Resetting uncontrolled quantum systems

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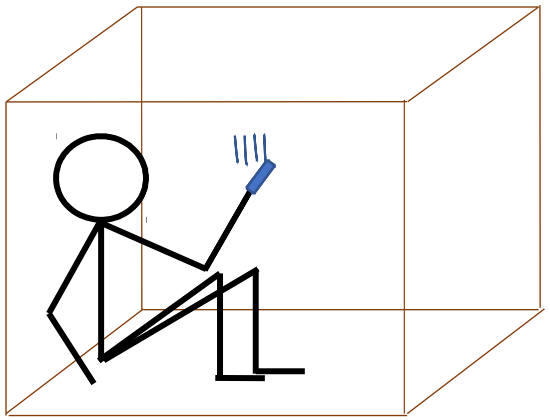
MN, arXiv:1710.02470

Time-warp

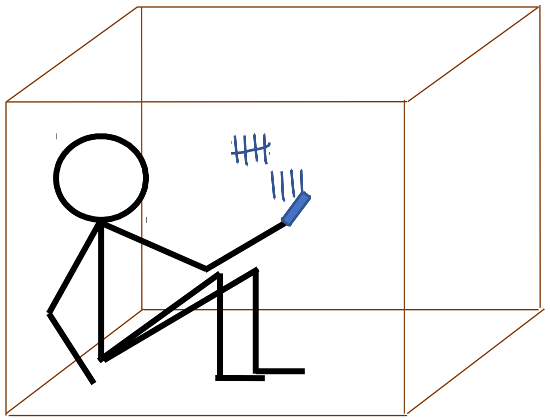
**noun | \ ˈtīm ˈwȯrp **

Definition of TIME-WARP

1. an anomaly, discontinuity, or suspension held to occur in the progress of time

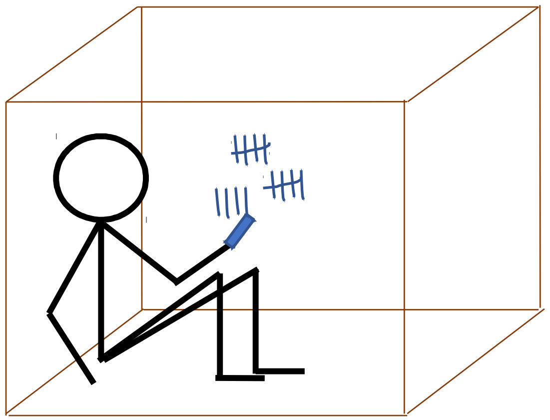


$t = 0$



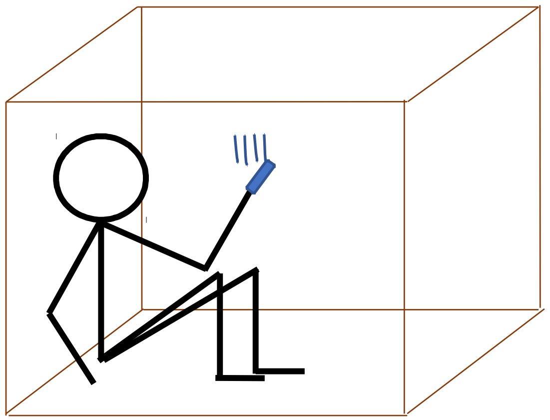
$t = 1$ hour

hour



$t = 12$ hours

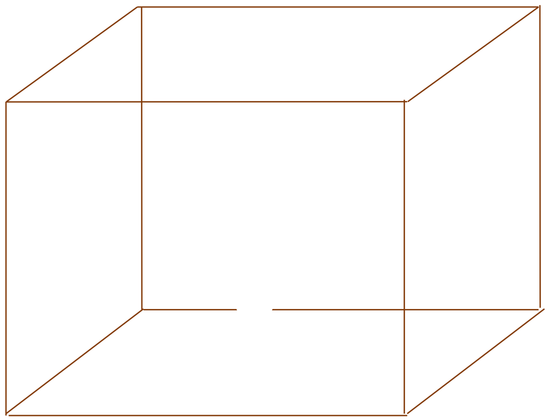
hours



$t = 0$

Time warp for two hours

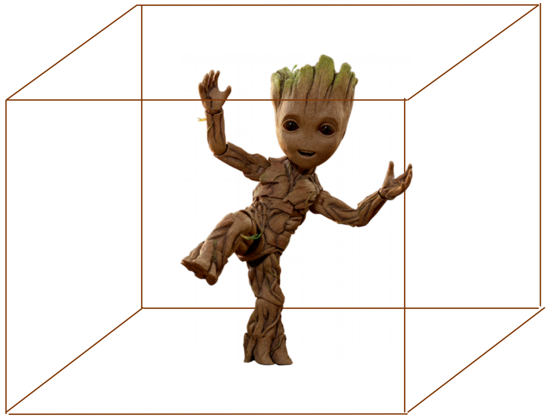
What should we find in the box if we are to claim a time warp experience?

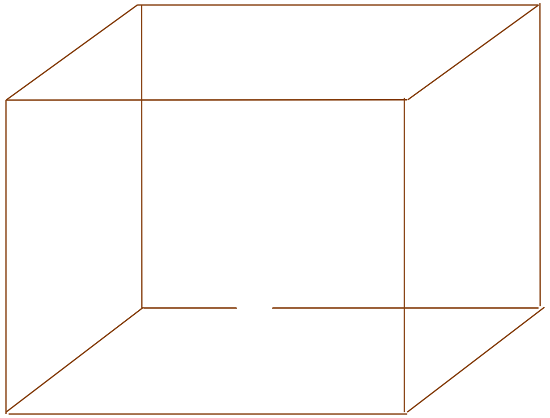


$t = 2$ hours

hours

Not expected

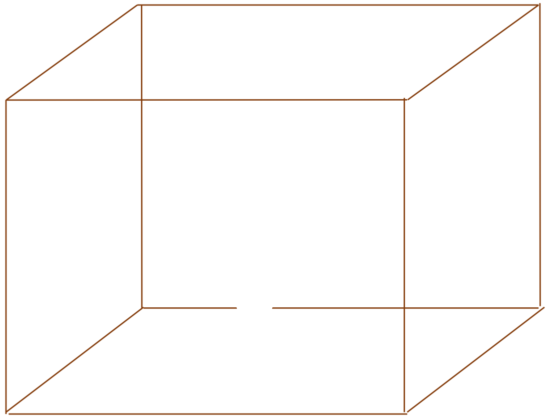




$t = 2$ hours

hours

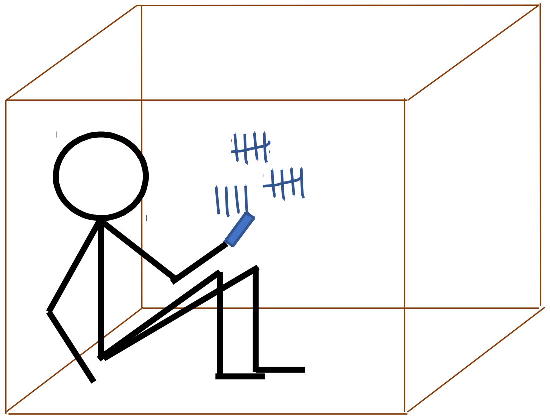
Not expected

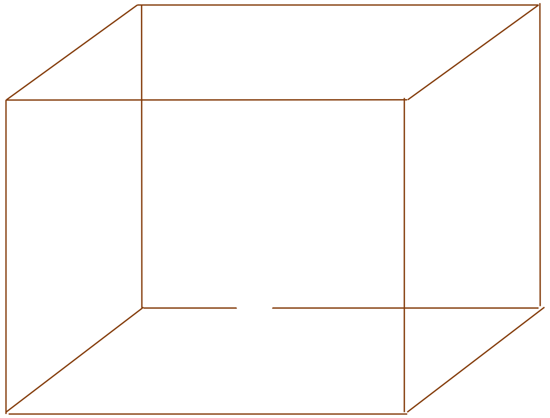


$t = 2$ hours

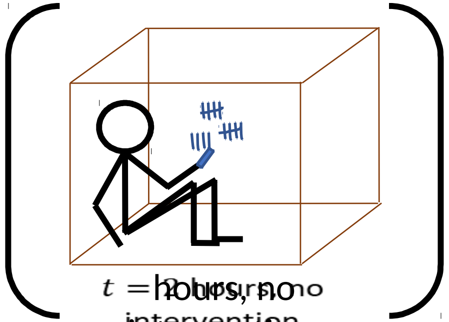
hours

Not expected



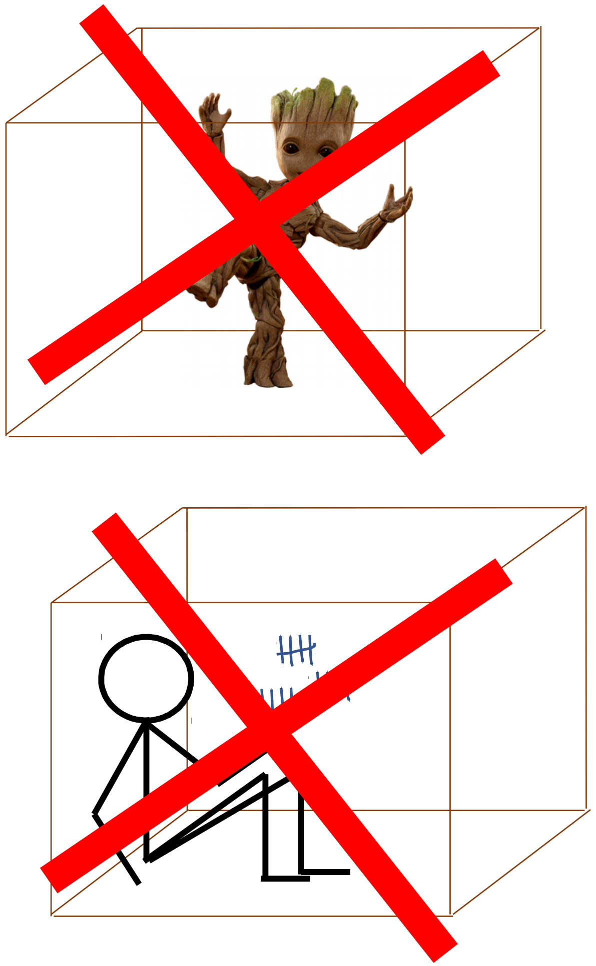


$t = 2$ hours

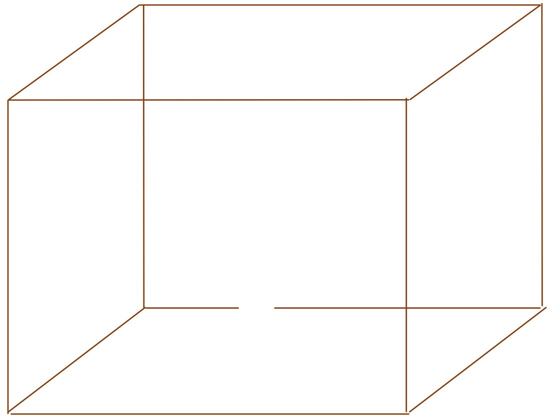


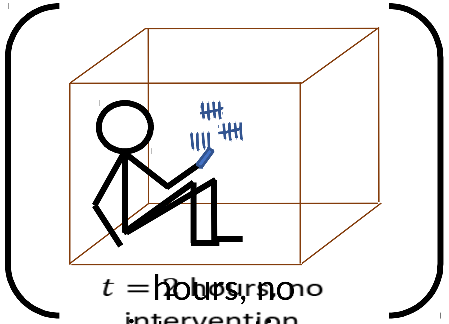
$t = 2$ hours, no intervention

Not expected



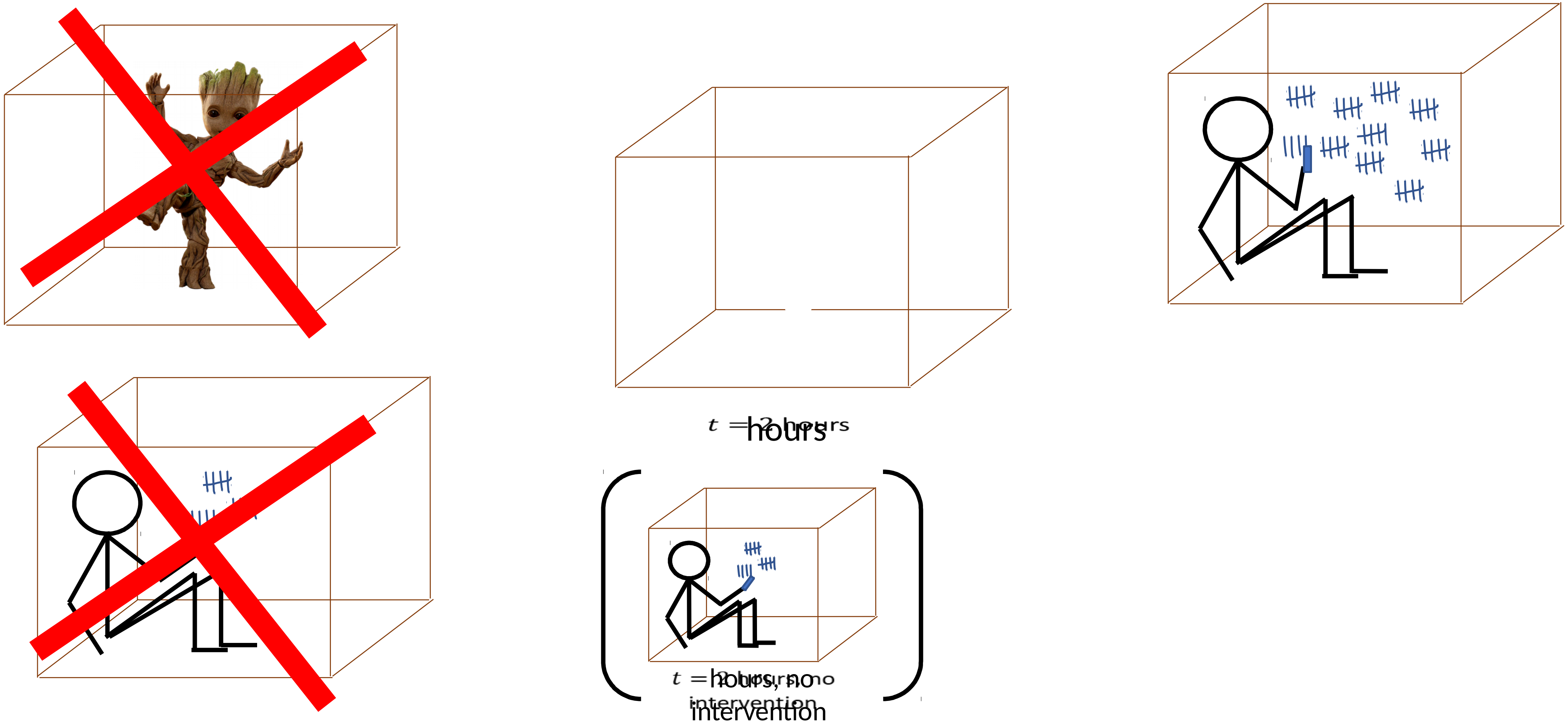
Expected

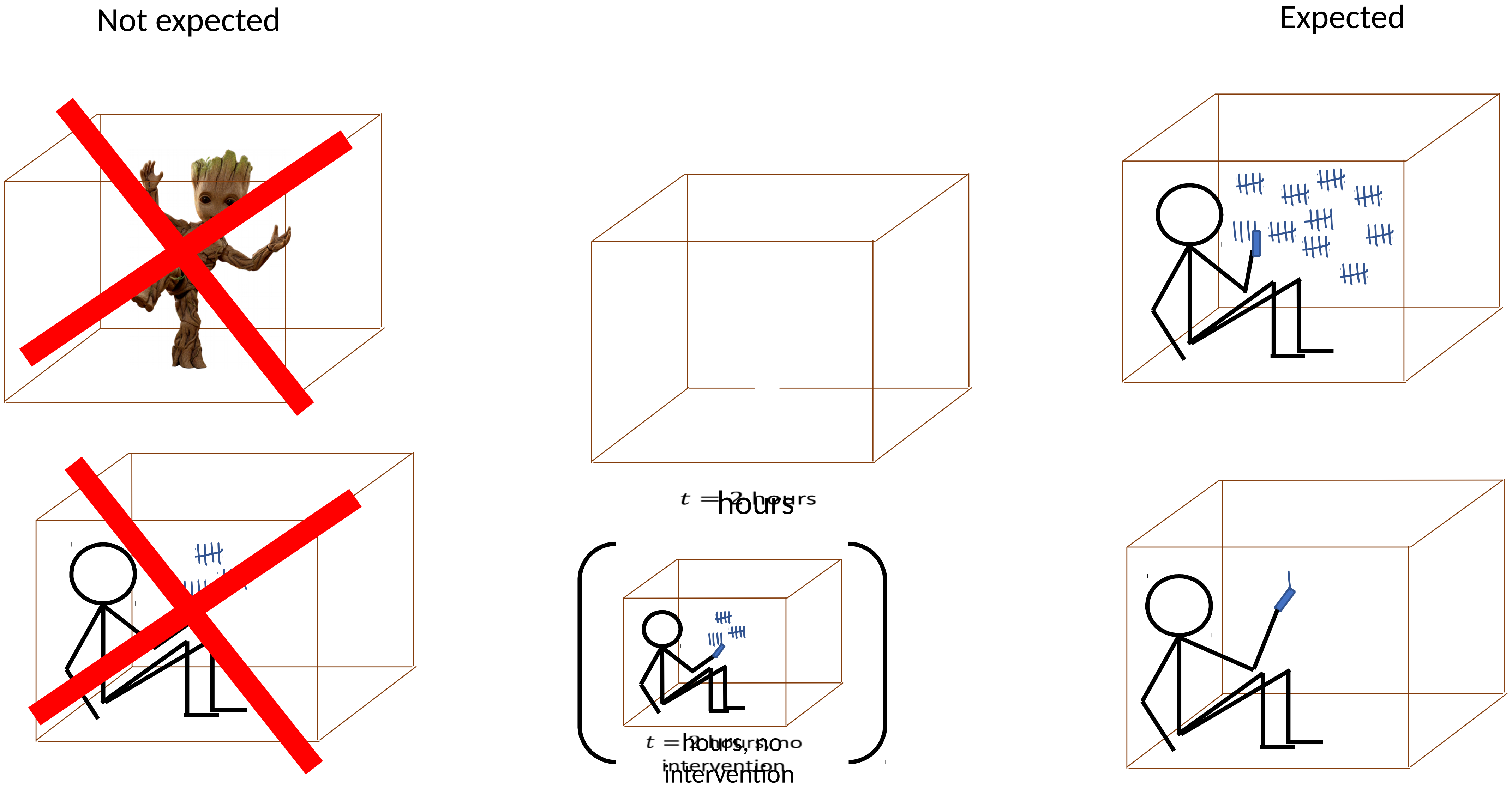




Not expected

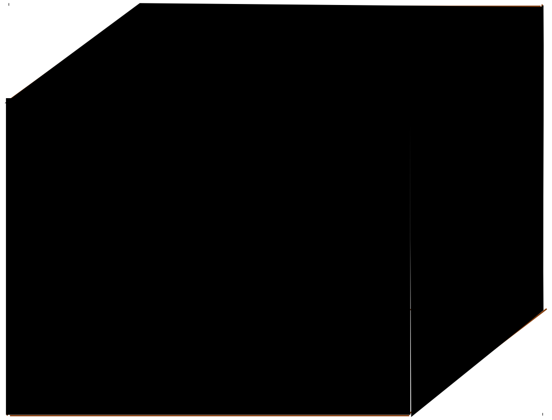
Expected





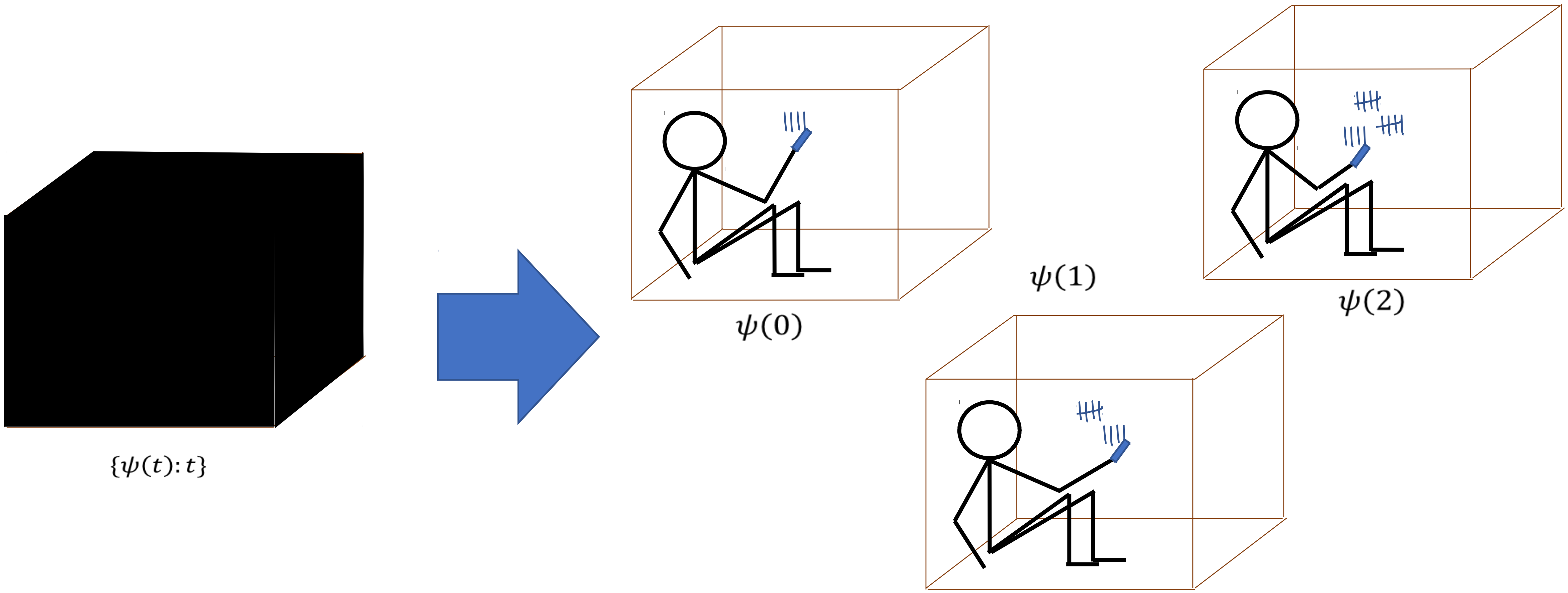
Not expected
Expected
t = 2 hours
t = 2 hours, no intervention

Time warp: operational definition



$\{\psi(t) : t\}$

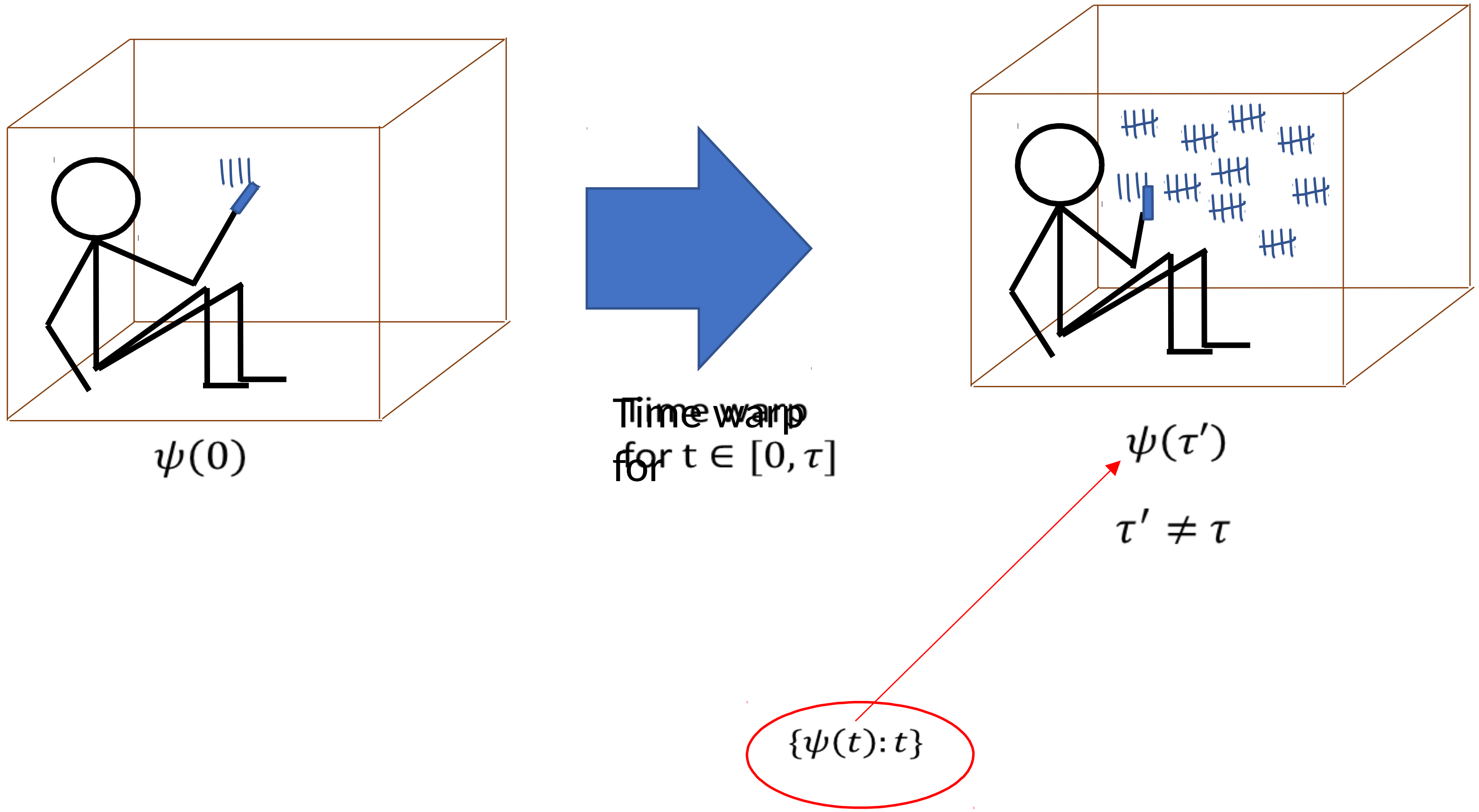
Time warp: operational definition



Time warp: operational definition

Time warp protocol for $t \in [0, \tau]$
Time warp protocol for

Time warp: operational definition

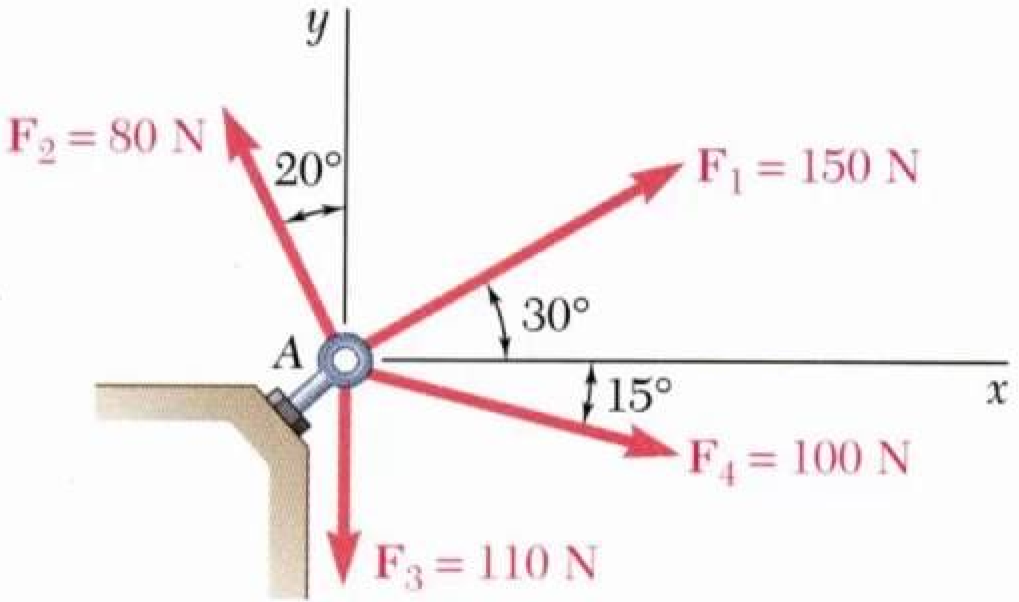



A brief history of time warp

King Raivata and princess Revati (400BC?)

Peter Damian
(1007-1072)

(first edition in 1895)

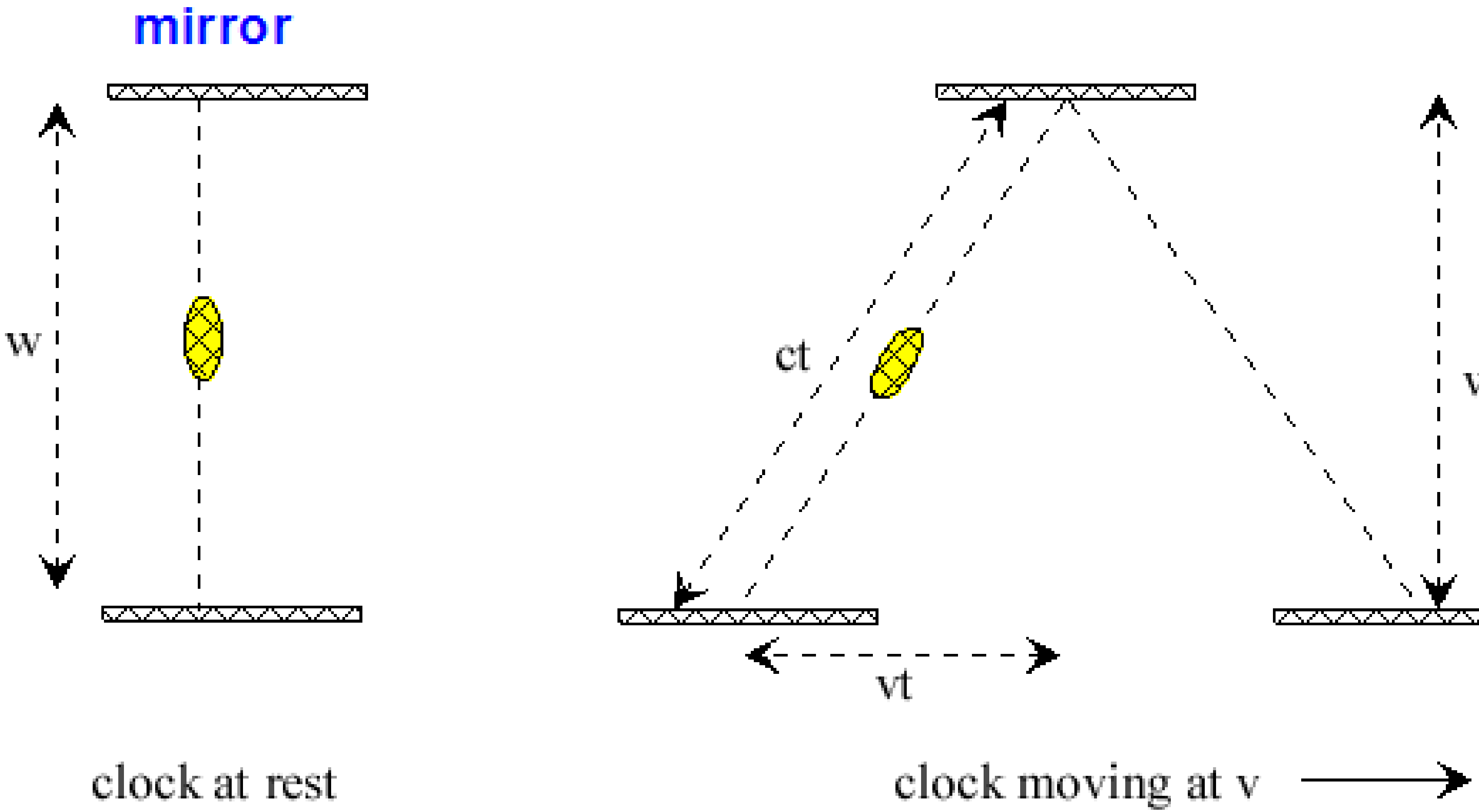


- Resolve each force into rectangular components.
- Determine the components of the resultant by adding the corresponding force components.
- Calculate the magnitude and direction of the resultant.

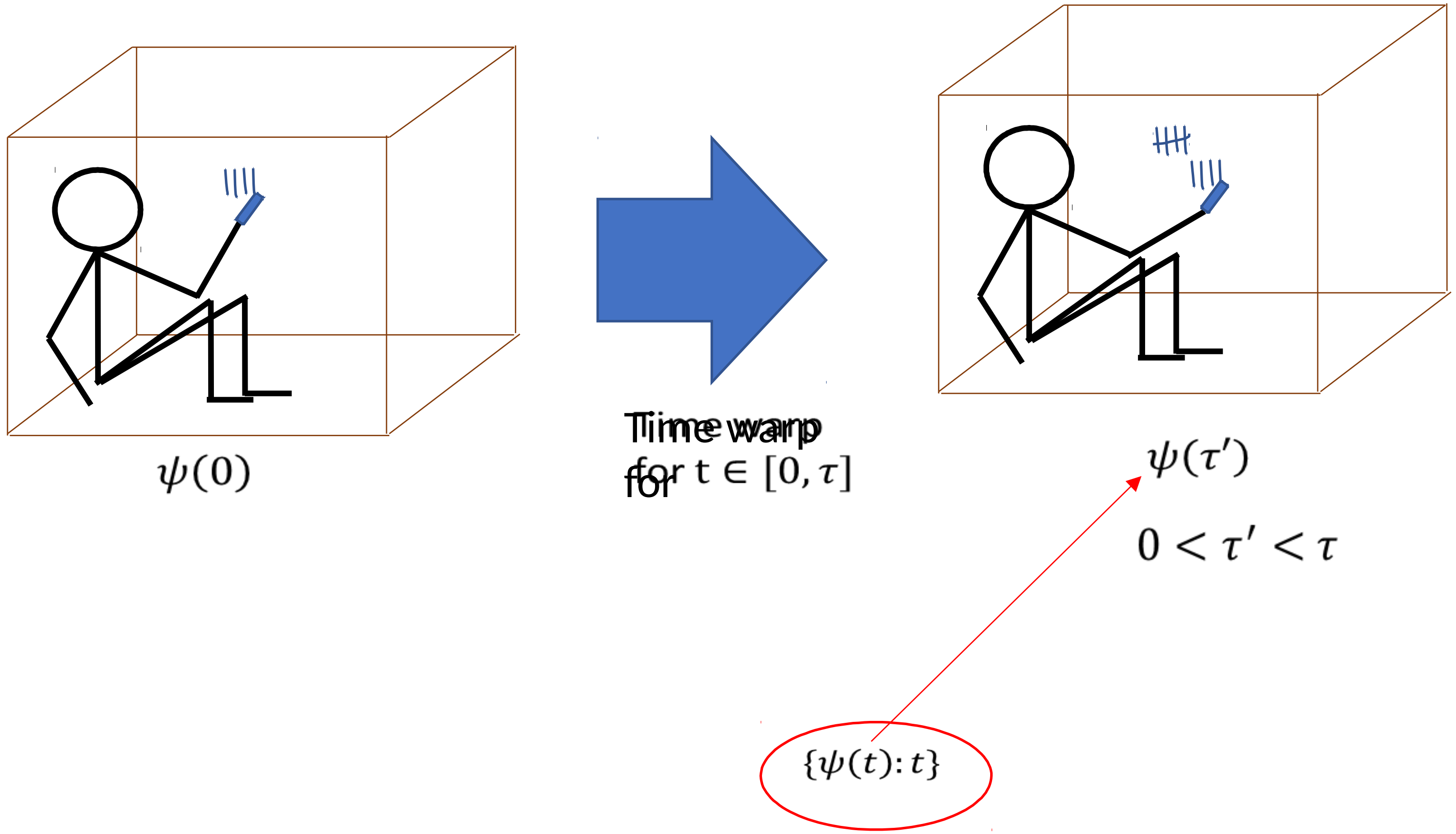
Four forces act on bolt *A* as shown. Determine the resultant of the force on the bolt.


