Rule (C): Be consistent with conclusions of others

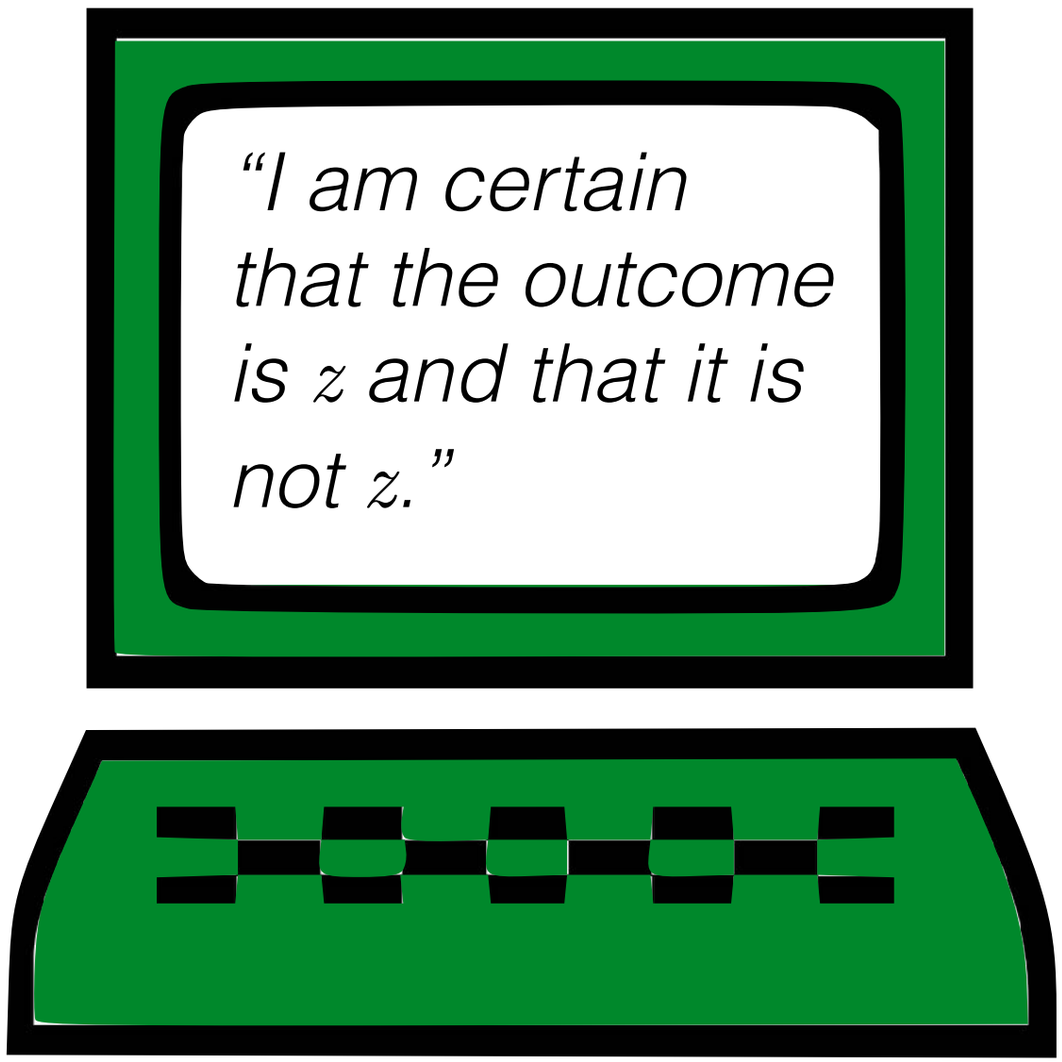


(C)

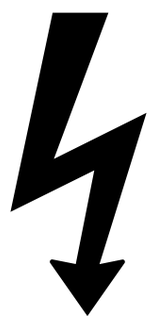


The green computer is certain that the blue computer is *at this moment* certain that the outcome is z.

