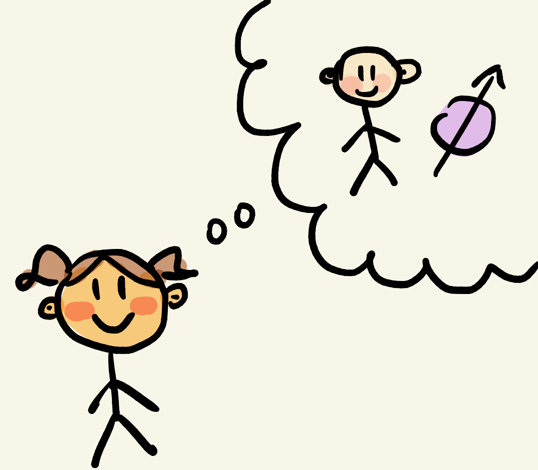
# Testing quantum theory with thought experiments



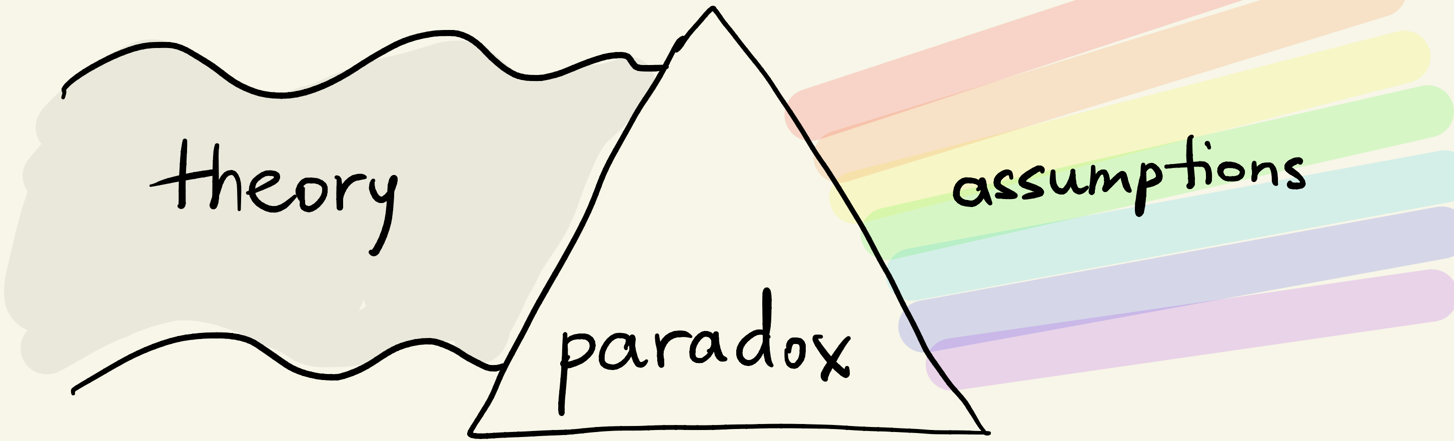
Quantum Information & Frontiers of Quantum Theory workshop

Lyon, 2022

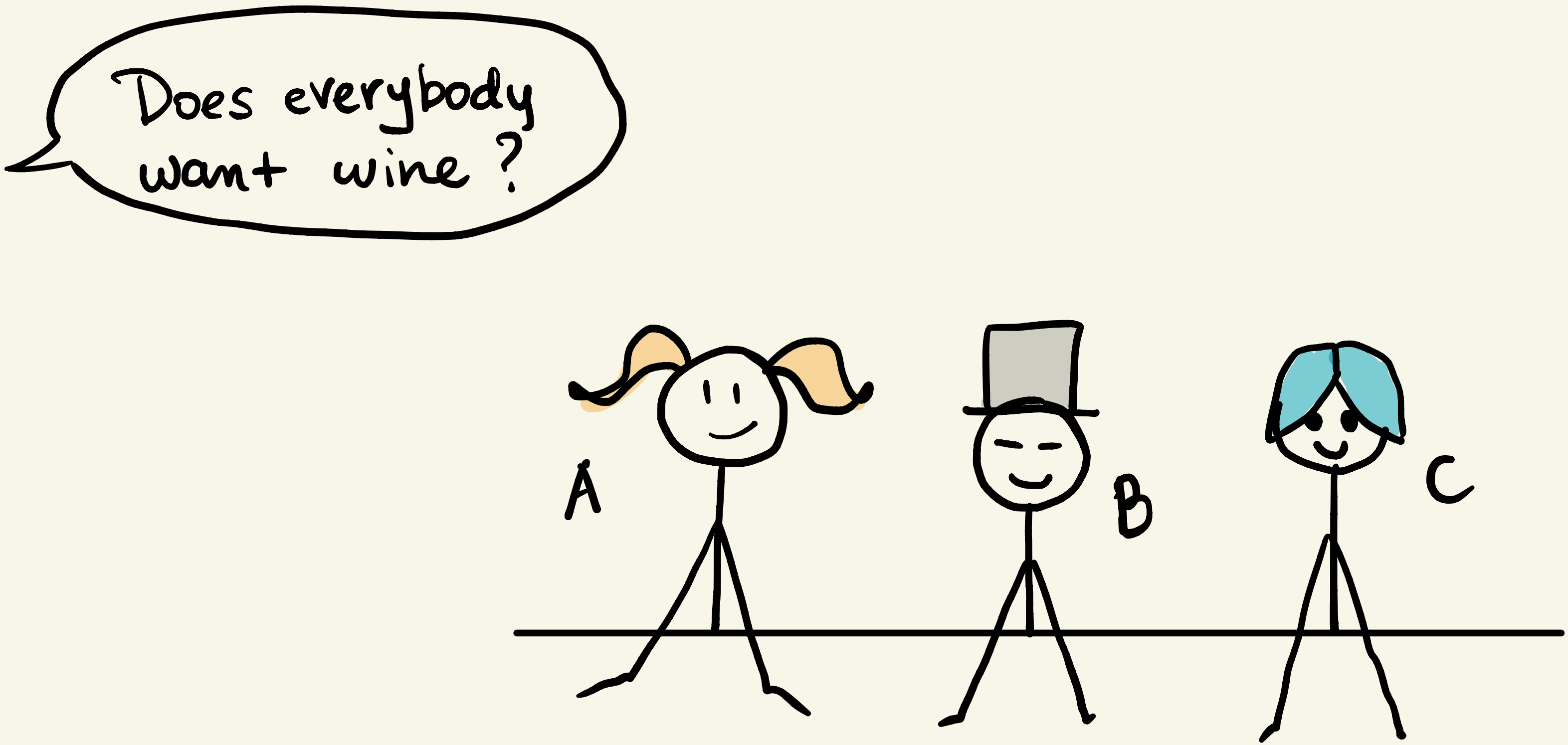
based on works :

and to be continued ...