CALIFORNIA

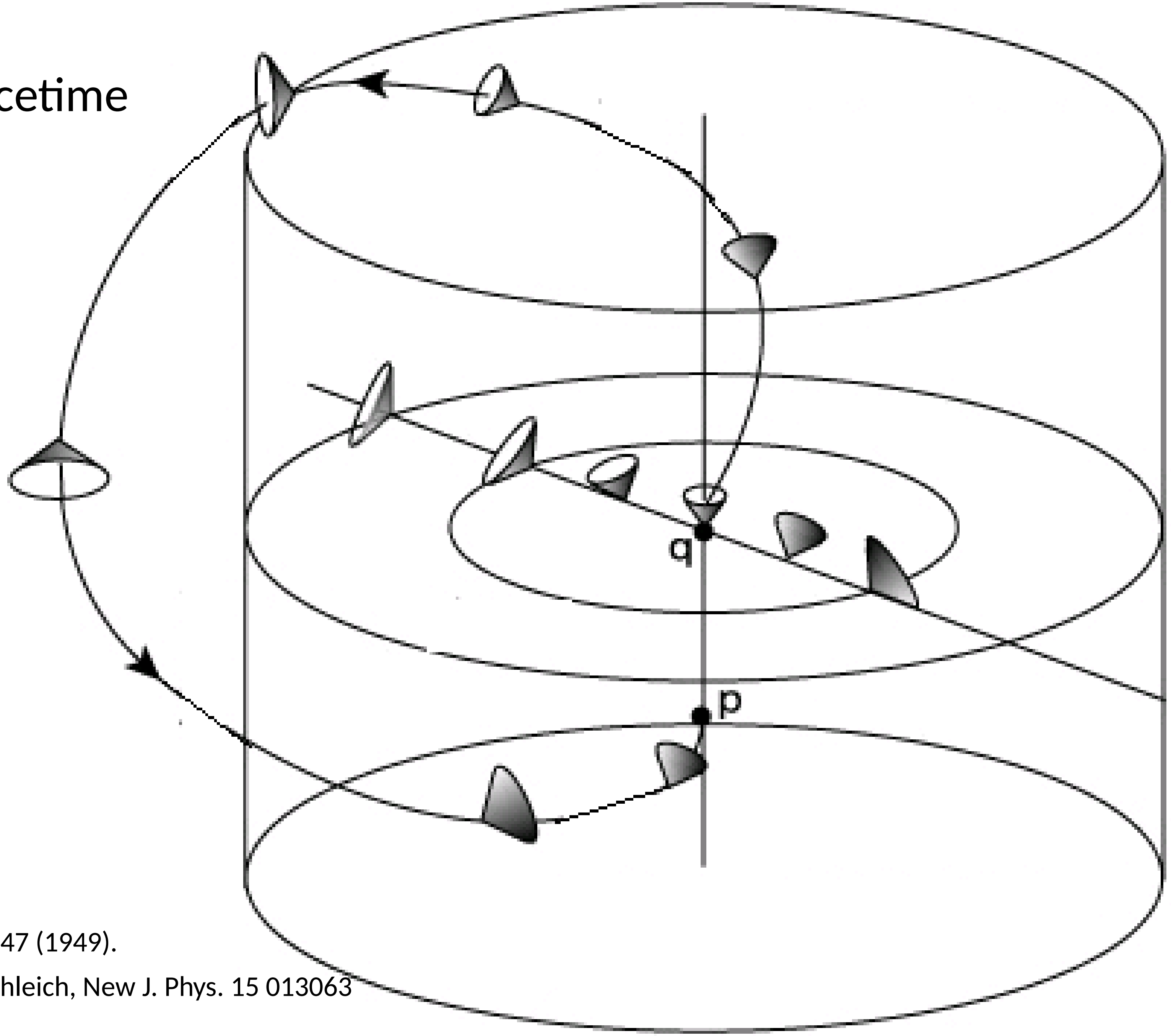
Warping time physically


mirror
w
ct
w
vt
clock at rest
clock moving at v

Time warp in special relativity



Gödel spacetime



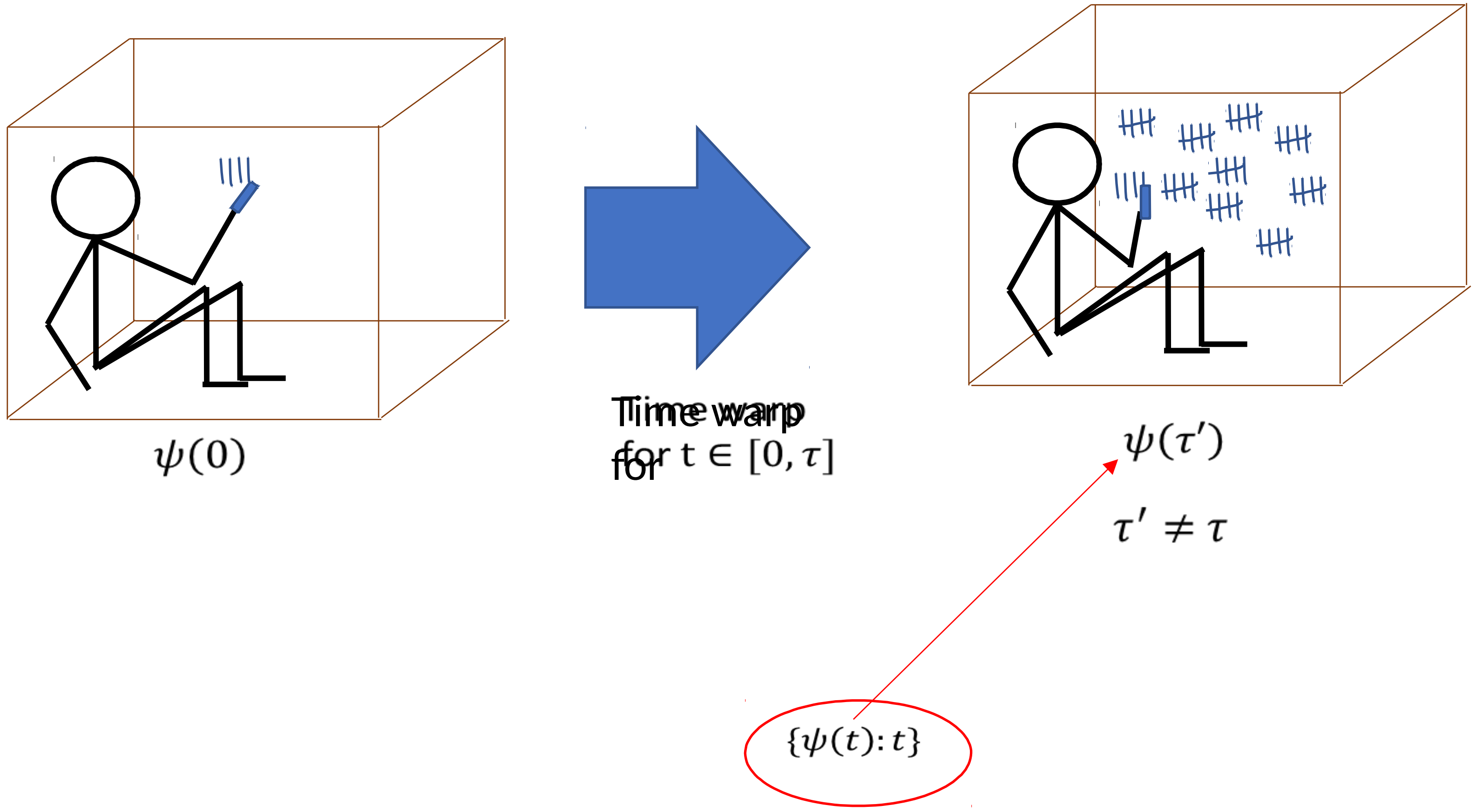
K. Gödel, *Rev. Mod. Phys.* **21** 447 (1949).

M. Buser, E. Kajari and W. P. Schleich, New J. Phys. 15 013063 (2013).

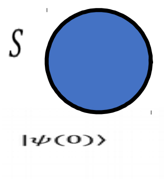
Time travel with wormholes

K. Thorne, Black Holes and Time Warps: Einstein's Outrageous Legacy, Commonwealth Fund Book Program (1994).

Time warp with time machines



The time translator

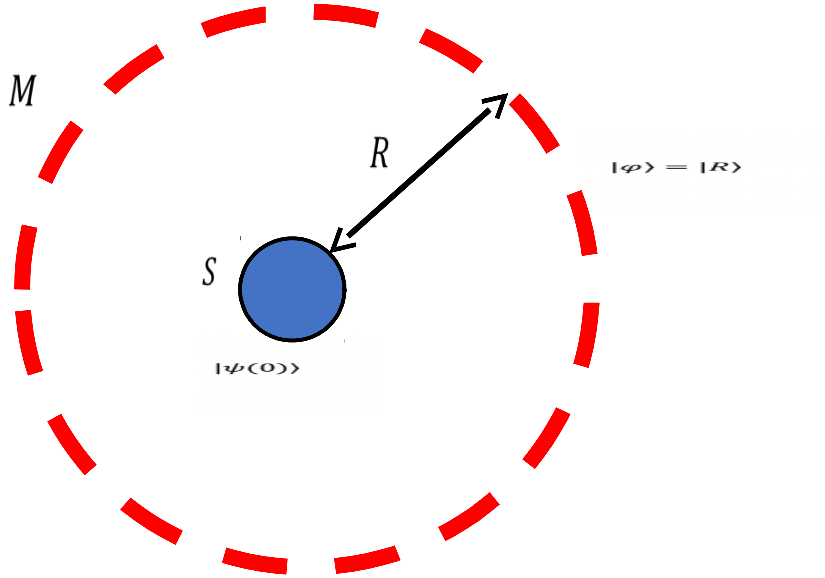


Evolution after time T

$$e^{-iH_0T}|\psi(0)\rangle$$

Y. Aharonov, J. Anandan, S. Popescu and L. Vaidman Phys. Rev. Lett. 64, 2965 (1990).

The time translator

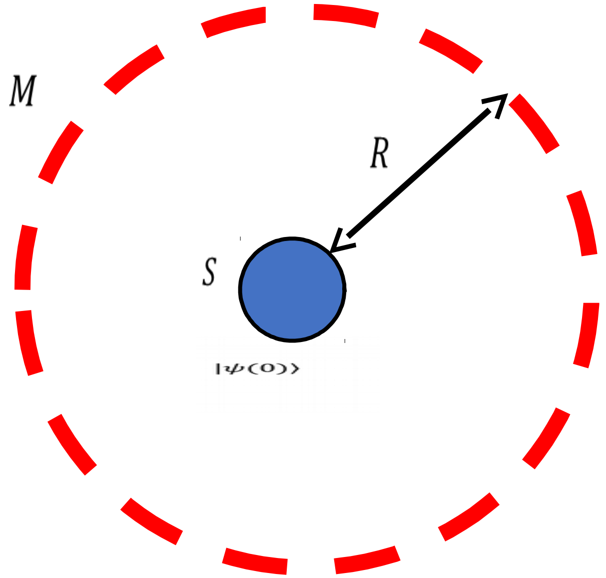


Evolution after time T

$$e^{-iH_0\gamma_R T}|\psi(0)\rangle|R\rangle$$

Y. Aharonov, J. Anandan, S. Popescu and L. Vaidman Phys. Rev. Lett. 64, 2965 (1990).

The time translator



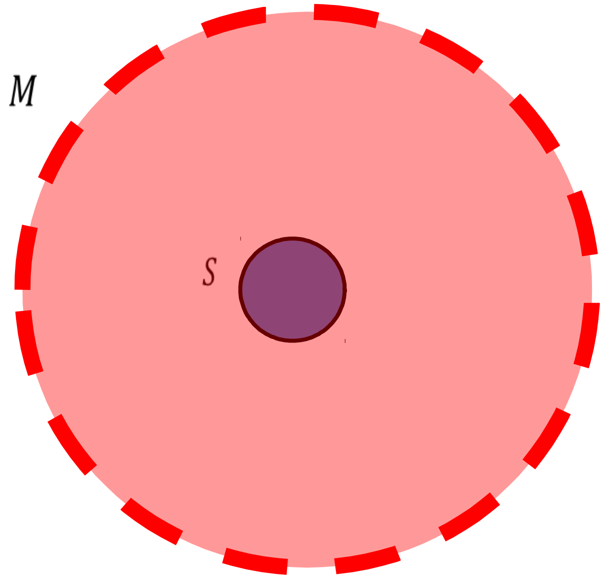
$$\gamma_R = \sqrt{1 - \frac{2GM}{Rc^2}}$$

Evolution after time T

$$e^{-iH_0\gamma_R T}|\psi(0)\rangle|R\rangle$$

Y. Aharonov, J. Anandan, S. Popescu and L. Vaidman Phys. Rev. Lett. 64, 2965 (1990).

The time translator



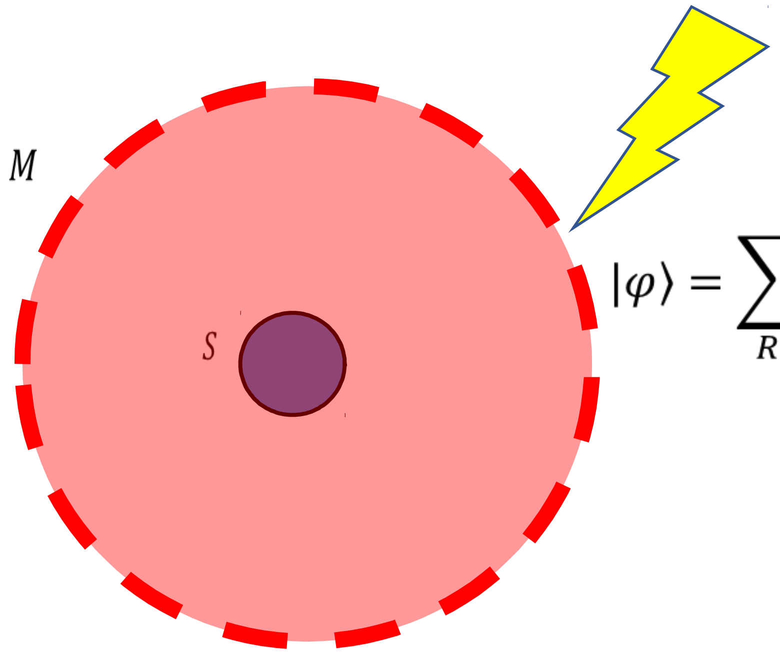
$$|\varphi\rangle = \sum_R c_R\, |R\rangle$$

Evolution after time T

$$\sum_R c_R\, e^{-iH_0\gamma_R T} |\psi(0)\rangle |R\rangle$$

Y. Aharonov, J. Anandan, S. Popescu and L. Vaidman Phys. Rev. Lett. 64, 2965 (1990).

The time translator



Measurement $\sum_R |R\rangle$

$$|\varphi\rangle = \sum_R c_R \, |R\rangle$$

Evolution after time T

$$\sum_R c_R \, e^{-iH_0\gamma_R T} |\psi(0)\rangle |R\rangle$$

Y. Aharonov, J. Anandan, S. Popescu and L. Vaidman Phys. Rev. Lett. 64, 2965 (1990).

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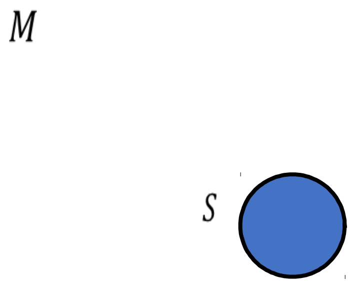

Evolution after time T

$$\sum_R c_R\, e^{-iH_0\gamma_R T}|\psi(0)\rangle$$

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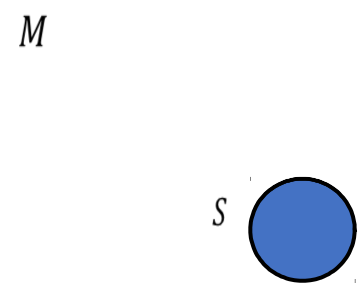


Evolution after time $T \ll 1$

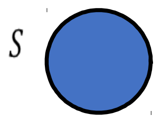
Evolution after time

$$\sum_R c_R \, e^{-iH_0 \gamma_R T} |\psi(0)\rangle \approx e^{-iH_0 \alpha T} |\psi(0)\rangle$$

Y. Aharonov, J. Anandan, S. Popescu and L. Vaidman Phys. Rev. Lett. 64, 2965 (1990).

The time translator

M



Interesting cases $\begin{cases} \alpha \gg 1 \\ \alpha \leq 0 \end{cases}$

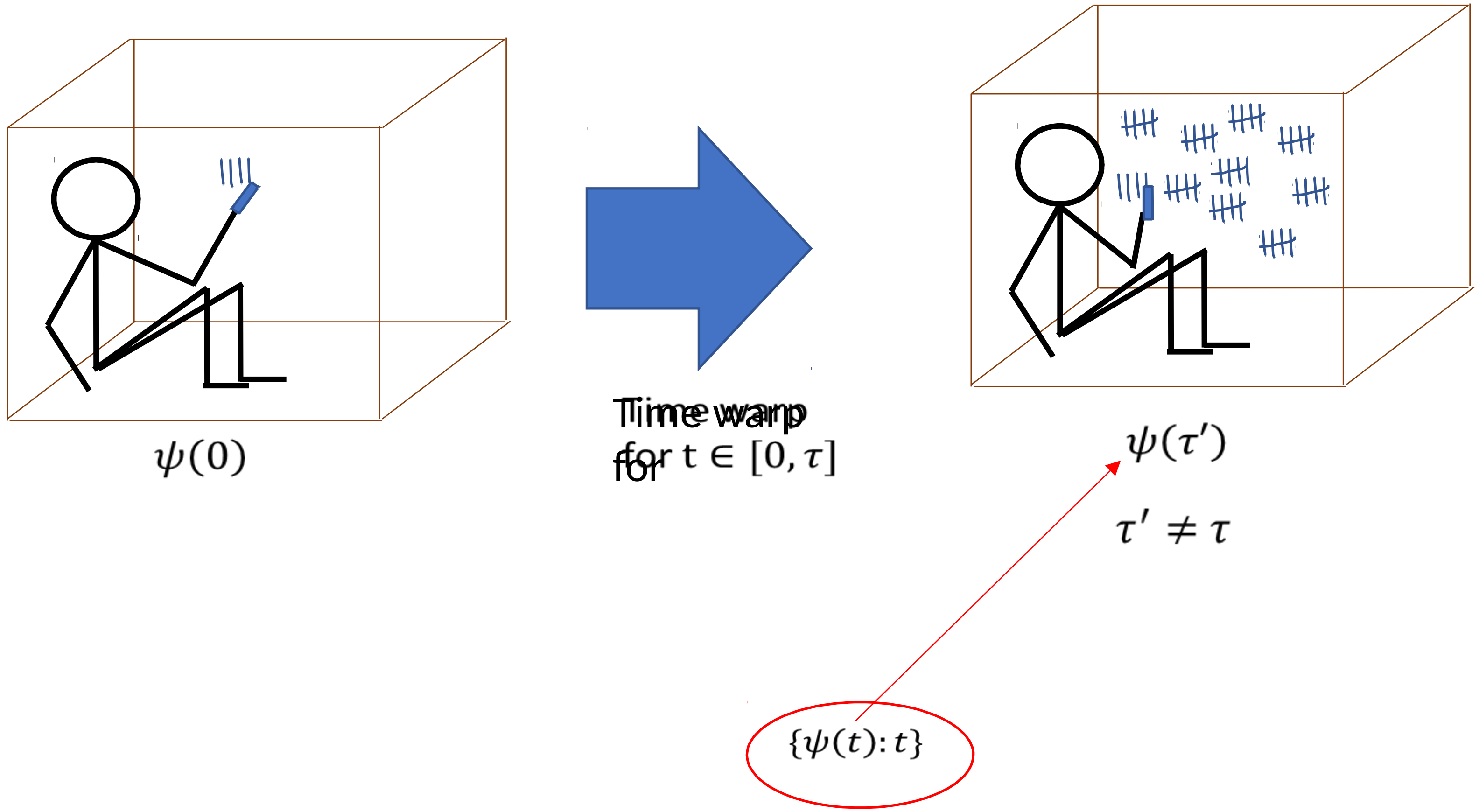
Evolution after time $T \ll 1$

Evolution after time

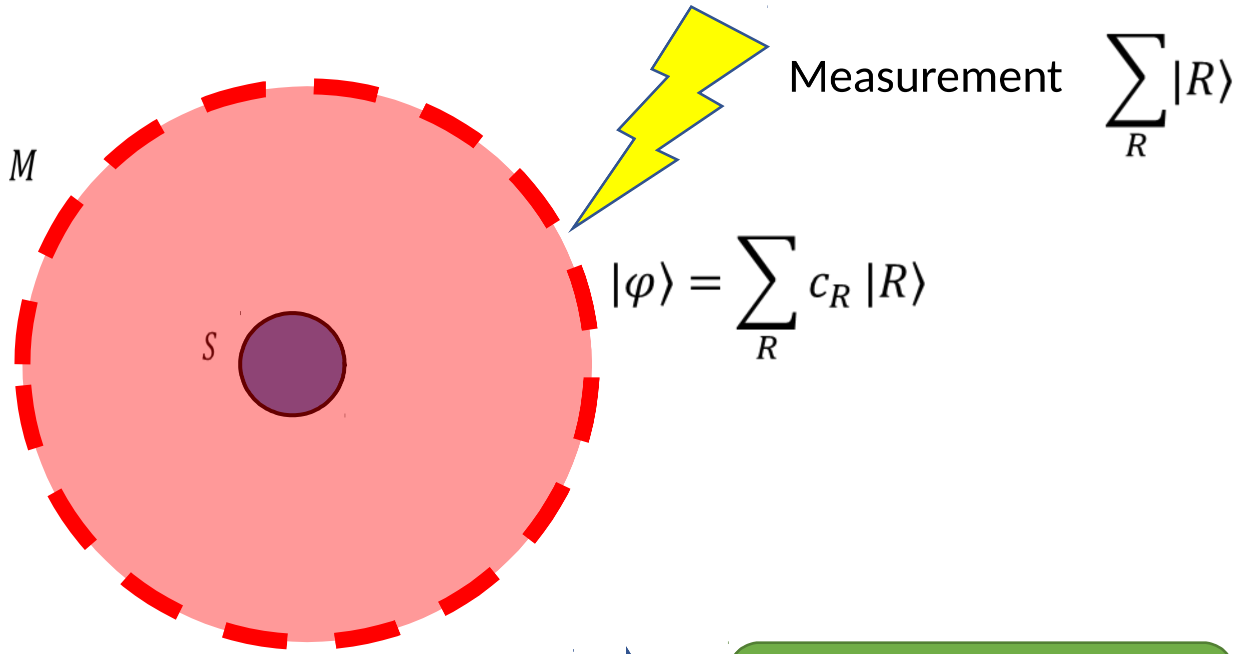
$$\sum_R c_R\, e^{-iH_0\gamma_R T}|\psi(0)\rangle \approx e^{-iH_0\alpha T}|\psi(0)\rangle$$

Y. Aharonov, J. Anandan, S. Popescu and L. Vaidman Phys. Rev. Lett. 64, 2965 (1990).

Time warp with the time translator



The time translator



$$\sum_R c_R\, e^{-iH_0\gamma_R T}|\psi(0)\rangle \approx e^{-iH_0\alpha T}|\psi(0)\rangle$$

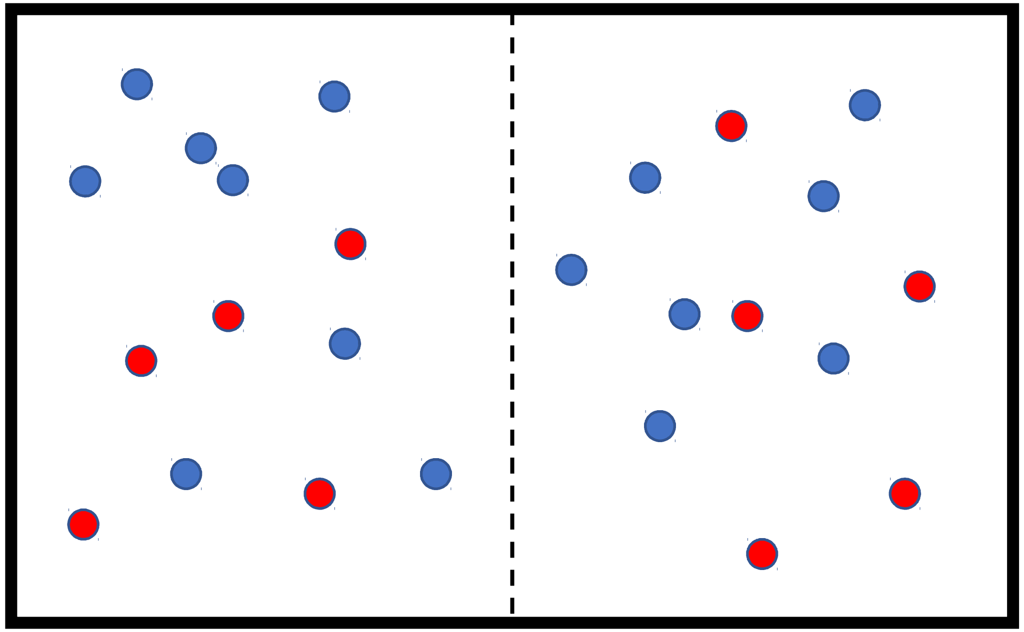
Problem: astronomically small probability of postselection

Y. Aharonov, J. Anandan, S. Popescu and L. Vaidman Phys. Rev. Lett. 64, 2965 (1990).

“The time translator has the same chances of succeeding as I have of delocalizing and relocalizing somewhere else”

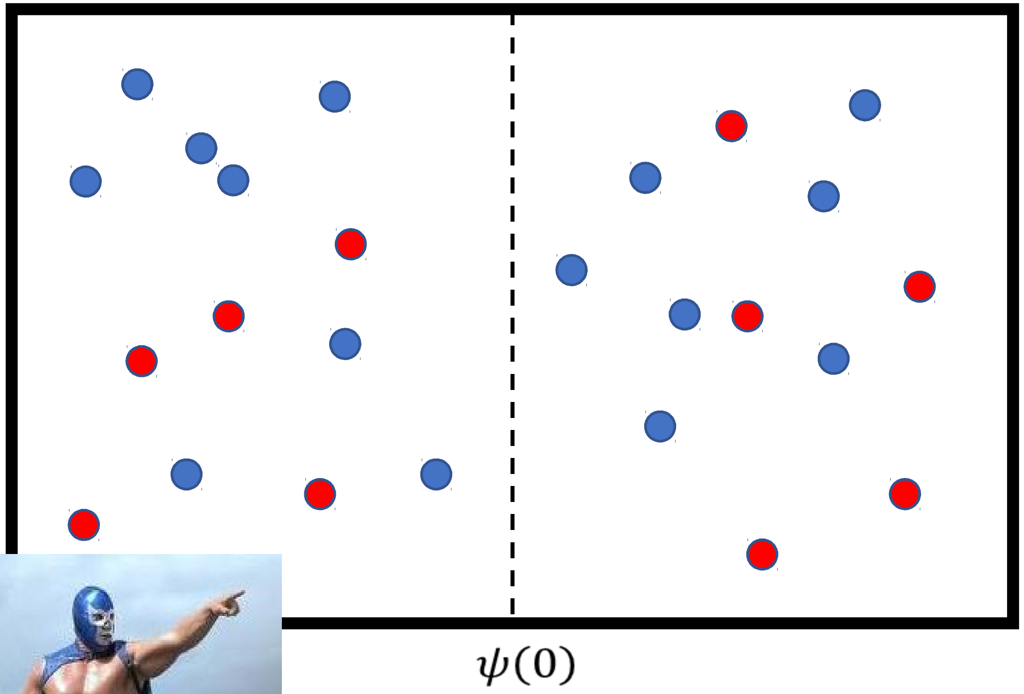
L. Vaidman

Time warp, the lame way

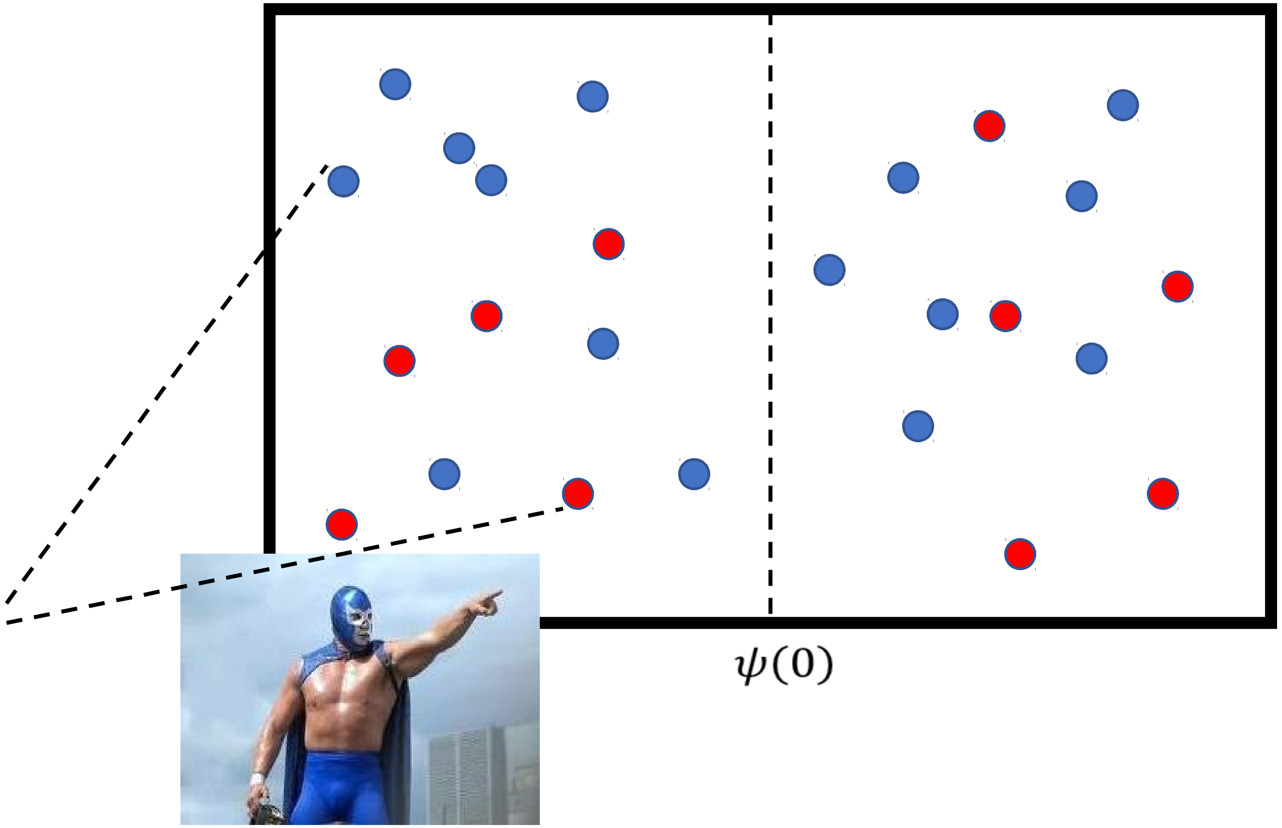


$\psi(0)$

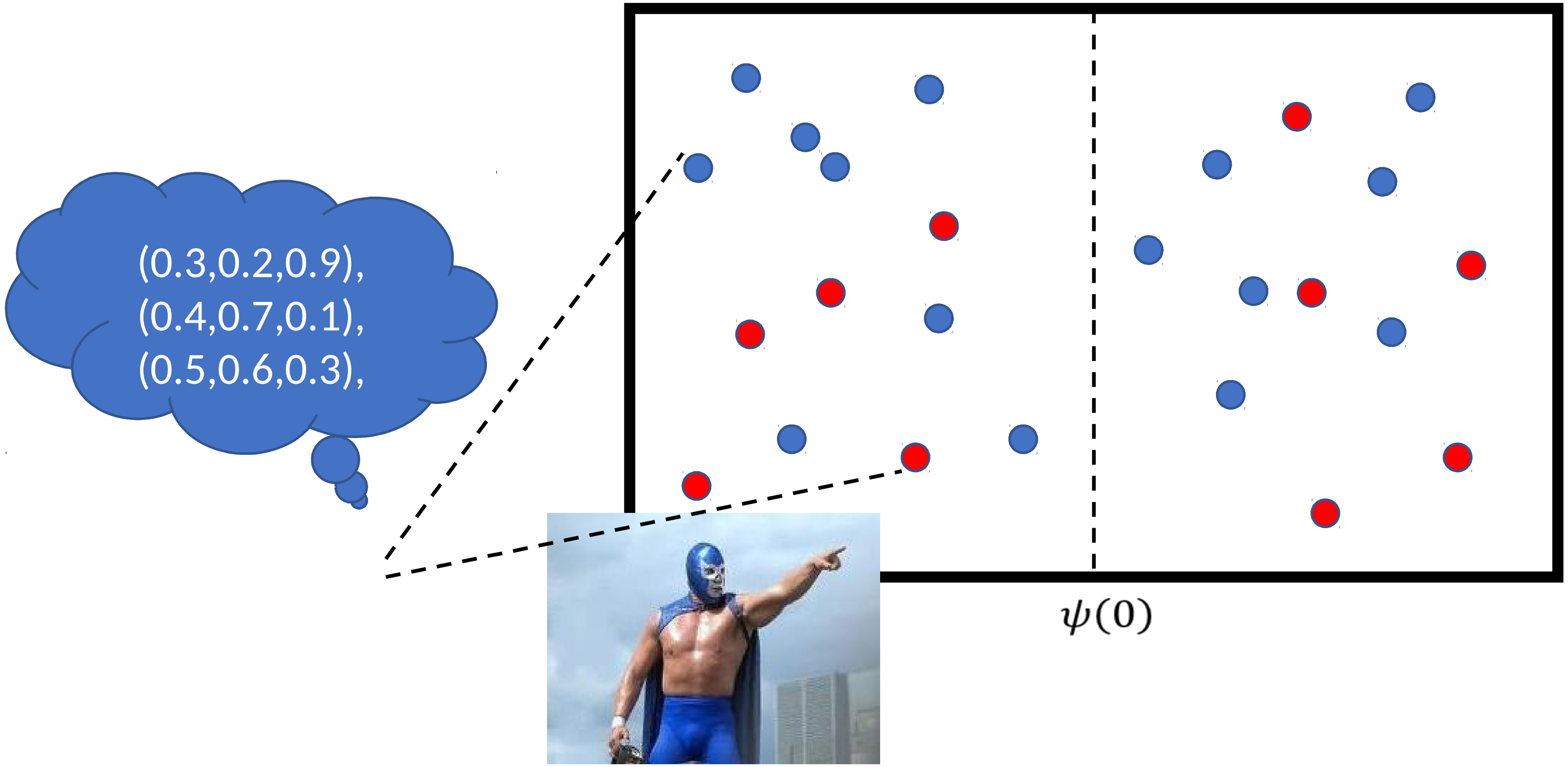
Time warp, the lame way



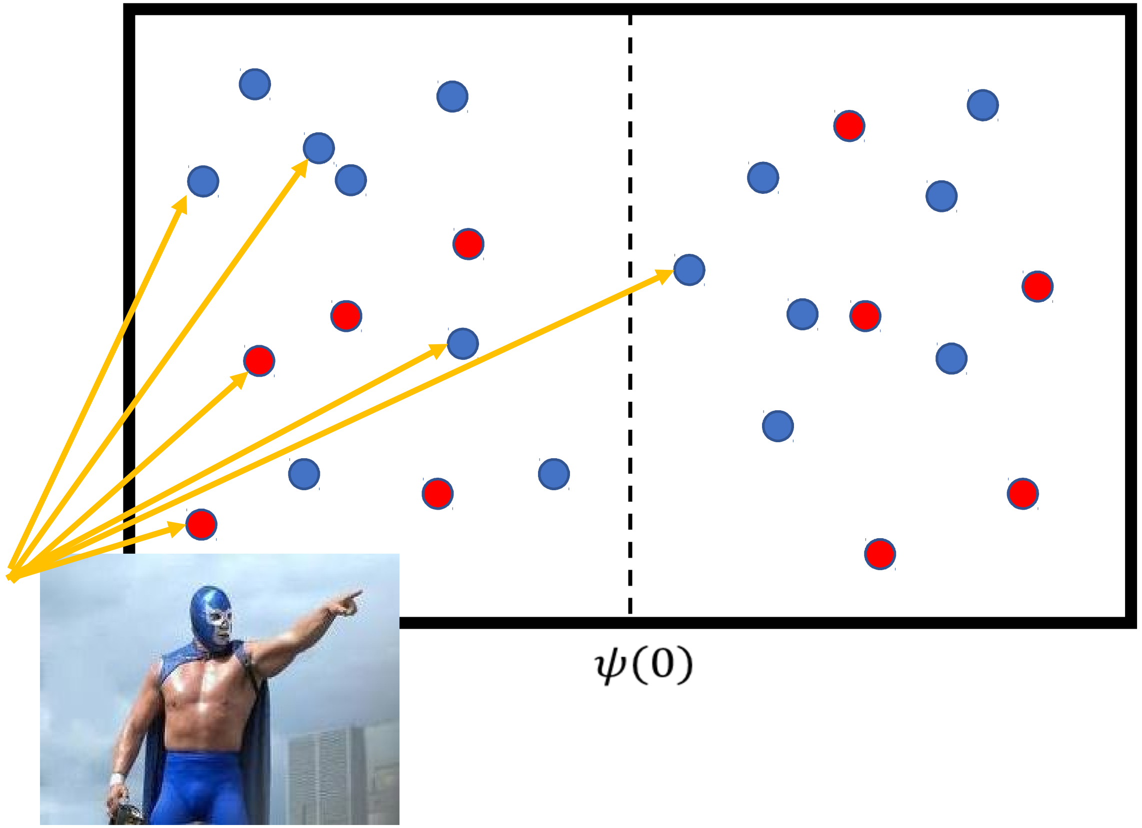
Time warp, the lame way



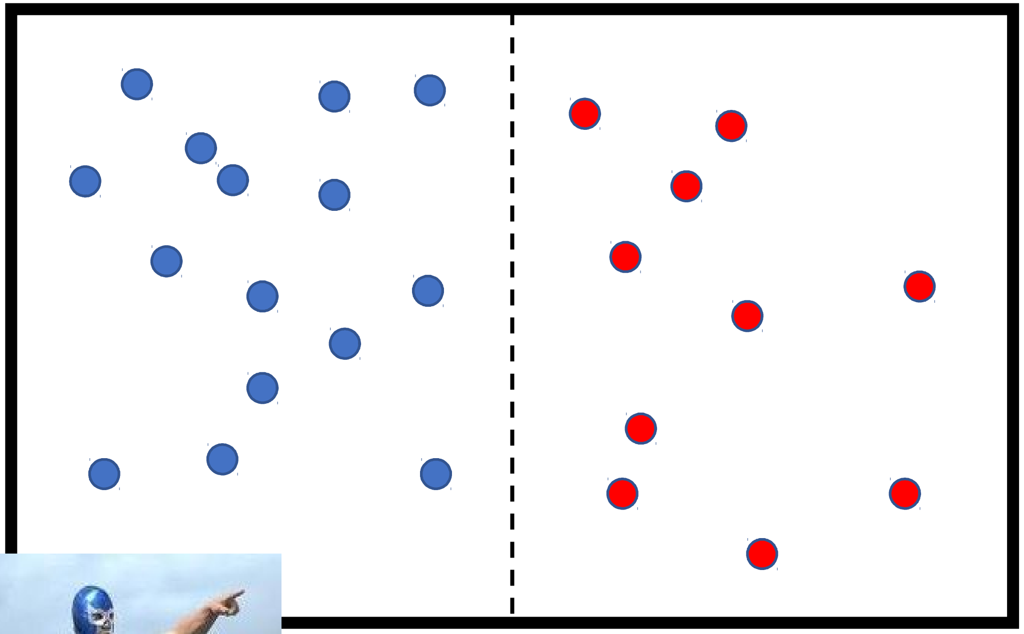
Time warp, the lame way



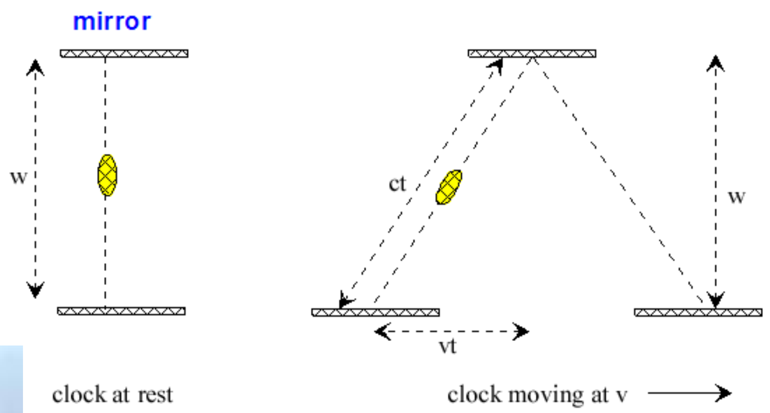
Time warp, the lame way



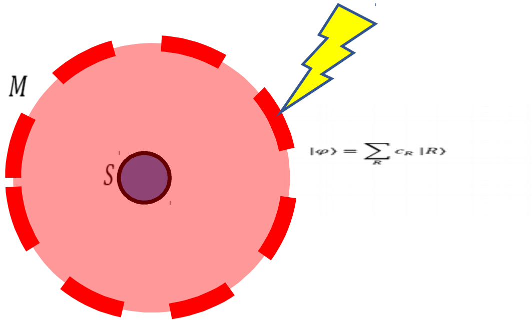
Time warp, the lame way

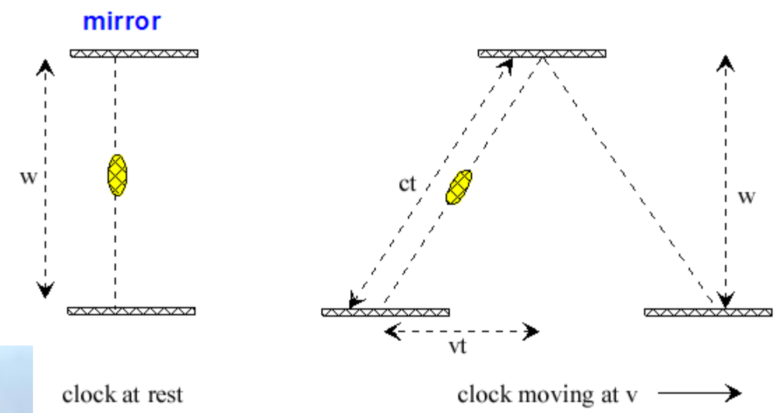


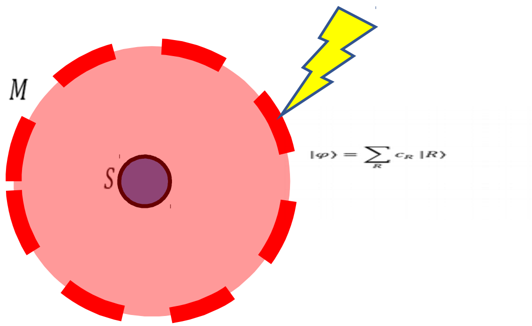
$\psi(-5732)$


mirror
w
ct
w
vt
clock at rest
clock moving at v

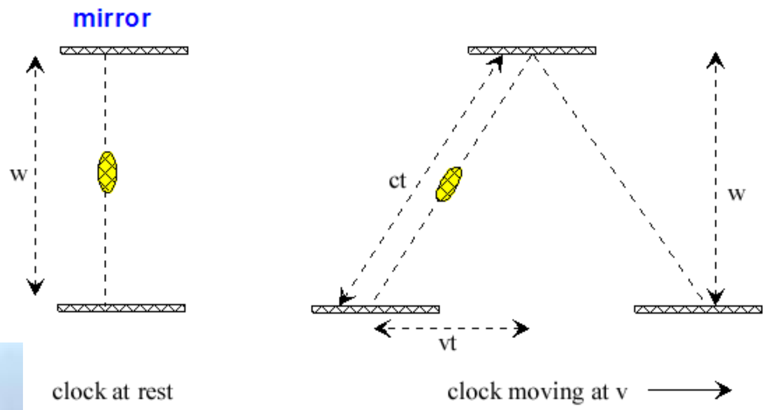

V.S.