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

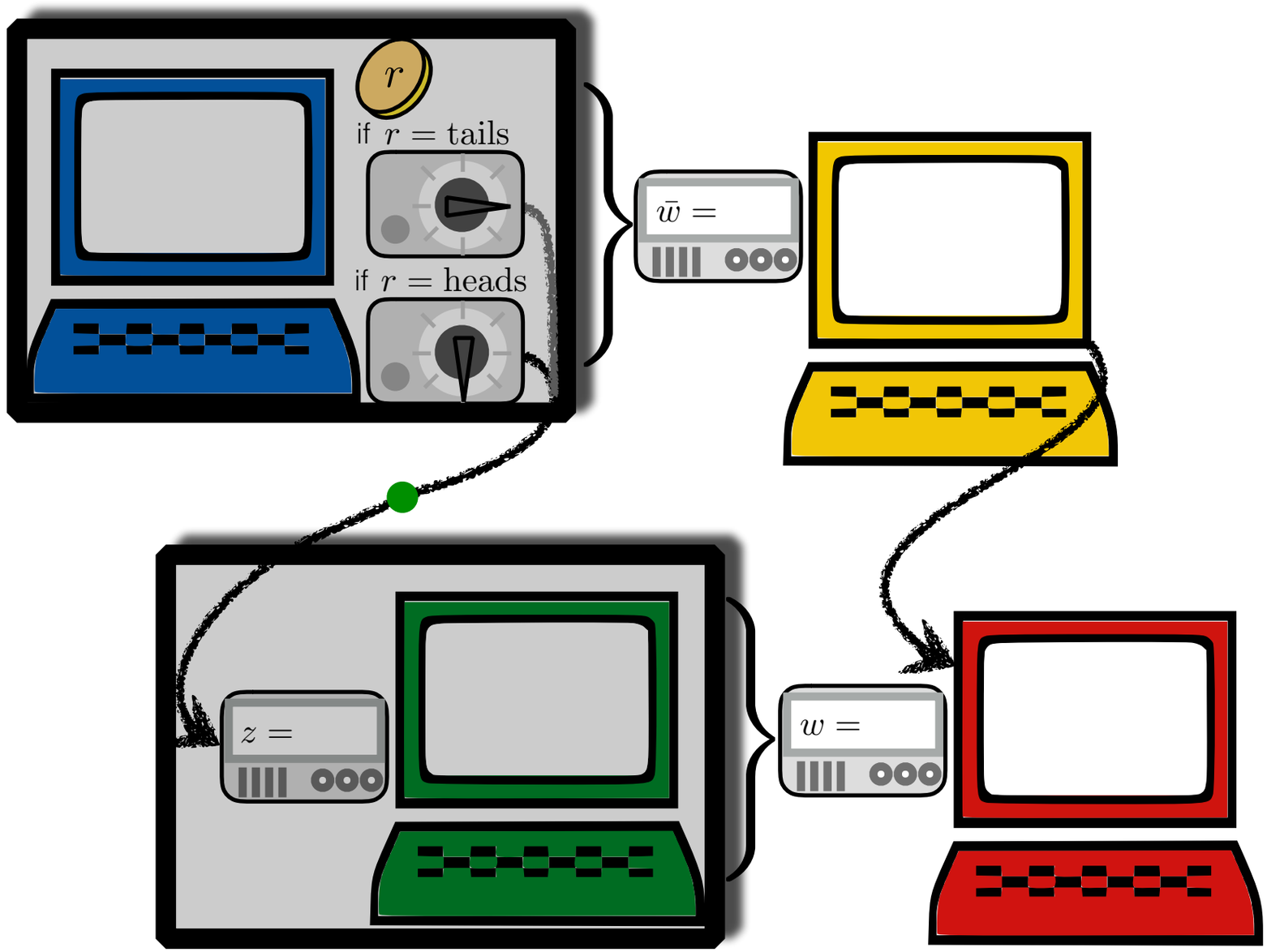


(S)

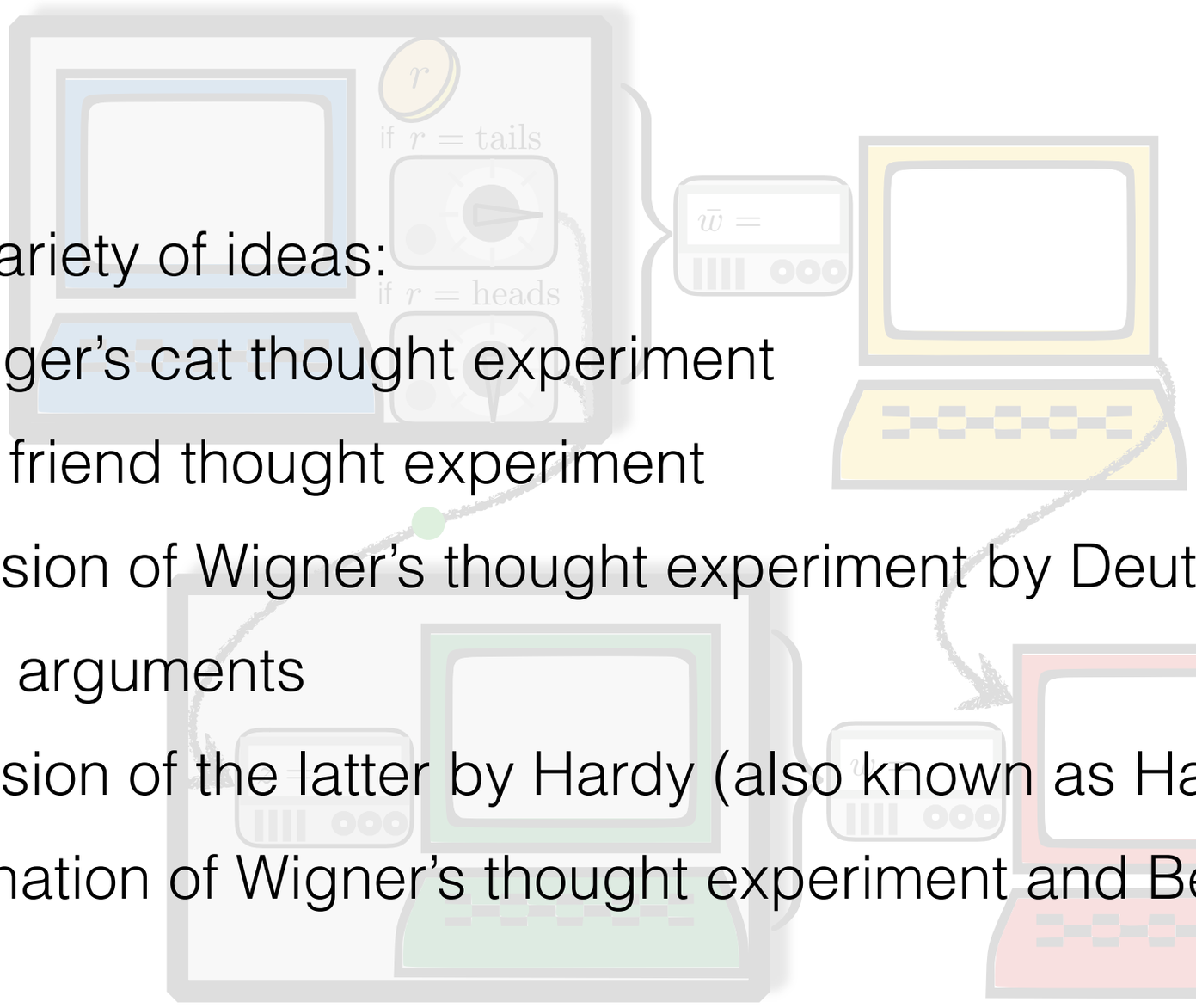


Question

Could it happen that computers, when programmed with these rules, run into a contradiction?