# Motivation: thought experiments



# Motivation: reasoning agents



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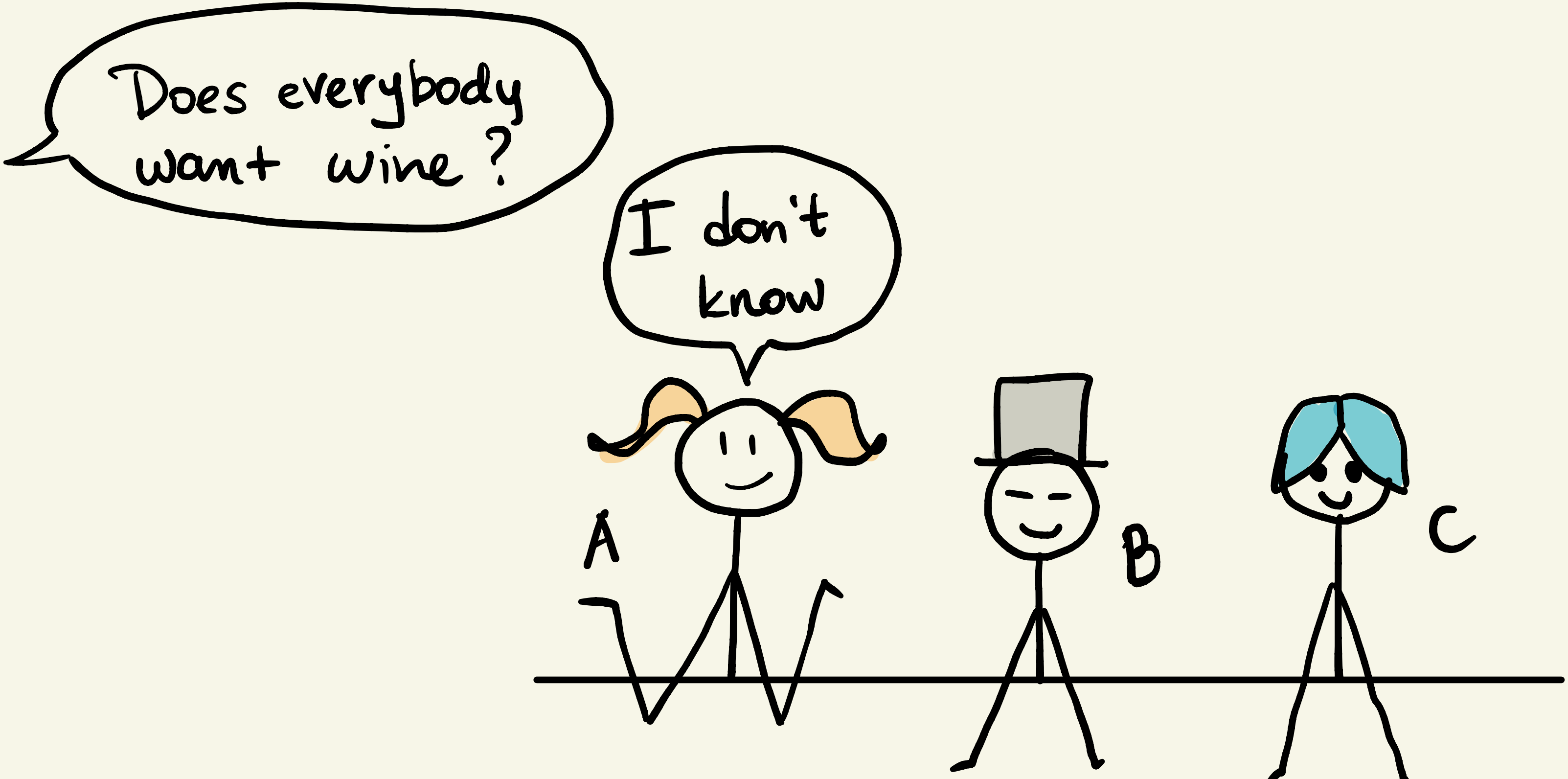
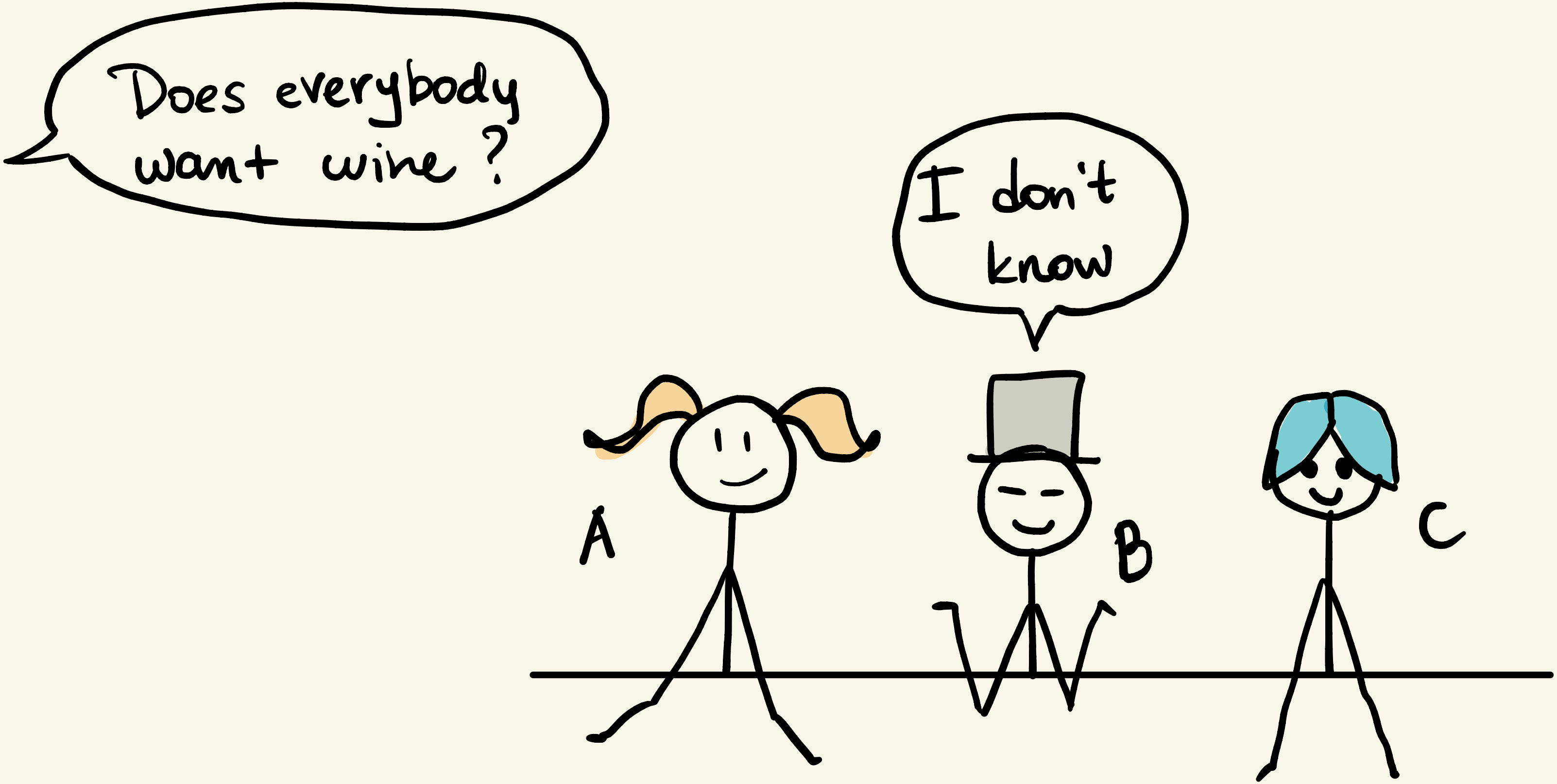
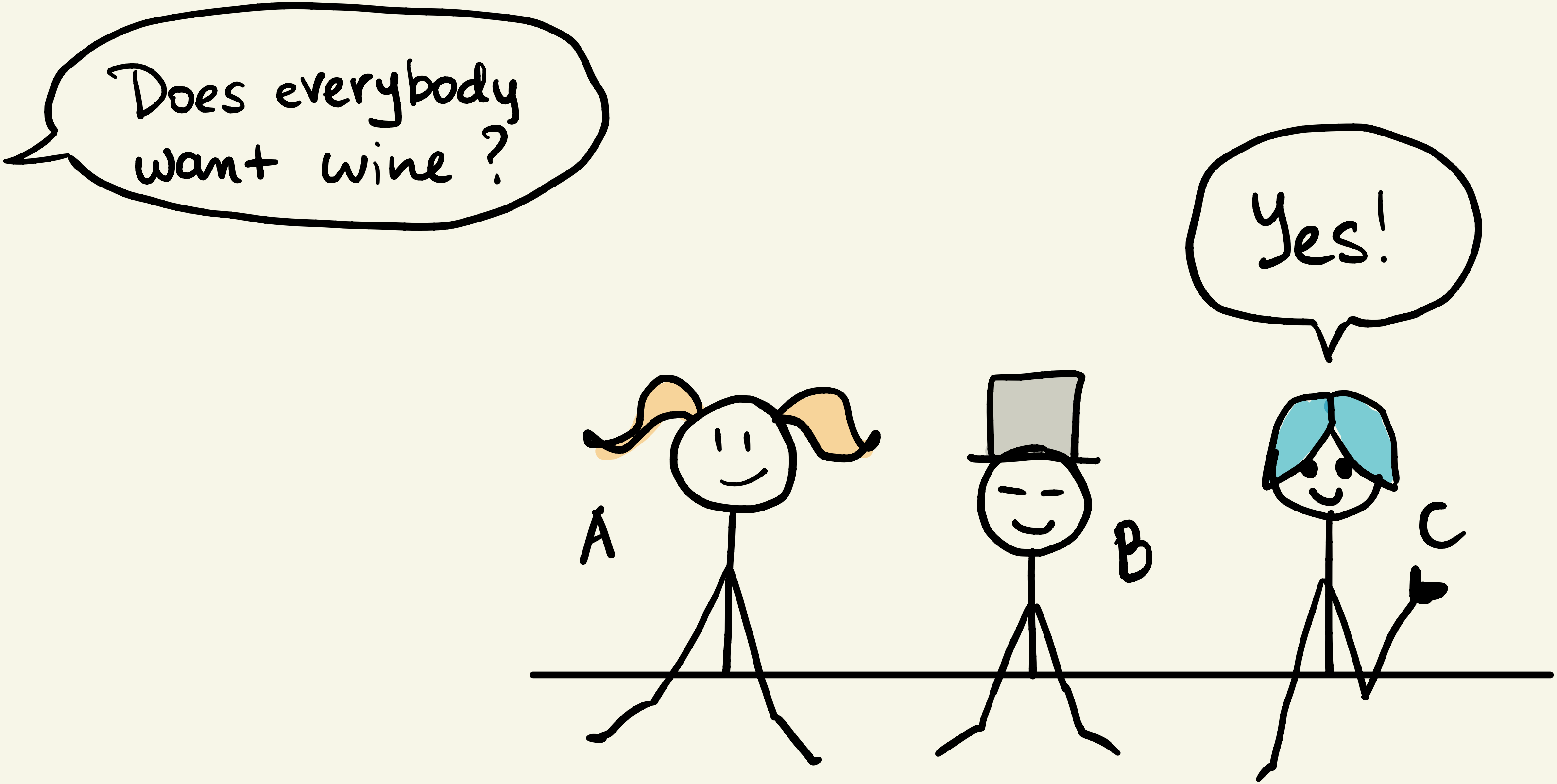