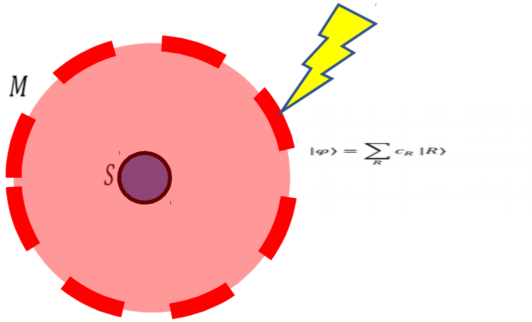

M
S
$|\varphi\rangle = \sum_R c_R |R\rangle$





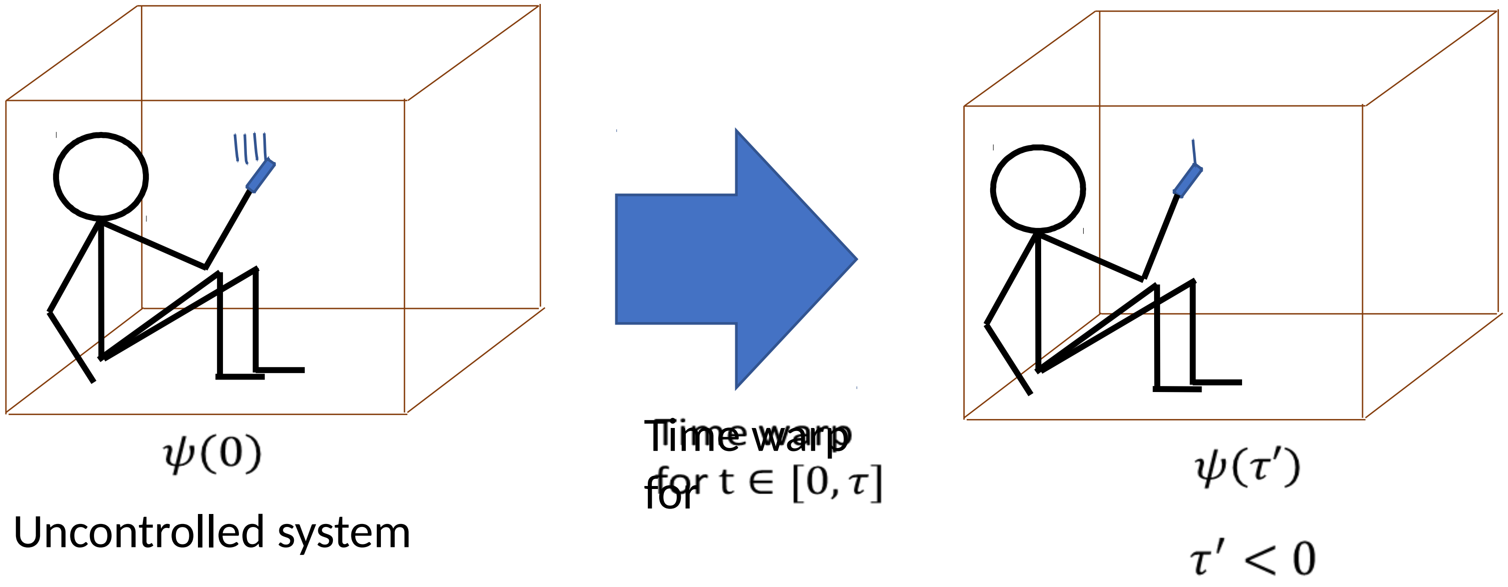
Do not require control or knowledge of the physical system that we influence





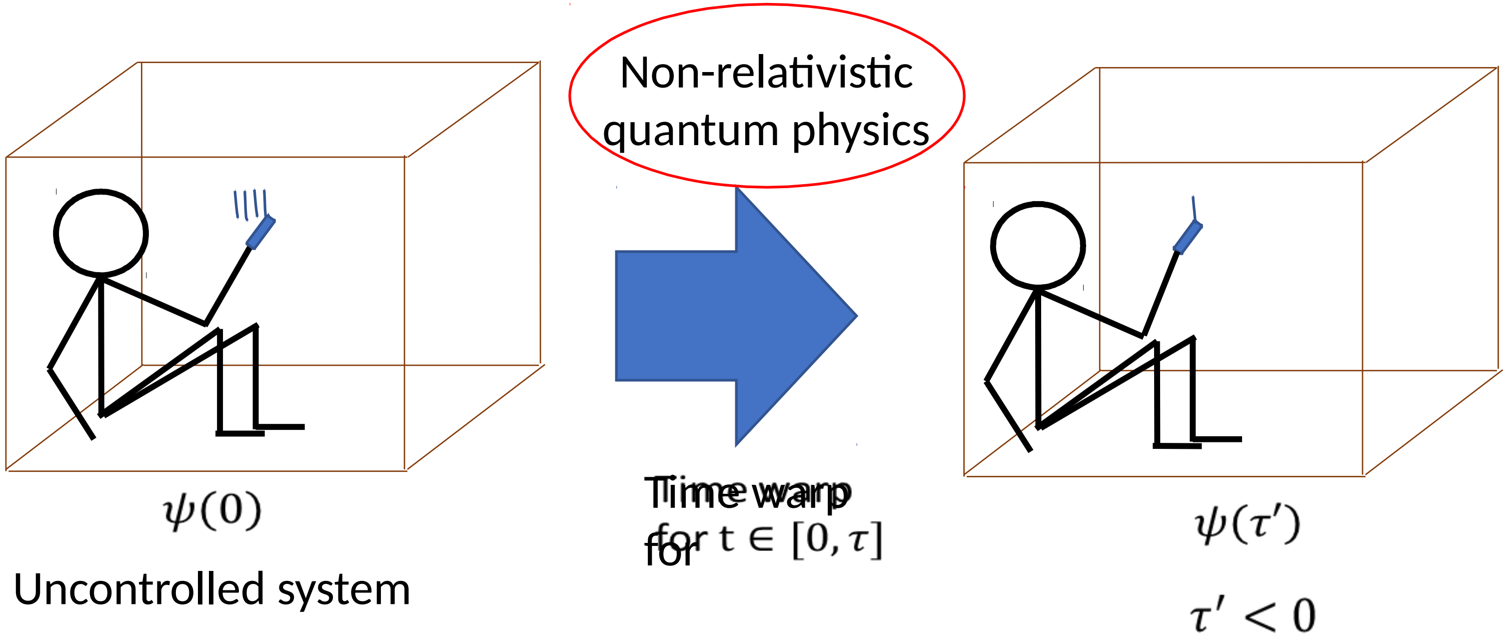
Rely on special or general relativity

Main result



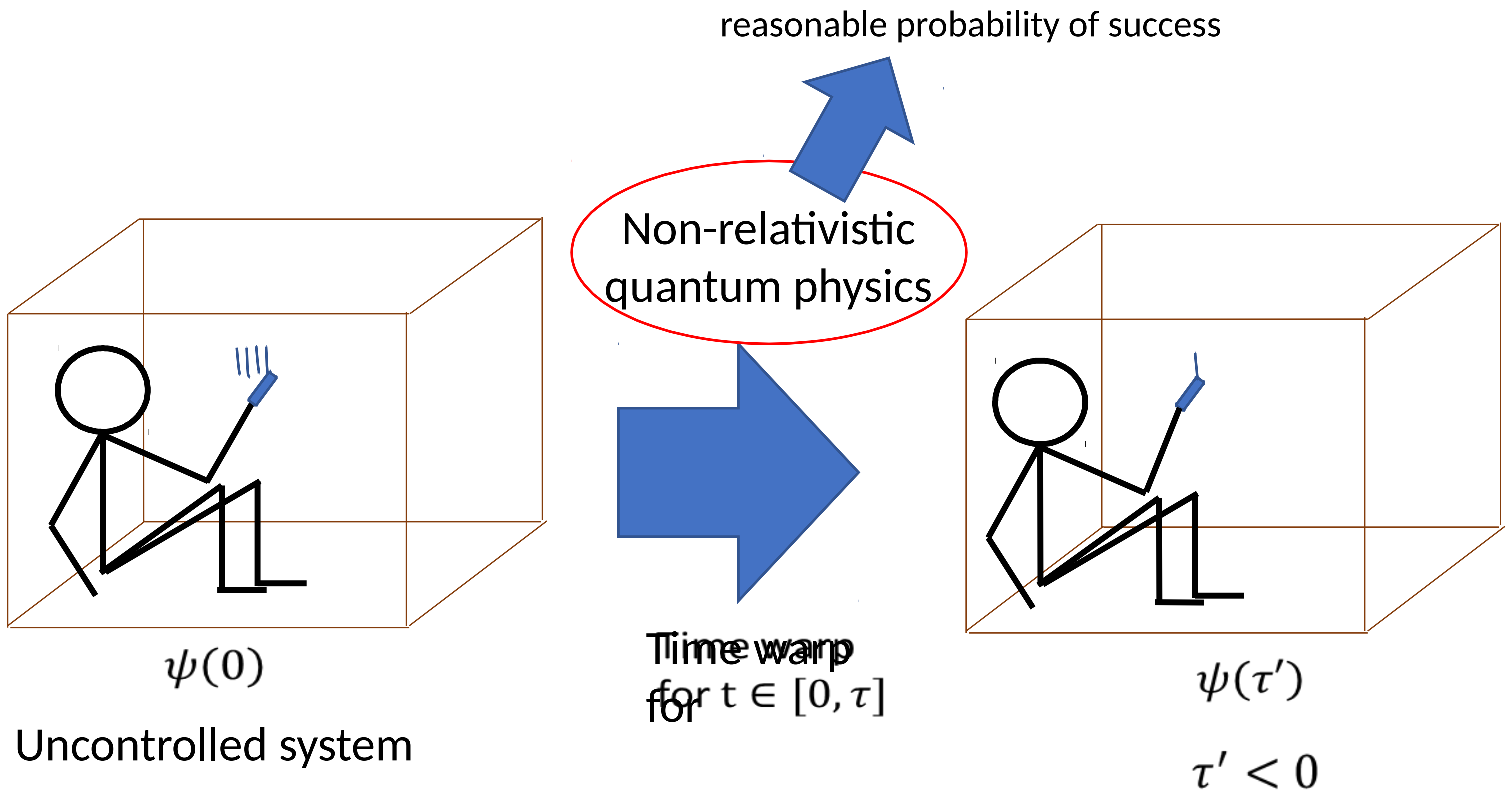
MN, arXiv:1710.02470

Main result



MN, arXiv:1710.02470

Main result

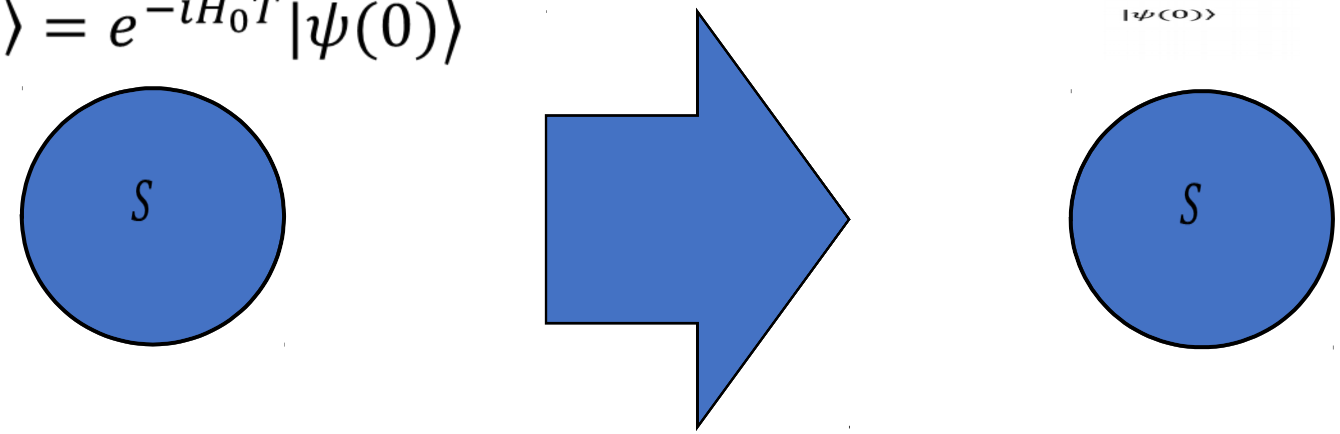


MN, arXiv:1710.02470

Scenario

Goal

$$|\psi(T)\rangle = e^{-iH_0T}|\psi(0)\rangle$$

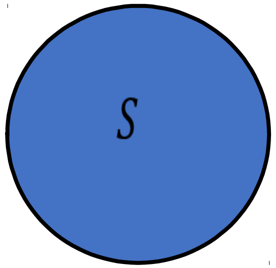


$t = T > 0$

$t = T + \Delta$

Obvious solution

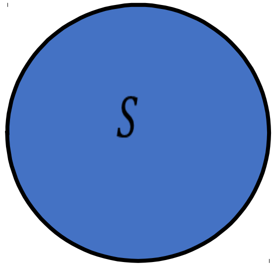
$$|\psi(T)\rangle = e^{-iH_0T}|\psi(0)\rangle$$



$$|\psi(0)\rangle = e^{+iH_0T}|\psi(T)\rangle$$

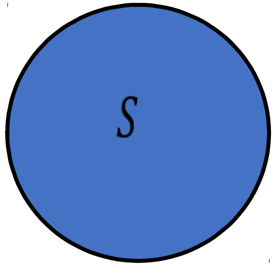
Obvious solution

$$|\psi(T)\rangle = e^{-iH_0T}|\psi(0)\rangle$$

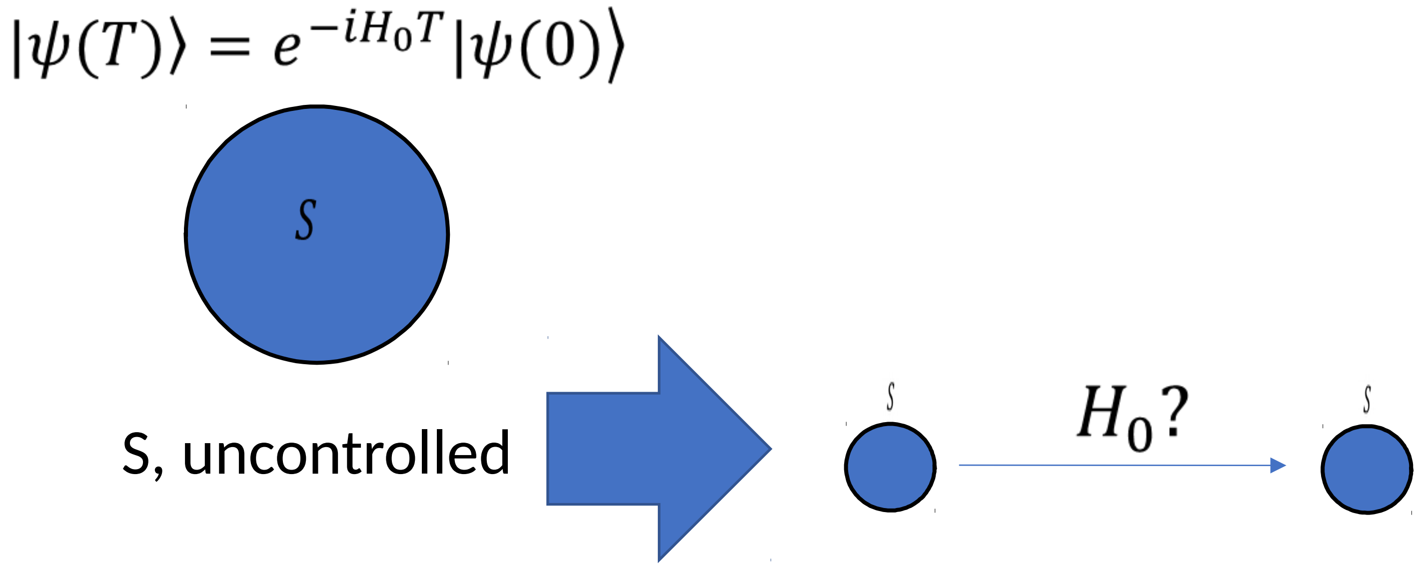


$$|\psi(0)\rangle = e^{+iH_0T}|\psi(T)\rangle$$

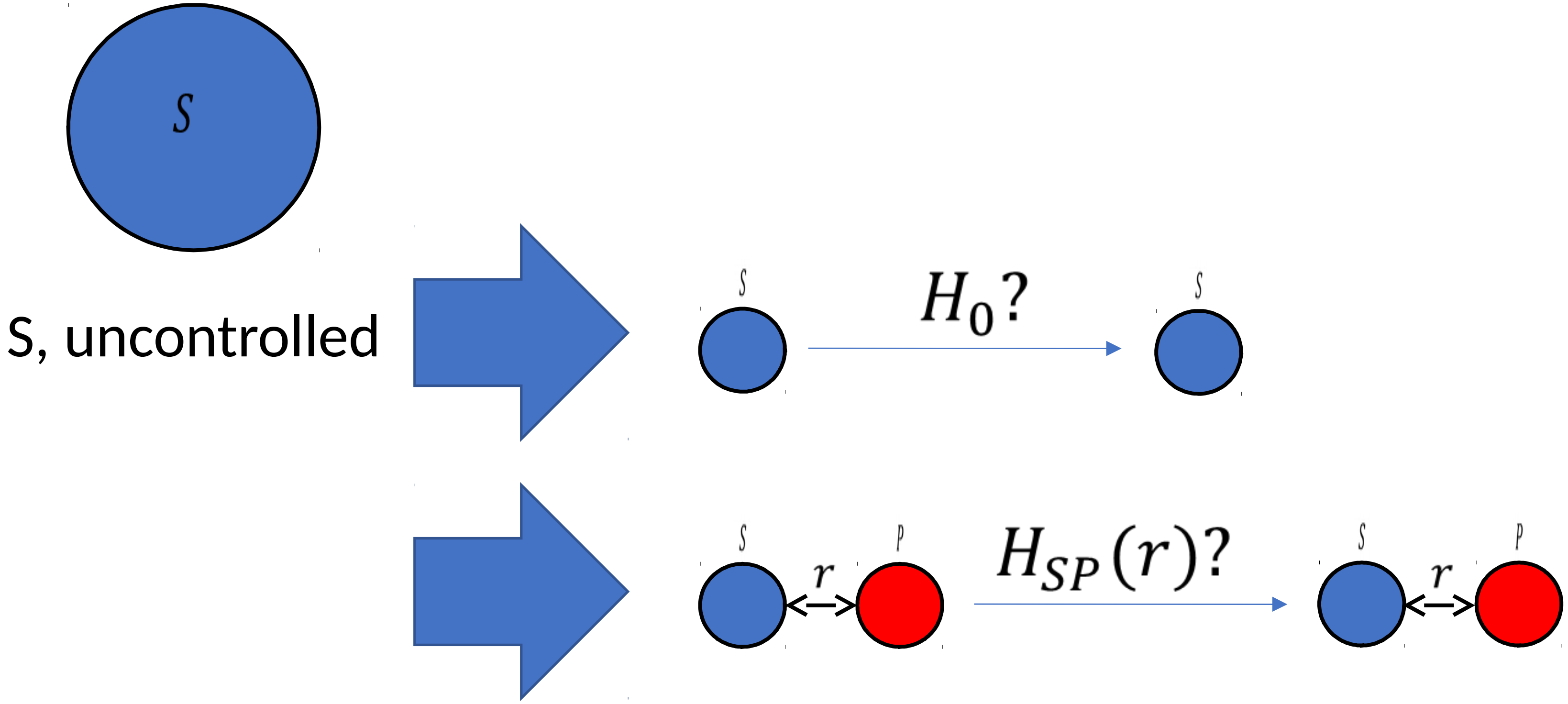
$$|\psi(T)\rangle = e^{-iH_0 T}|\psi(0)\rangle$$



S, uncontrolled

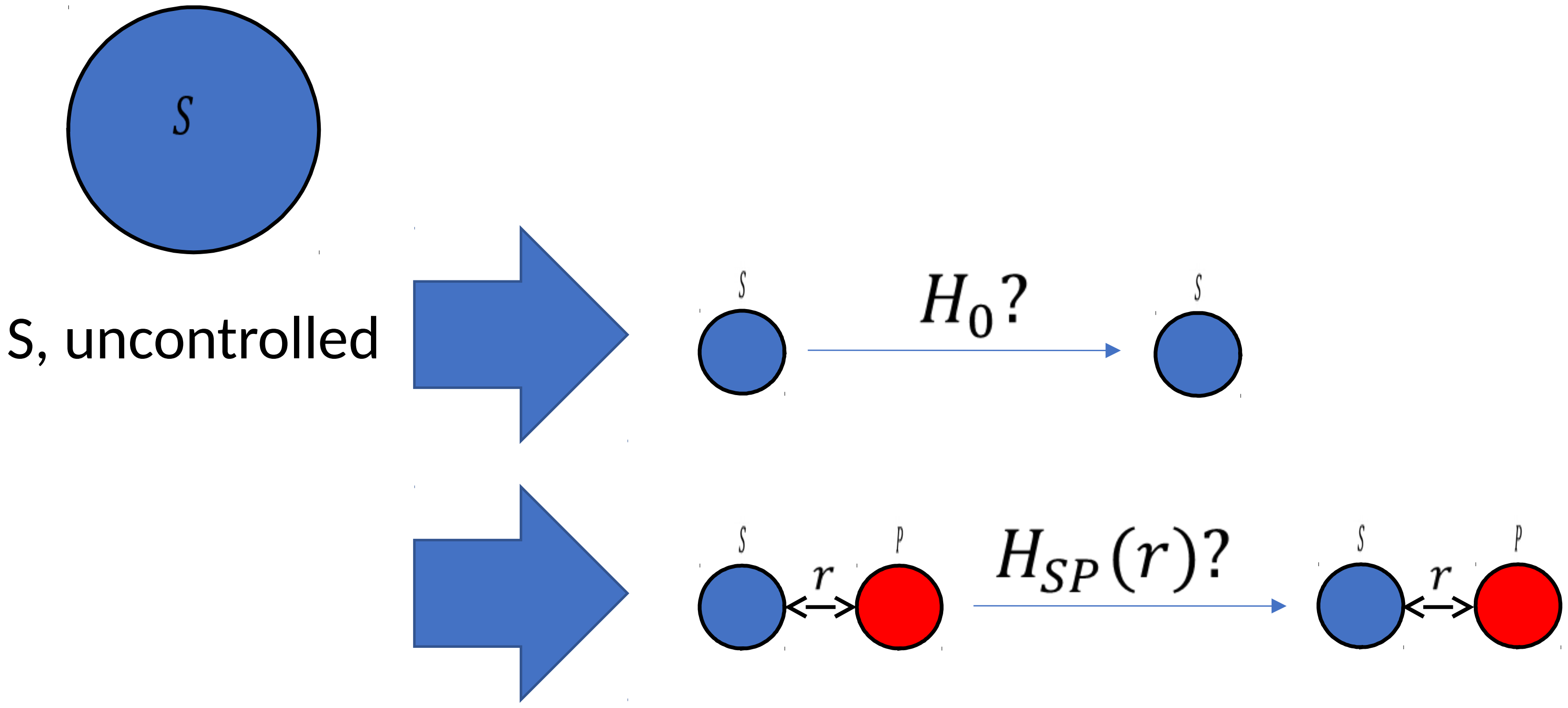

$|\psi(T)\rangle = e^{-iH_0T}|\psi(0)\rangle$
S
S, uncontrolled
S
H_0?
S

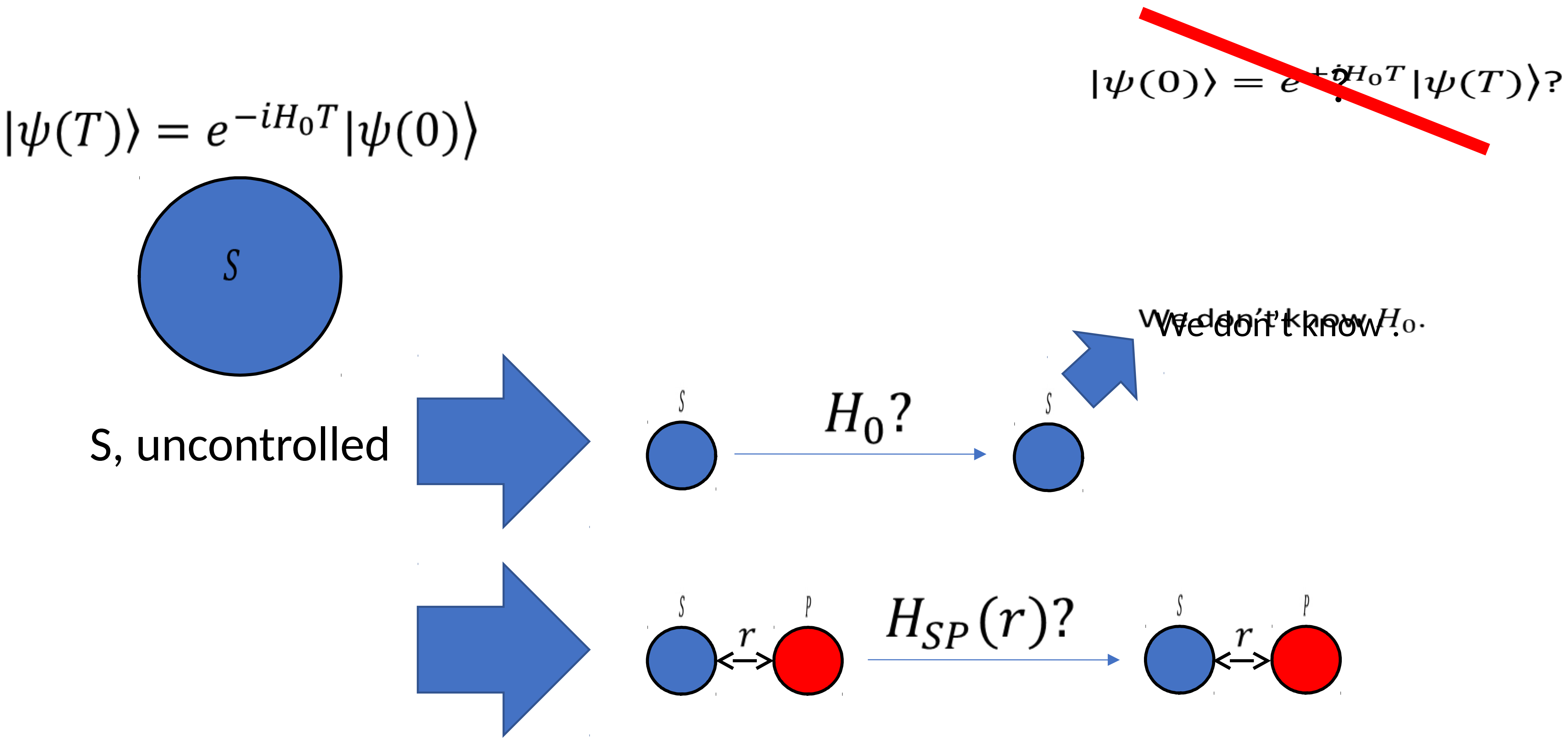
$$|\psi(T)\rangle = e^{-iH_0T}|\psi(0)\rangle$$

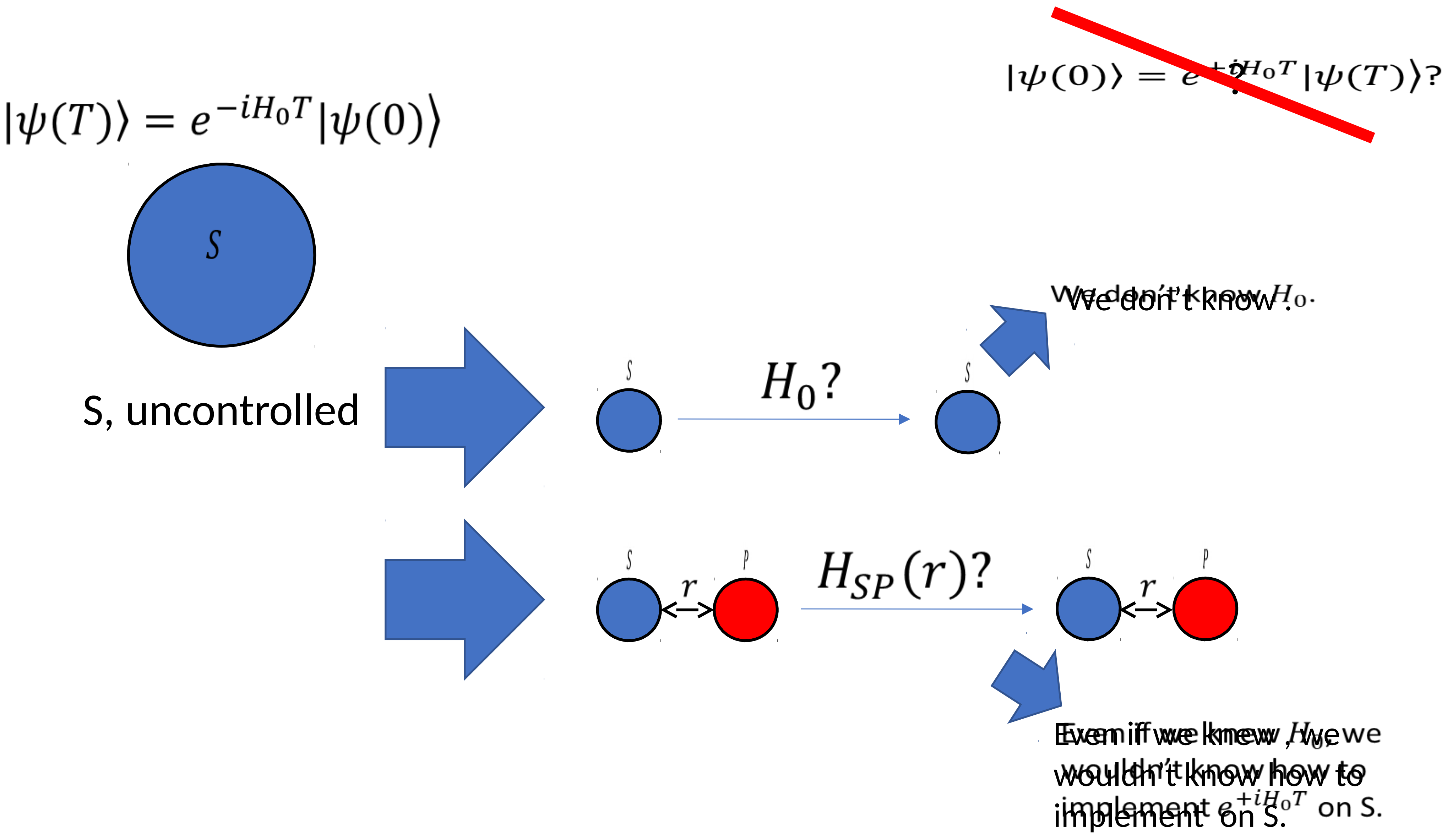


$$|\psi(T)\rangle = e^{-iH_0T}|\psi(0)\rangle$$

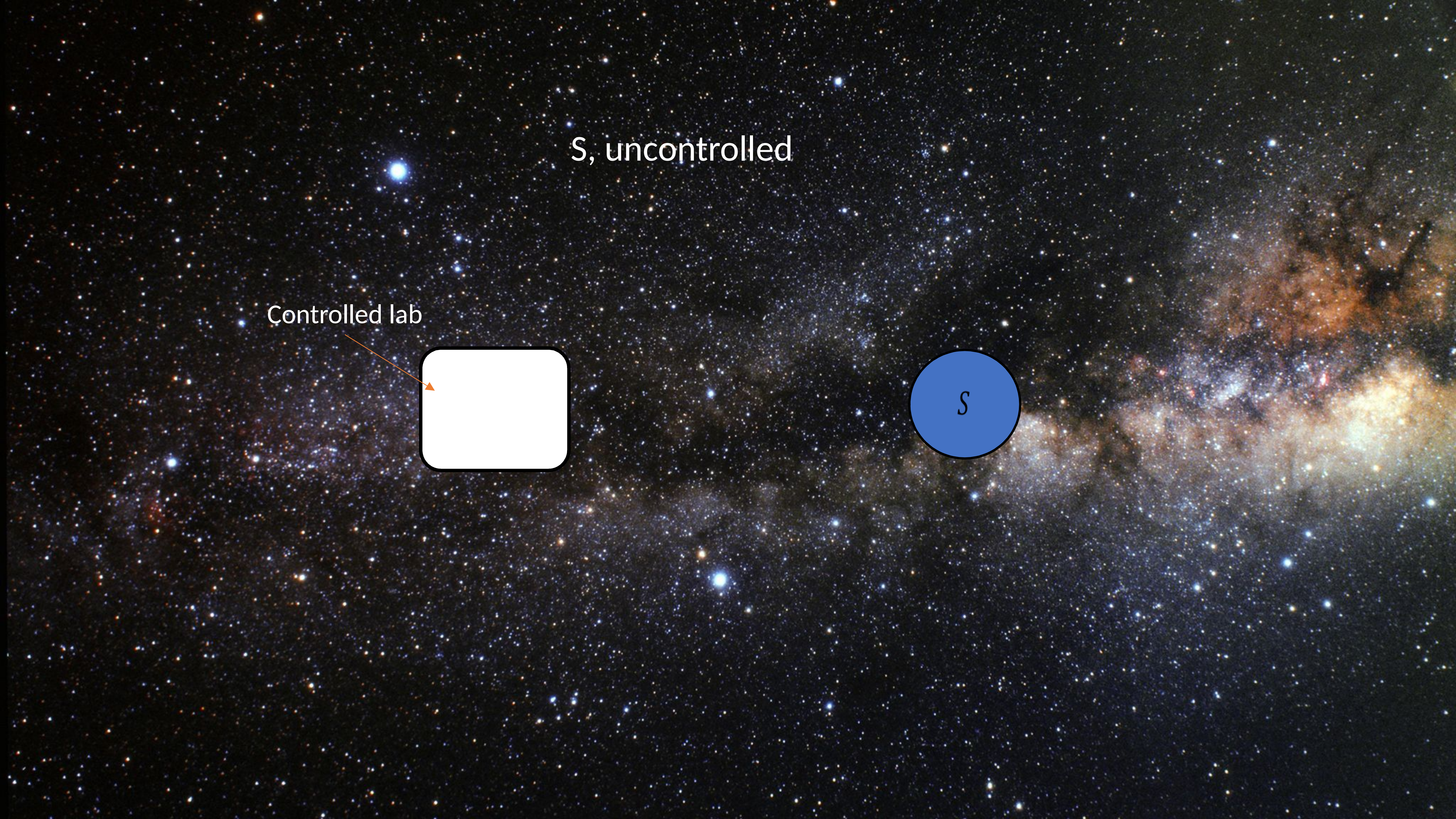
~~$|\psi(0)\rangle = e^{+iH_0T}|\psi(T)\rangle$?~~



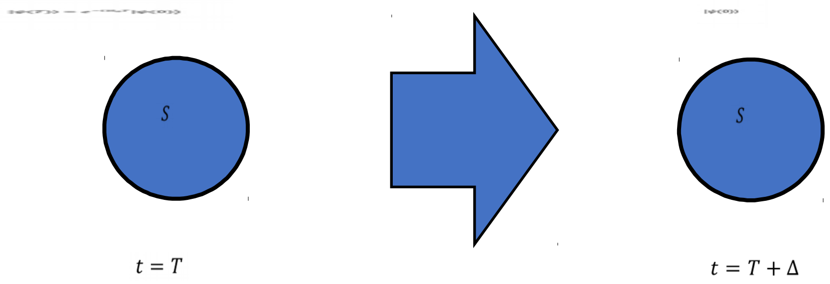

$|\psi(T)\rangle = e^{-iH_0T}|\psi(0)\rangle$
$|\psi(0)\rangle = e^{+iH_0T}|\psi(T)\rangle$?
S
S, uncontrolled
S
H_0?
S
We don't know H_0.
S
P
r
$H_{SP}(r)$?
S
P
r



$|\psi(T)\rangle = e^{-iH_0T}|\psi(0)\rangle$
$|\psi(0)\rangle = e^{+iH_0T}|\psi(T)\rangle$?
S
S, uncontrolled
S
H_0?
S
We don't know H_0.
S
P
r
$H_{SP}(r)$?
S
P
r
Even if we knew H_0, we wouldn't know how to implement e^{+iH_0T} on S.