A mix of paradoxes



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

r

if $r = \text{tails}$

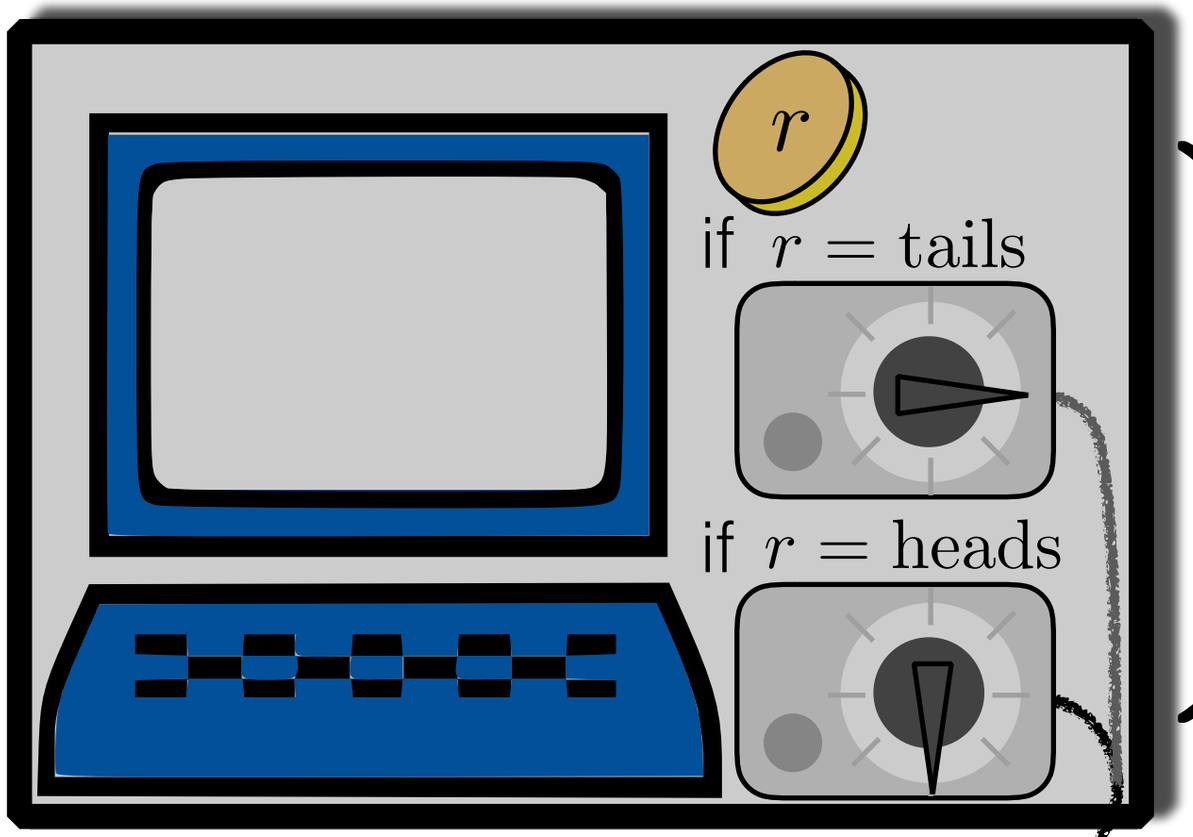
if $r = \text{heads}$

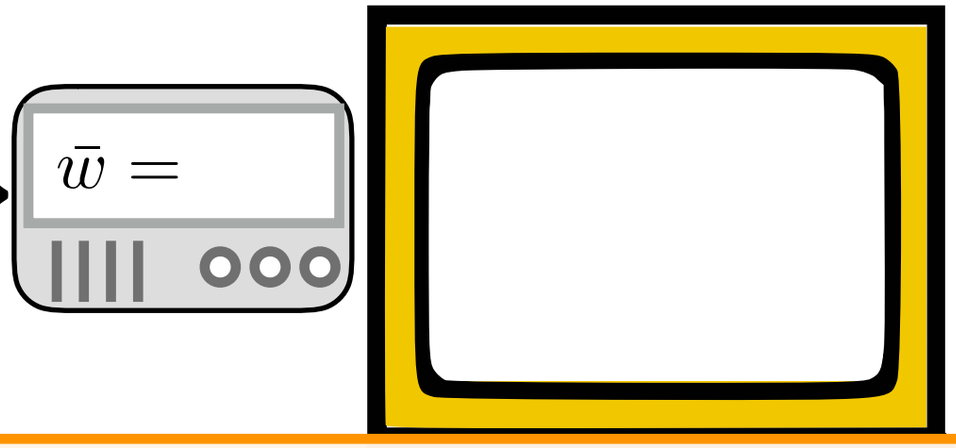
Spin right: $|\rightarrow\rangle = \dfrac{|\downarrow\rangle + |\uparrow\rangle}{\sqrt{2}}$

Spin down: $|\downarrow\rangle$

$z =$

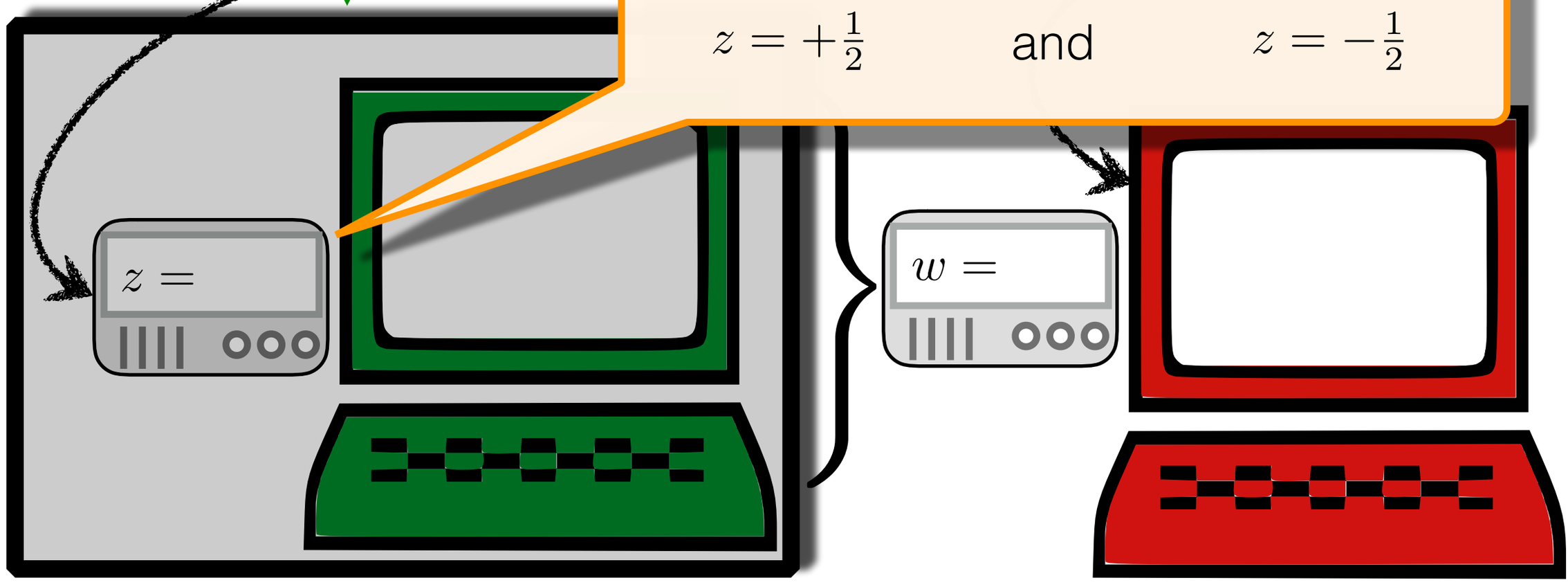
$w =$





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

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



r

if $r = \text{tails}$

if $r = \text{heads}$

$\bar{w} =$

$z =$

Outcome $\bar{w}$ is communicated.