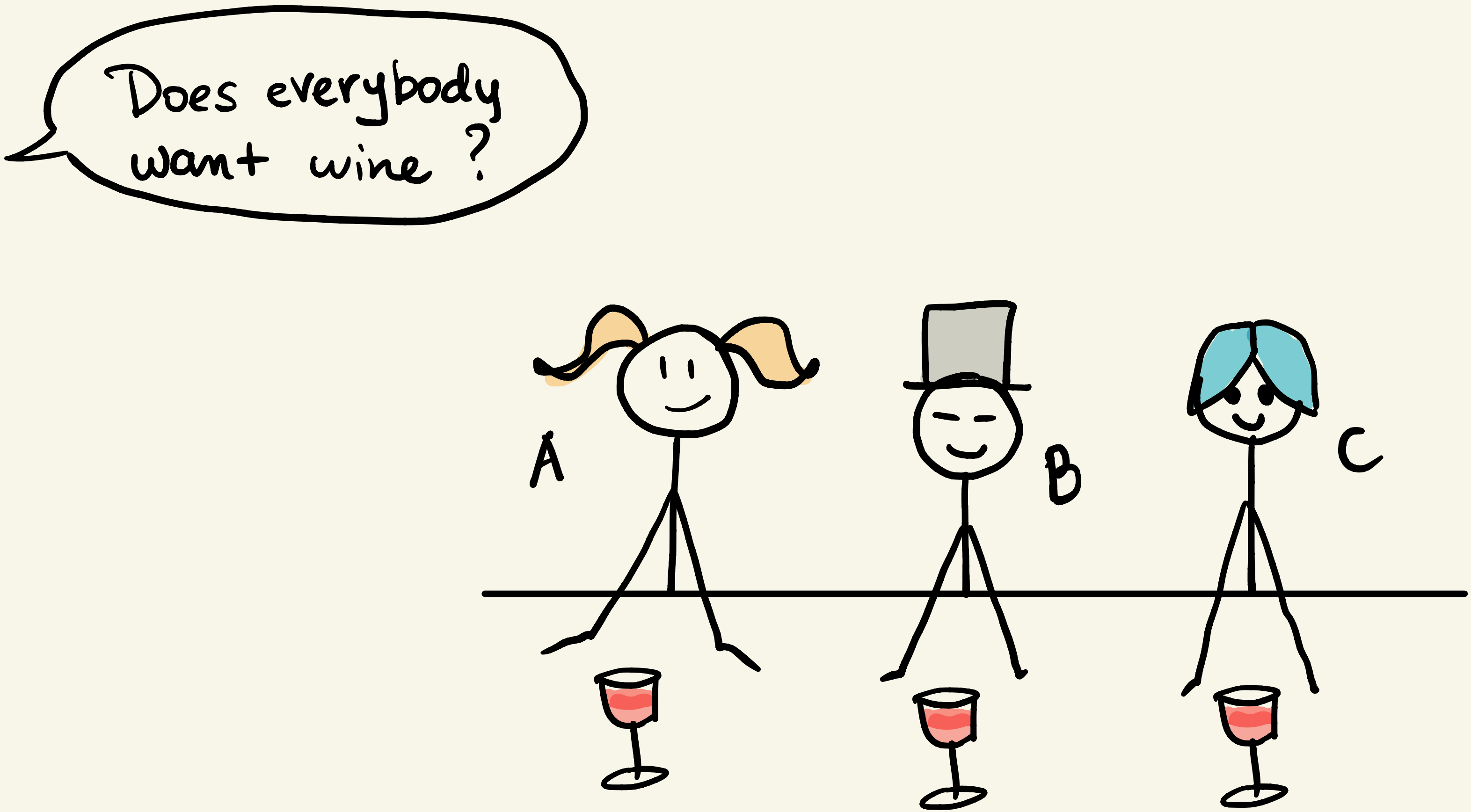
# Motivation: reasoning agents



# Motivation: reasoning agents



# Motivation: reasoning agents

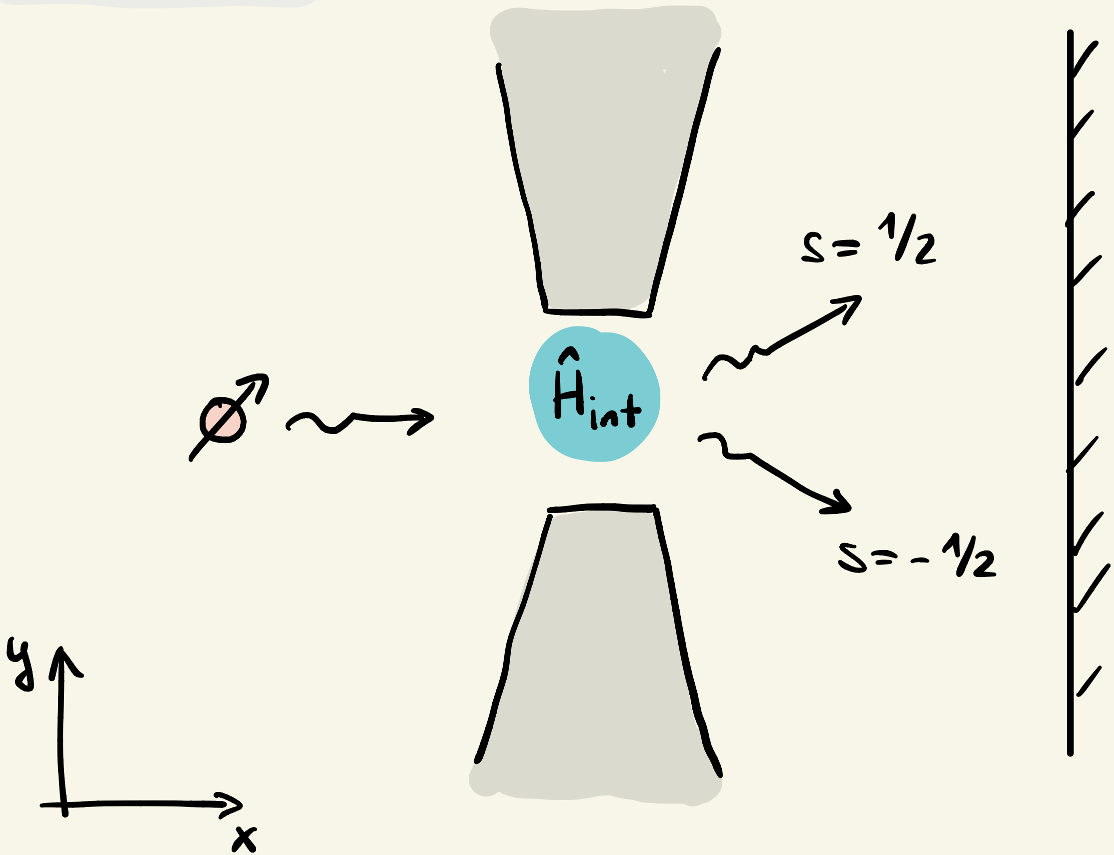


# Contents

# Part I. Building a paradox

* modeling measurements
* Wigner's friend
* Deutsch's friend
* reasoning agents & reasoning circuit
* FR thought experiment
* assumptions of FR

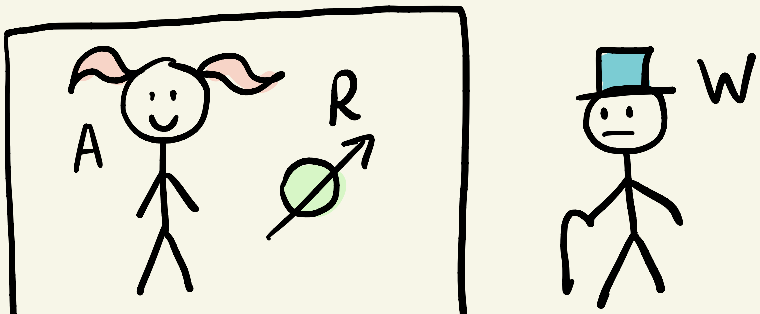
# Example: Stern-Gerlach experiment




$$\hat{H}_{int} = \hat{Z}_s \otimes \hat{Y}_y$$

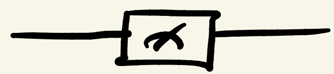
$$U = e^{-i\hat{H}_{int}t}$$

# Example: CNOT as memory update



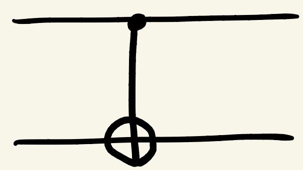

(Wigner's friend)

Alice: R $\alpha|0\rangle_R + \beta|1\rangle_R$



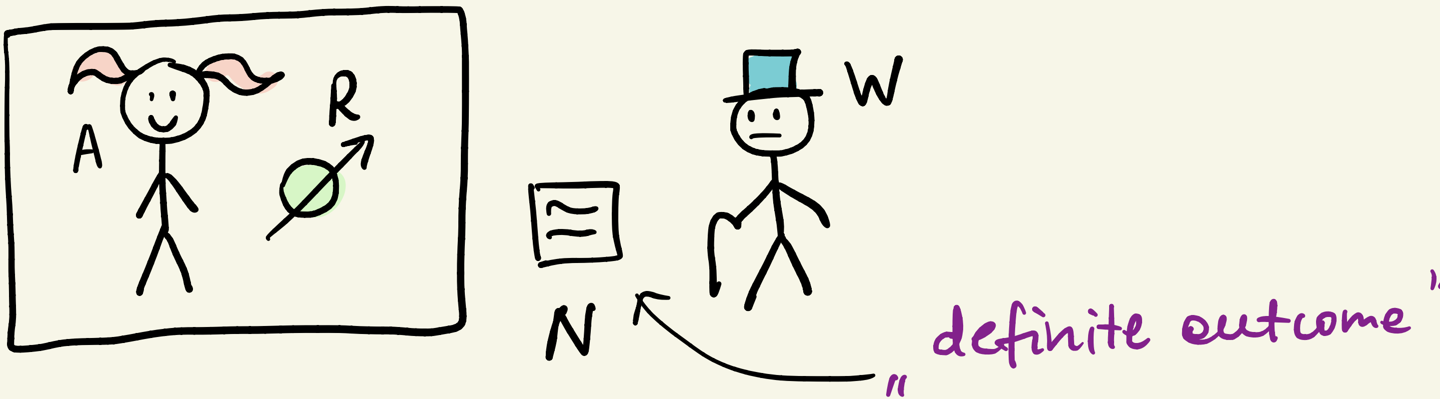
Wigner: R $\alpha|0\rangle_R + \beta|1\rangle_R$