S, uncontrolled
Controlled lab
S

Resetting

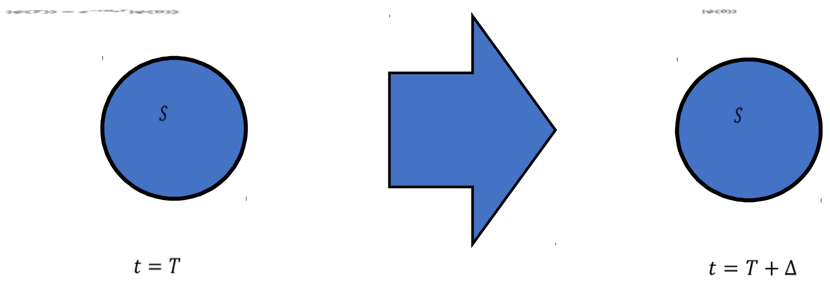


We ignore how S evolves (unitarily) by itself and with other quantum systems

We know $d_S = \dim(H_S)$
We know

MN, arXiv:1710.02470

Resetting



We ignore how S evolves (unitarily) by itself and with other quantum systems

We know $d_S = \dim(H_S)$

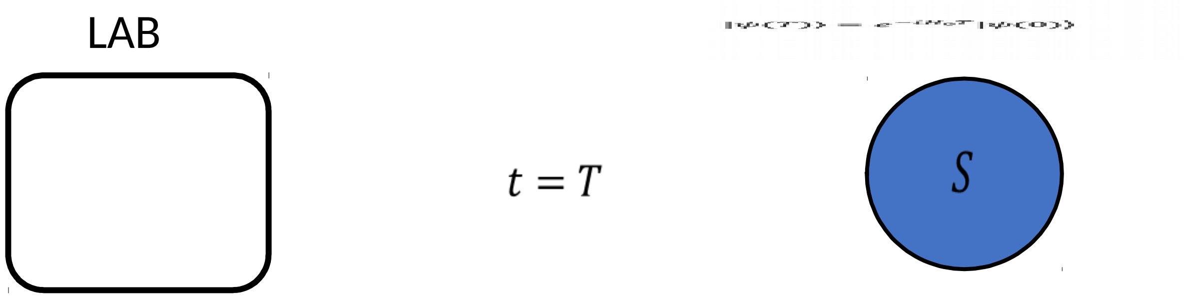
We know

Imposible if we drop any of the two assumptions

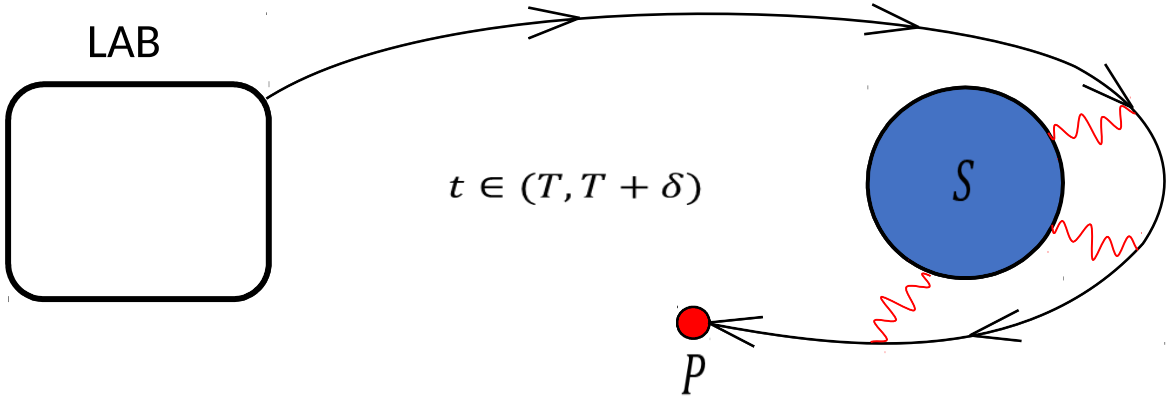
MN, arXiv:1710.02470

Sketch of a quantum resetting protocol

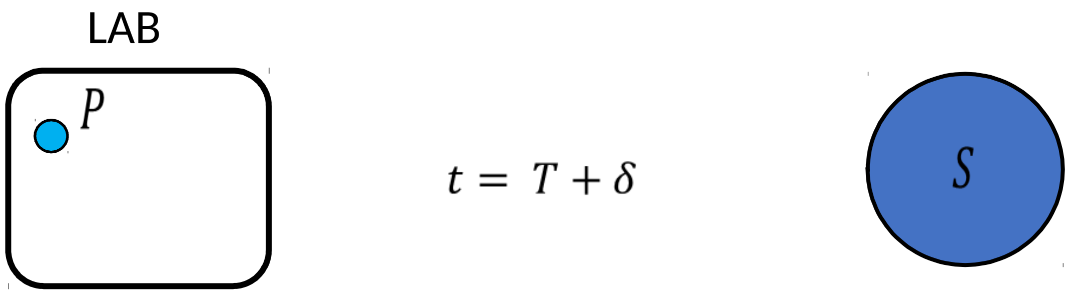
Initial conditions



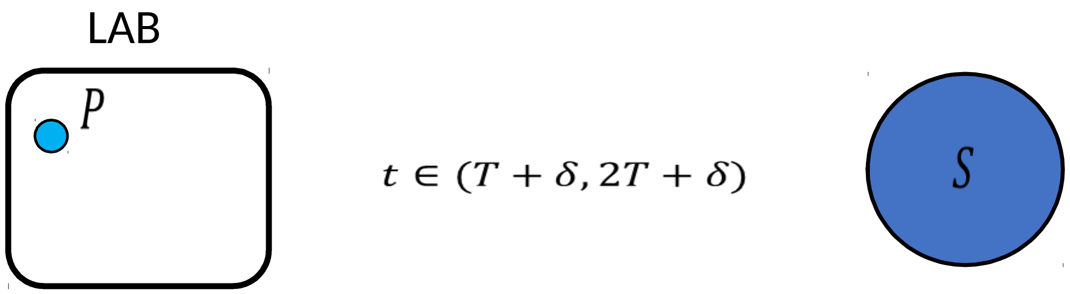
(a) Probe interaction



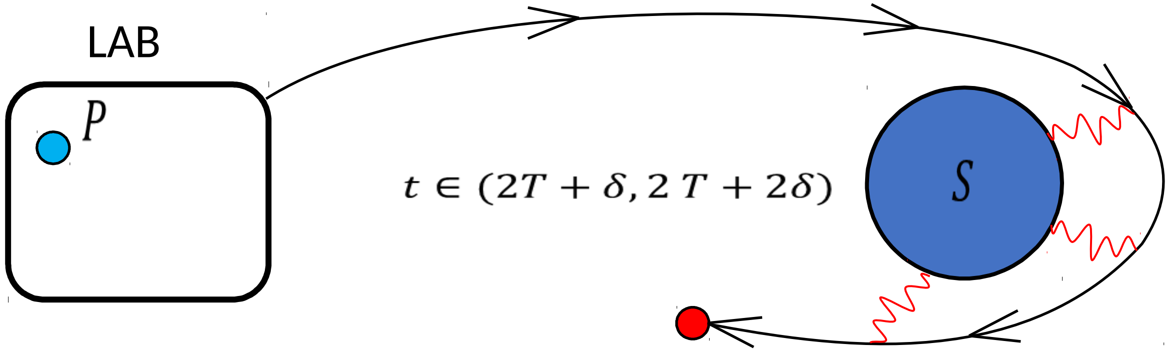
(a) Probe interaction



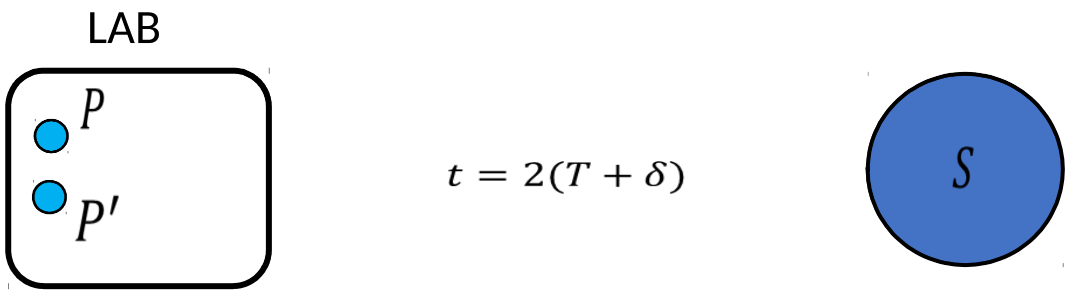
(b) Rest



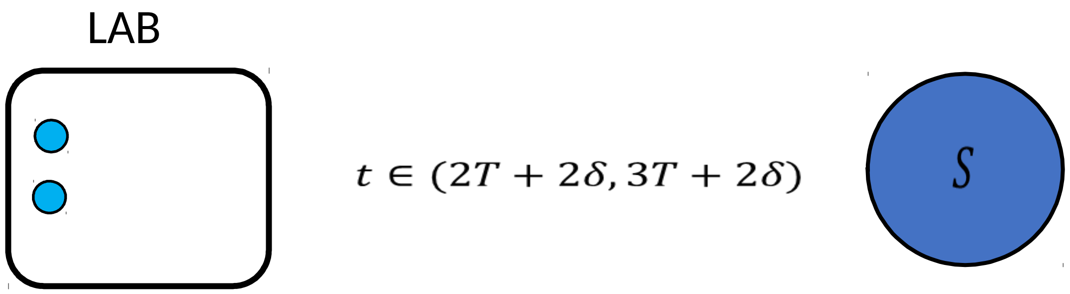
(a) Probe interaction



(a) Probe interaction

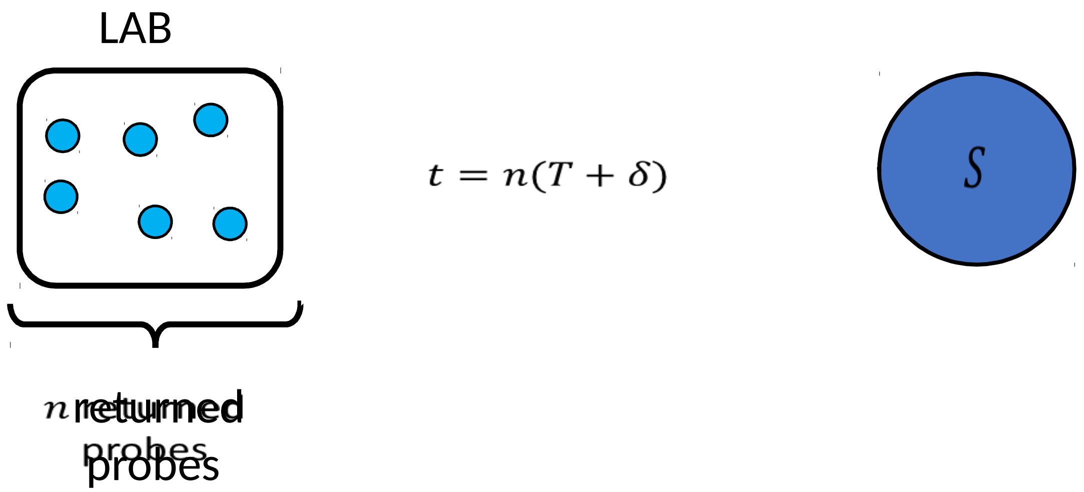


(b) Rest

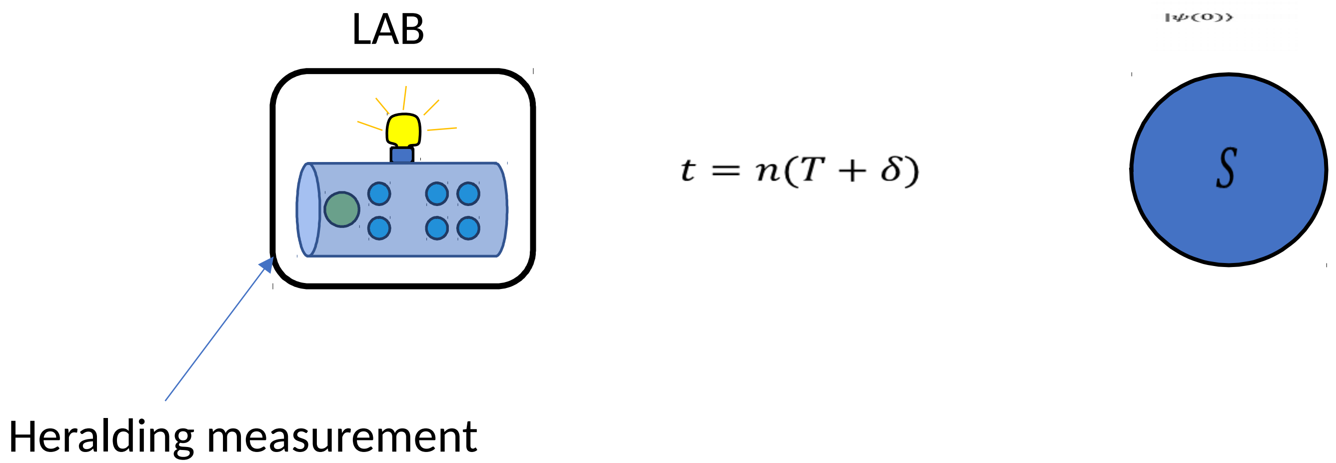


⋮

(a) Probe interaction

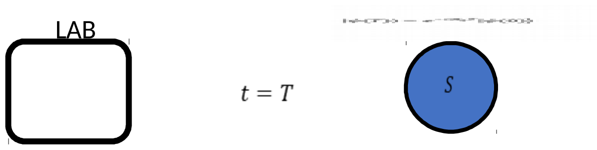


(c) Probe processing

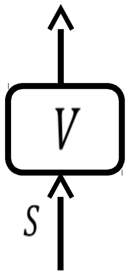


In the language of process diagrams

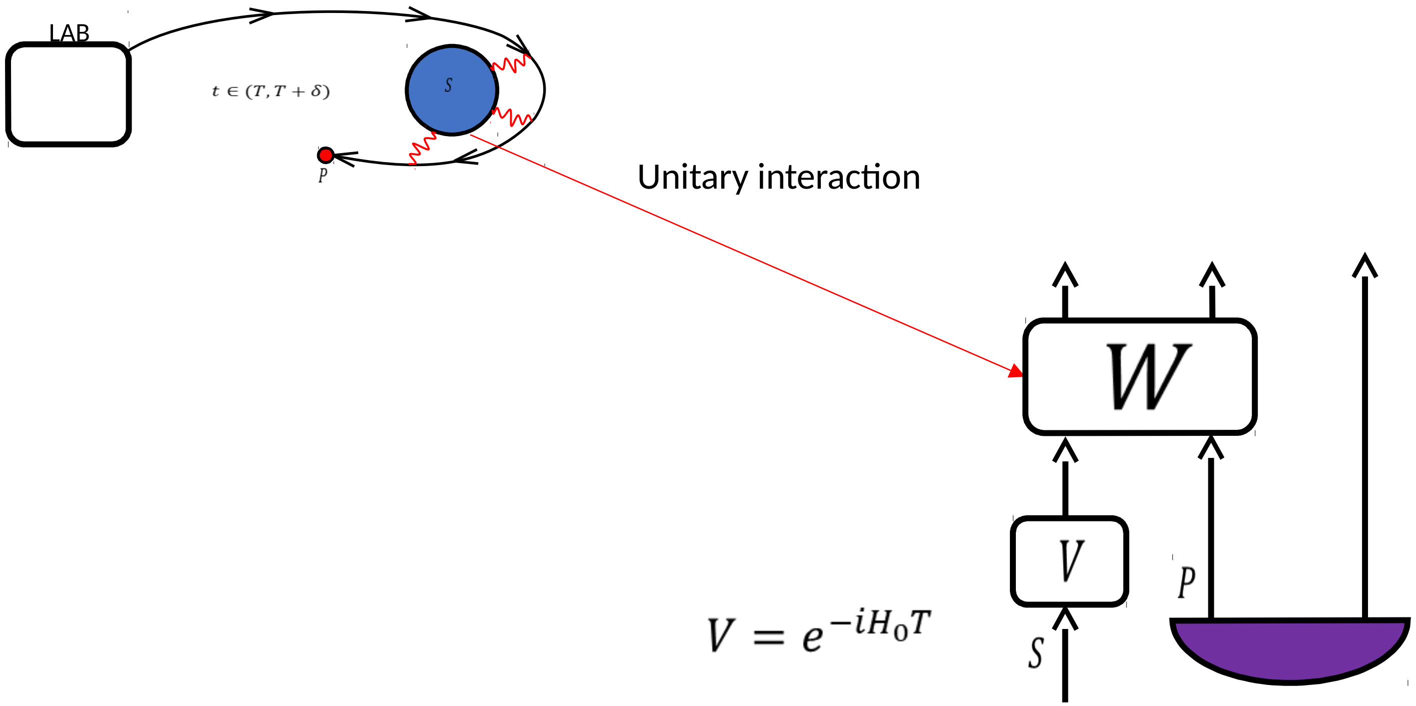
Initial conditions



$$V = e^{-iH_0 T}$$

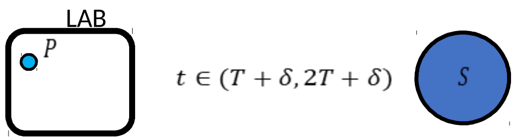


(a) Probe interaction

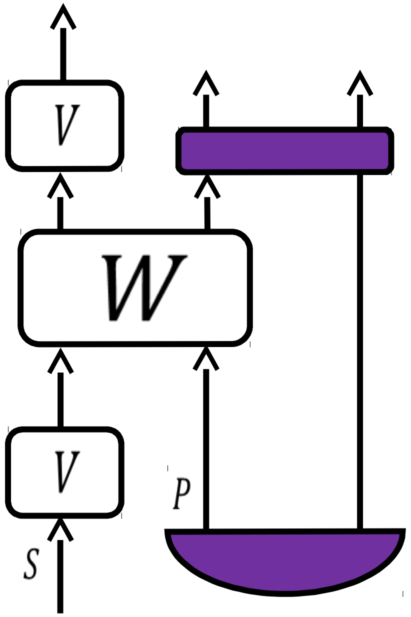


$$V = e^{-iH_0 T}$$

(b) Rest

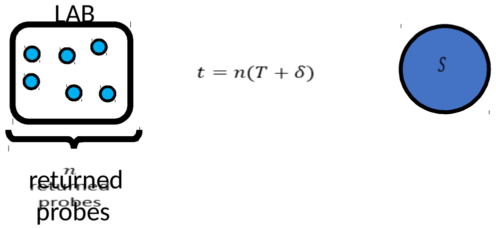


$$V = e^{-iH_0 T}$$

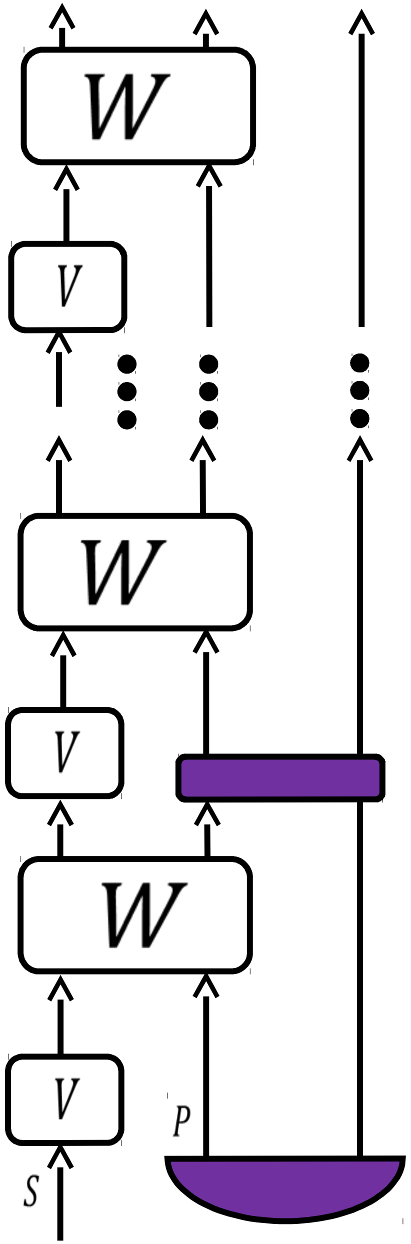


⋮

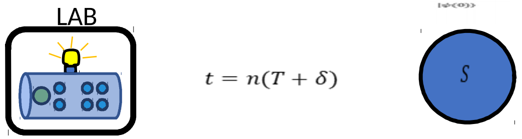
(a) Probe interaction

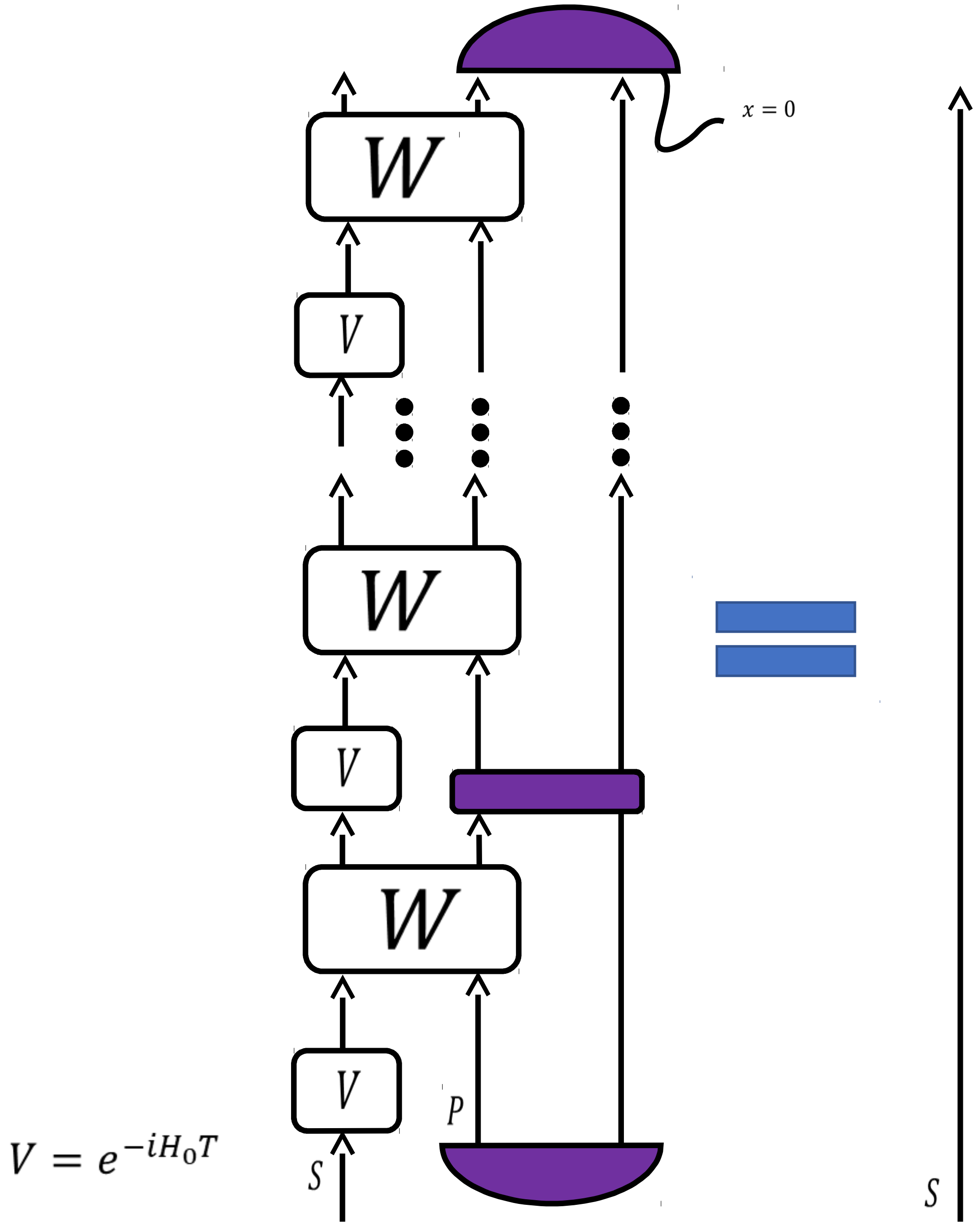


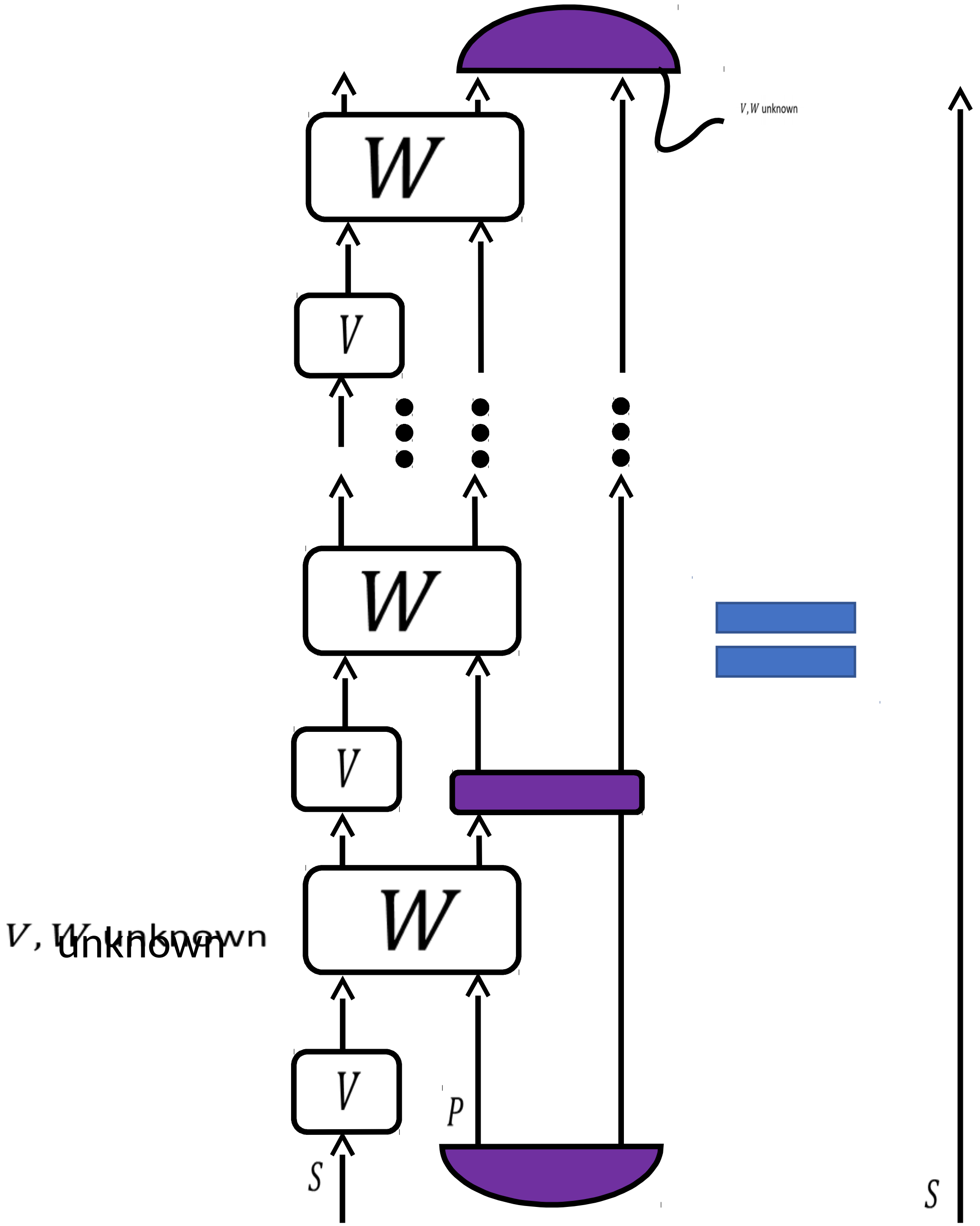
$$V = e^{-iH_0T}$$

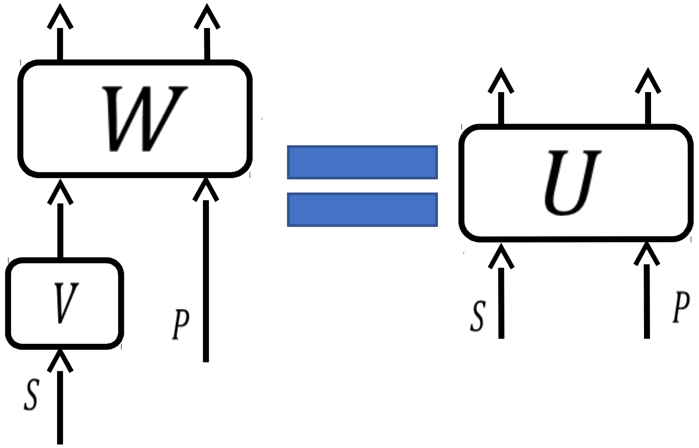


(c) Probe processing

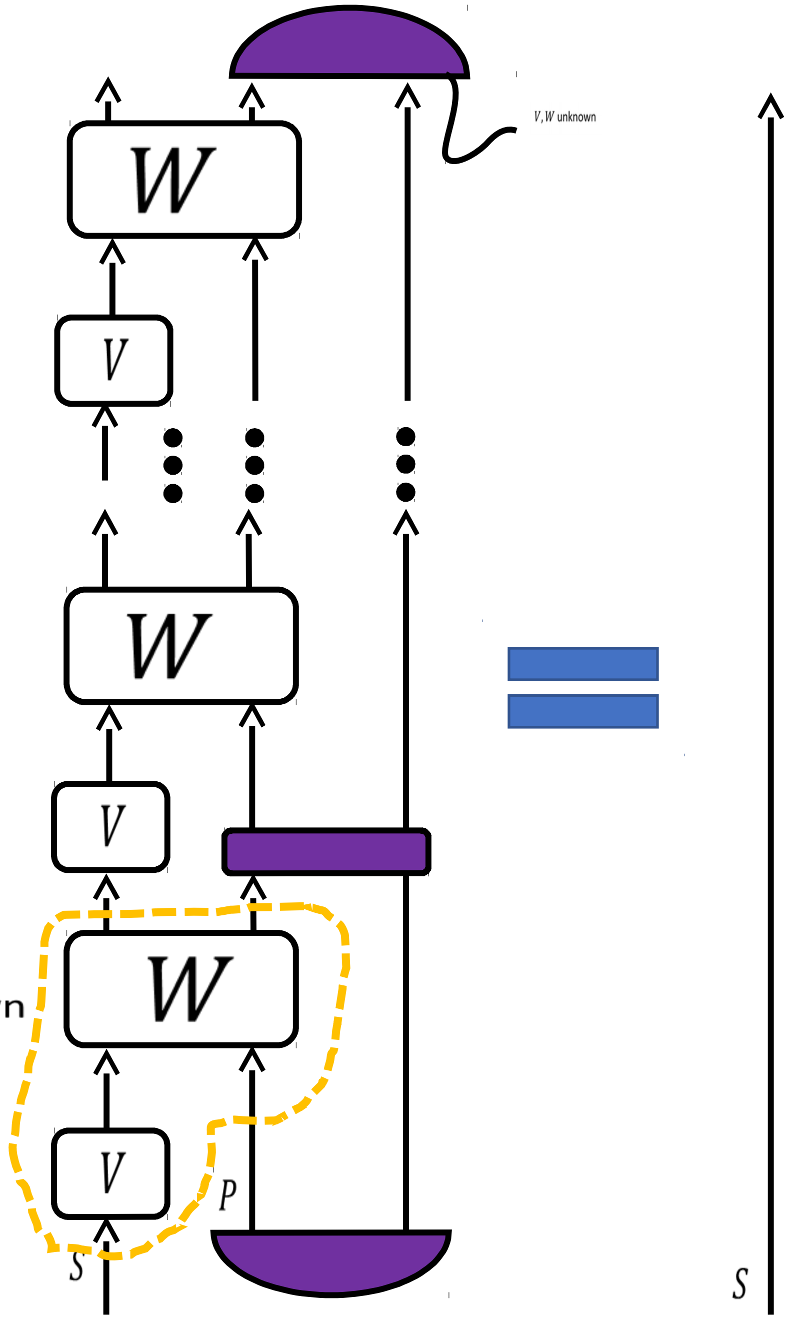




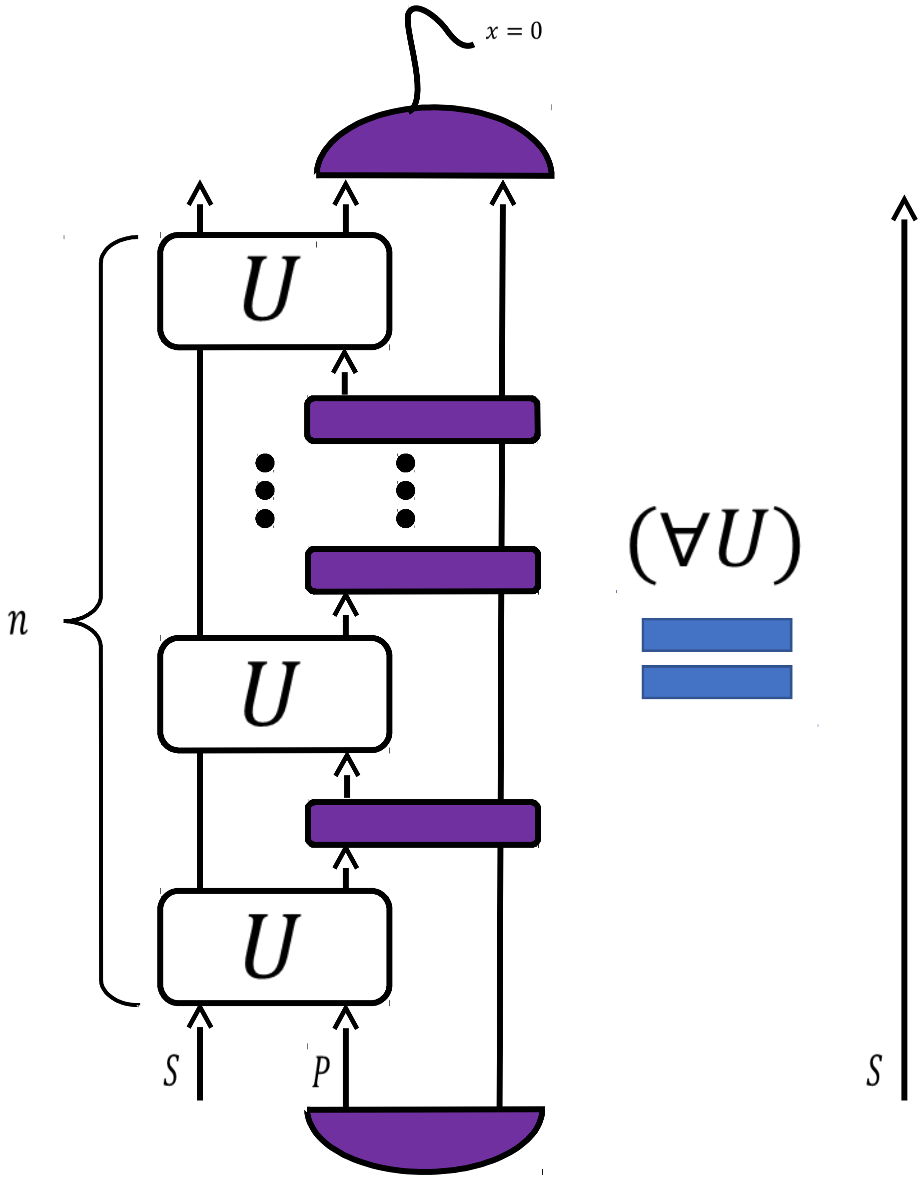

W
W
W
V
V
V
V, W unknown
V, W unknown
unknown
P
S
S



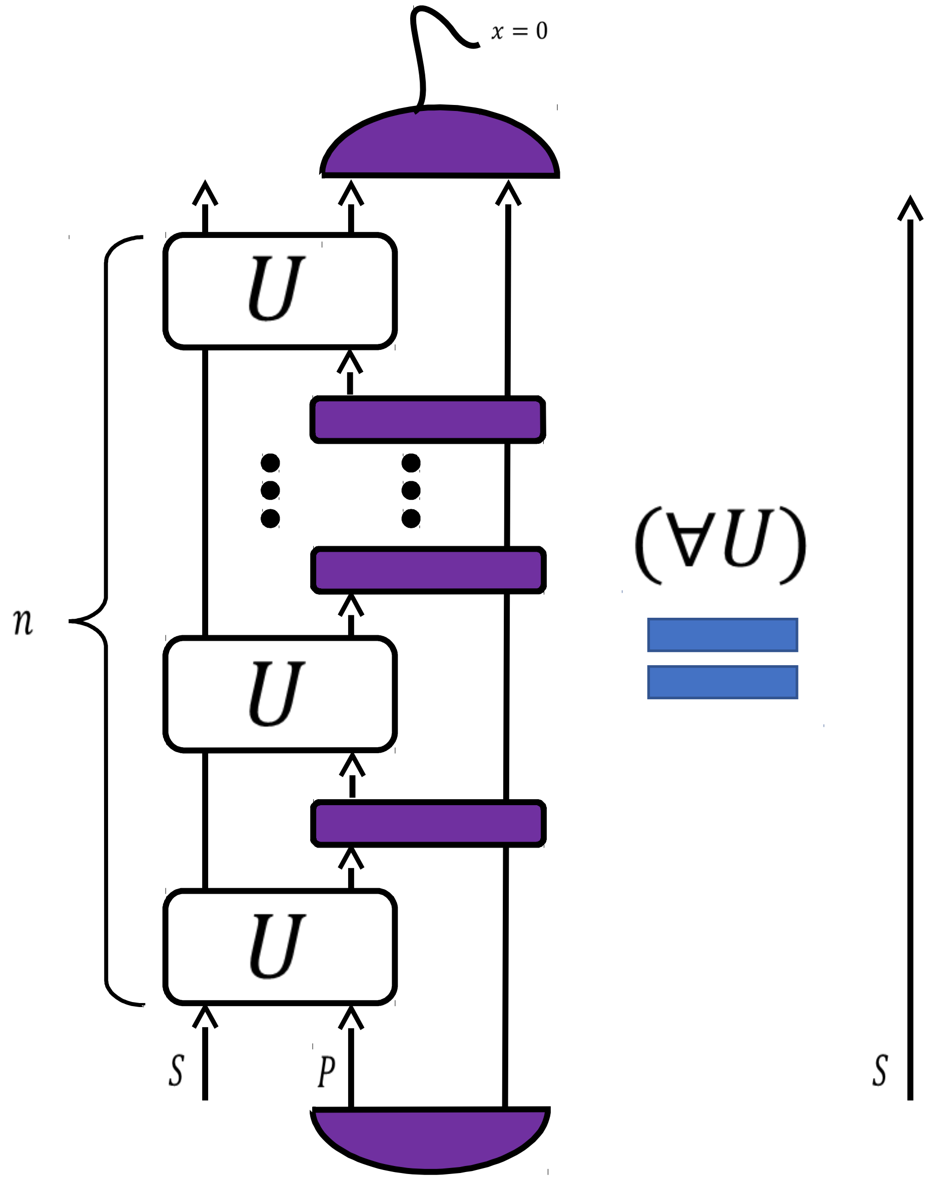
V , W unknown



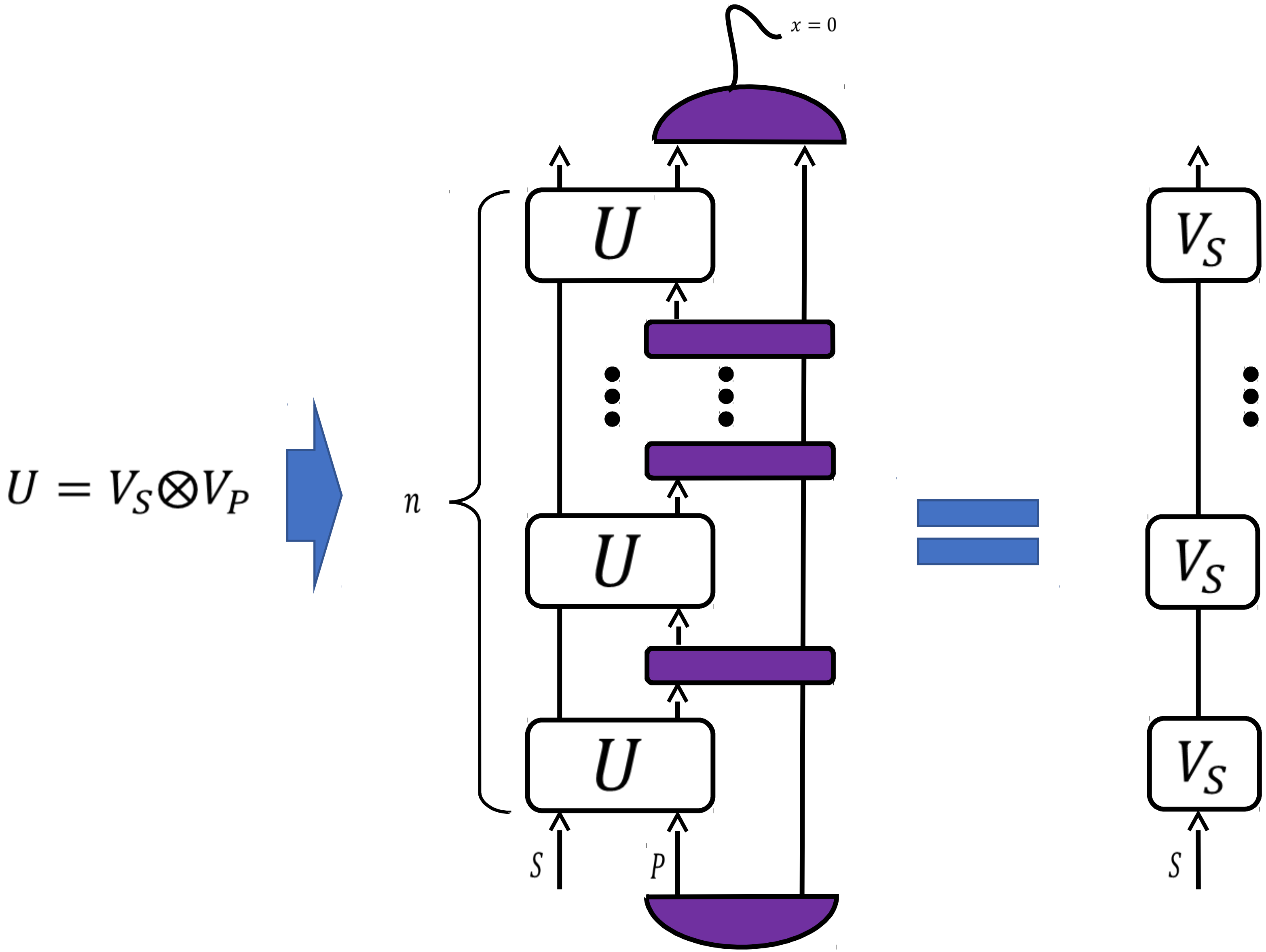
Quantum resetting protocol



Quantum resetting protocol



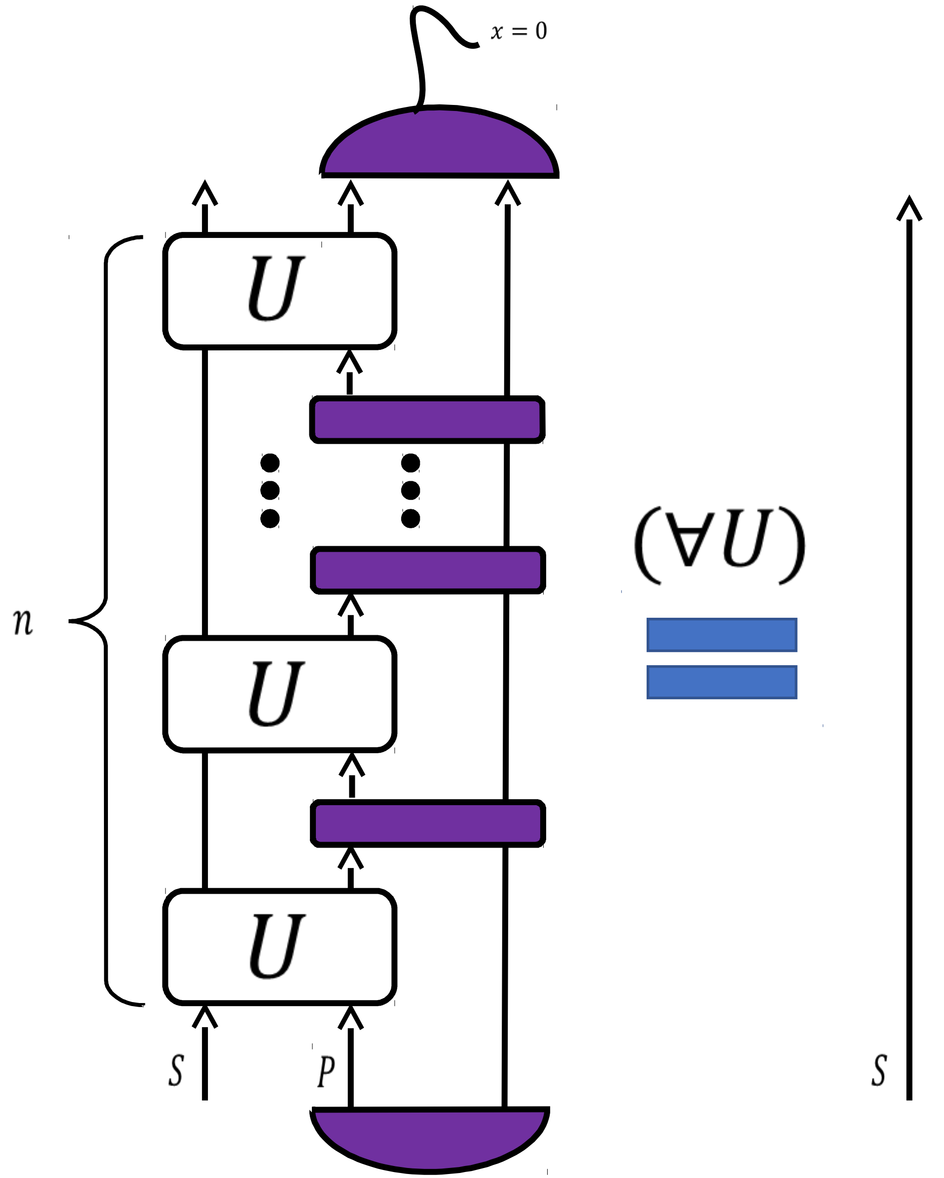
Desideratum: $P(x = 0|U) \neq 0$, for all U for all



U = V_S⊗V_P
n
U
U
U
x = 0
S
P
V_S
V_S
V_S
S

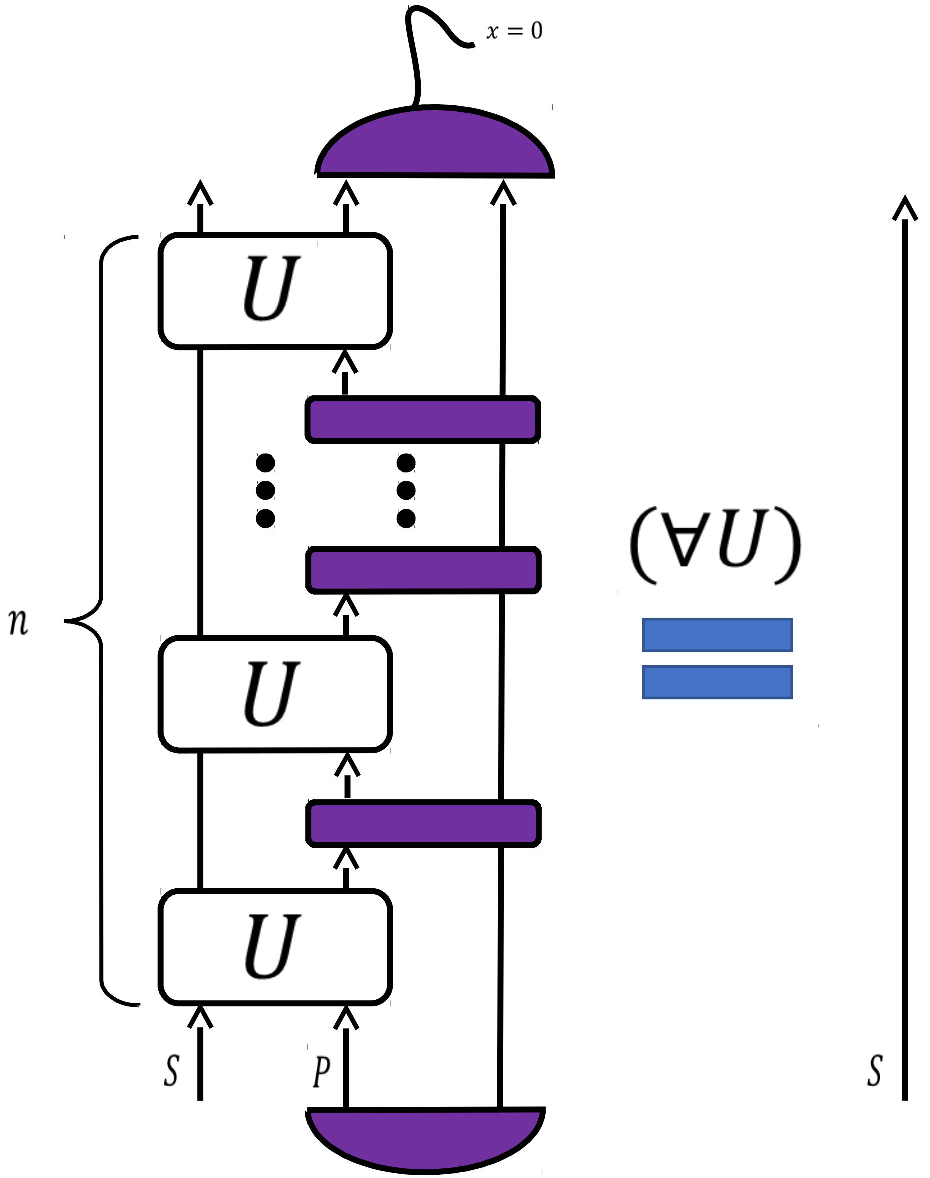
$U = V_S \otimes V_P$ ⇒ Resetting protocol will fail with probability 1

Quantum resetting protocol



Desideratum: $P(x = 0|U) = p$, for all U for all

Quantum resetting protocol

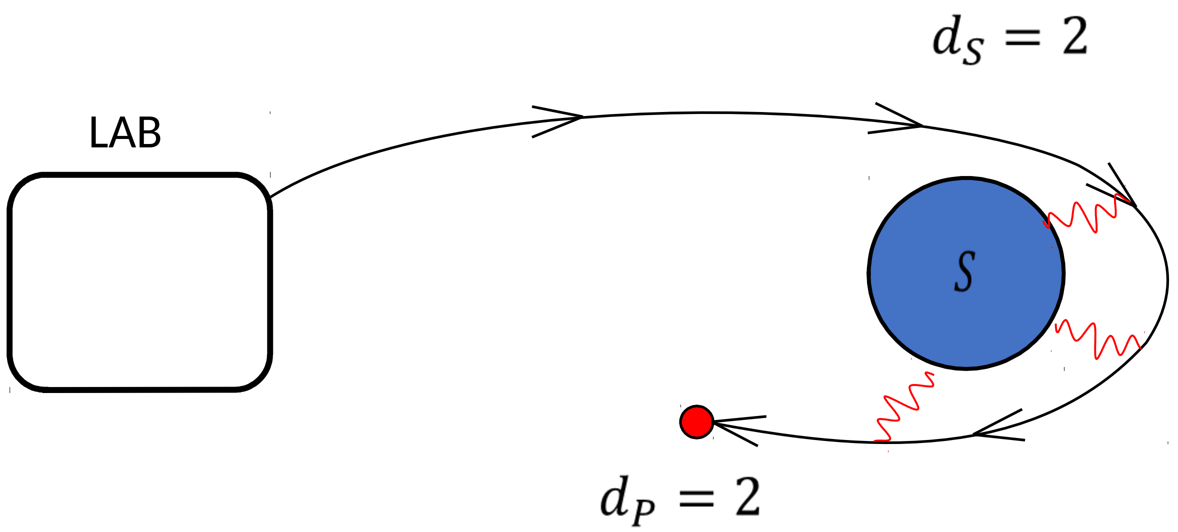


$P(x = 0|U) \neq 0$ except for a subset of unitaries of zero measure

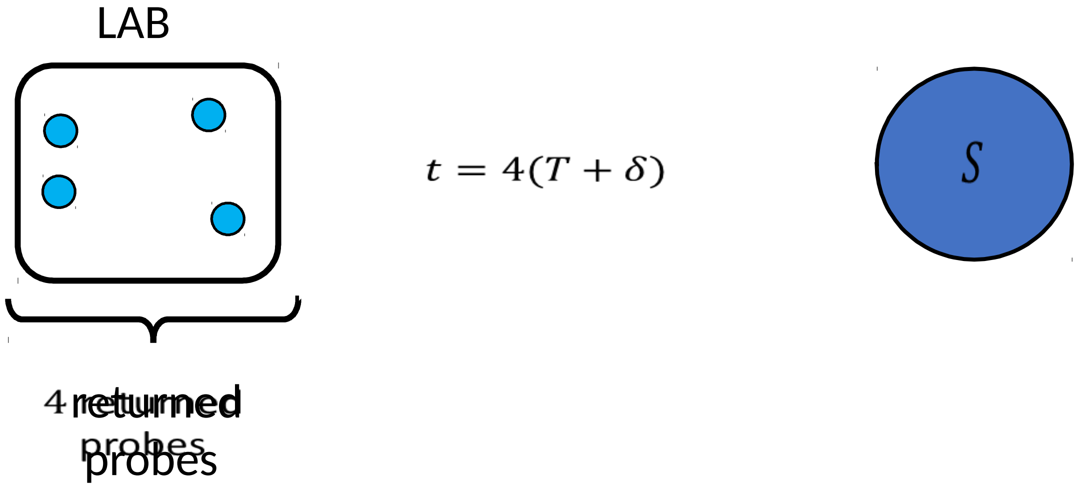