Value $\bar{w}$ obtained by measuring entire box in “superposition basis” with possible outcomes

$\bar{w} = \bar{\text{ok}}$ and $\bar{w} = \bar{\text{fail}}$

r

if $r = \text{tails}$

if $r = \text{head}$

Value w obtained by measuring entire box in a “superposition basis” with possible outcomes

$w = \text{ok}$ and $w = \text{fail}$

$z =$

$w =$

$r = \text{tails}$

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

$w = \text{fail}$

$r = \text{tails}$

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

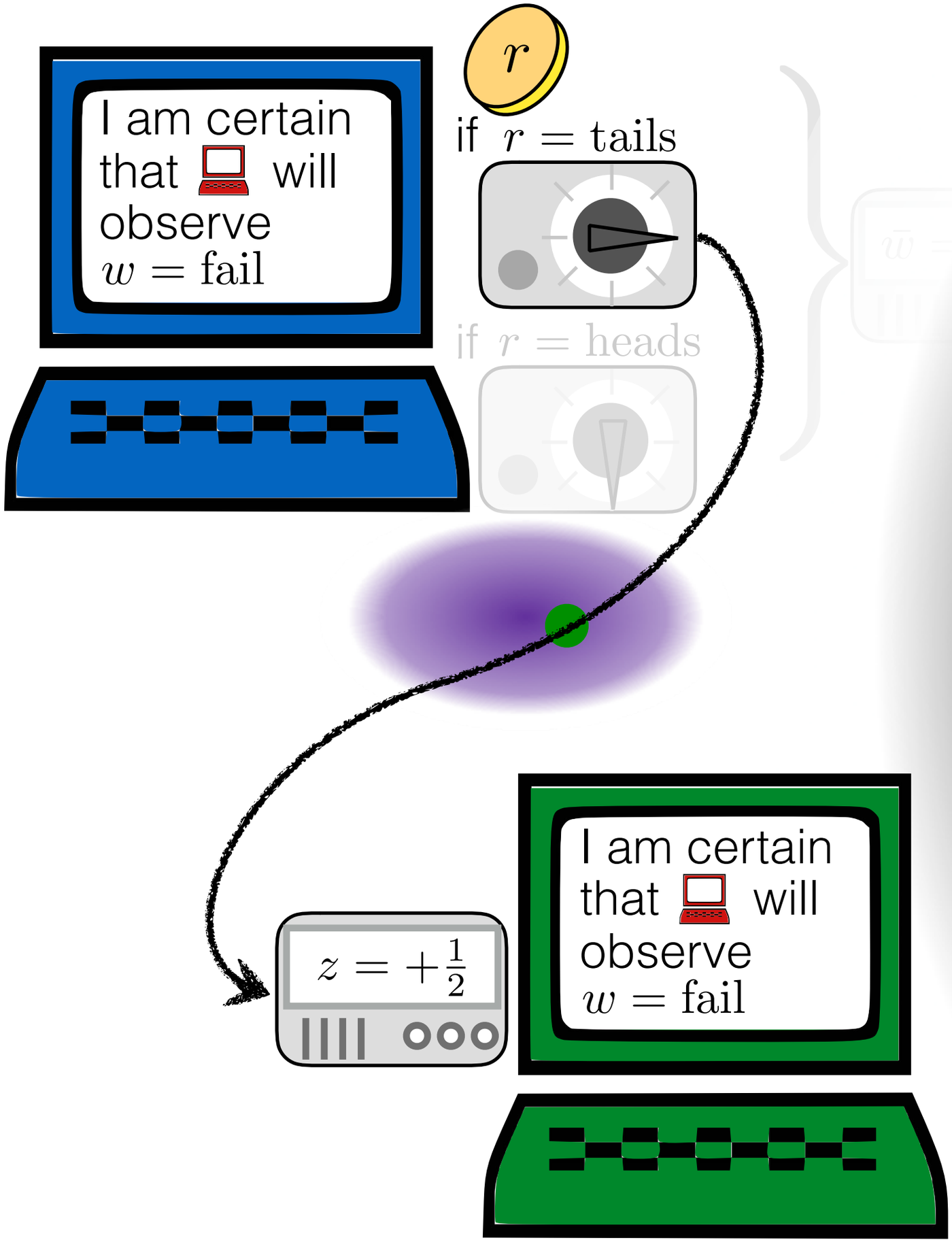
if $r = \text{tails}$

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 $r = \text{tails}$

B

if $r = \text{heads}$

$\bar{w} = \bar{\text{ok}}$

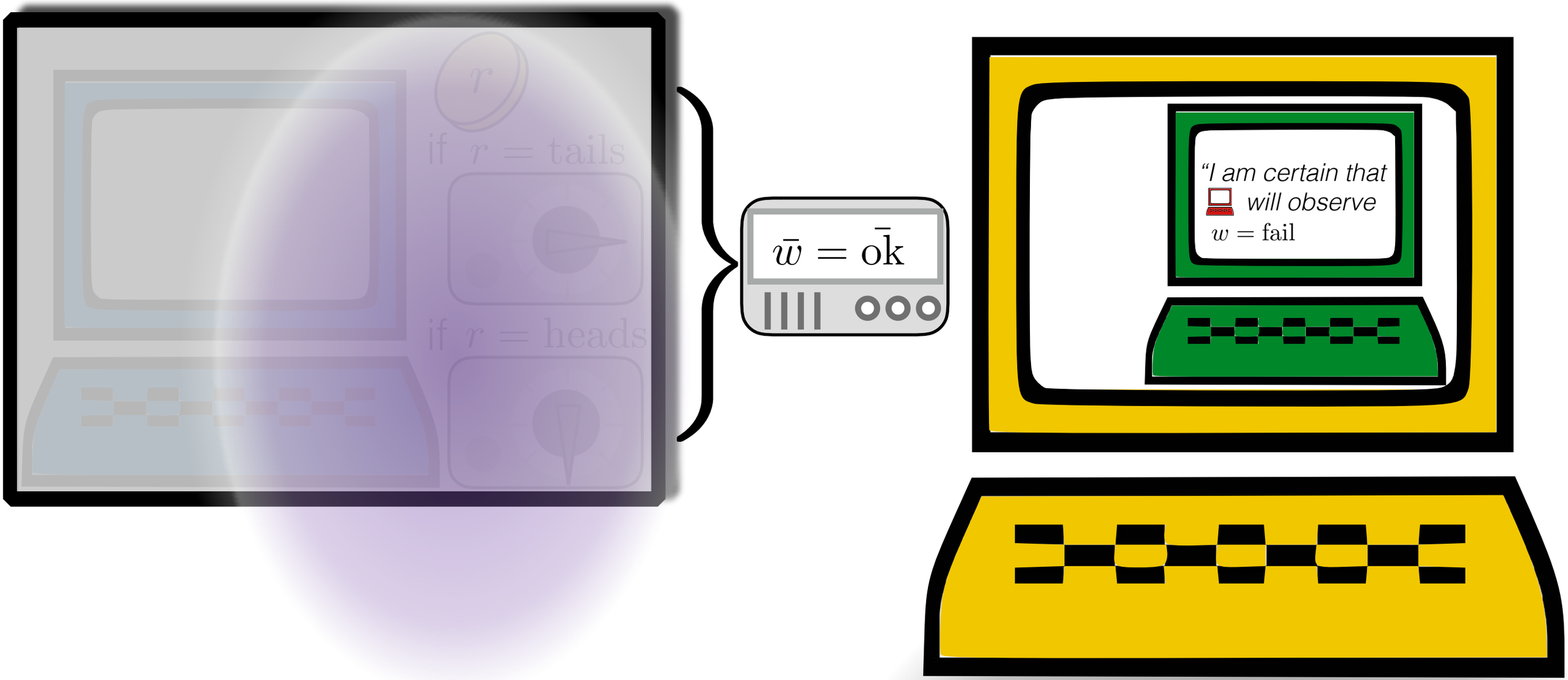
I am certain that  observed $z = +\frac{1}{2}$