A $|0\rangle_A$



$\alpha|00\rangle_{RA} + \beta|11\rangle_{RA}$

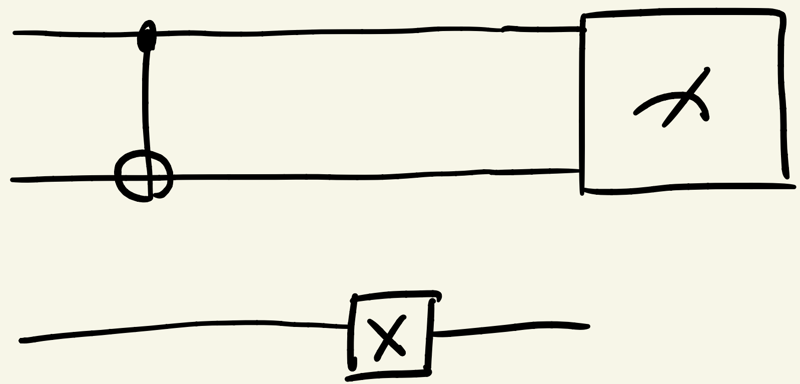
# Example: Deutsch's version of Wigner's friend




R $\alpha|0\rangle_R + \beta|1\rangle_R$

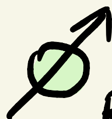
A $|0\rangle_A$

N $|0\rangle_N$



# Reasoning agents: example

A

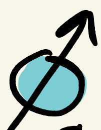


R

$$\frac{1}{\sqrt{3}}|0\rangle_R + \sqrt{\frac{2}{3}}\,|1\rangle_R$$

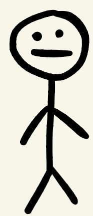
if $a=0$ $\quad |0\rangle_S$

if $a=1$ $\quad \frac{1}{\sqrt{2}}|0\rangle_S + \frac{1}{\sqrt{2}}|1\rangle_S$



S

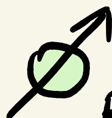
B



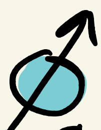
$b=1$

if $b=1$ what did Alice measure?