except for a subset of unitaries of zero measure

Do quantum resetting protocols exist?

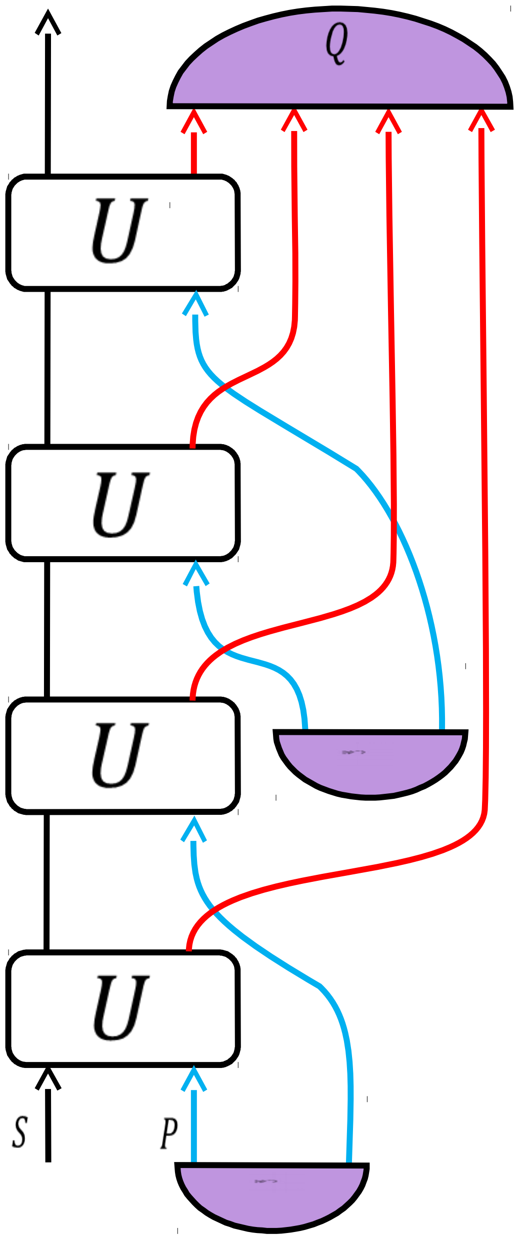
Scenario

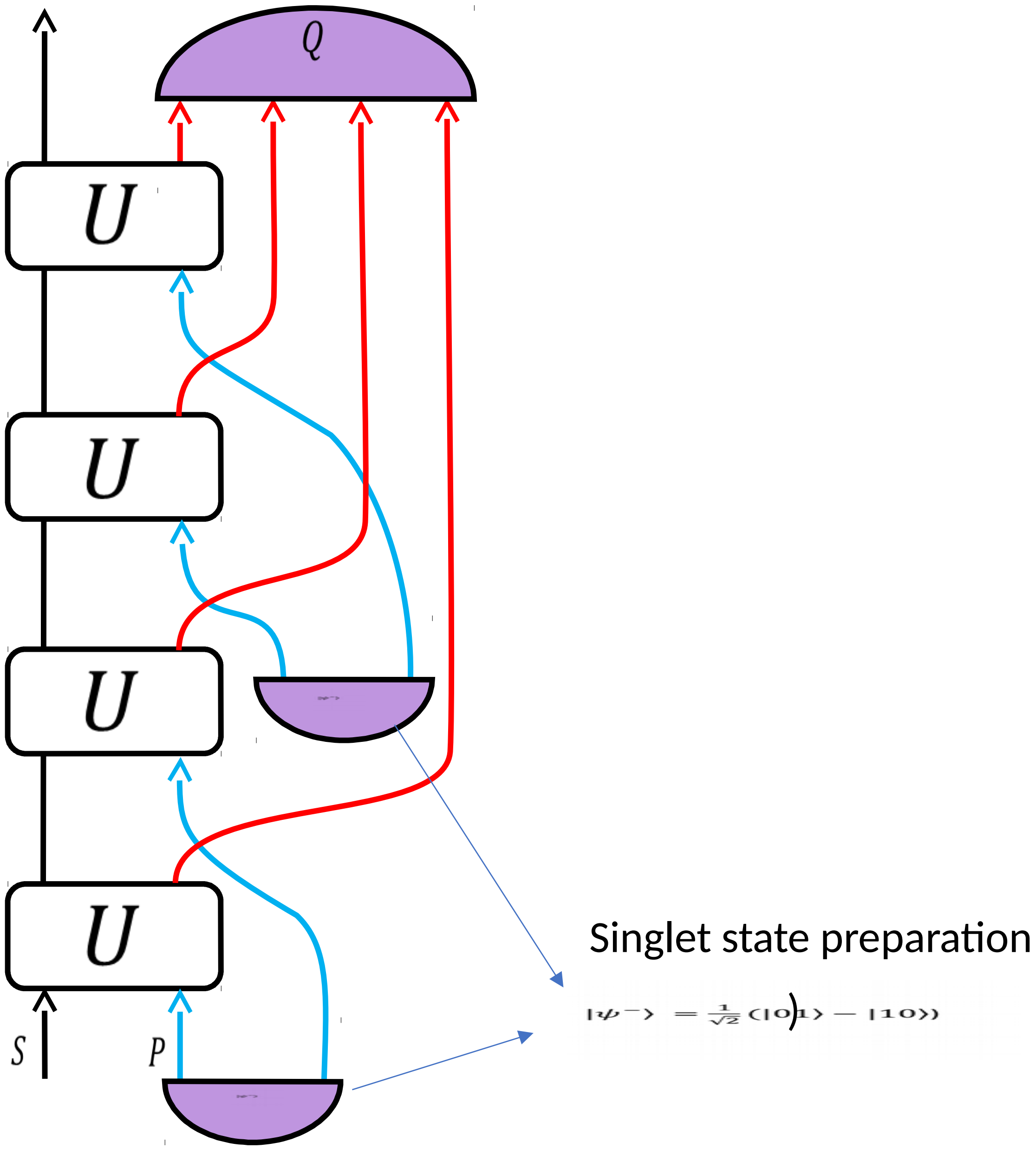


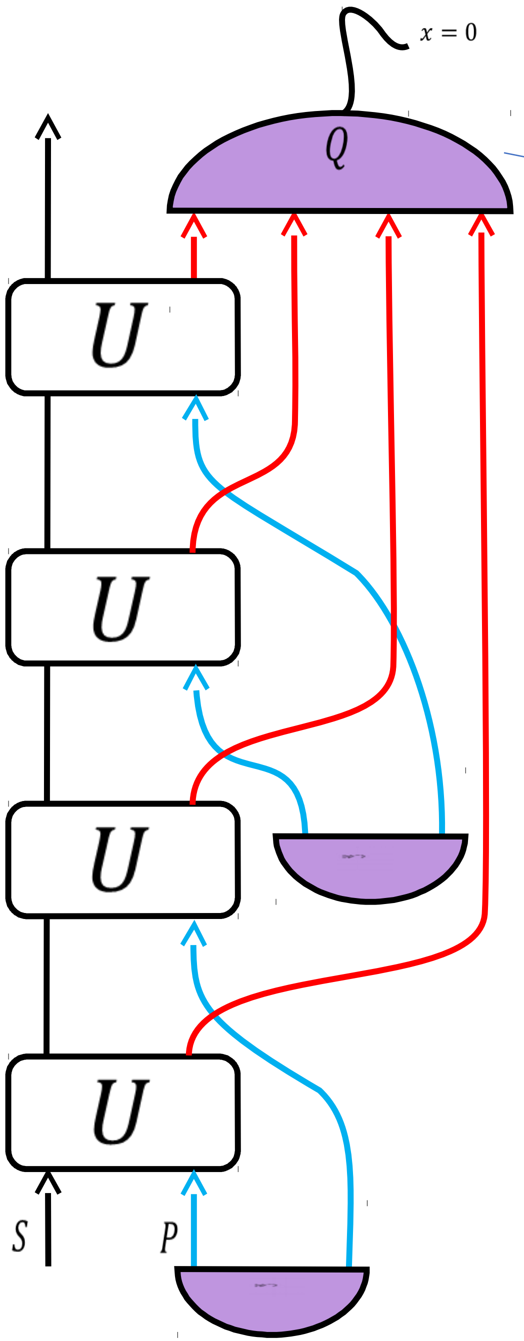
Scenario



$$t = 4(T + \delta)$$


Q
U
U
U
U
S
P

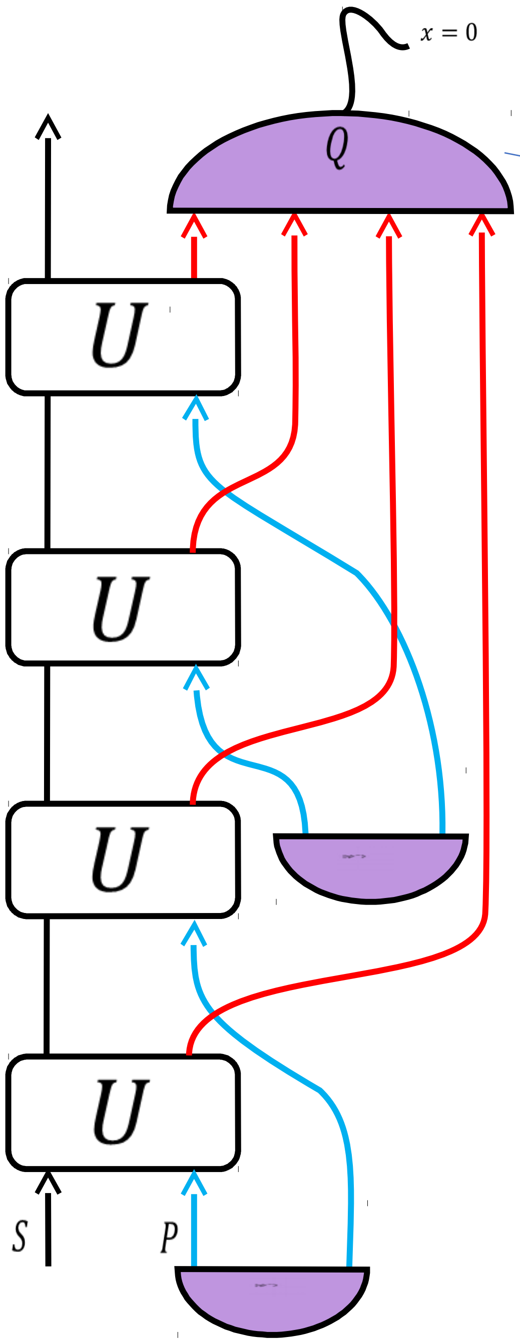

Q
U
U
U
U
S
P
Singlet state preparation
|ψ⁻⟩ = 1/√2 (|01⟩ − |10⟩)



Projection onto the space spanned by

$$|m_1\rangle = |0,0,0,0\rangle,$$
$$|m_2\rangle = \tfrac{1}{2}(|1,0,0,0\rangle + |0,1,0,0\rangle + |0,0,1,0\rangle + |0,0,0,1\rangle),$$
$$|m_3\rangle = \tfrac{1}{2}(|1,0,1,0\rangle + |0,1,0,1\rangle + |1,0,0,1\rangle + |0,1,1,0\rangle),$$
$$|m_4\rangle = \tfrac{1}{\sqrt{2}}(|0,0,1,1\rangle + |1,1,0,0\rangle),$$
$$|m_5\rangle = \tfrac{1}{2}(|1,1,1,0\rangle + |0,1,1,1\rangle + |1,0,1,1\rangle + |1,1,0,1\rangle),$$
$$|m_6\rangle = |1,1,1,1\rangle$$

Why does this work?



Projection onto the space spanned by

$$|m_1\rangle = |0,0,0,0\rangle,$$
$$|m_2\rangle = \frac{1}{2}(|1,0,0,0\rangle + |0,1,0,0\rangle + |0,0,1,0\rangle + |0,0,0,1\rangle),$$
$$|m_3\rangle = \frac{1}{2}(|1,0,1,0\rangle + |0,1,0,1\rangle + |1,0,0,1\rangle + |0,1,1,0\rangle),$$
$$|m_4\rangle = \frac{1}{\sqrt{2}}(|0,0,1,1\rangle + |1,1,0,0\rangle),$$
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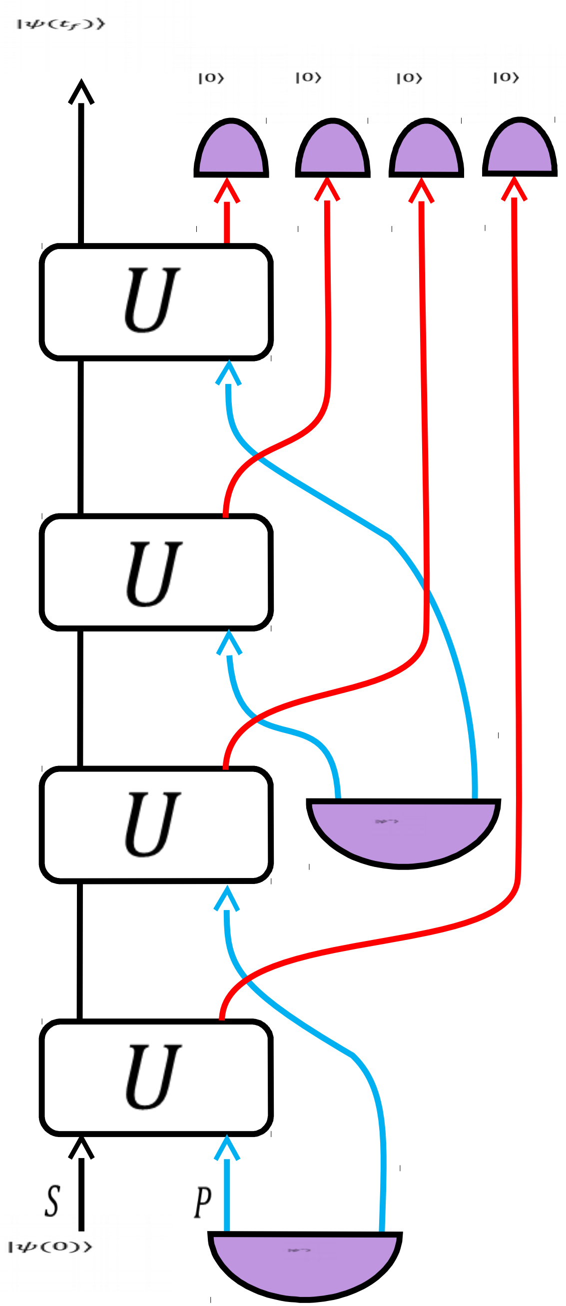
$$|m_6\rangle = |1,1,1,1\rangle$$

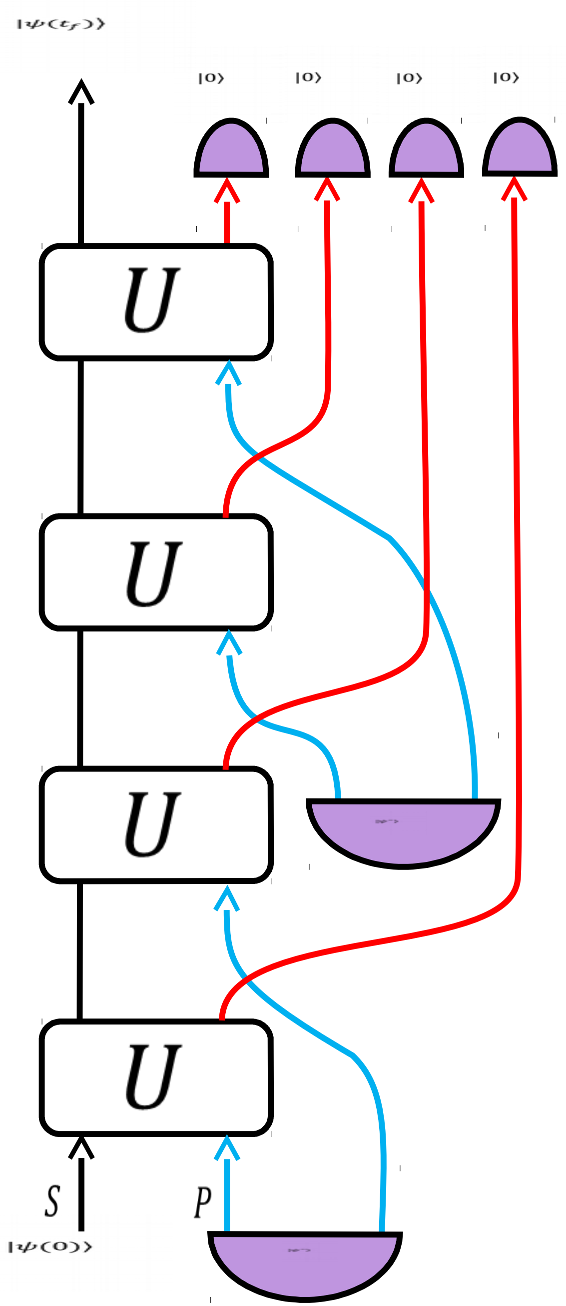


|ψ(t_f)⟩
|0⟩
|0⟩
|0⟩
|0⟩
U
U
U
U
S
P
|ψ(0)⟩

$$|\psi(t_f)\rangle = \frac{1}{2}[U_{0,0}, U_{0,1}]^2 |\psi(0)\rangle$$

$$U_{ij} = (\mathbb{I}_S \otimes \langle i|_P) U (\mathbb{I}_S \otimes |j\rangle_P)$$

2x2 complex matrices



$A, B, 2 \times 2$ matrices

matrices

$A, B, 2 \times 2$ matrices

matrices

$$[A,B] = \sum_{i=0,1,2,3} c_i \sigma_i$$

σ_i, Pauli matrices

σ_i, Pauli matrices

$A, B,\ 2\times 2$ matrices
matrices

$$[A,B] = \sum_{i=0,1,2,3} c_i \sigma_i$$

$$\mathrm{Tr}([A,B]) = 0 \Rightarrow c_0 = 0$$

σ_i, Pauli matrices
i, Pauli matrices

A, B, 2×2 matrices

matrices

$$[A, B] = \sum_{i=1,2,3} c_i \sigma_i$$

σ_i, Pauli matrices

σ_i, Pauli matrices

A, B, 2×2 matrices
matrices

$$[A,B]^2 = \left(\sum_{i=1,2,3} c_i \sigma_i\right)^2 = \left(\sum_{i=1,2,3} c_i^2\right)\mathbb{I}$$

σ_i, Pauli matrices
$_i$, Pauli matrices

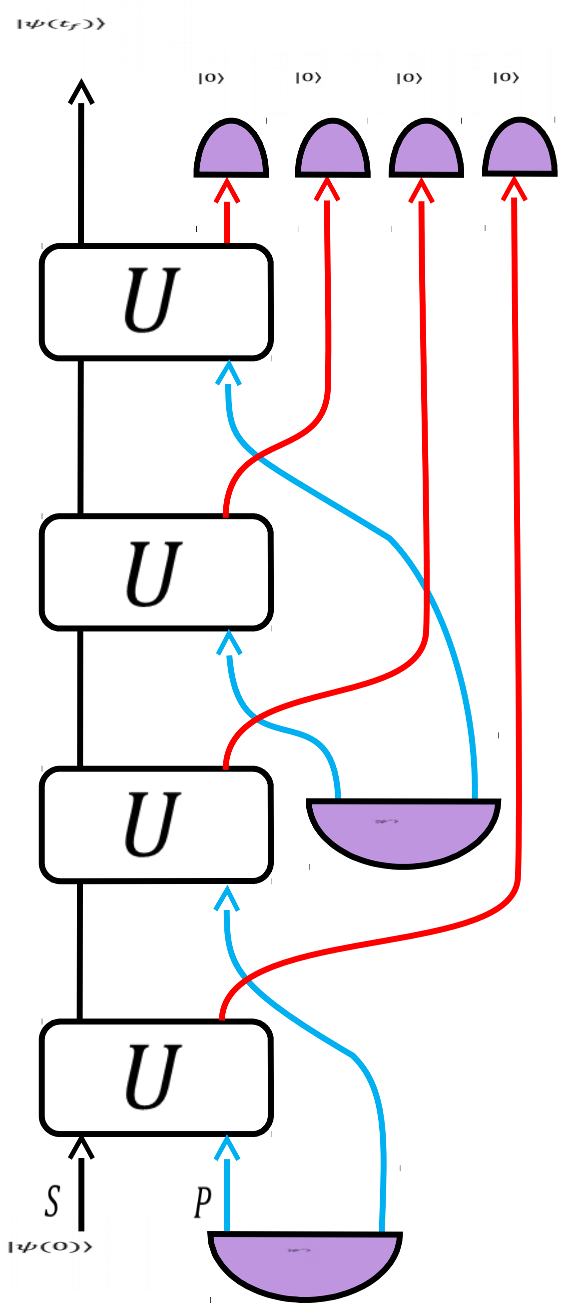
$A, B,\ 2 \times 2$ matrices

Central polynomial for dimension 2

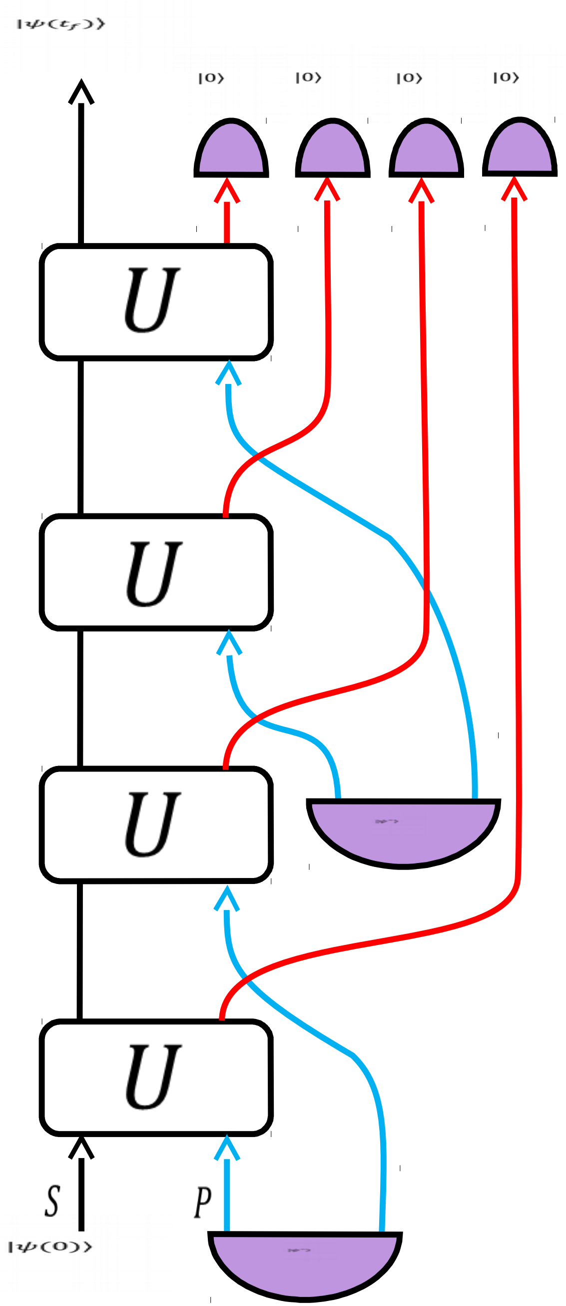
$$[A,B]^2 = \left(\sum_{i=1,2,3} c_i \sigma_i \right)^2 = \left(\sum_{i=1,2,3} c_i^2 \right) \mathbb{I}$$