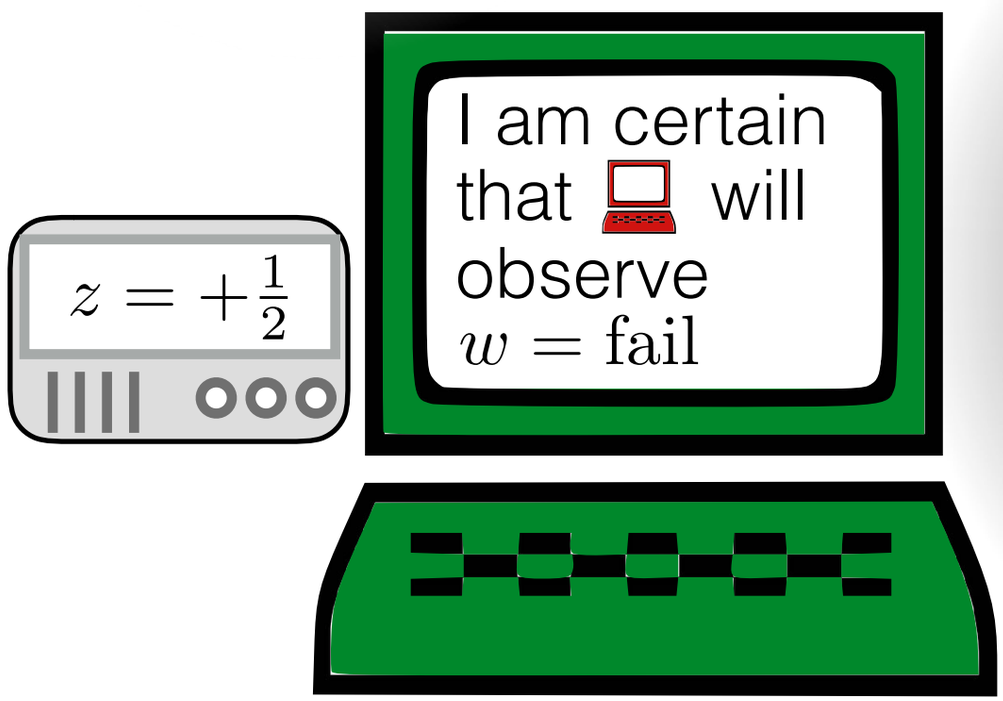
S

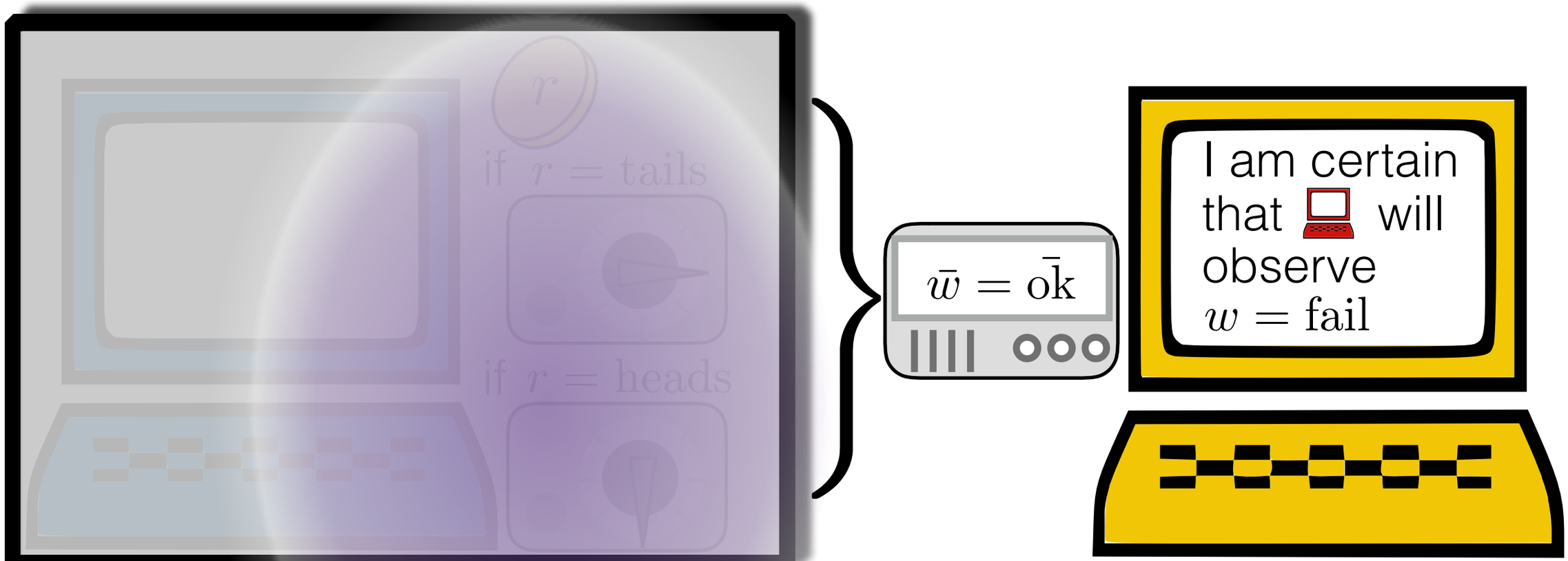
$\Psi_{BS} \perp |\bar{\text{ok}}\rangle \otimes |{\downarrow}\rangle$