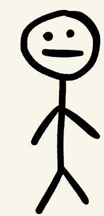
# Reasoning agents : example

A   R

$$\frac{1}{\sqrt{3}}|0\rangle_R + \sqrt{\frac{2}{3}}|1\rangle_R$$

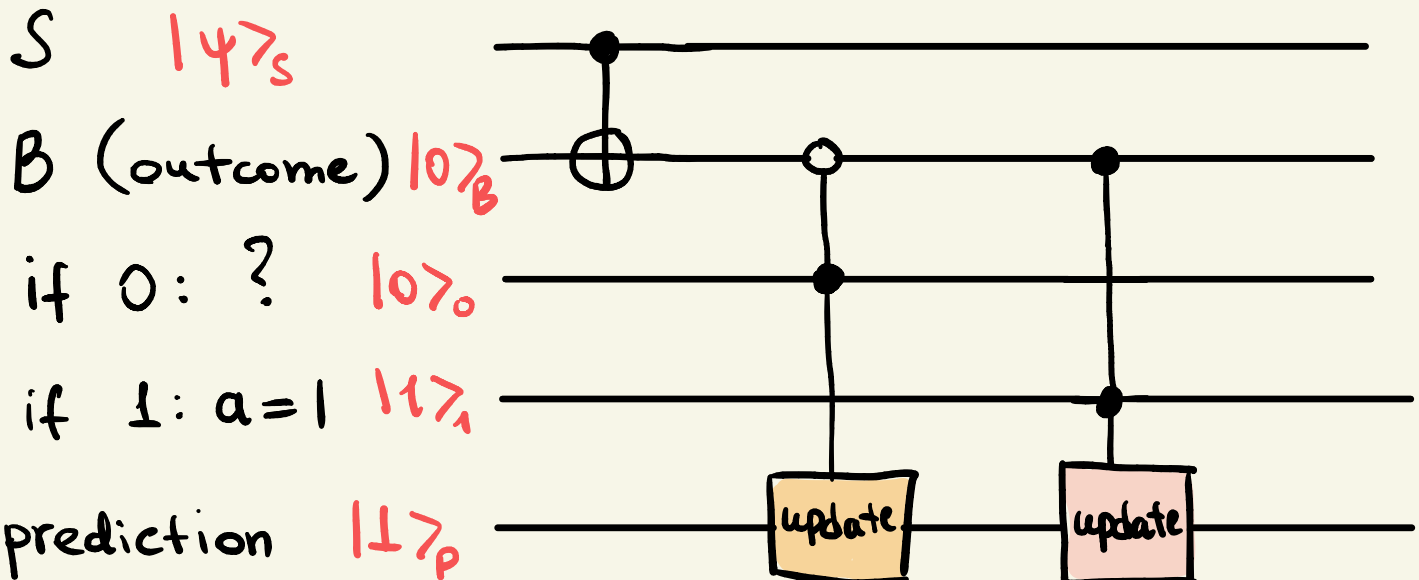
if $a=0$  S $|0\rangle_S$

if $a=1$ $\frac{1}{\sqrt{2}}|0\rangle_S + \frac{1}{\sqrt{2}}|1\rangle_S$

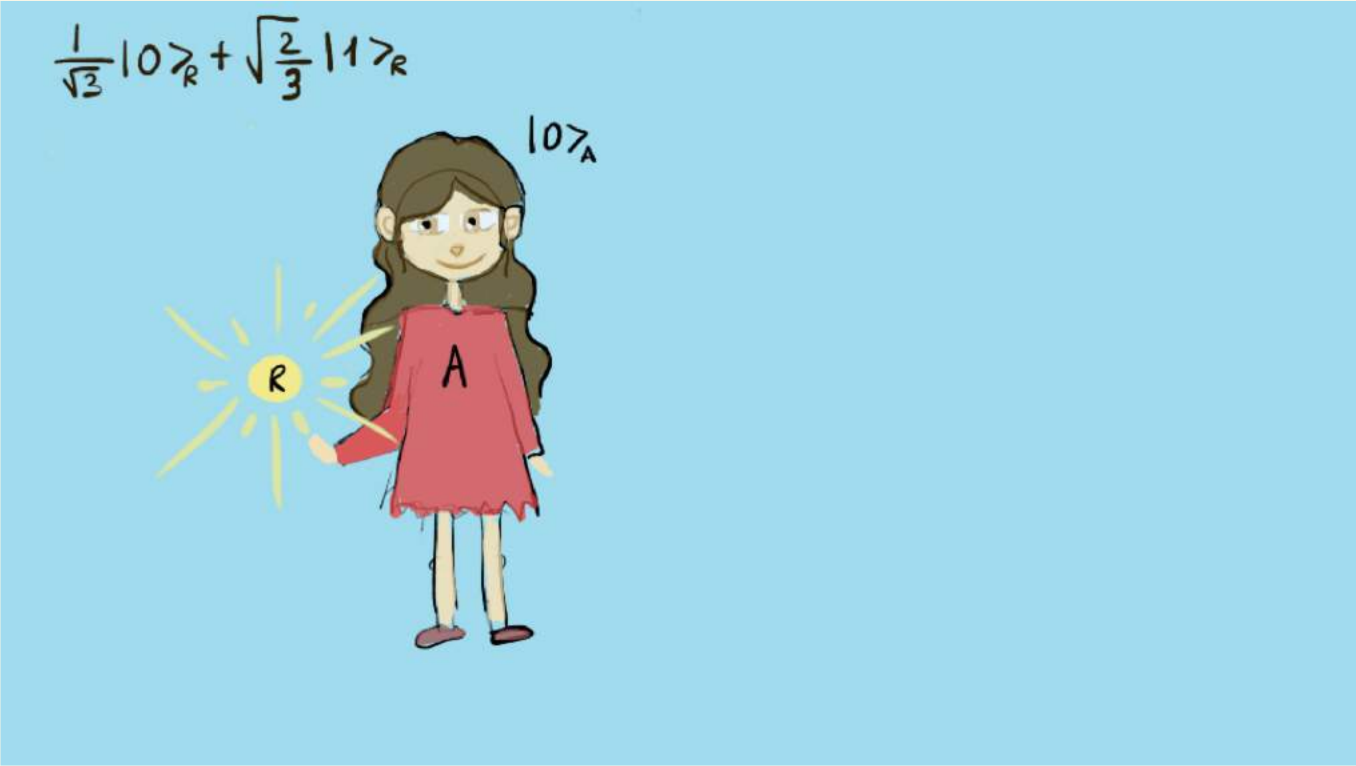
B  $b=1$

if $b=1$ what did Alice measure? $a=1$

# Example : reasoning as a circuit



# Testing example : FR thought experiment



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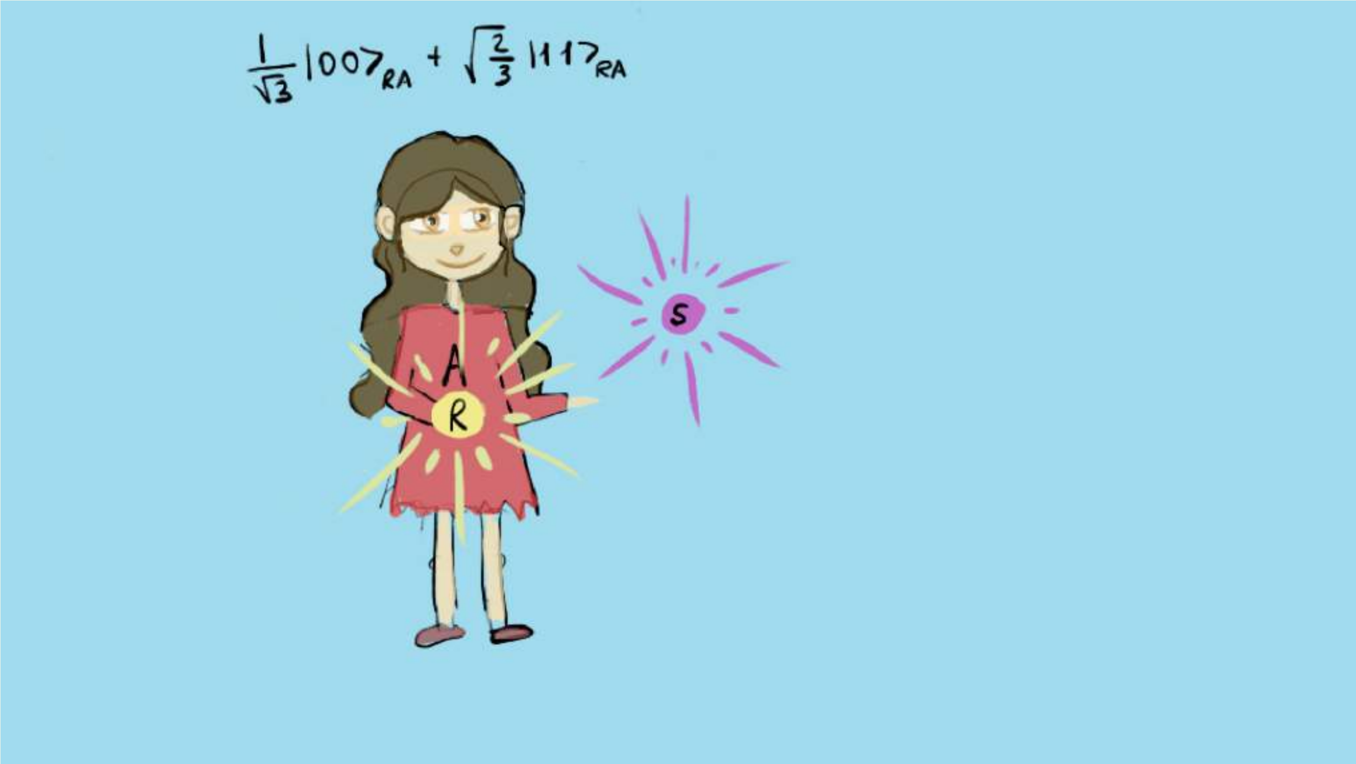

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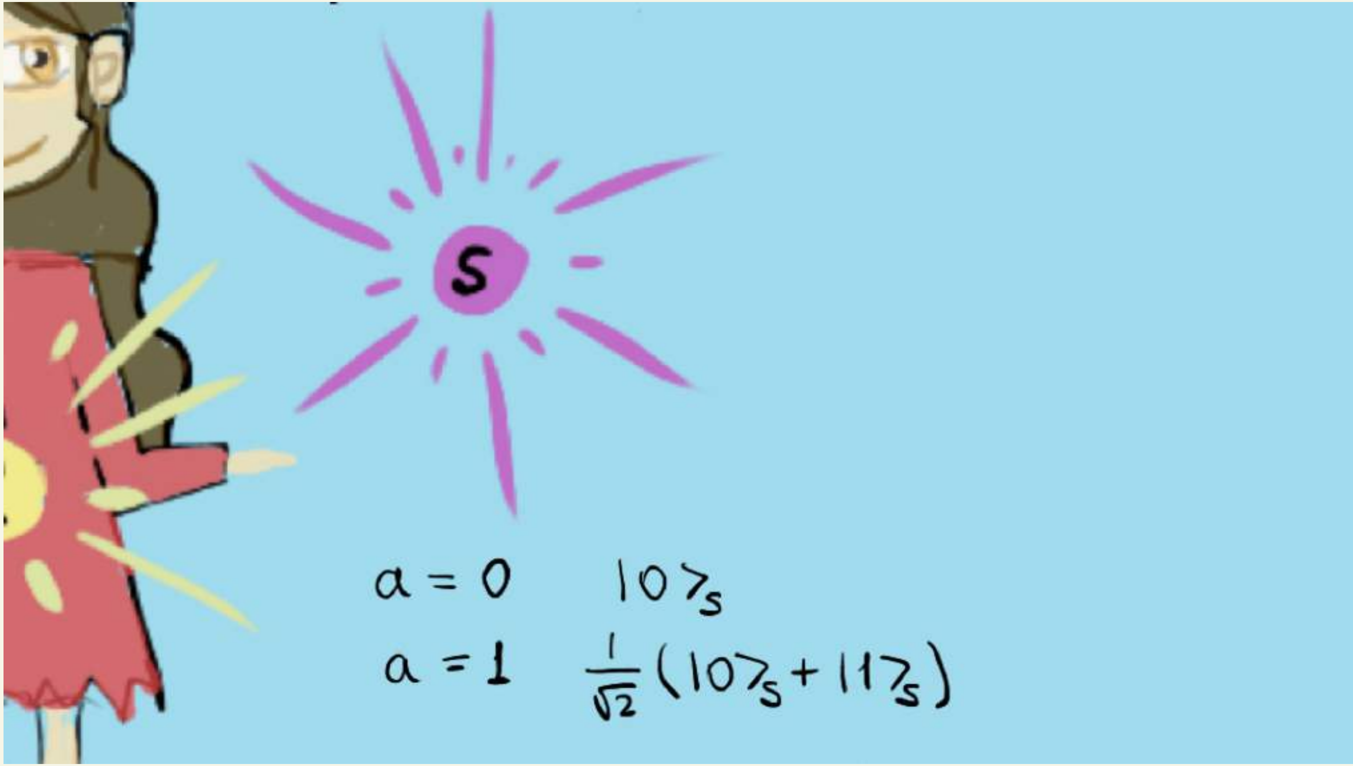

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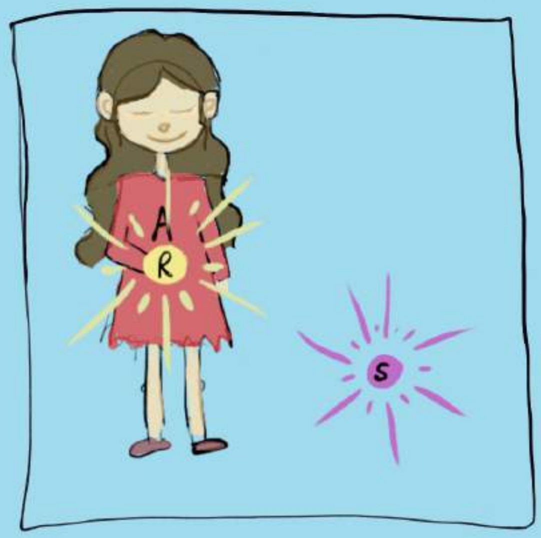
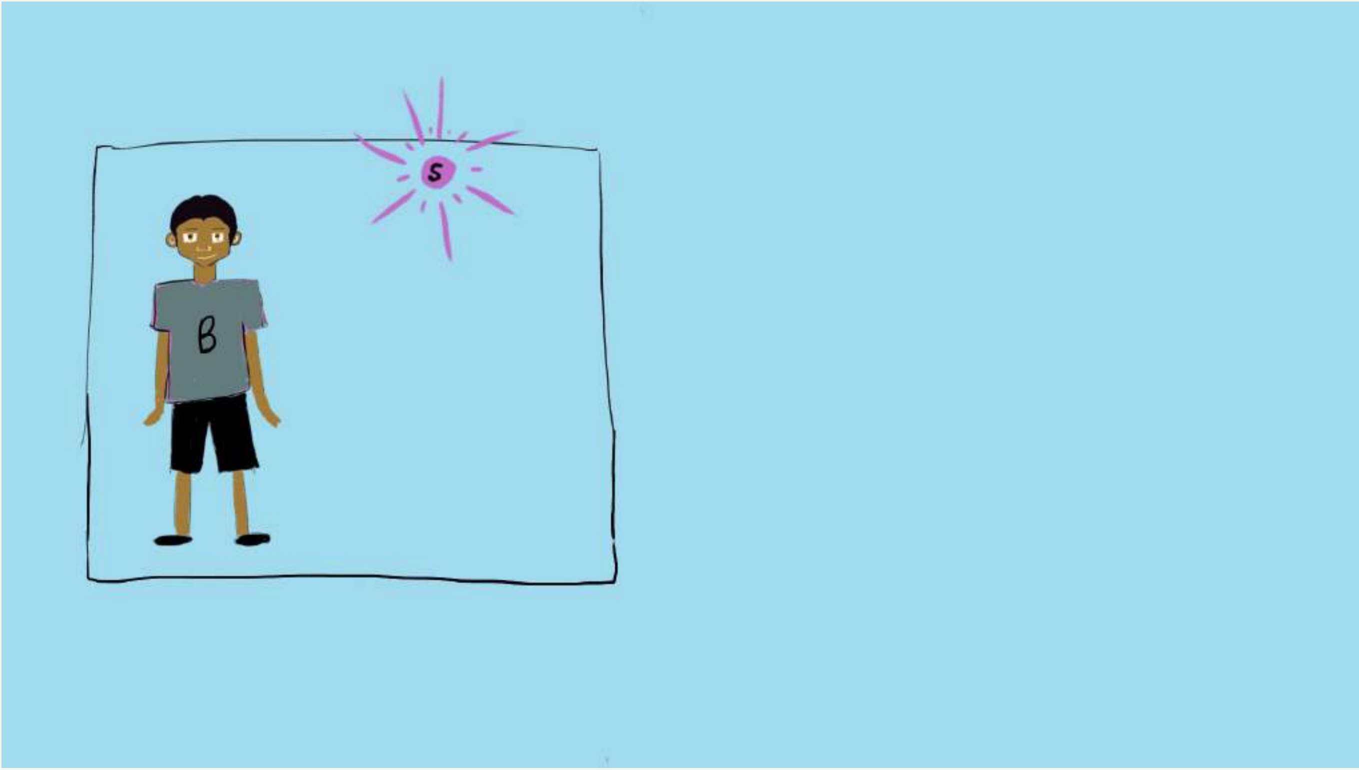
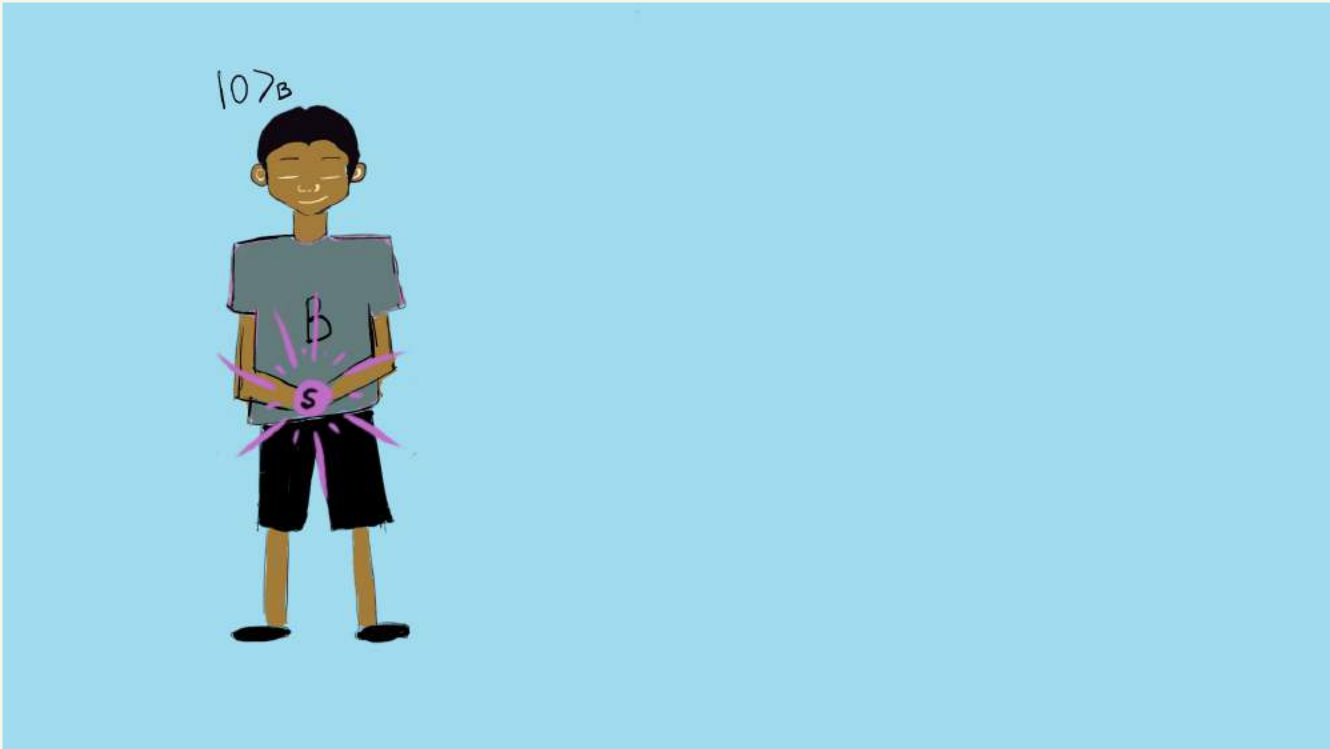