σ_i, Pauli matrices

$$|\psi(t_f)\rangle = \frac{1}{2}[U_{0,0}, U_{0,1}]^2 |\psi(0)\rangle$$



$$|\psi(t_f)\rangle = \frac{1}{2}[U_{0,0}, U_{0,1}]^2 |\psi(0)\rangle \propto |\psi(0)\rangle$$



Similarly,

$$|\psi(t_f)\rangle \propto |\psi(0)\rangle$$

$$|m_1\rangle = |0,0,0,0\rangle,$$
$$|m_2\rangle = \tfrac{1}{2}(|1,0,0,0\rangle + |0,1,0,0\rangle + |0,0,1,0\rangle + |0,0,0,1\rangle),$$
$$|m_3\rangle = \tfrac{1}{2}(|1,0,1,0\rangle + |0,1,0,1\rangle + |1,0,0,1\rangle + |0,1,1,0\rangle),$$
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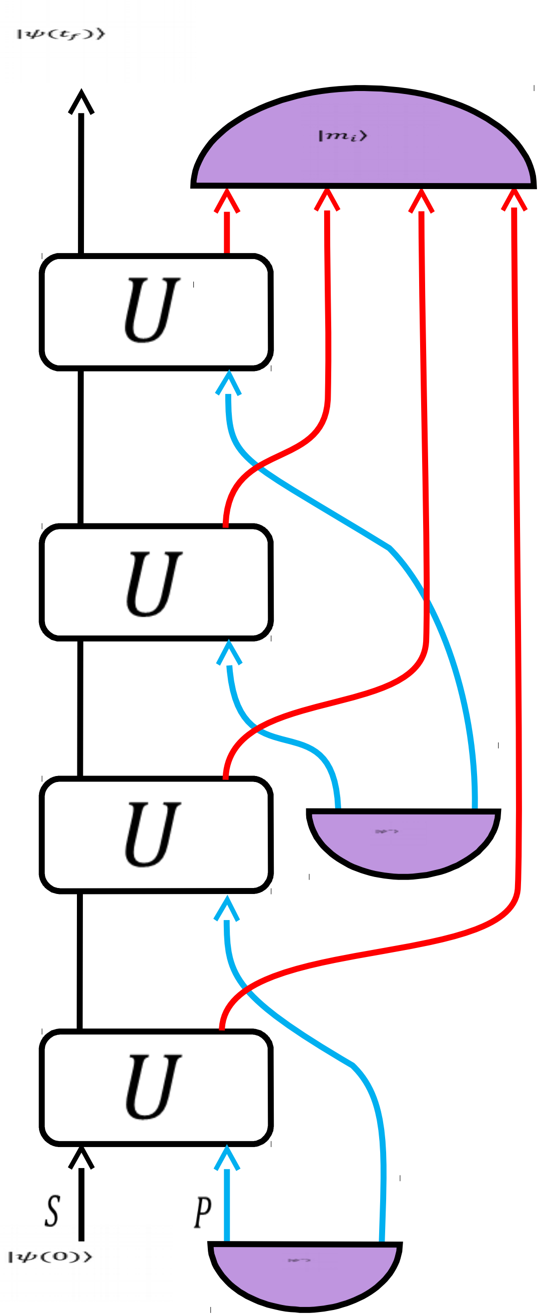
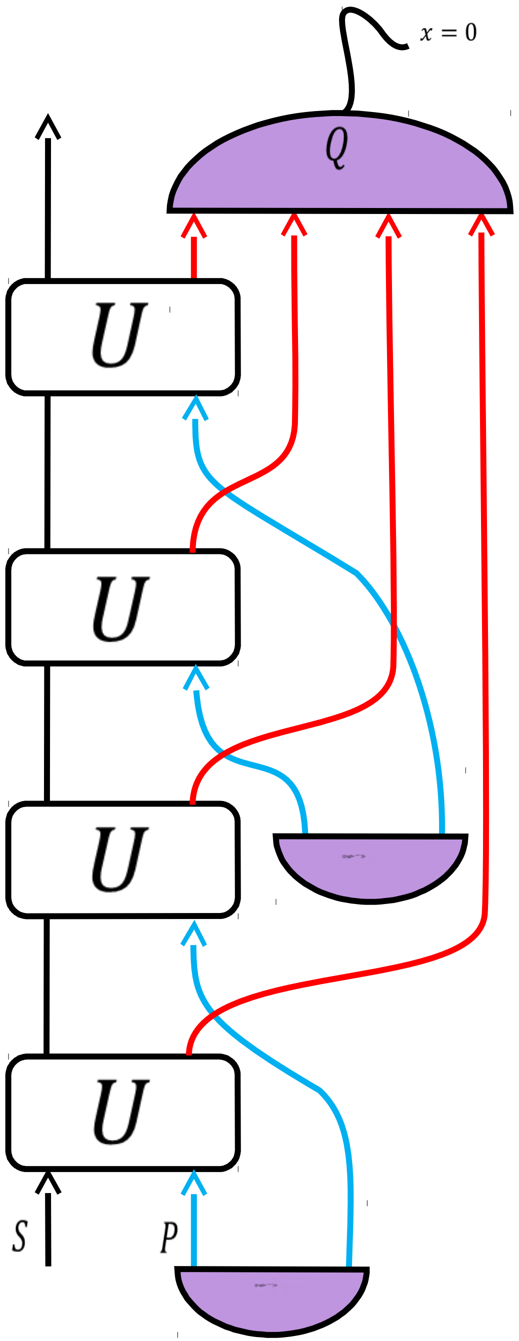
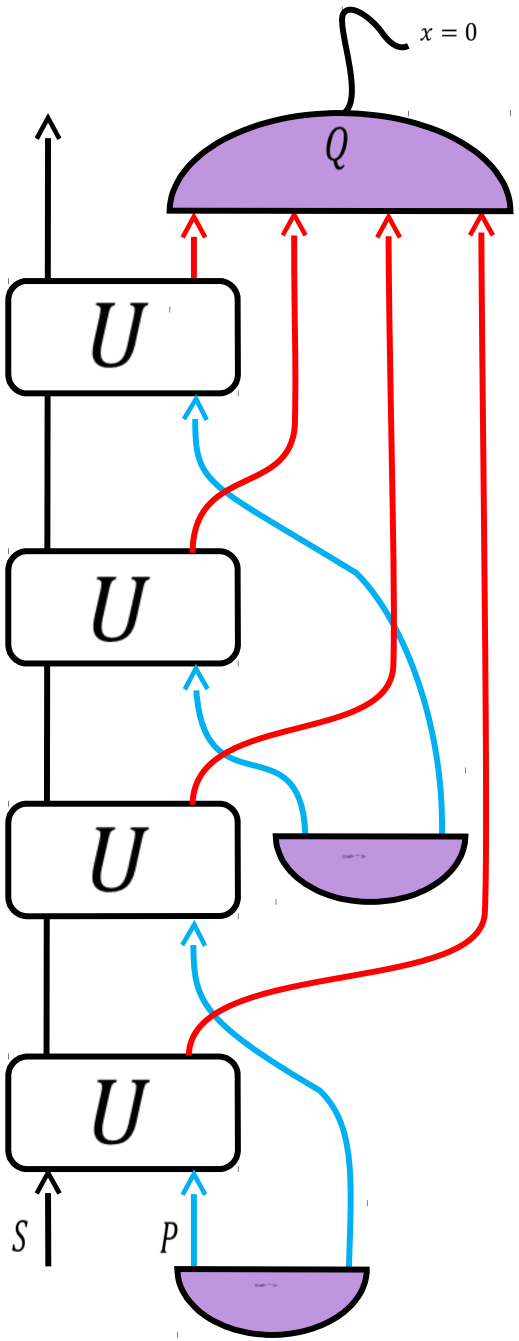


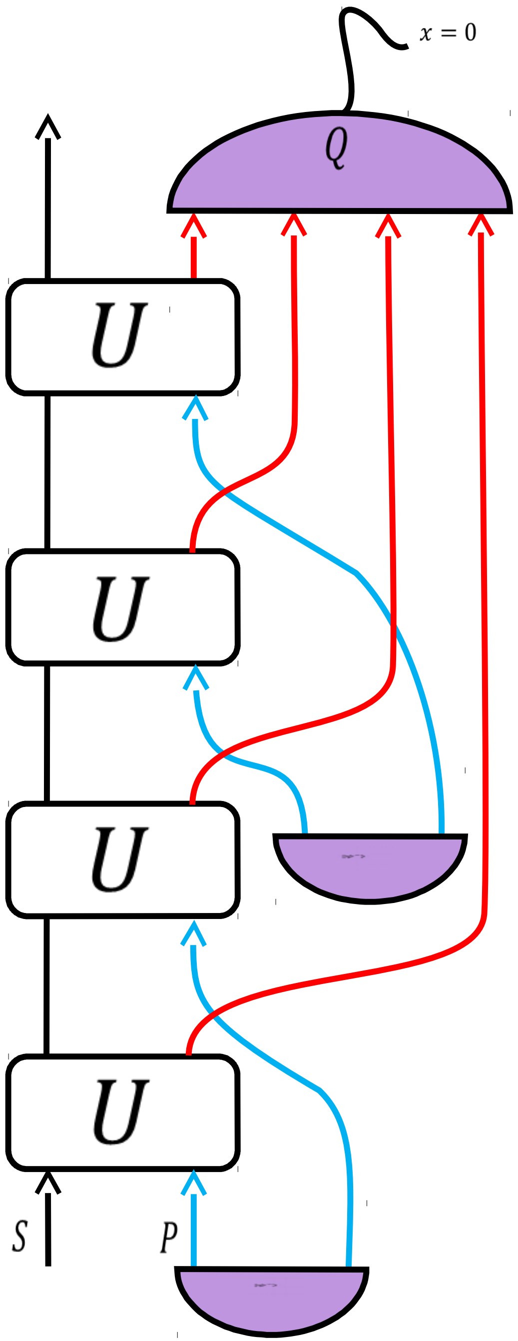


$$P(x = 0|U) \in [0, 1]$$



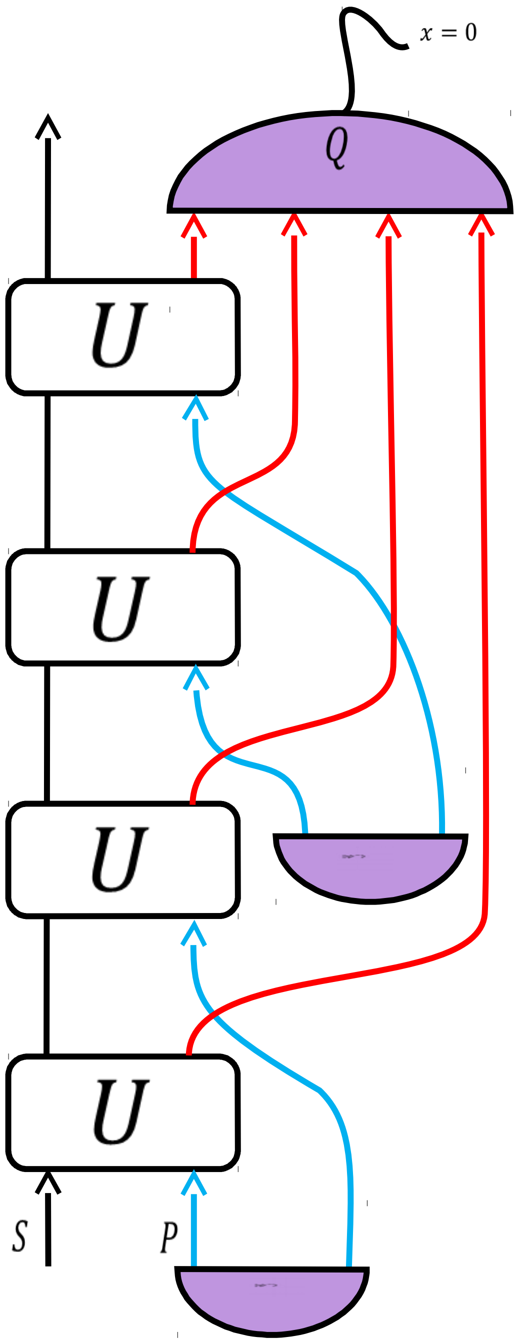
$$P(x = 0|U) \in [0, 1]$$

E.g.: $U = V_S \otimes V_P$ E.g.:



$$P(x = 0|U) \in [0,1]$$

E.g.: $U = \frac{\sigma_x \otimes \sigma_z + i\sigma_y \otimes \sigma_x}{\sqrt{2}}$



Average probability of success for completetey unknown U

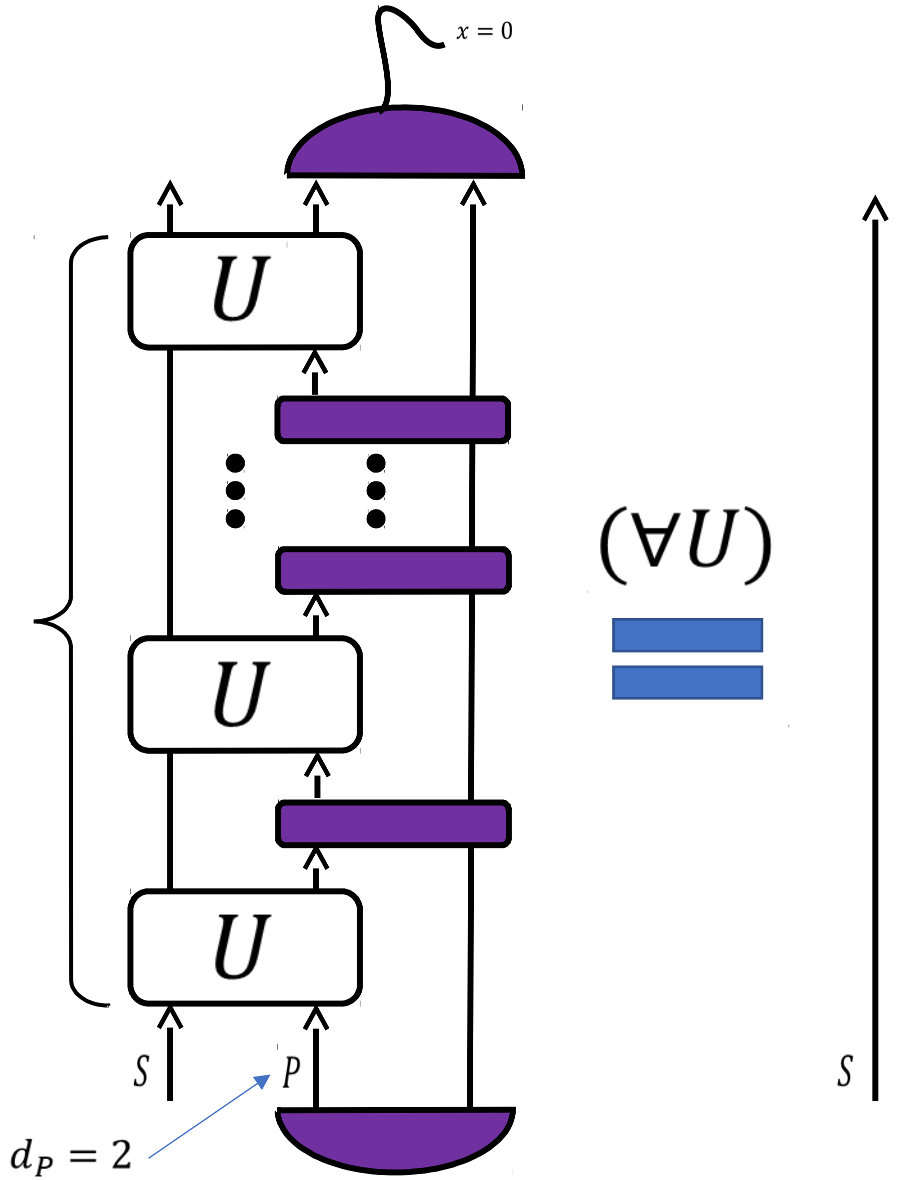
Average probability of success for completetey unknown

$$\int dU\, P(x=0|U) \approx 0.2170$$

Generalization

MN, arXiv:1710.02470

For all d_S $\Rightarrow$ $n = O(d_S^3)$ $[O(d_S^2 \log d_S)]$



$P(x = 0|U) \neq 0$ except for a subset of unitaries of zero measure

except for a subset of unitaries of zero measure

MN, arXiv:1710.02470

Characterization of all quantum resetting protocols (practical for n=4)

$$\max \operatorname{tr}(M_0^T X(\rho))$$

$$\text{s.t.} \quad \operatorname{supp}(M_0^T) \in \mathcal{H}^c, M_0, M_1 \geq 0$$

$$M_0 + M_1 = \mathbb{I}_{A_n^{out}} \otimes \Gamma^{(n)},$$

$$\operatorname{tr}_{I_k}(\Gamma^{(k)}) = \mathbb{I}_{O_{k-1}} \otimes \Gamma^{(k-1)},$$

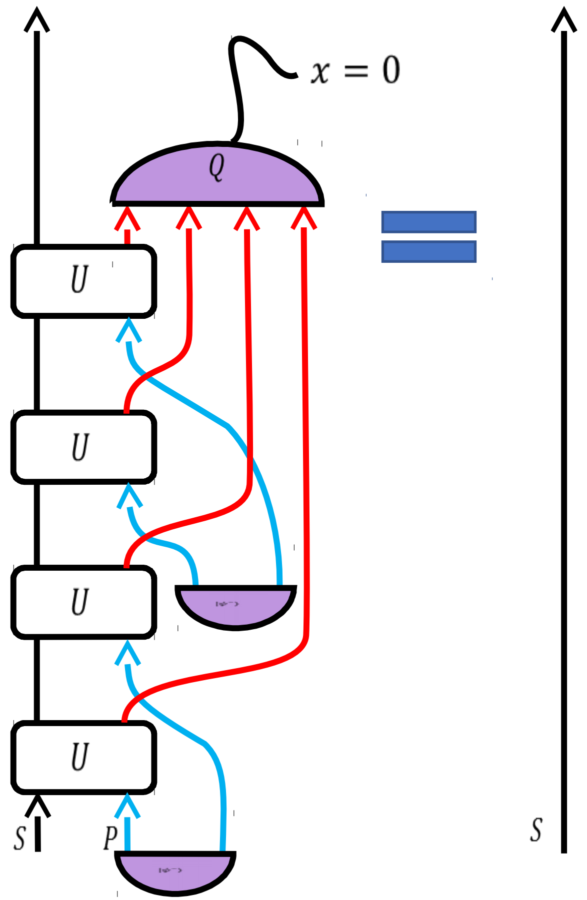
MN, arXiv:1710.02470

Heuristics to identify optimal strategies for high numbers of probes

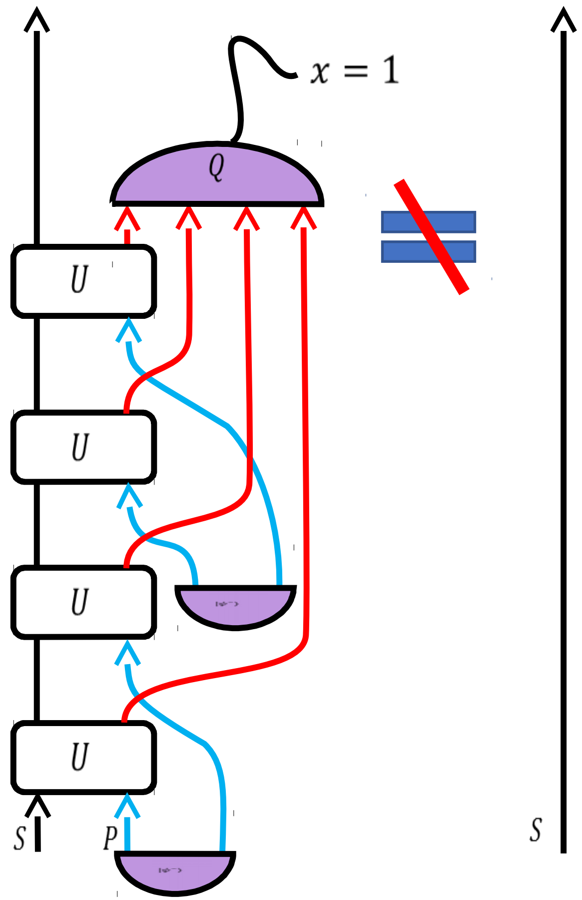
$\mathcal{W}_8, \widetilde{\mathcal{W}}_8,$ $n = 8, d_S = 2$

$\mathcal{W}_9$ $n = 9, d_S = 3$

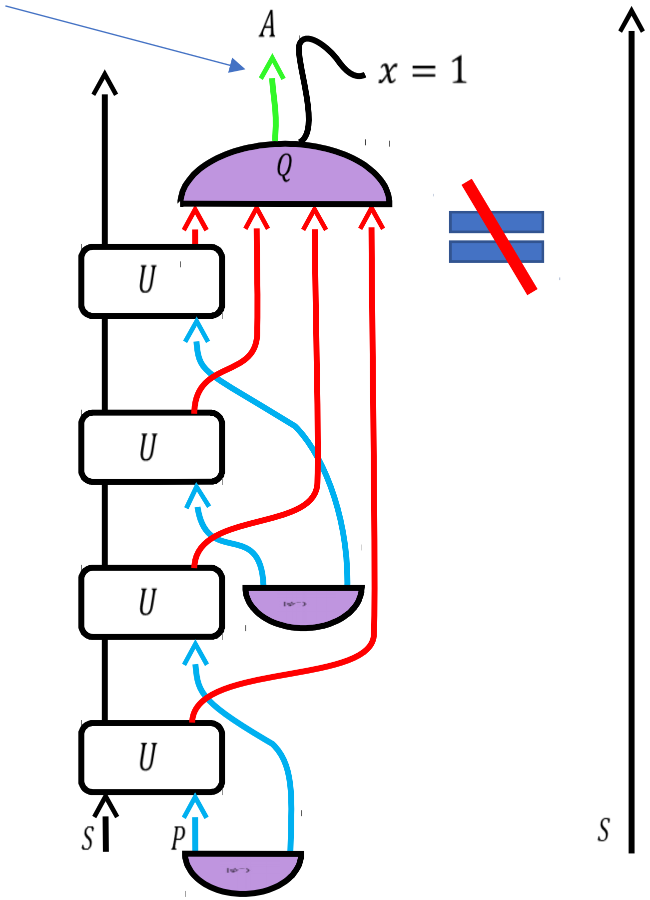
What if the protocol fails?

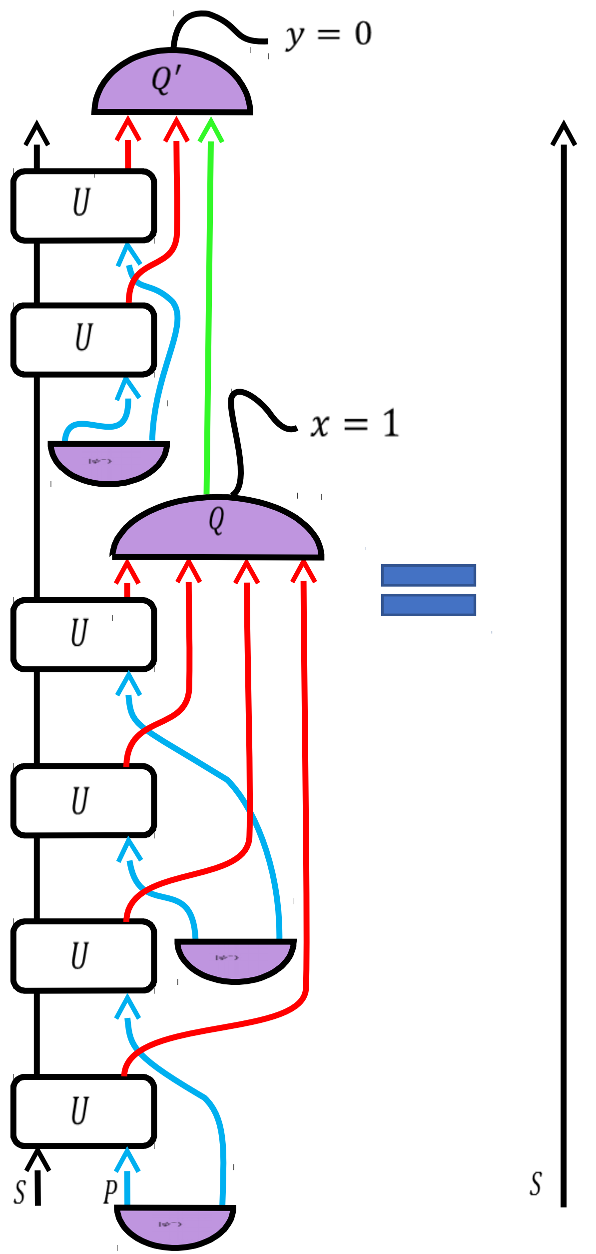


x = 0
Q
U
U
U
U
S
P
S


x = 1
Q
U
U
U
U
S
P
S

Suppose that the last measurement is a non-demolition one





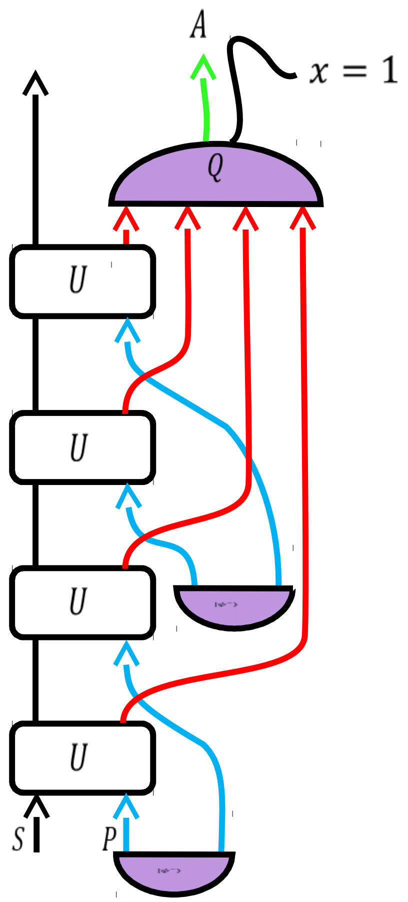
y = 0
Q′
U
U
x = 1
Q
U
U
U
U
S
P
S

$$|\omega\rangle_{SA} = \sum_i f_i(U)\,|\psi\rangle_S |i\rangle_A$$

$f_i(U)$: non-central matrix polynomials of degree 4 on the variables

non-central matrix polynomials of degree 4 on the variables

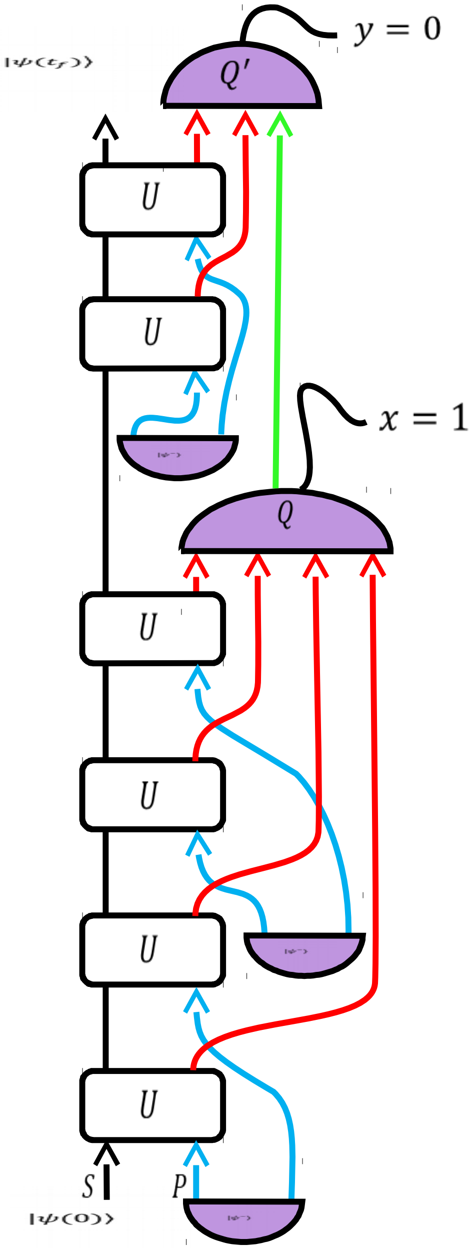
$$U_{ij} = (\mathbb{I}_S \otimes \langle i|_P)\,U\,(\mathbb{I}_S \otimes |j\rangle_P)$$



$$|\psi(t_f)\rangle_S = \sum_i g_i(U) f_i(U)\,|\psi(0)\rangle_S$$

matrix polynomials of degree 2, such that is a central polynomial

$g_i(U)$ matrix polynomials of degree 2, such that $\sum_i g_i(U) f_i(U)$ is a central polynomial



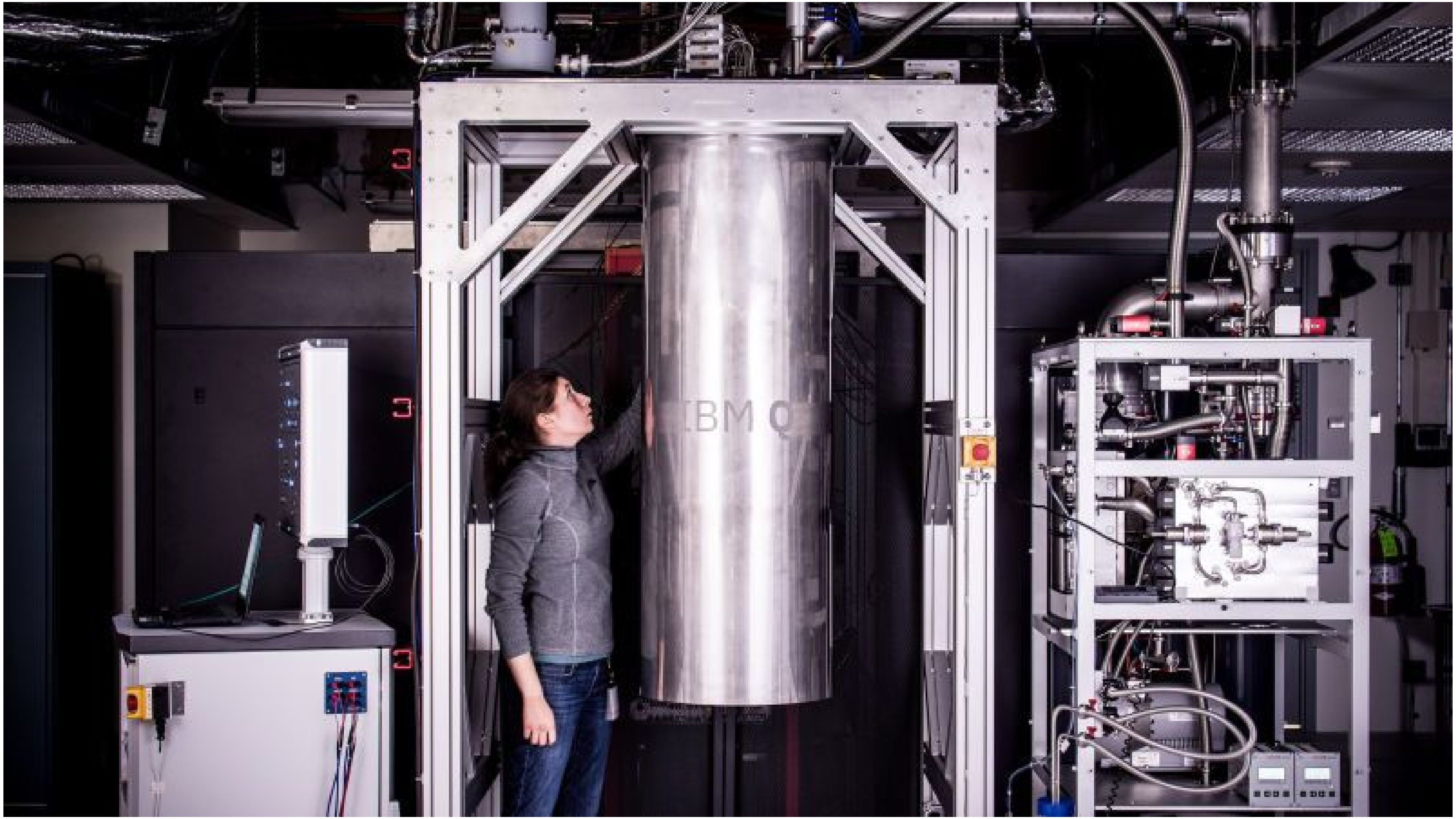
Undoing six possible failures

Average probability of success for completey unknown U

Average probability of success for completey unknown

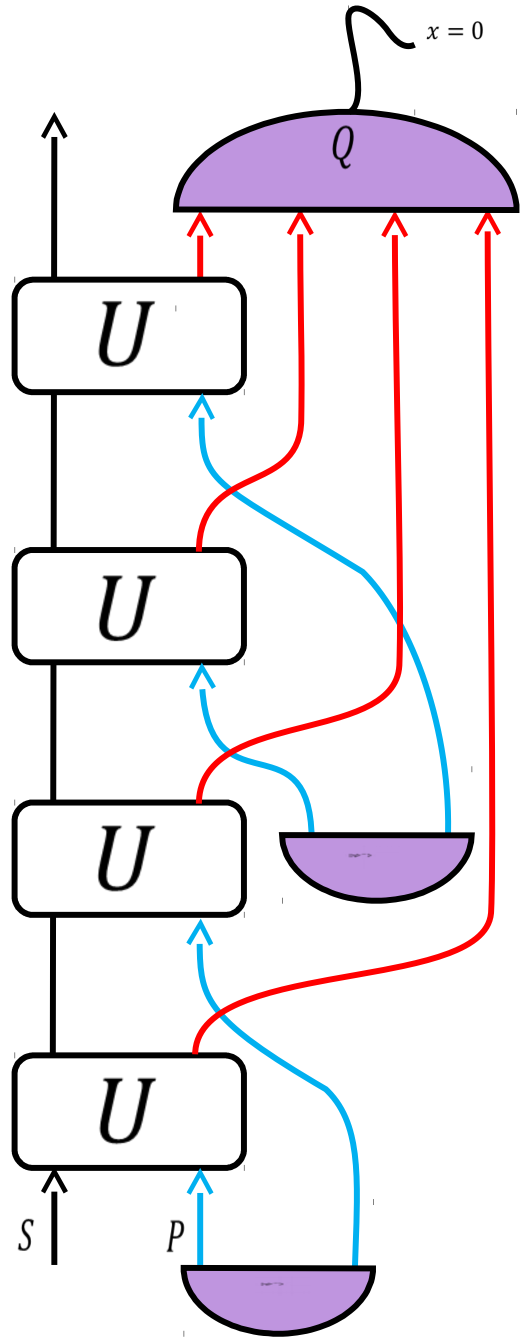
$$\int dU\, P(x = 0|U) \approx 0.6585$$

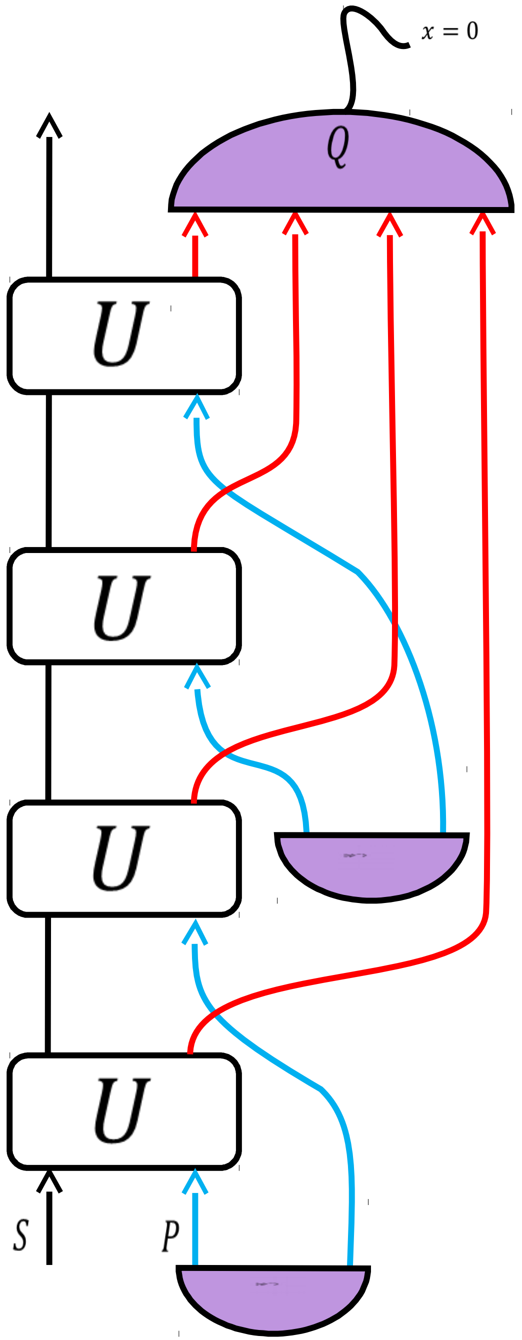
Experimental implementation?