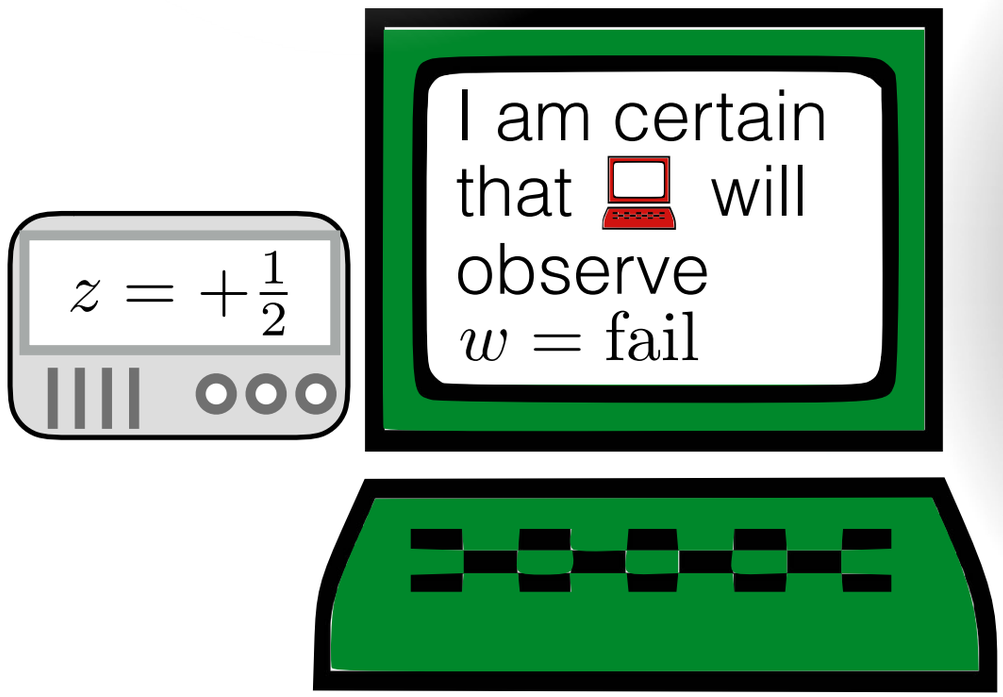
$z = +\frac{1}{2}$

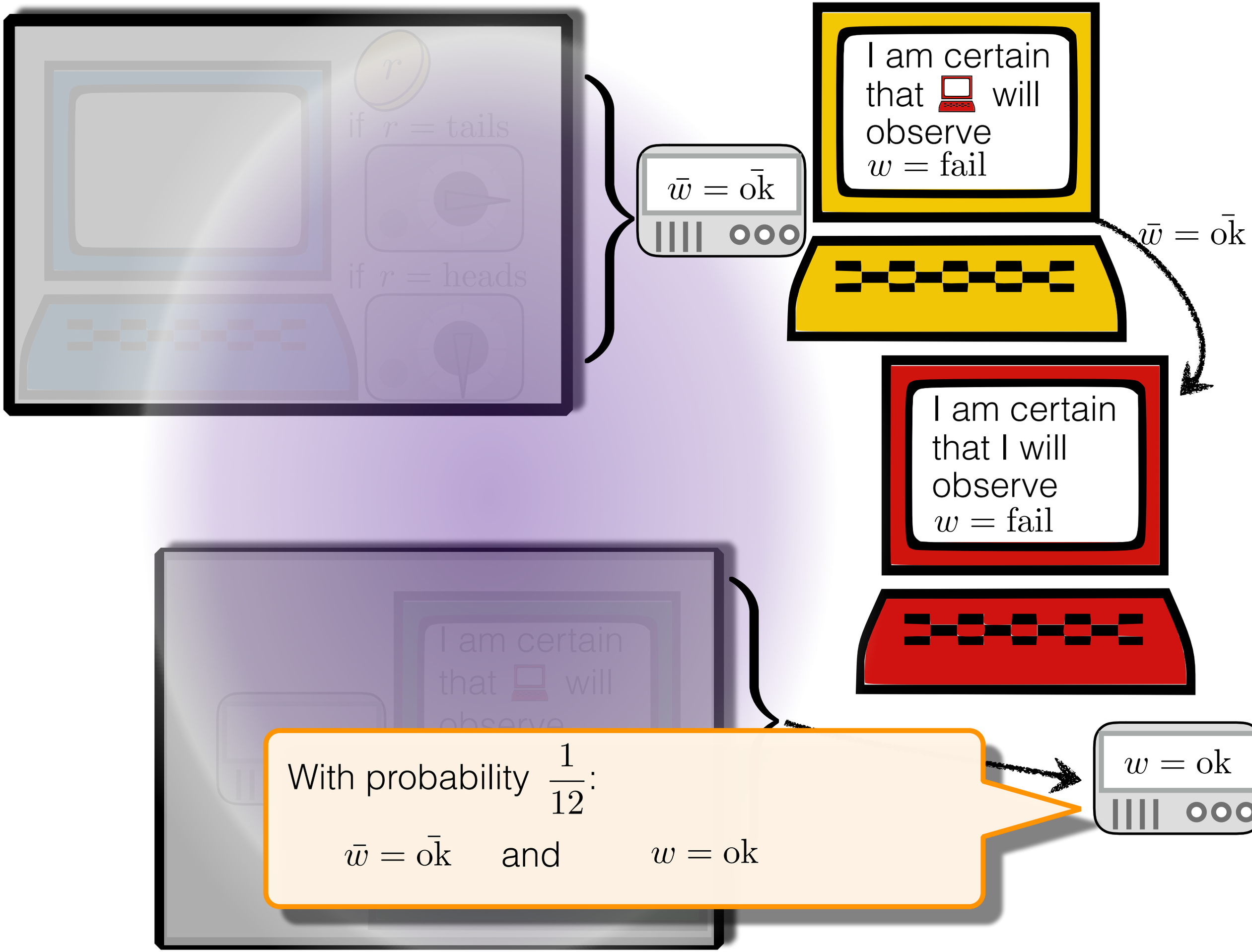
I am certain that  will observe $w = \text{fail}$


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 $w = \text{fail}$


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 $w = \text{fail}$


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

$w = \text{ok}$

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)