$$\frac{1}{\sqrt{3}}|00\rangle_{RA}|0\rangle_S + \frac{1}{\sqrt{3}}|11\rangle_{RA}|0\rangle_S + \frac{1}{\sqrt{3}}|11\rangle_{RA}|1\rangle_S$$

# Testing example: FR thought experiment



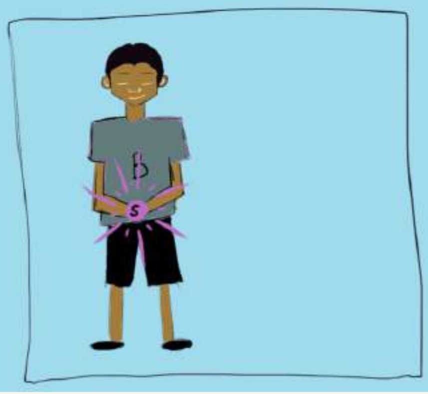
# Testing example : FR thought experiment



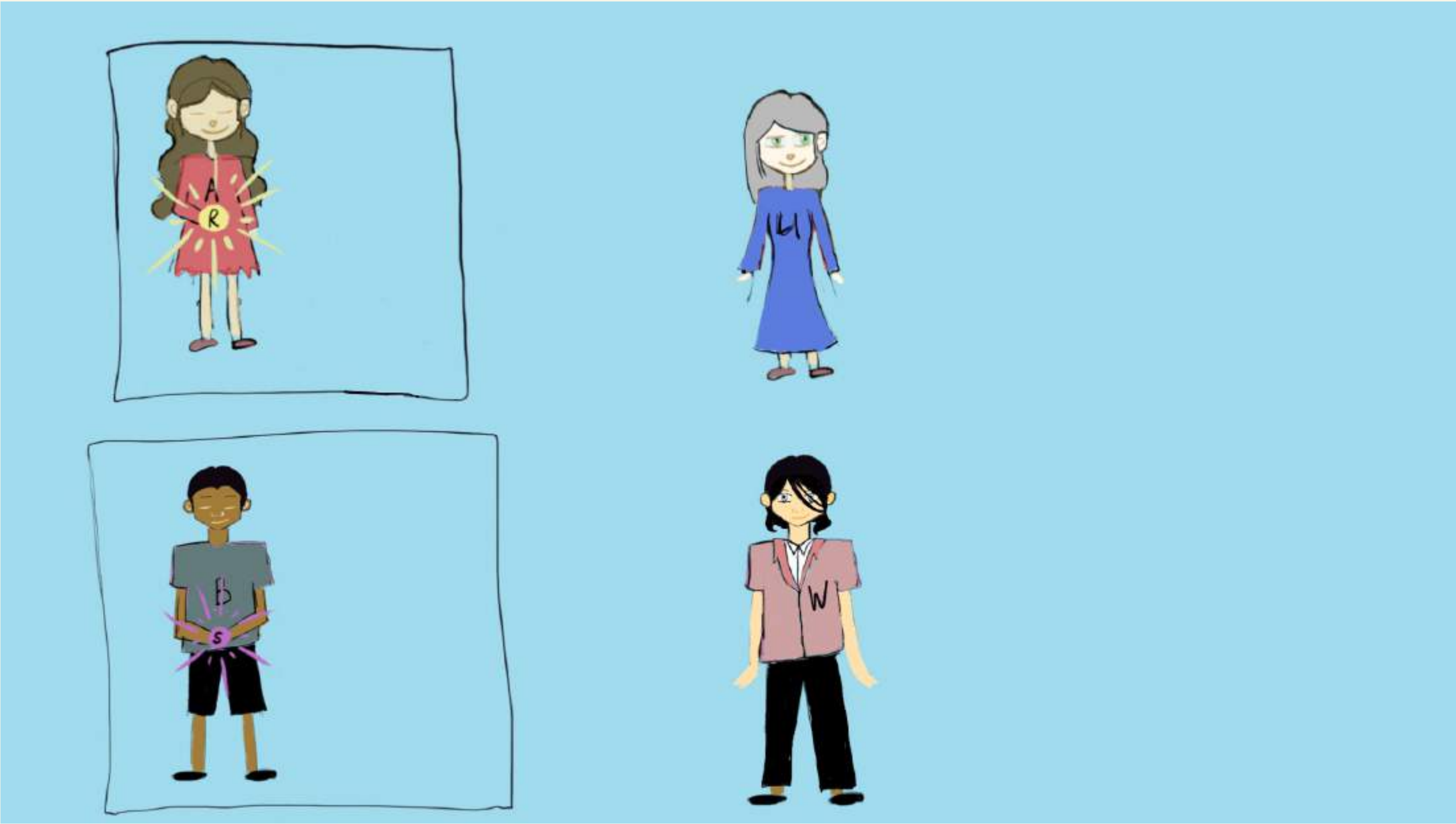
# Testing example : FR thought experiment


$$\frac{1}{\sqrt{3}}|00\rangle_{RA}|00\rangle_{SB}+\frac{1}{\sqrt{3}}|11\rangle_{RA}|00\rangle_{SB}+$$

$$+\frac{1}{\sqrt{3}}|11\rangle_{RA}|11\rangle_{SB}$$



# Testing example : FR thought experiment



# Testing example : FR thought experiment


$$|ok\rangle_{RA} = \frac{|00\rangle_{RA} - |11\rangle_{RA}}{\sqrt{2}}$$

$$|fail\rangle_{RA} = \frac{|00\rangle_{RA} + |11\rangle_{RA}}{\sqrt{2}}$$

$$|ok\rangle_{SB} = \frac{|00\rangle_{SB} - |11\rangle_{SB}}{\sqrt{2}}$$

$$|fail\rangle_{SB} = \frac{|00\rangle_{SB} + |11\rangle_{SB}}{\sqrt{2}}$$

## Testing example : FR thought experiment

$$\frac{1}{\sqrt{3}}|00\rangle_{RA}|00\rangle_{SB} + \frac{1}{\sqrt{3}}|11\rangle_{RA}|00\rangle_{SB} + \frac{1}{\sqrt{3}}|11\rangle_{RA}|11\rangle_{SB}$$

$$\frac{1}{\sqrt{3}}\underbrace{\left(|00\rangle_{RA}+|11\rangle_{RA}\right)}_{\substack{|fail\rangle_{RA} \\ (\text{Ursula})}}|00\rangle_{SB} + \frac{1}{\sqrt{3}}|11\rangle_{RA}|11\rangle_{SB}$$