IBM Q Experience

Experimental implementation: Prototype II

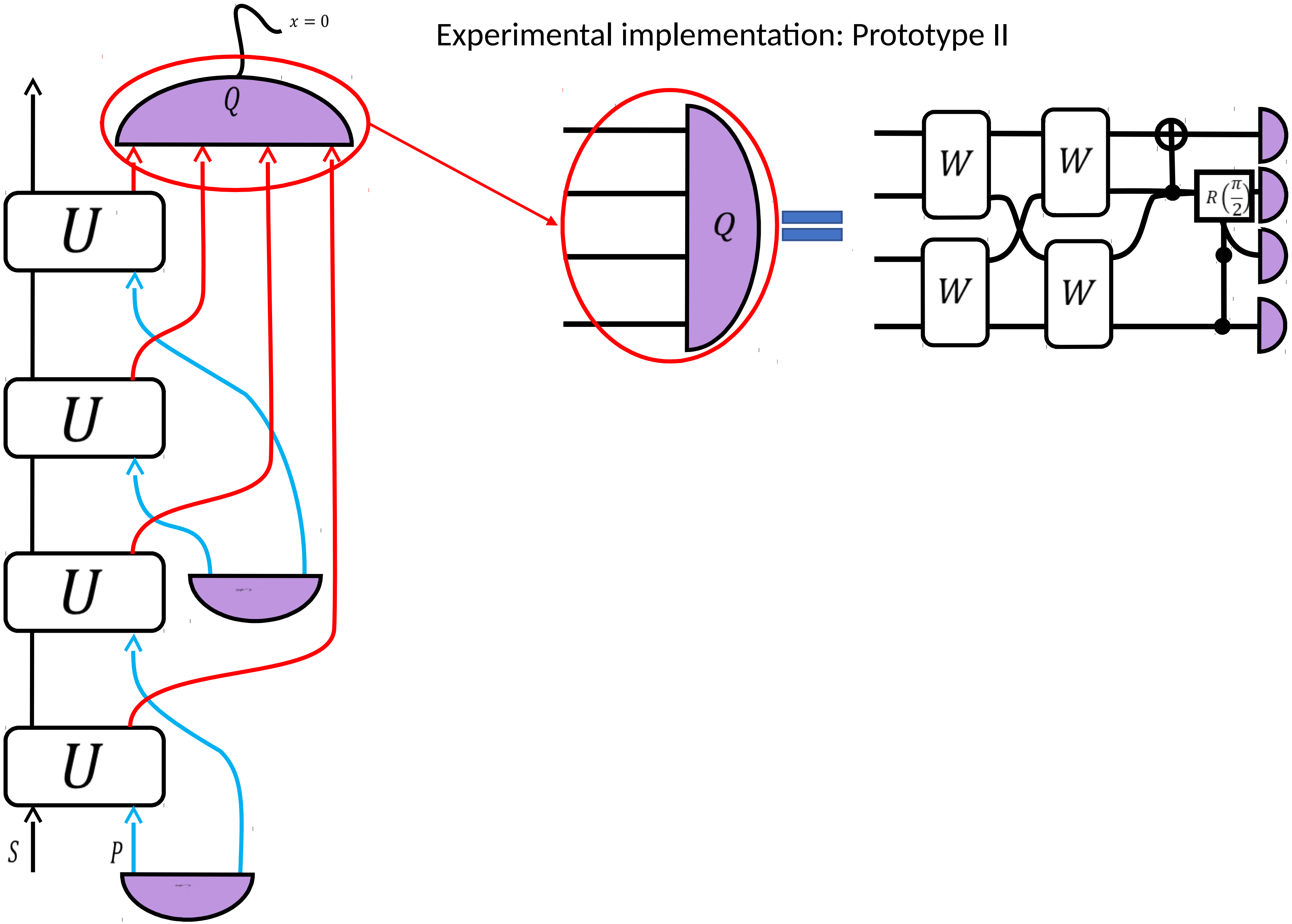




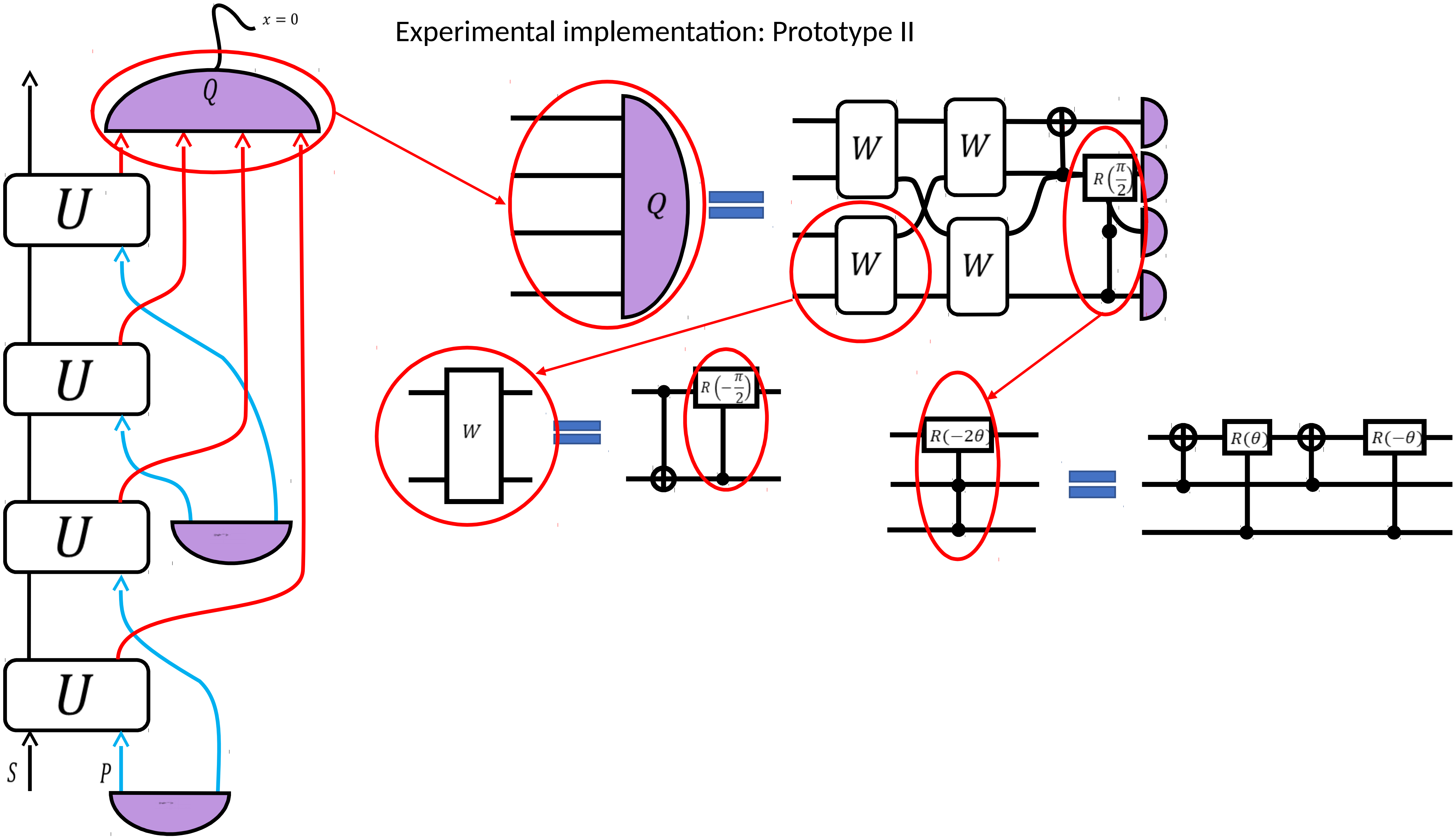
Experimental implementation: Prototype II

Implementation with single-qubit gates and CNOTS?

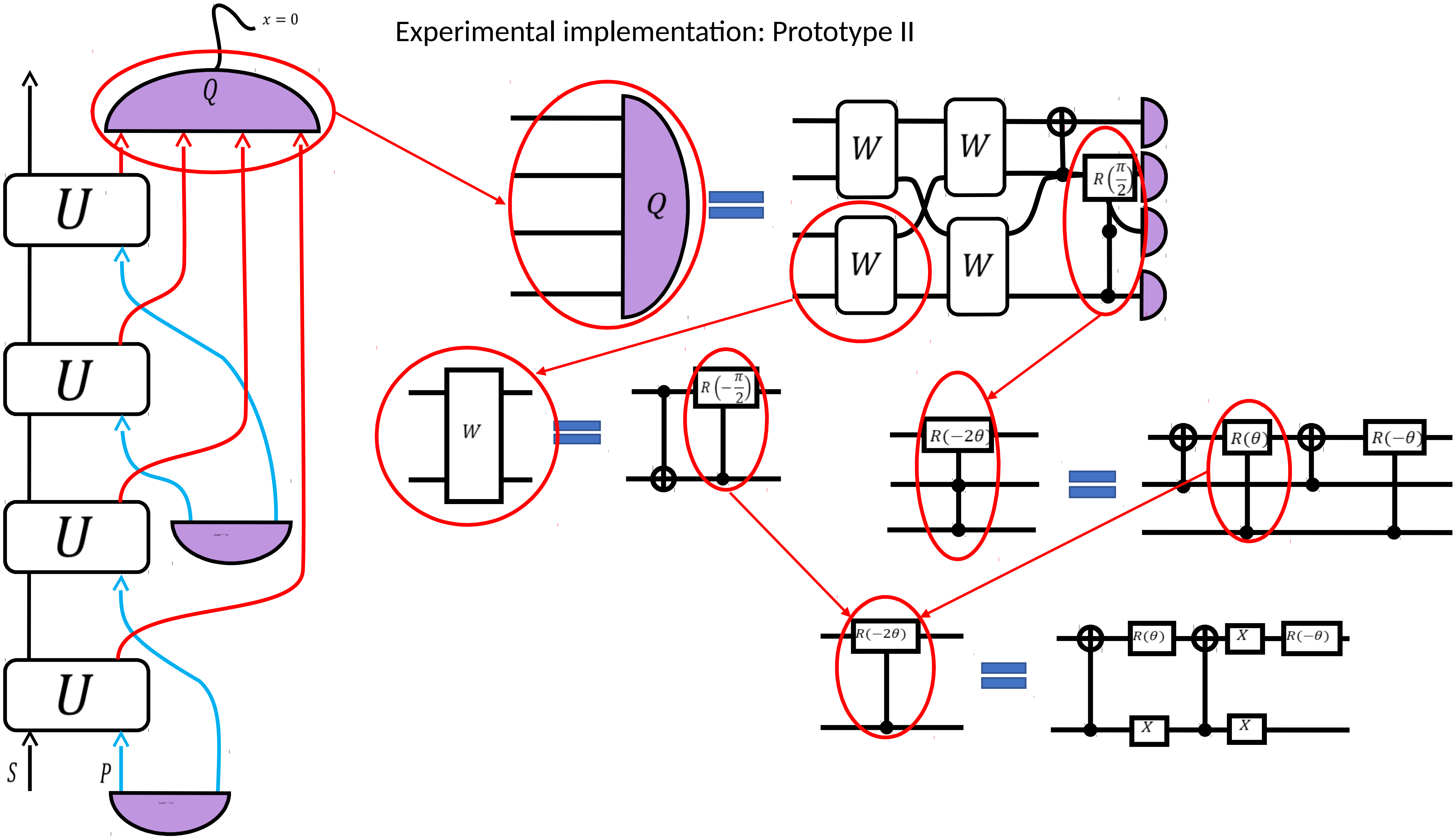
Experimental implementation: Prototype II



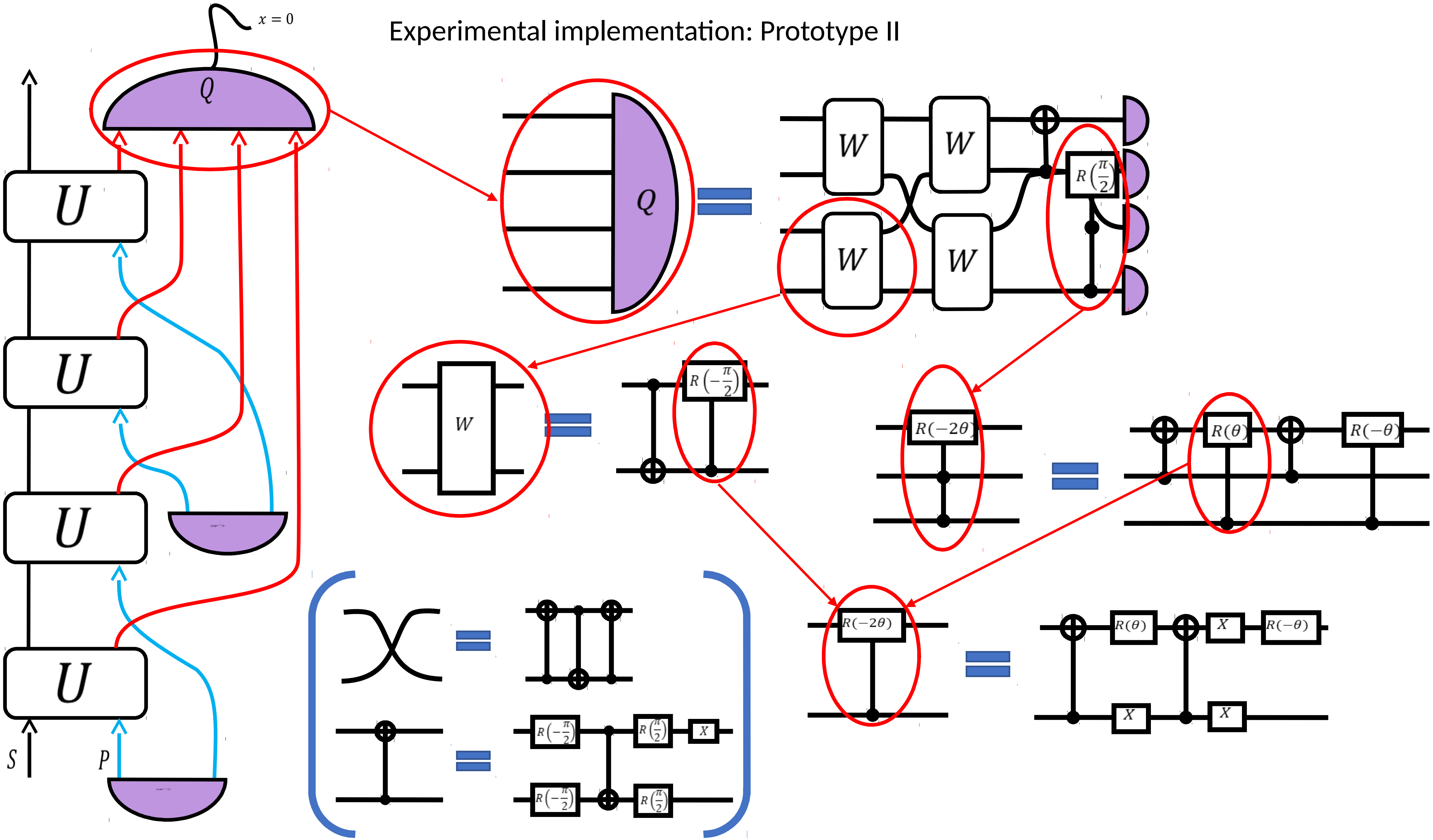
Experimental implementation: Prototype II

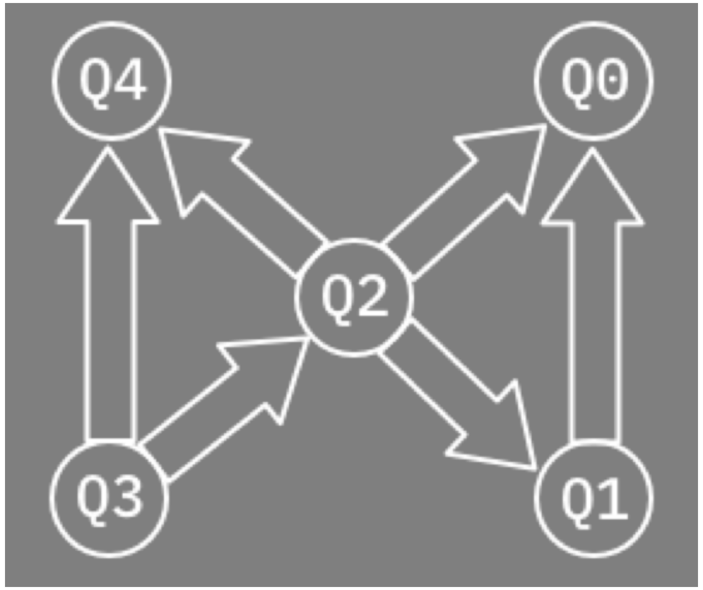


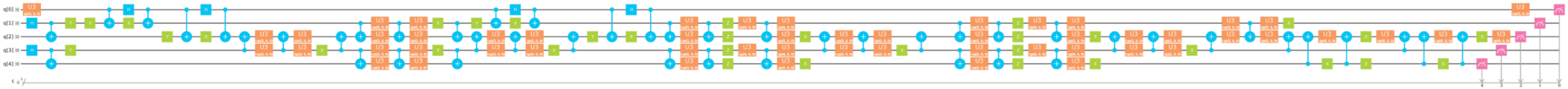
Experimental implementation: Prototype II



Experimental implementation: Prototype II

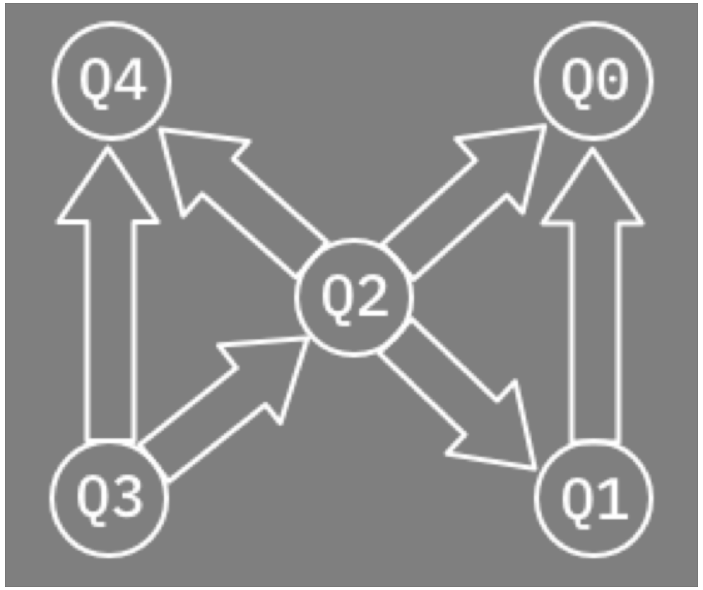






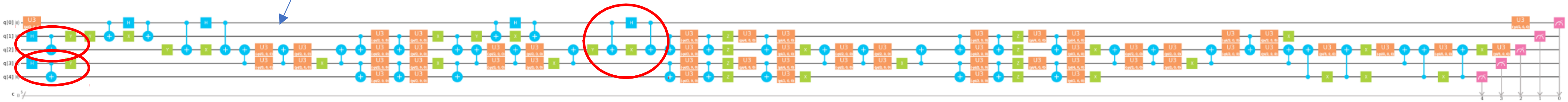
Largest circuit depth allowed!

IBM QX4: Raven



Target system

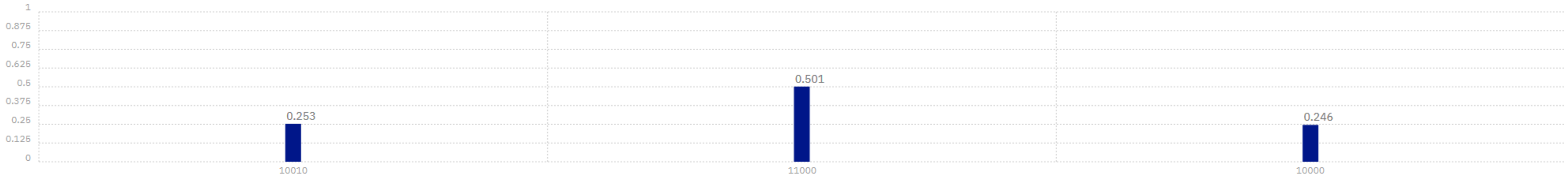
U



Preparation of

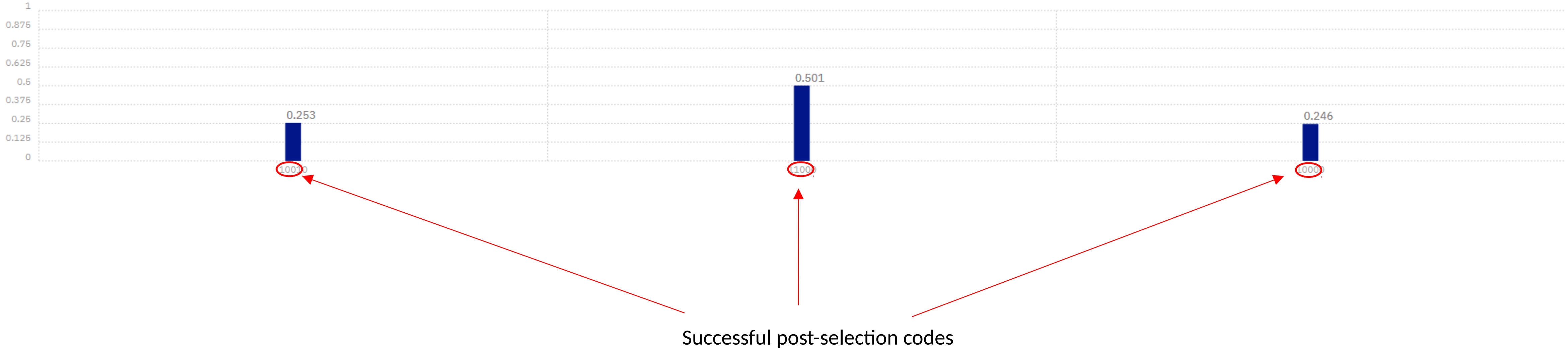
IBM QX4: Raven

Theoretical simulation



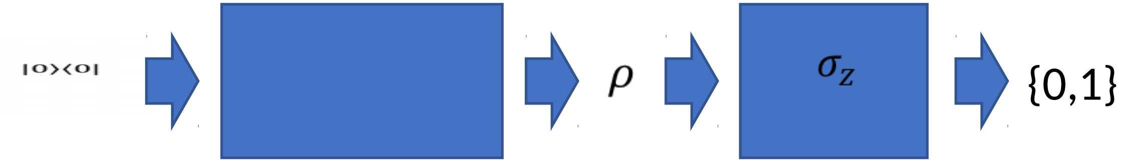
IBM QX4: Raven

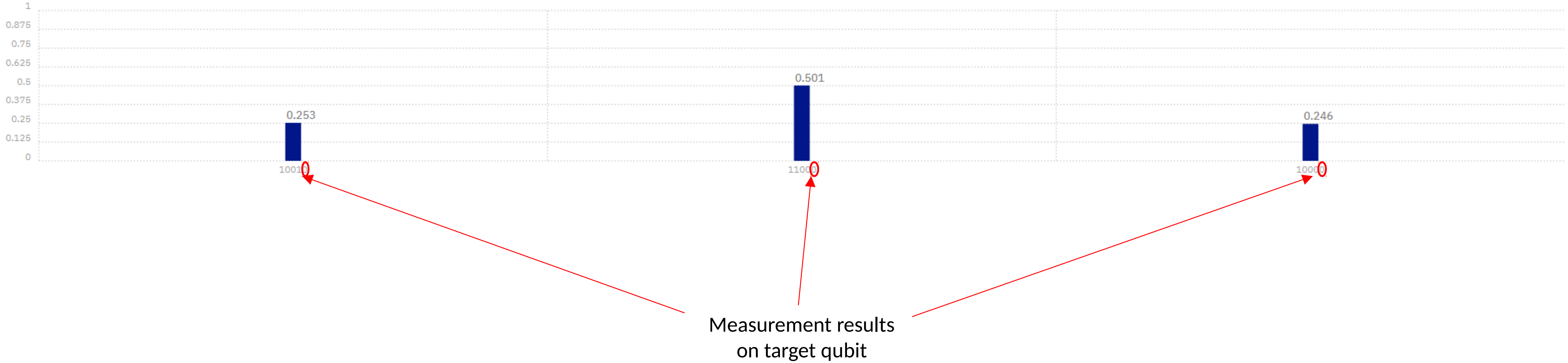
Theoretical simulation



IBM QX4: Raven

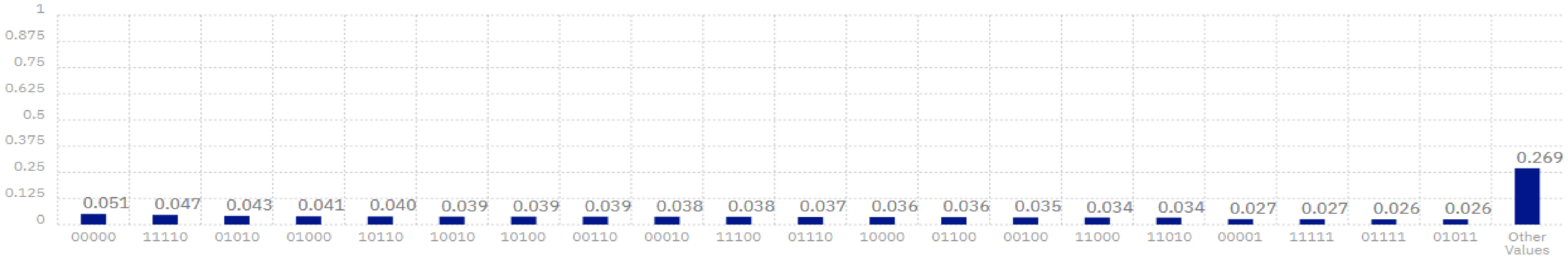
Theoretical simulation



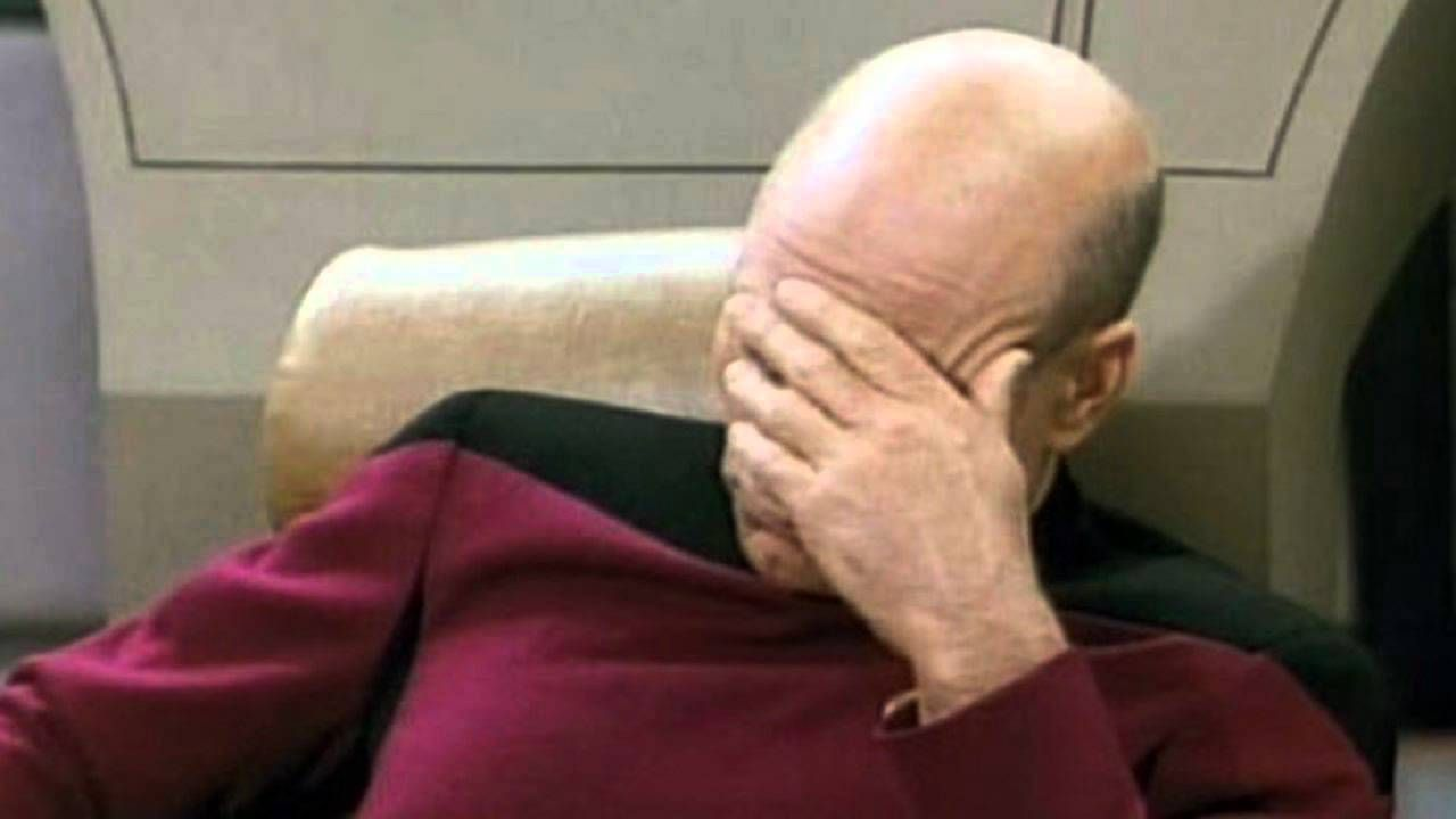


IBM QX4: Raven

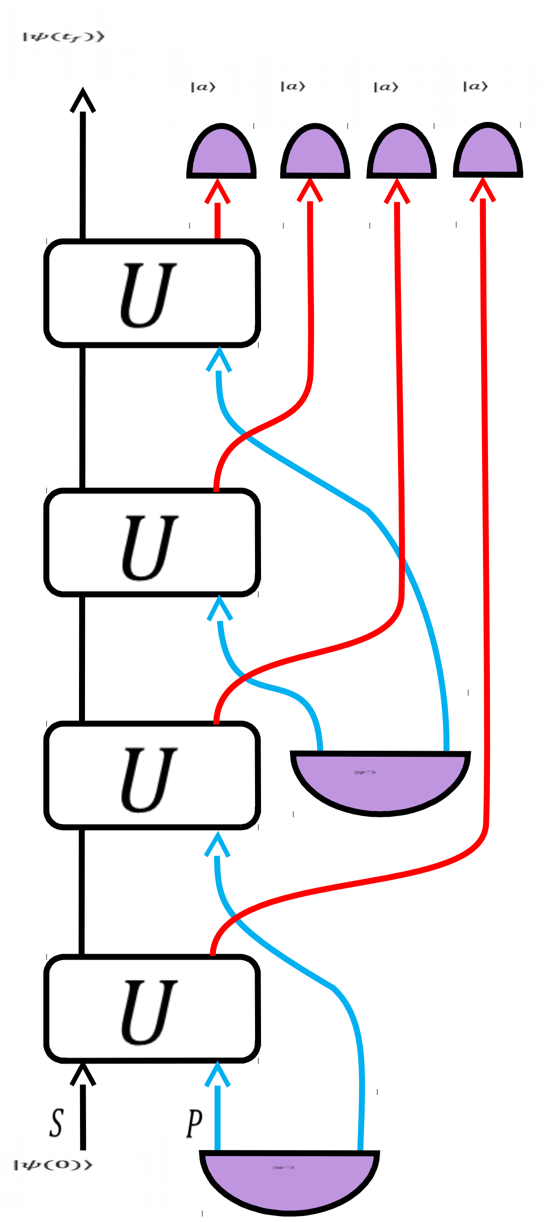
Crude reality

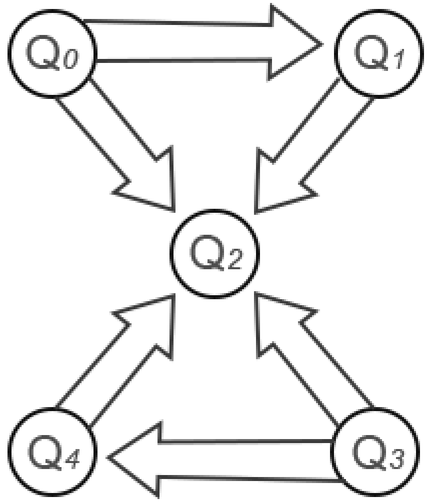


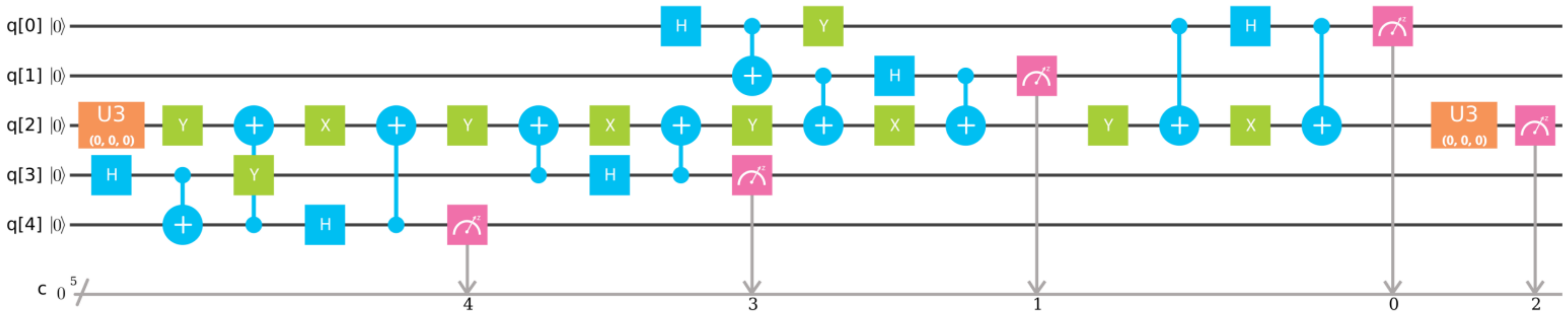
IBM QX4: Raven



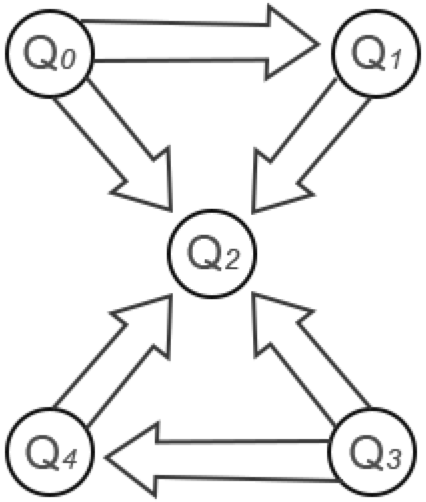
Experimental implementation: Prototype II

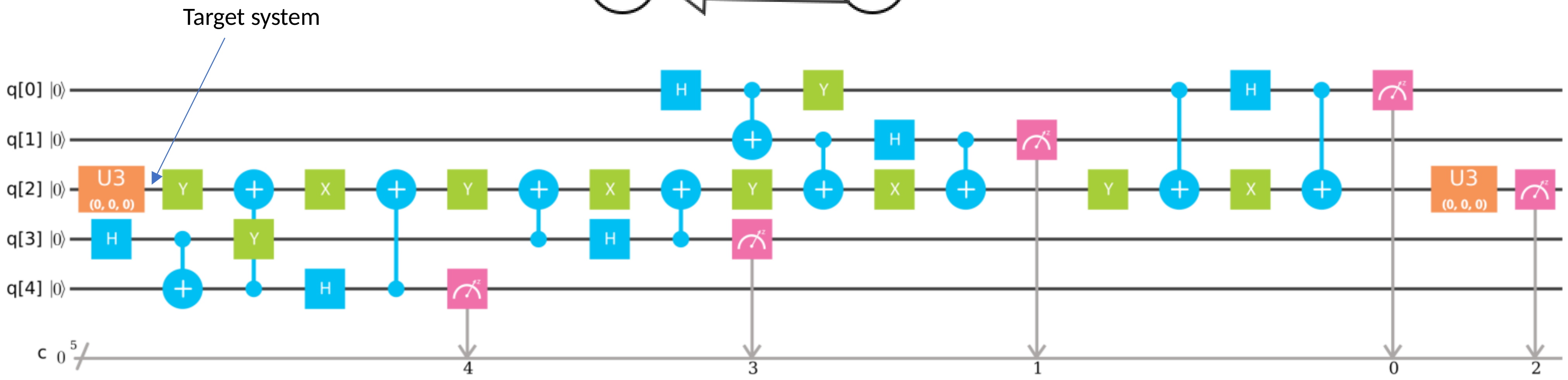






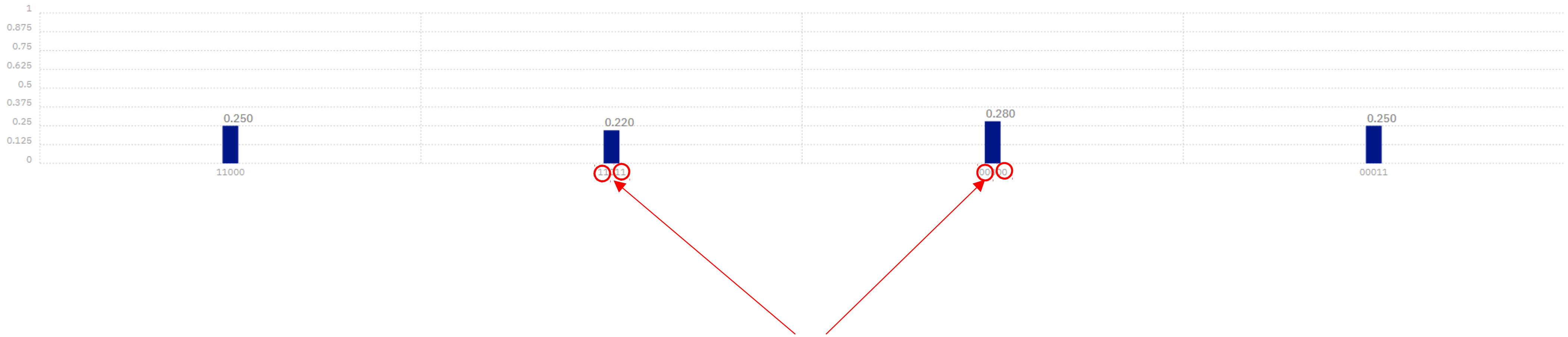
IBM QX2: Sparrow





IBM QX2: Sparrow

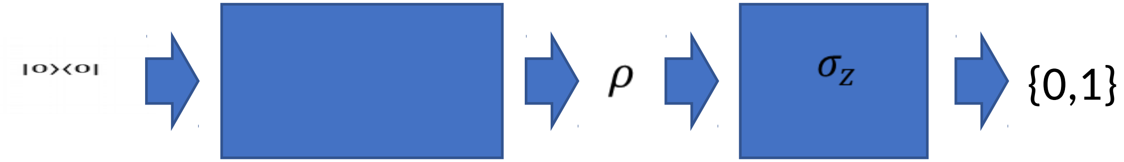
Theoretical simulation

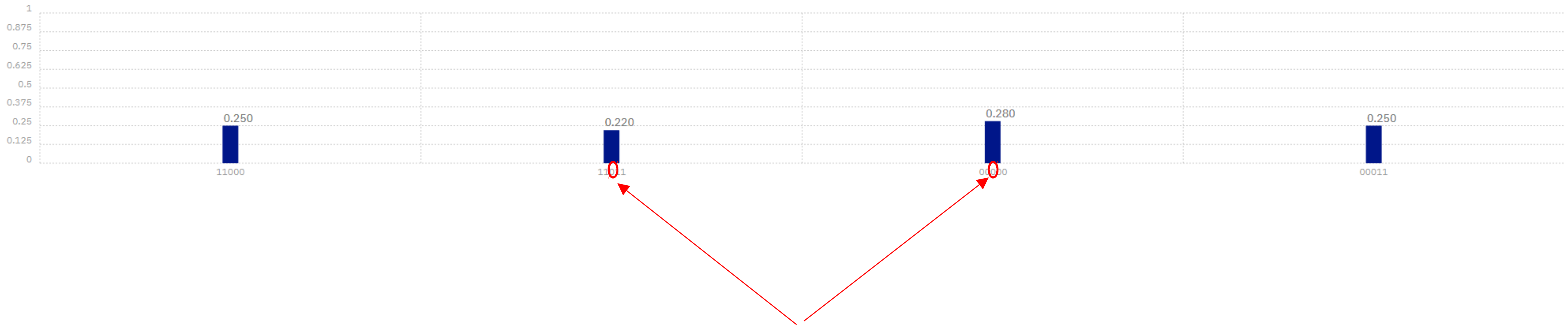


Successful post-selection codes

IBM QX2: Sparrow

Theoretical simulation

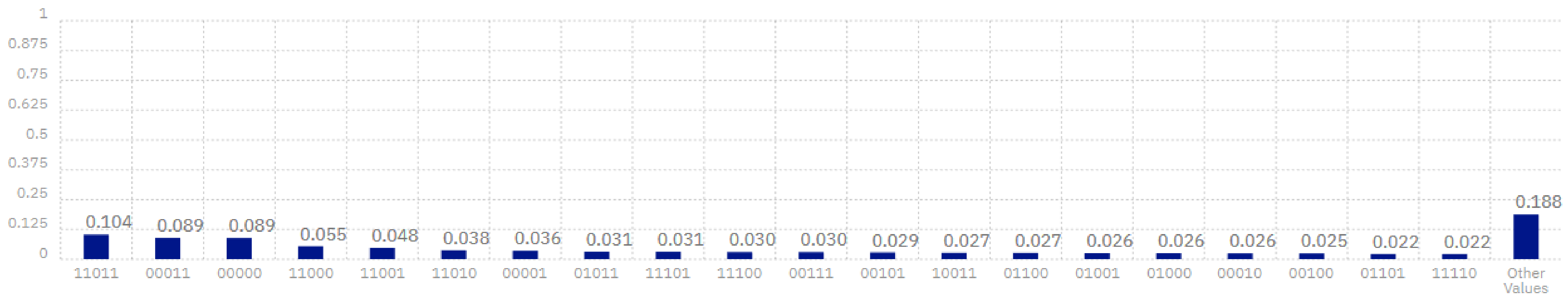




Measurement results
on target qubit

IBM QX2: Sparrow

Crude reality



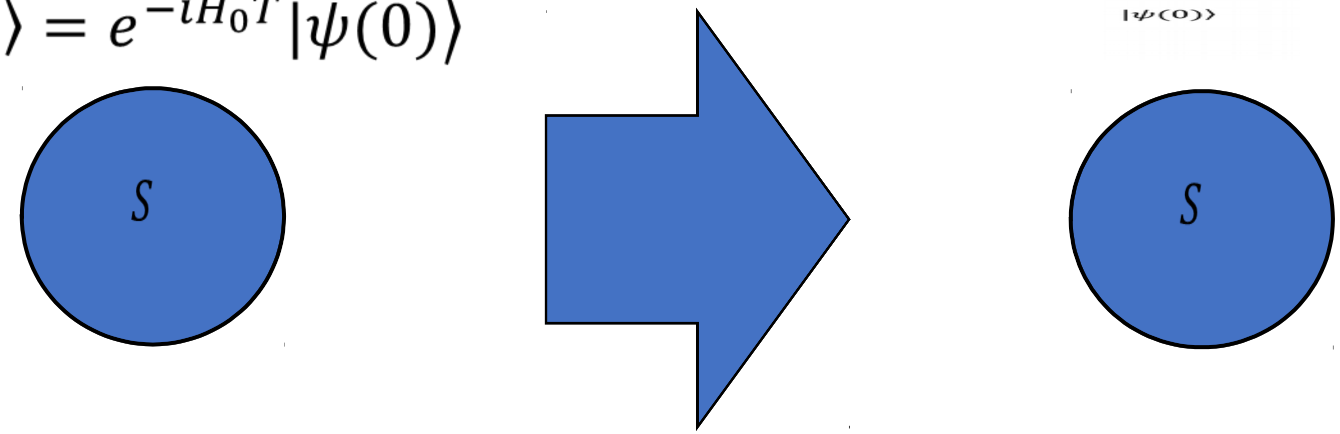
IBM QX2: Sparrow

Conclusion

Do there exist protocols with average probability of success (with prior dU) arbitrarily close to 1?