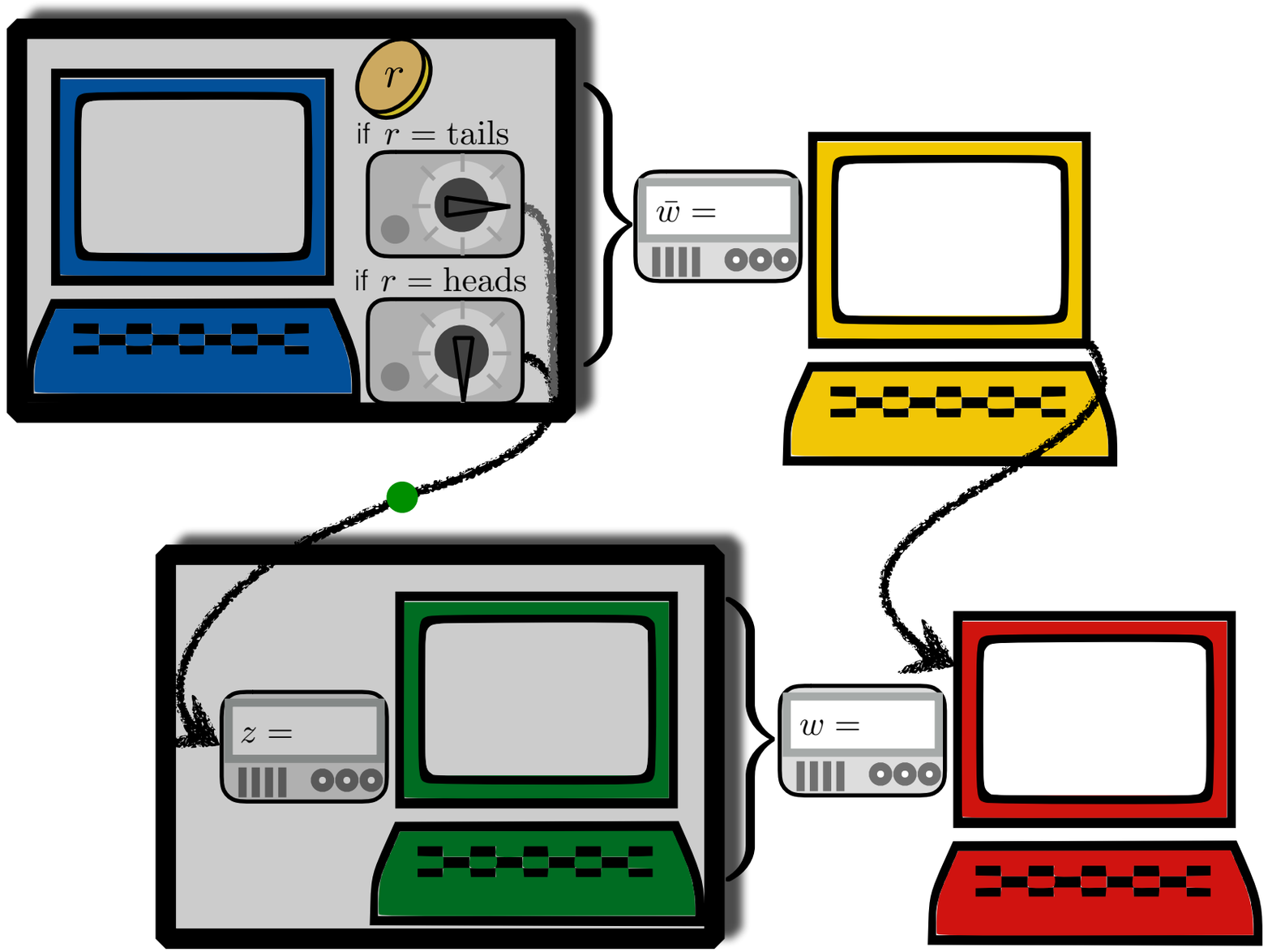
Rule (S): Do not claim "alternative facts"

Conclusion: Following these rules leads to a contradiction!

Where to go from here?

Challenge:

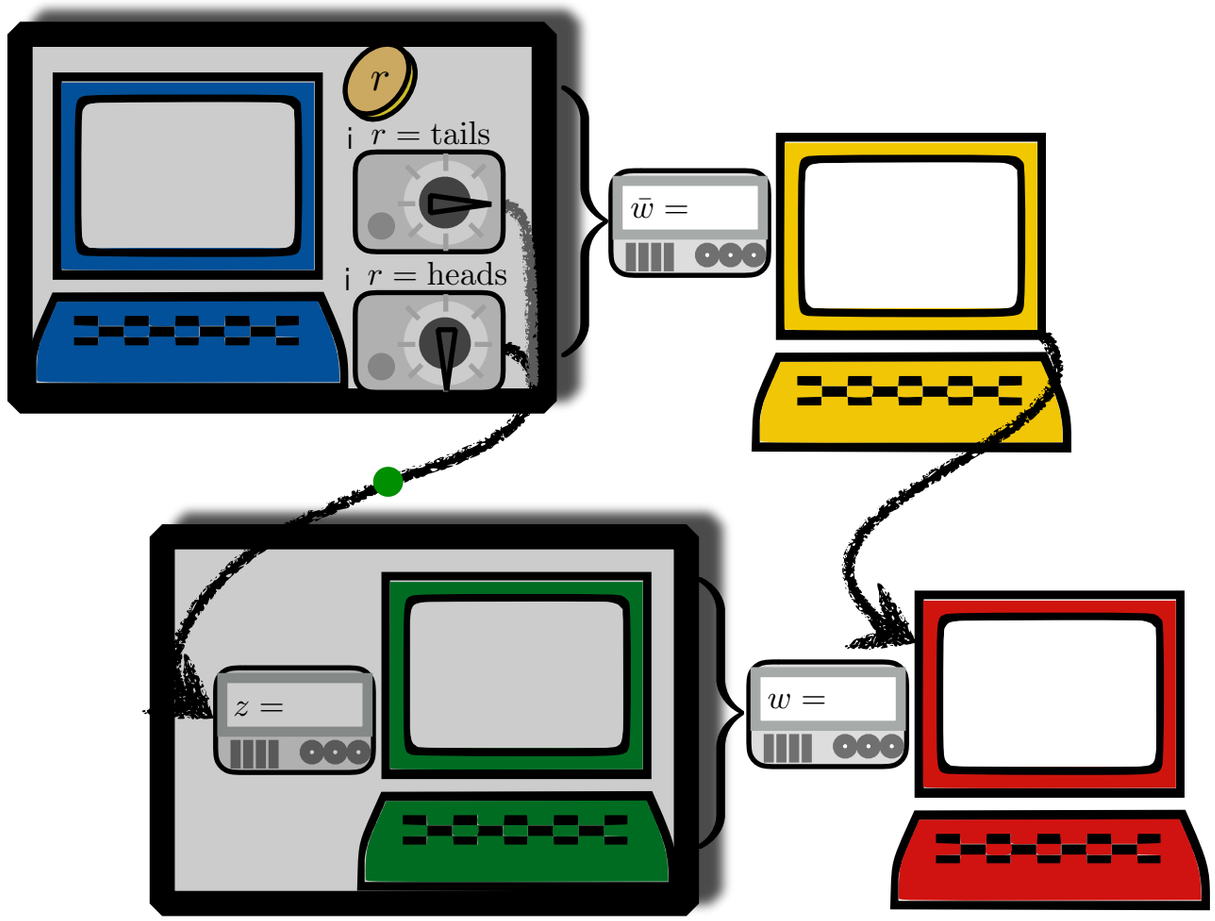
Modify quantum theory such that agents programmed to follow its rules do not run into a contradiction.