$$\boxed{u = ok \implies b = 1}$$

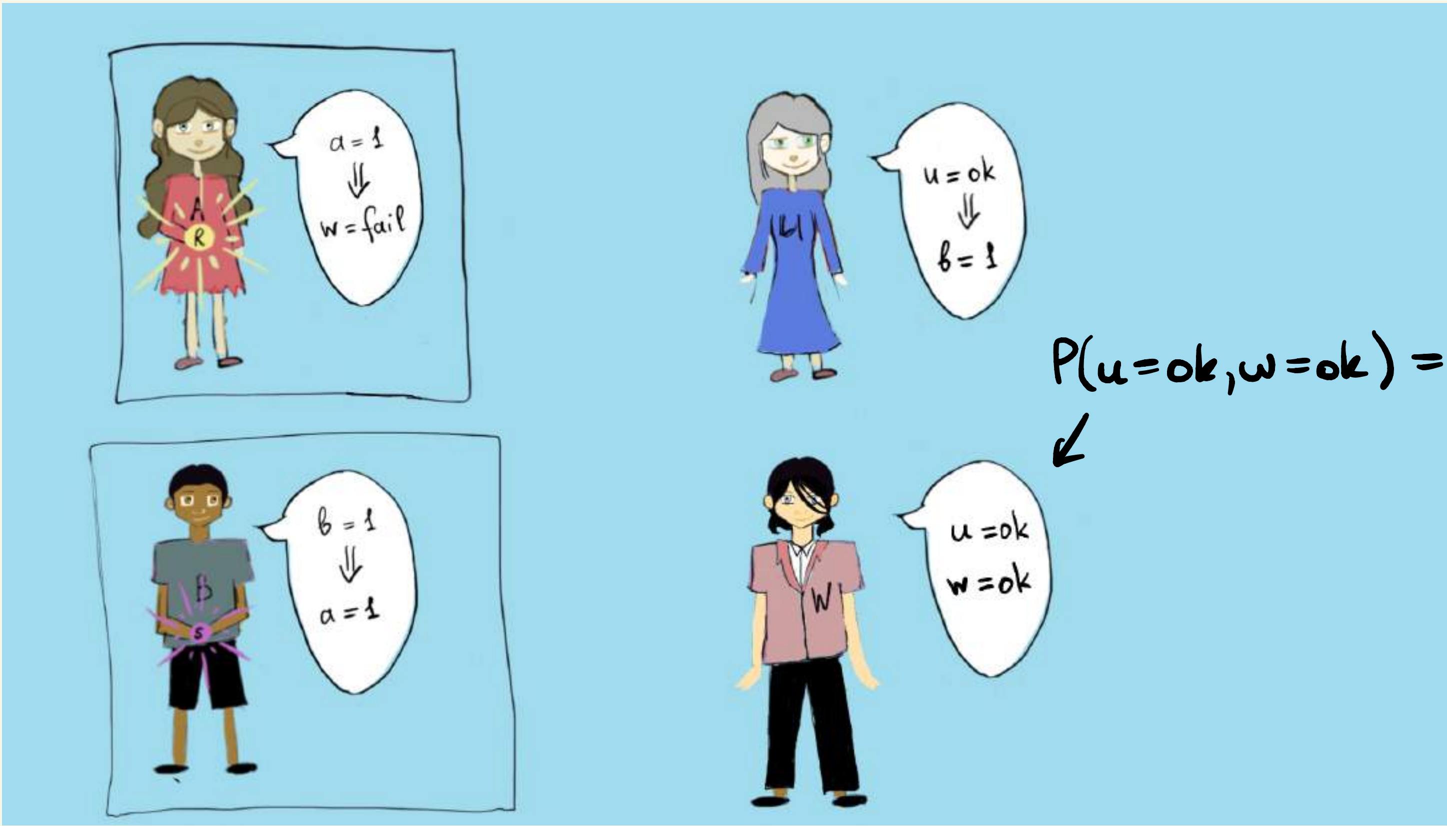
## Testing example: FR thought experiment

$$\frac{1}{\sqrt{3}}|00\rangle_{RA}|00\rangle_{SB} + \frac{1}{\sqrt{3}}|11\rangle_{RA}|00\rangle_{SB} + \frac{1}{\sqrt{3}}|11\rangle_{RA}|11\rangle_{SB}$$

$$\frac{1}{\sqrt{3}}|00\rangle_{RA}|00\rangle_{SB} + \frac{1}{\sqrt{3}}|11\rangle_{RA}\underbrace{\left(|00\rangle_{SB} + |11\rangle_{SB}\right)}_{|\text{fail}\rangle_{SB}\ (\text{Wigner})}$$

$$\boxed{a=1 \Rightarrow w=\text{fail}}$$

# Testing example: FR thought experiment




$$P(u=ok, w=ok) = \frac{1}{12} > 0$$

# Testing example : FR thought experiment

# Testing example : FR thought experiment

. . .

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

$\rightarrow$ paradox!

# Assumptions

Logic

Consistency : $b=1$ and $b=1 \Rightarrow a=1$ $\Rightarrow$ $a=1$

Single outcome : $b=1$ or $b=0$

Interpretation

Quantum theory : deterministic Born rule

( Unitarity : modeling evolution as unitary )

# Part II. Paradoxes and interpretations.

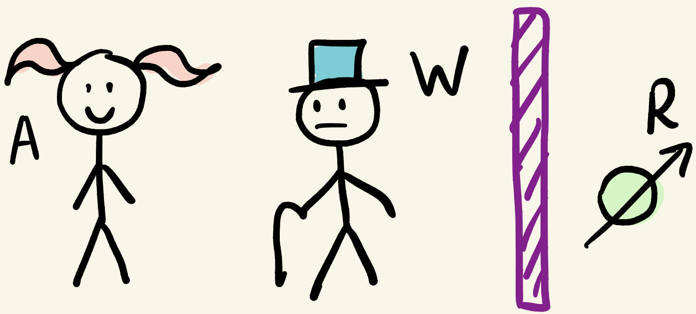
* interpretations : crash course & classification
* FR and interpretations
* main objections
* software to test interpretations & objections

# Interpretations

## Range of applicability + role of agents

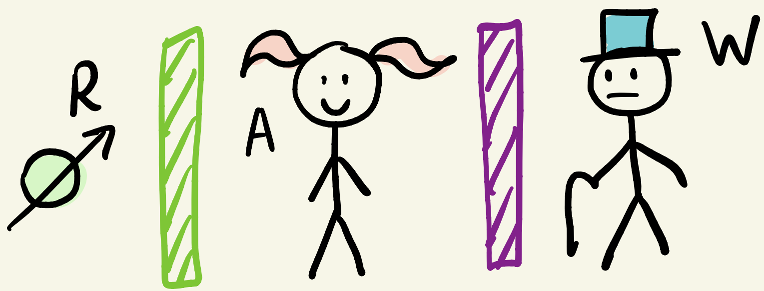
| Observer required | | |
|---|---|---|
| *Interpretation* | *Features* | *Range of applicability of QT* |
| Conventional Copenhagen | objective cut between the observer and the observed | any system under the cut |
| Neo-Copenhagen | subjective cut between the observer and the observed | any system under the cut |
| QBism | theory applied from perspective of observer | any system excluding the observer |
| Many-worlds | measurements by observer induce branching into worlds | entire universe |
| **No observer required** | | |
| *Interpretation* | *Features* | *Range of applicability of QT* |
| Bohmian mechanics | complements quantum theory with hidden variables | entire universe |
| Relational quantum mechanics | description always relative to another system | any system in relation to another |
| ETH approach | considers restricted set of observables | dependent on set of observables |
| Consistent histories | considers restricted set of possible events | dependent on set of events |
| Objective collapse theories (GRW) | modification of Schrödinger equation yields non-unitarity | microscopic systems |
| Montevideo interpretation | gravitation induces non-unitarity | microscopic systems |

# Interpretations (& FR)




## Copenhagen:

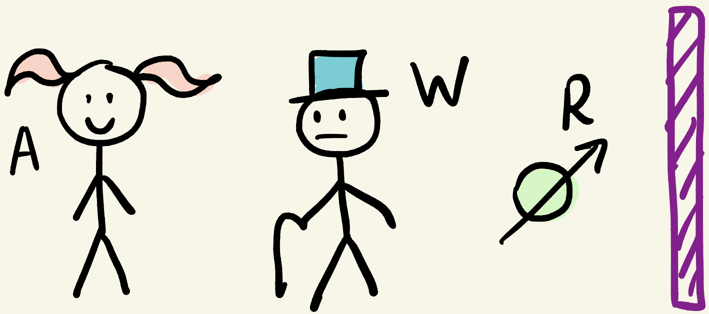
cut the same for all observers




## Neo-Copenhagen:

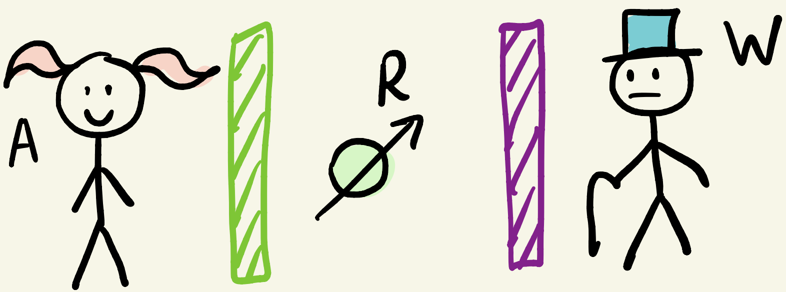
subjective cut

# Interpretations (& FR)




**Many-worlds:**

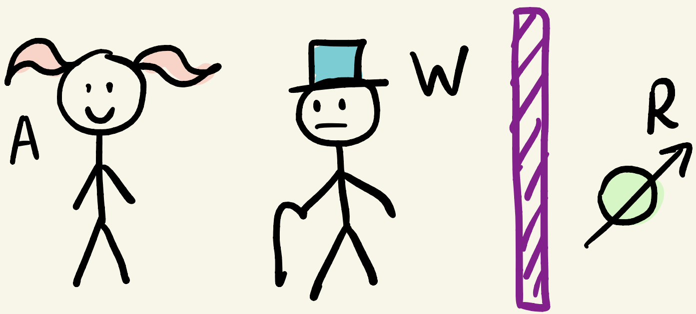
the entire universe is below the cut




**QBism:**

any observer is above their own cut

# Interpretations (& FR)




## Collapse theories:

the cut is fundamentally fixed

(only microscopic systems under)

# Main objections

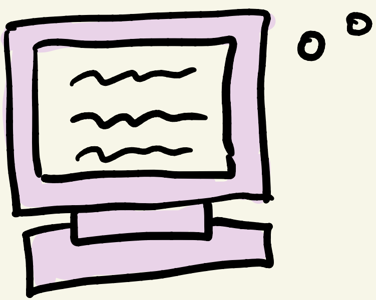
* agents = abstract info-processing systems ?
* sharing reference frames ?
* logic is bad ?
* statements are probabilistic ?
* agents are „Hadamarded" TM Scott Aaronson ?
* ... ?