Can we shorten resetting protocols?

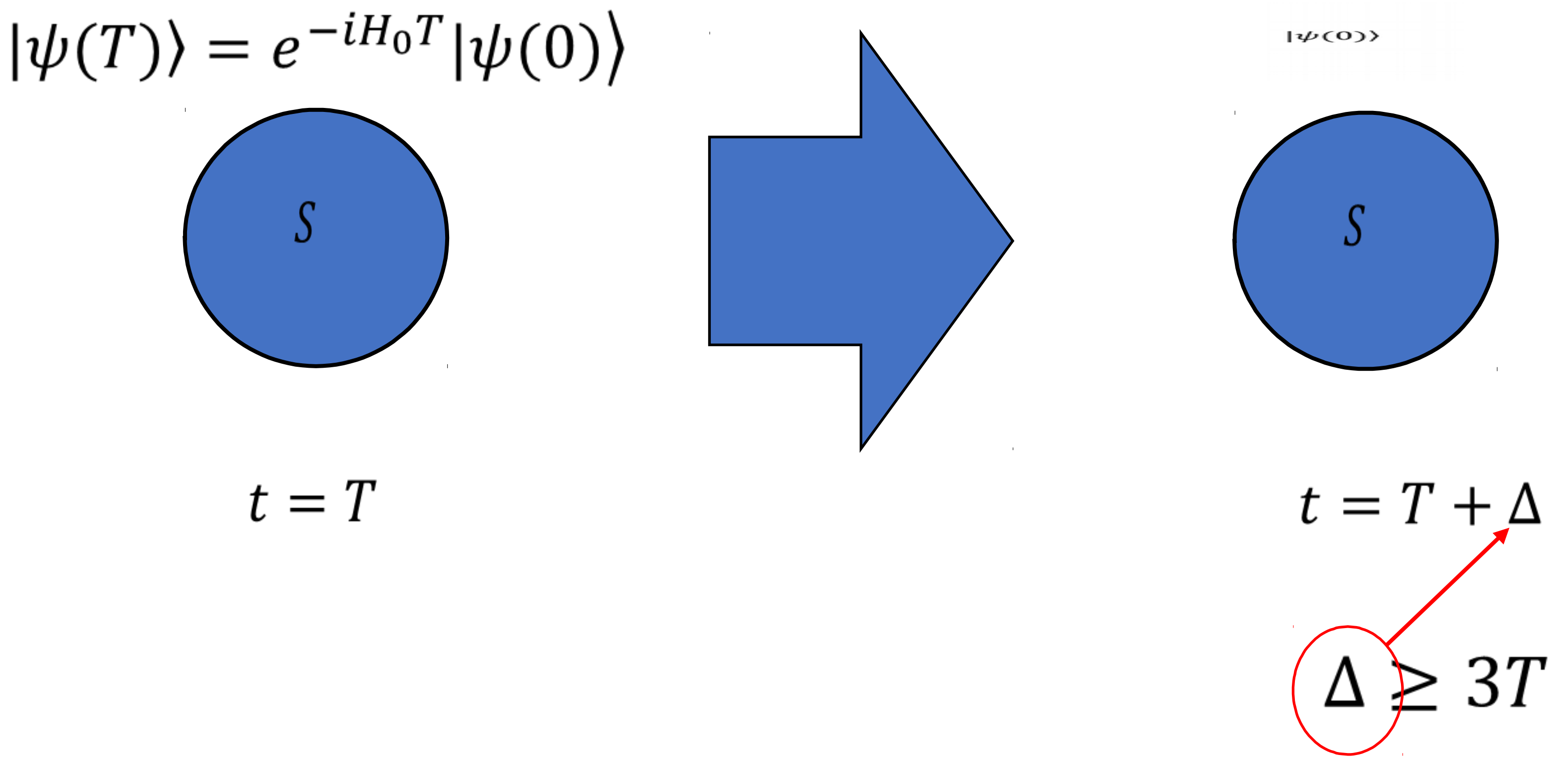
$$|\psi(T)\rangle = e^{-iH_0T}|\psi(0)\rangle$$



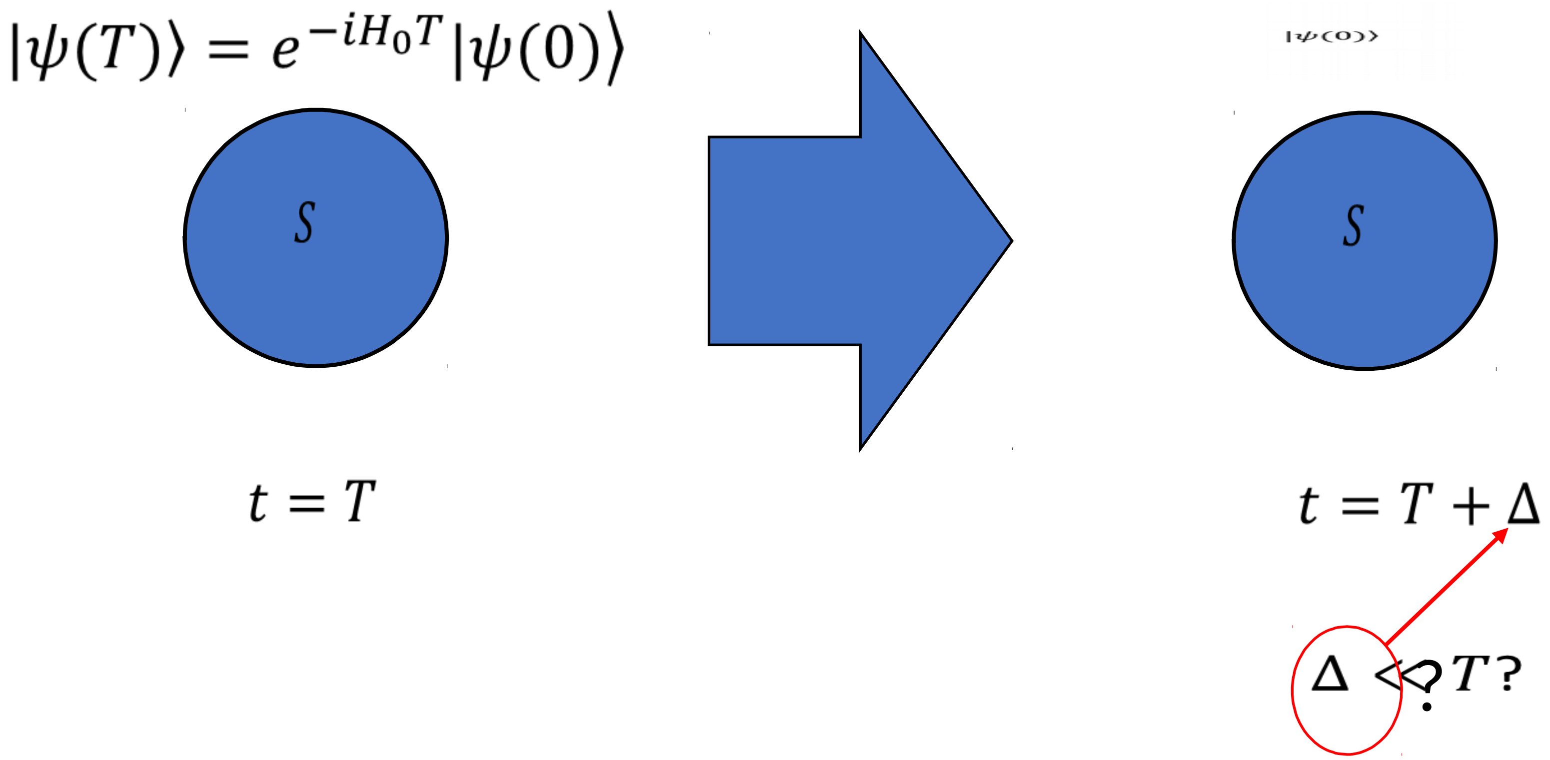
$t = T$

$t = T + \Delta$

Can we shorten resetting protocols?

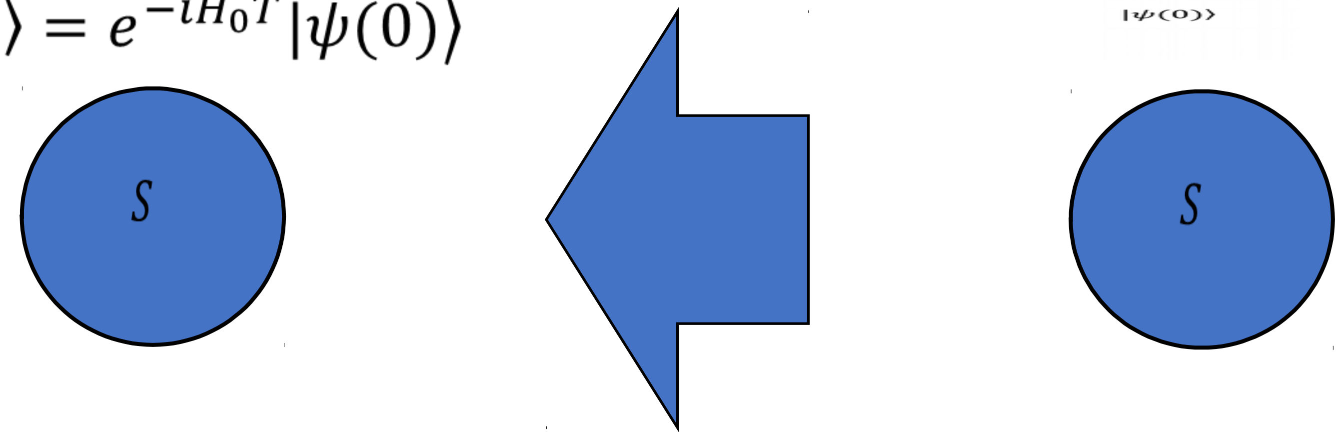


Can we shorten resetting protocols?



Can we fast-forward?

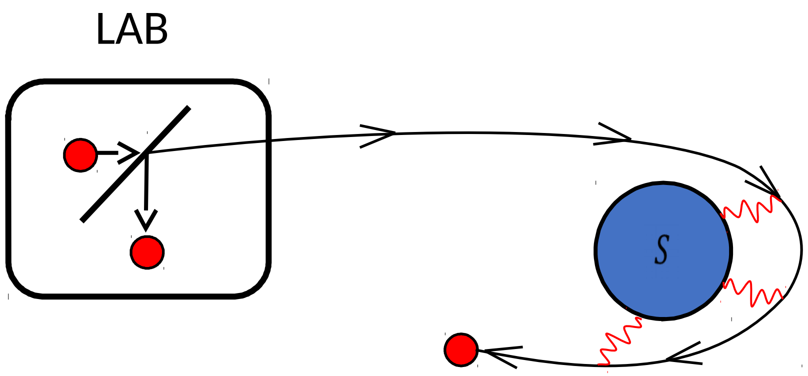
$$|\psi(T)\rangle = e^{-iH_0T}|\psi(0)\rangle$$



$t = \Delta$ $\qquad\qquad$ $t = 0$

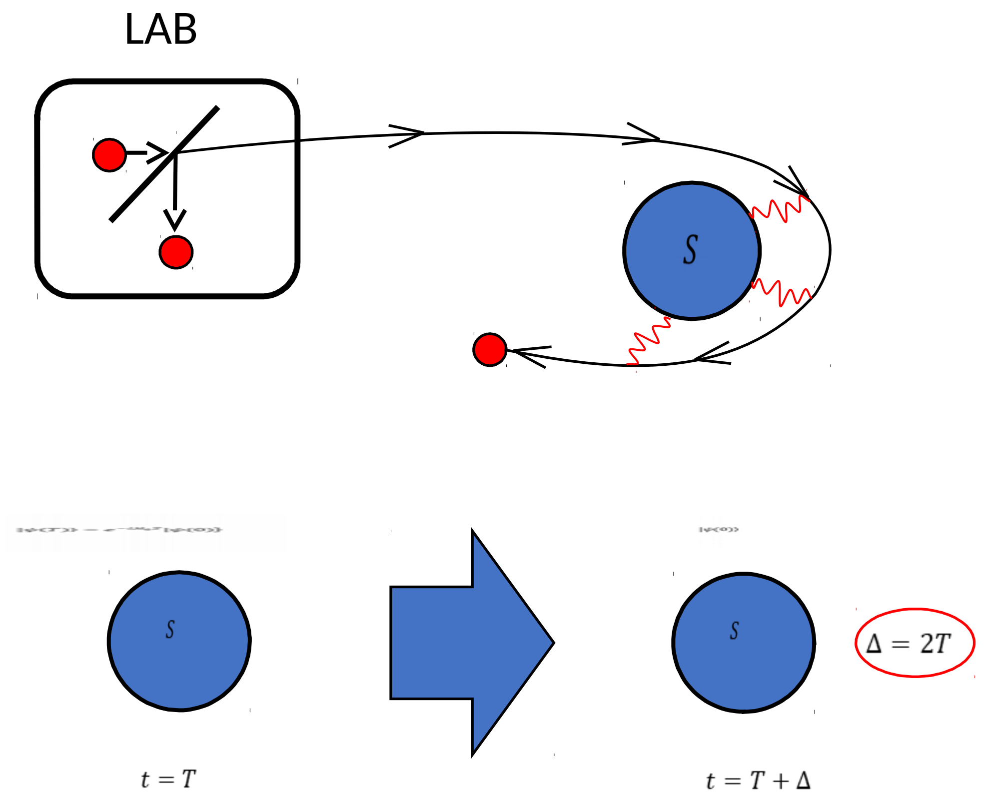
$\Delta \ll? \; T?$

Can we shorten resetting protocols?/Can we fast-forward?



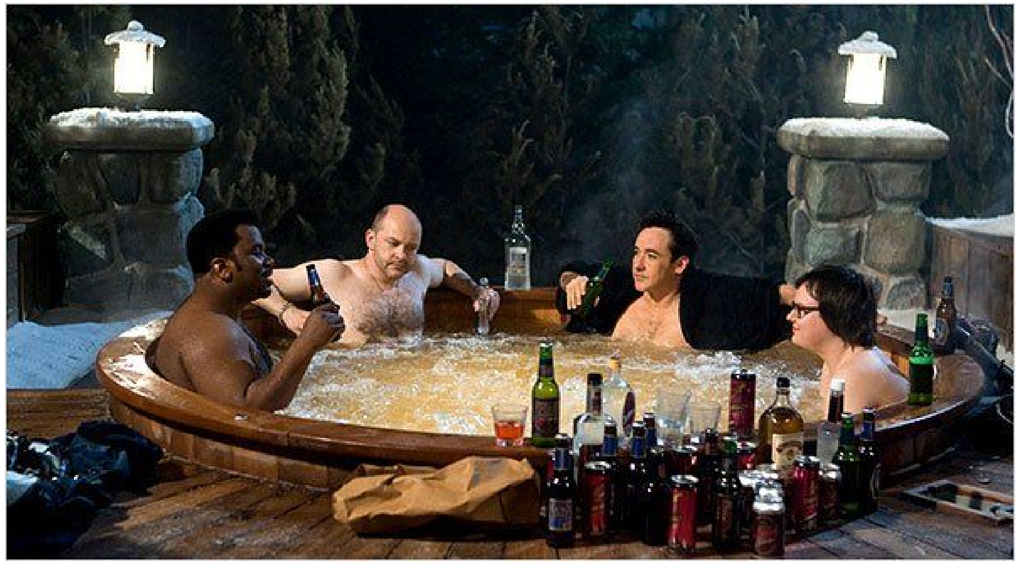
Hint: use which-path superpositions.

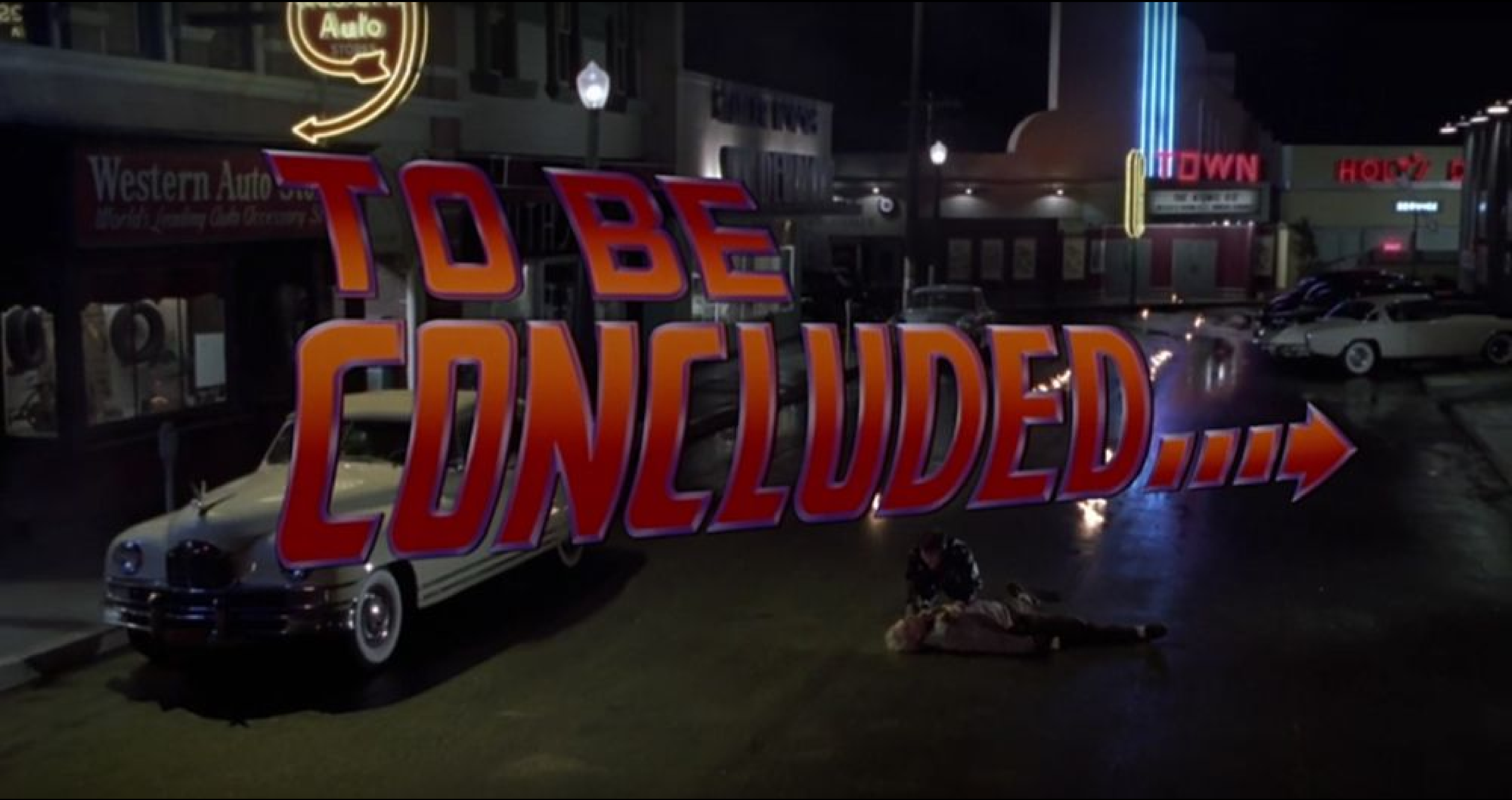
Can we shorten resetting protocols?/Can we fast-forward?



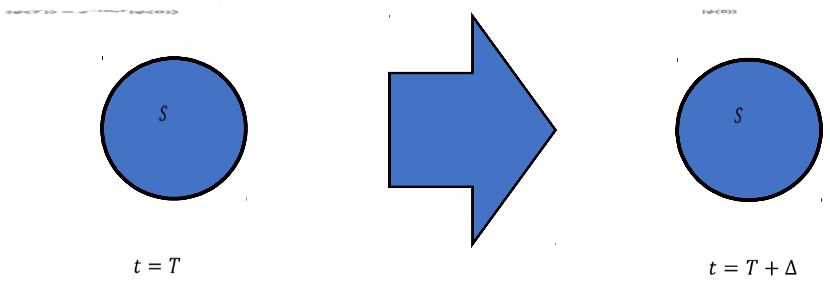
MN, work in progress.

Simple experimental implementation?



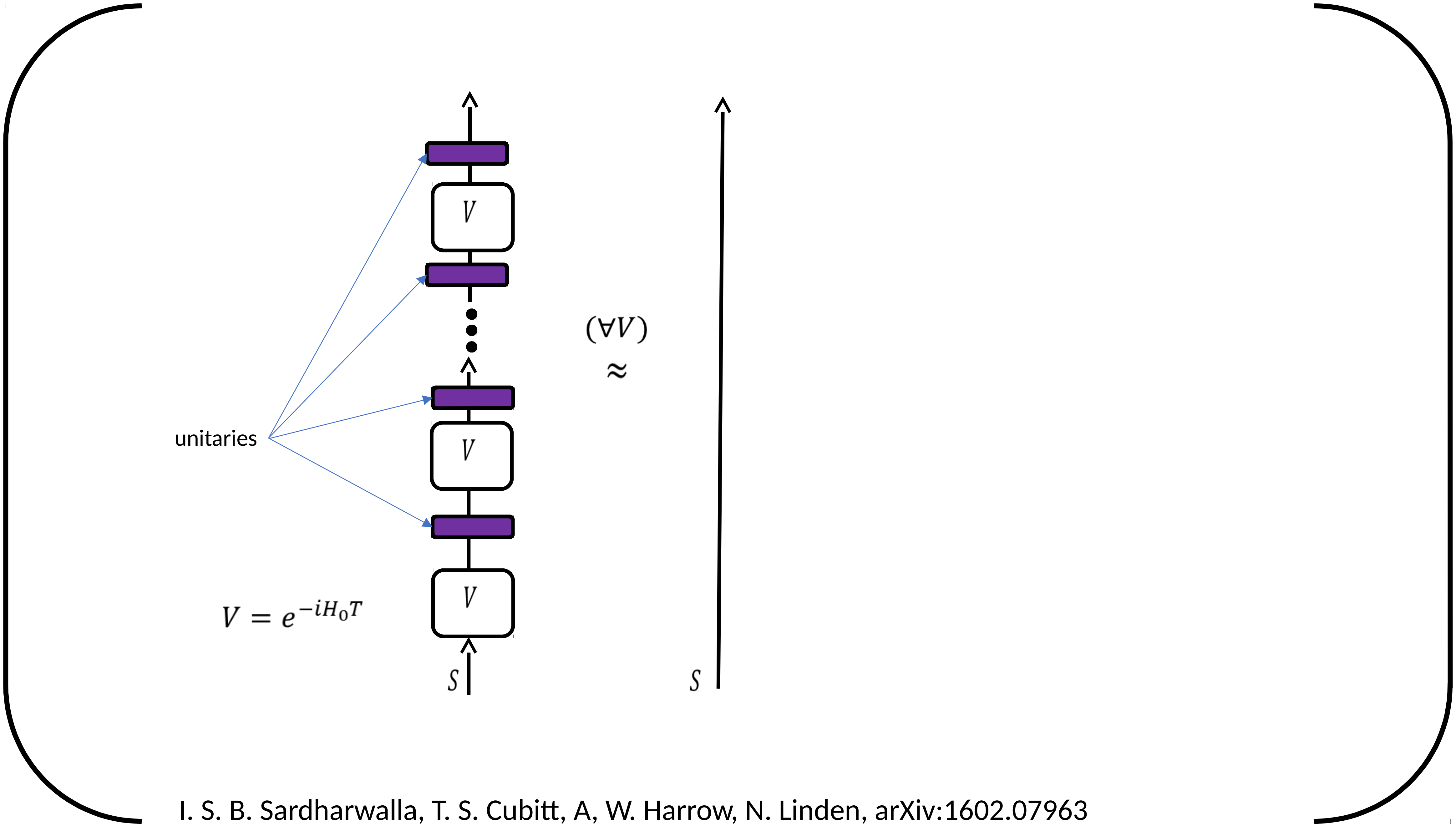

TO BE
CONCLUDED...
Western Auto
Auto
TOWN

Refocusing



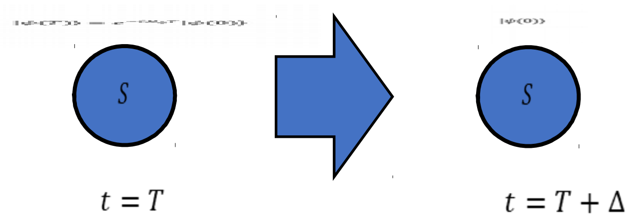
We ignore but any operation on S is allowed

I. S. B. Sardharwalla, T. S. Cubitt, A, W. Harrow, N. Linden, arXiv:1602.07963

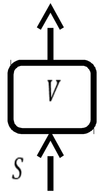


I. S. B. Sardharwalla, T. S. Cubitt, A, W. Harrow, N. Linden, arXiv:1602.07963

Refocusing (obvious solution)



$$V = e^{-iH_0 T}$$



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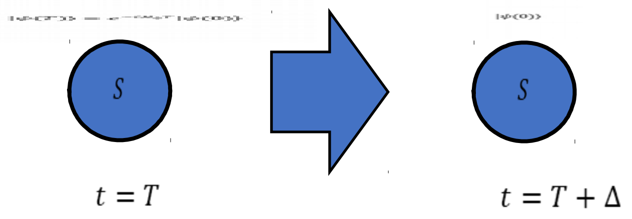
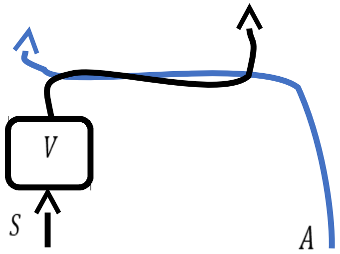


$$V = e^{-iH_0 T}$$



I. S. B. Sardharwalla, T. S. Cubitt, A, W. Harrow, N. Linden, arXiv:1602.07963

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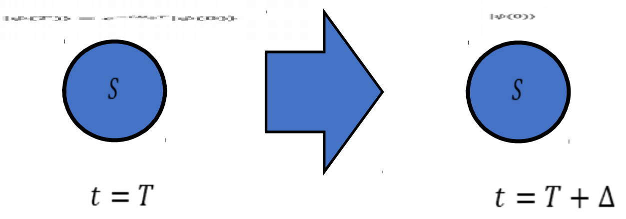
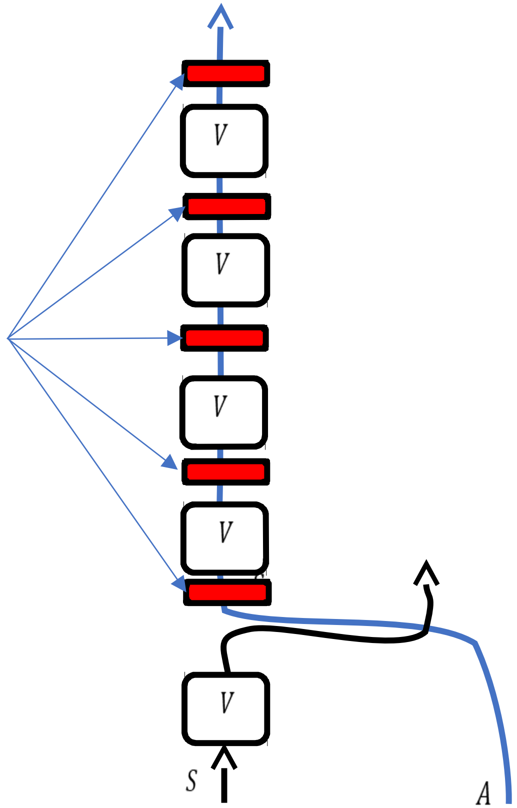


Channel tomography



I. S. B. Sardharwalla, T. S. Cubitt, A, W. Harrow, N. Linden, arXiv:1602.07963

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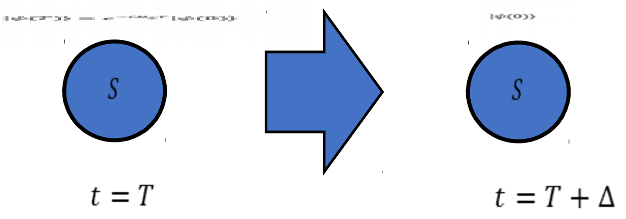

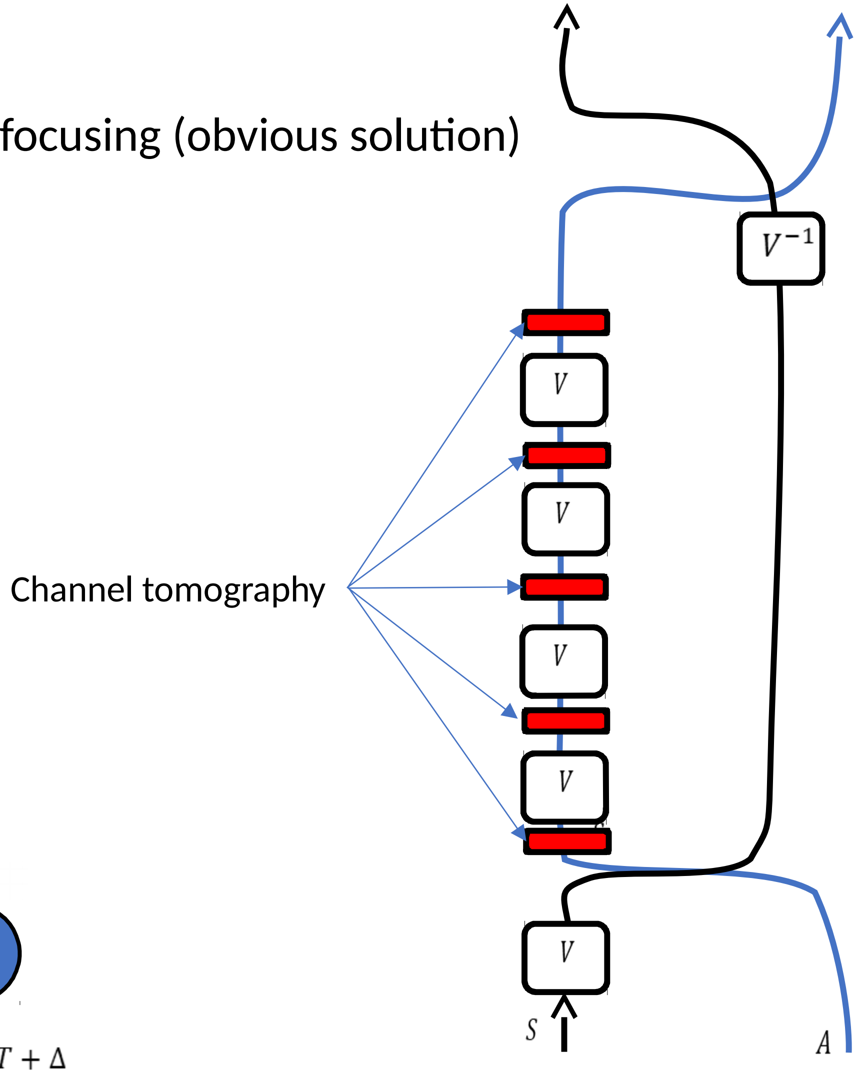

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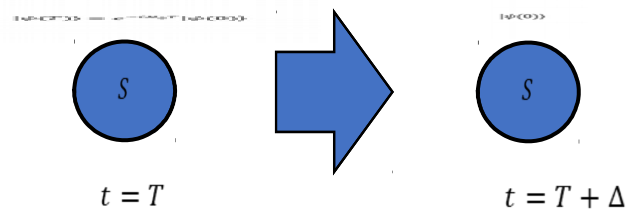
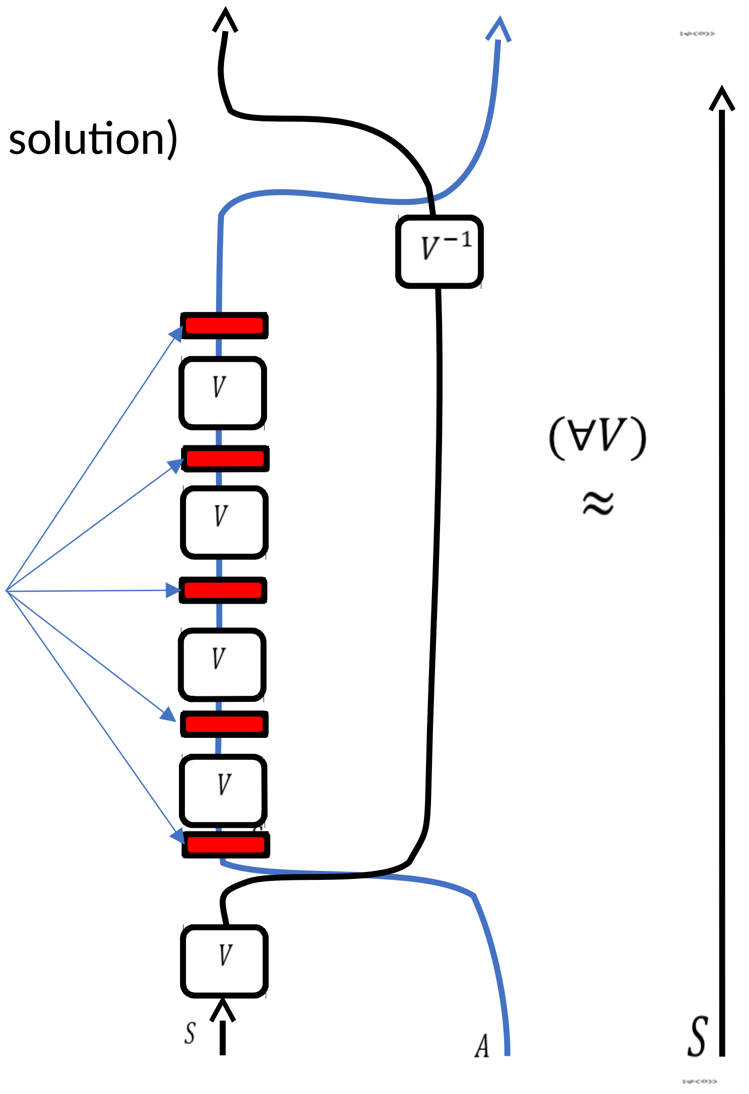


Channel tomography



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