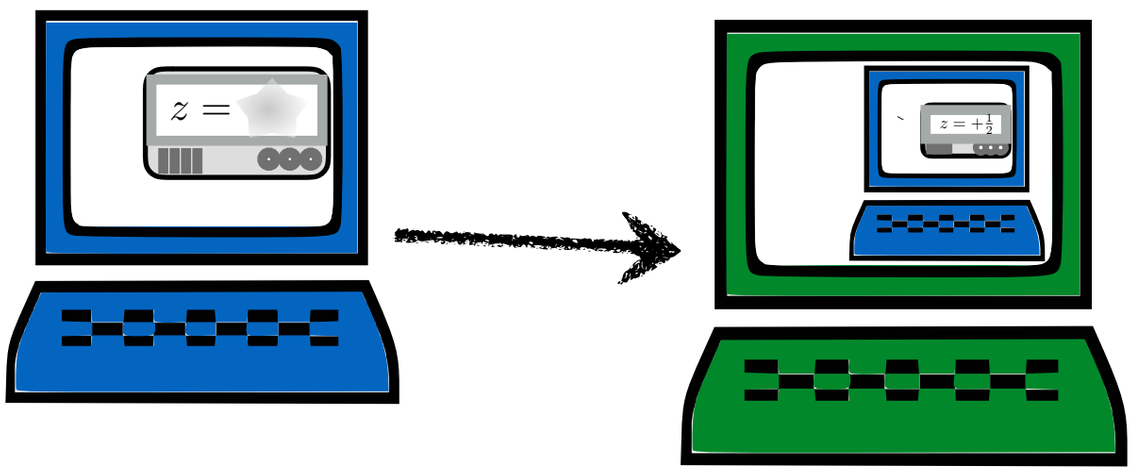
The Challenge

Program agents such that …

… no contradictory claims here …



… but useful claims here!



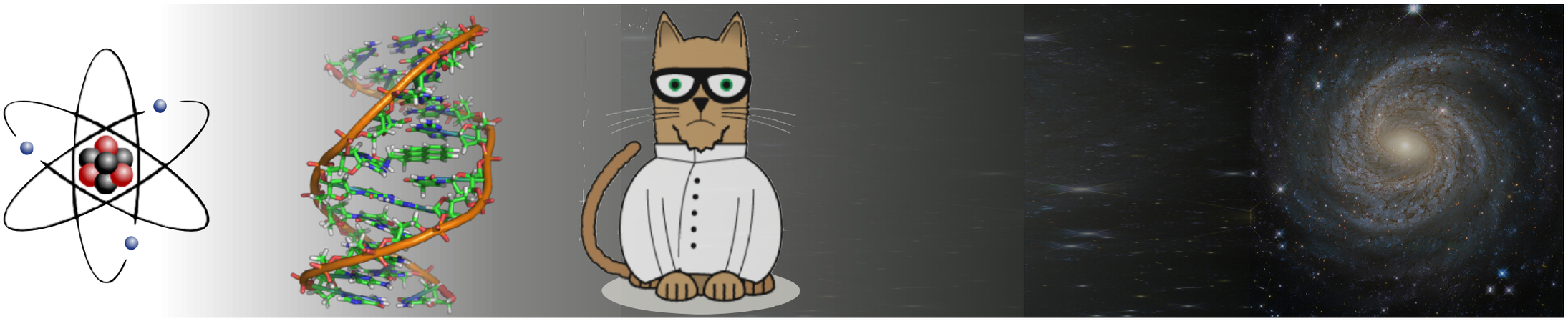
Software soon available (open access) …

Simon Mathis

Nuriya Nurgalieva

Lídia del Rio

Conclusion

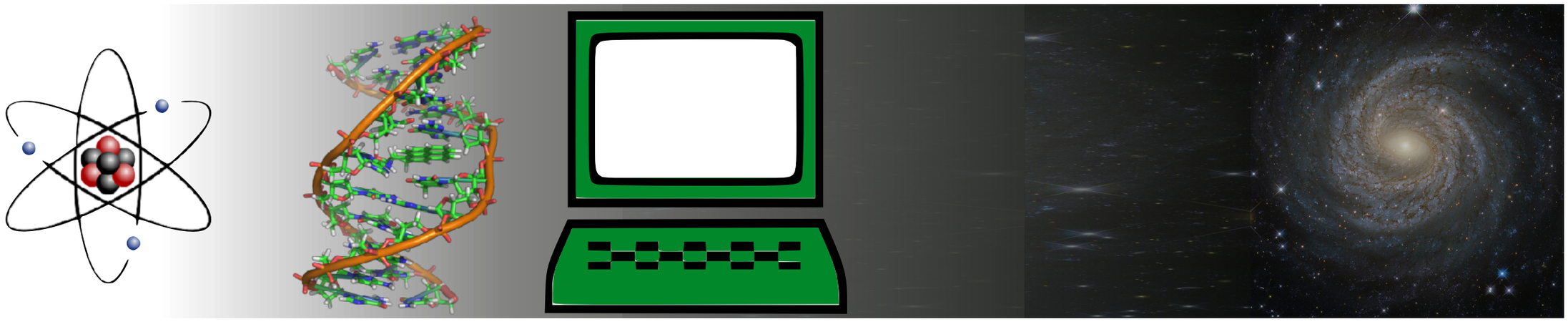


tested to high precision

tested to low accuracy

?

Conclusion



tested to high precision

tested to low accuracy

!

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)

National Centre of Competence in Research

Swiss National Science Foundation

Extra slide: Interpretations of quantum theory

	(Q)	(C)	(S)
Copenhagen (with movable cut)	✔	✘	✔
Det. HV Th. (applied to subsystems)	✔	✘	✔
Bohmian Th. (applied to universe)	✘	✔	✔
Many-worlds	✔	?	?
Collapse theories	✘	✔	✔
Consistent histories	✔	✘	✔
QBism	✔	✘	✔
Relational quantum mechanics	✔	✘	✔
…	.	.	.
Your own personal interpretation	.	.	.

Extra slide: Comparison to Gödel's theorem

Gödel's second incompleteness theorem

Assume F is a consistent formalised system which contains elementary arithmetic. Then

$$\neg\big(F \vdash \mathrm{Cons}(F)\big)$$

Claim presented in this talk (informal)

Assume F is a formalised system that includes (Q). Then

$$F \vdash \big(\neg\mathrm{Cons}(F)\big)$$