# Software package

Logic

Agent

Interpretation



Protocol

1. ....
2. ...
3. ....

→ conclusion!

# Come and test:

your favorite axiom system

**Logic**

- modal logic
- paraconsistent
- ...

your model for

**Agent**

your preferred

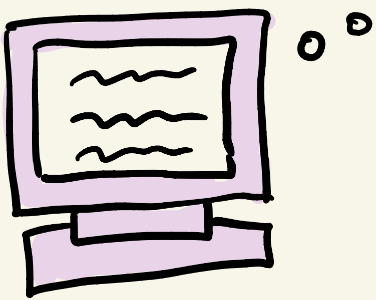
**Interpretation**

- (neo) Copenhagen
- collapse theories
- ...

desired communication

**Protocol**

1. ....
2. ...
3. ....



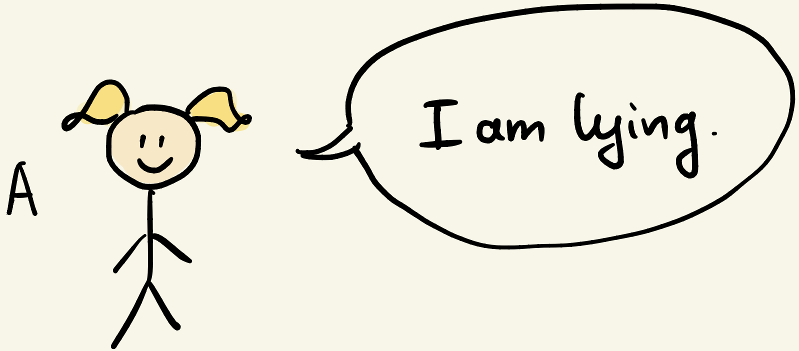
Conclusion!

[Consistent or inconsistent]

# Part III. Generalizing the paradox.

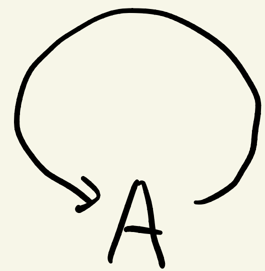
* classical paradoxes of knowledge
* reference relation graphs & cycles
* non-transitivity of QM
* contextuality & contexts in FR
* paradoxes $\Rightarrow$ contextuality

# Classical paradoxes of knowledge




$s_A = 1 \implies s_A = 0$

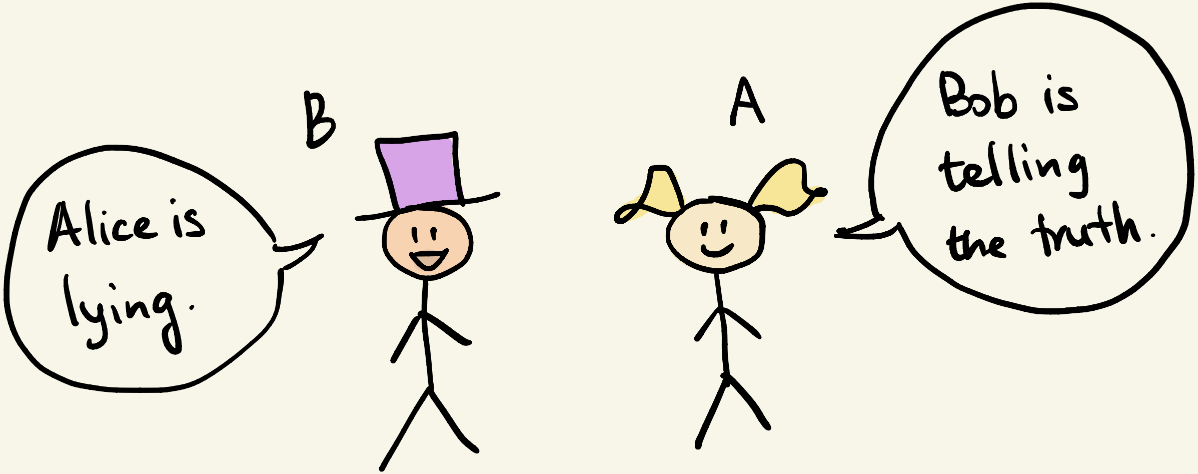
$s_A = 0 \implies s_A = 1$




(reference graph)

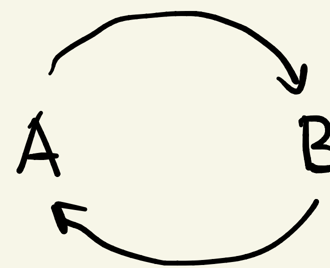
$\longrightarrow$ no valid evaluation of $s_A$ !

# Classical paradoxes of knowledge




$$S_A = 1 \Rightarrow S_B = 1 \Rightarrow S_A = 0$$

$$S_A = 0 \Rightarrow S_B = 0 \Rightarrow S_A = 1$$




2-cycle

# Non-transitivity of QM

Classical: $b=1 \Rightarrow a=1 \Rightarrow w=\text{fail}$

$\Rightarrow \quad b=1 \Rightarrow w=\text{fail}$

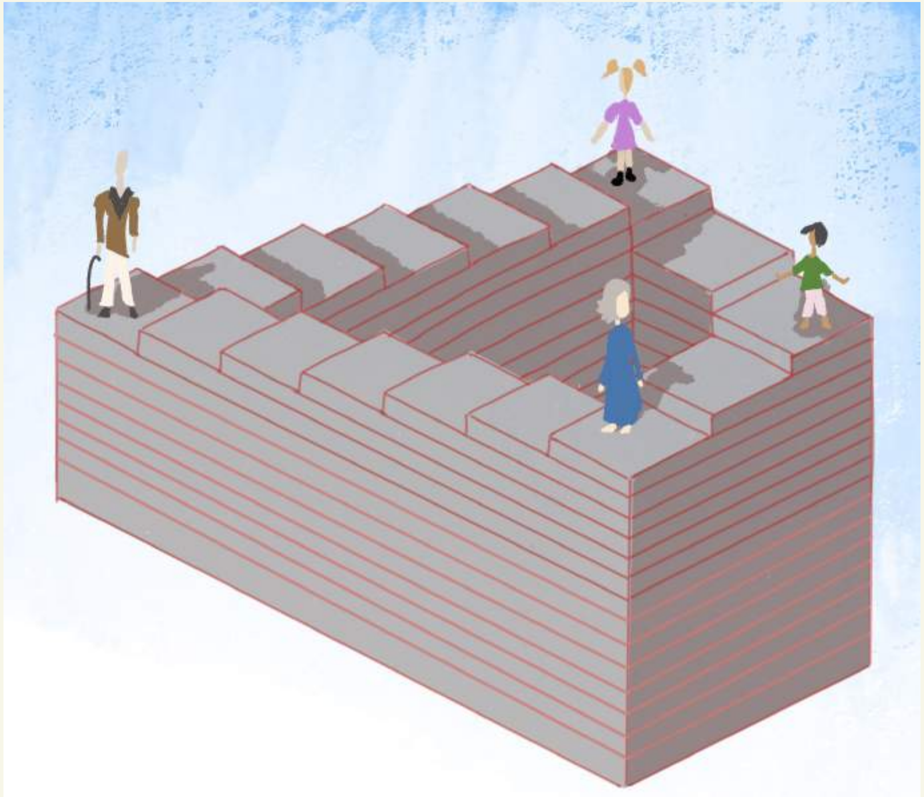
Quantum: $b=1 \Rightarrow a=1 \Rightarrow w=\text{fail}$

$\not\Rightarrow \quad b=1 \Rightarrow w=\text{fail}$

$[\Pi_b, \Pi_a] = 0 \qquad [\Pi_a, \Pi_w] = 0$

$[\Pi_b, \Pi_w] \neq 0$ $\longrightarrow$ no valid probability distribution

# Contexts



locally consistent
&
globally inconsistent

# Contexts

Meas. scenario : $(X, \mathcal{M}, O)$

Set of variab. Contexts Set of outcomes

$\boxed{C \in \mathcal{M}}$ $s : C \to O^C$ mapping of outcomes

Compatible assignments : $s_C|_{C \cap C'} = s_{C'}|_{C \cap C'}$

Contextuality : $\exists\, s$ which is not compatible

# Contextuality & paradox

we discover a multi-agent paradox

$\Downarrow$

we recover a reference cycle

$\Downarrow$

if non-contextual : $\exists \; P(a_1, \ldots, )$

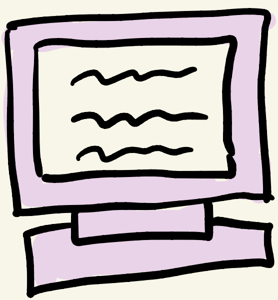
$\Downarrow$

no paradox! $\longrightarrow$ contextual!

Github repo →

Thought exp. & interpret. →

Thank you for your attention!



to be continued ...