Title: Measuring time with stationary quantum clocks

Speakers: Mischa Woods

Collection: Quantizing Time

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Abstract: Time plays a fundamental role in our ability to make sense of the physical laws in the world around us. The nature of time has puzzled people â€“- from the ancient Greeks to the present day -â€“ resulting in a long running debate between philosophers and physicists alike to whether time needs change to exist (the so-called relatival theory), or whether time flows regardless of change (the so-called substantival theory). One way to decide between the two is to attempt to measure the flow of time with a stationary clock, since if time were substantival, the flow of time would manifest itself in the experiment. Alas, conventional wisdom suggests that in order for a clock to function, it cannot be a static object, thus rendering this experiment seemingly impossible. We show that counter-intuitively, a quantum clock can measure the passage of time, even while being switched off, lending support for the substantival theory of time.

Measuring time with stationary quantum clocks arXiv:2106.07684

PI, Canada (kinda) 17/06/2021

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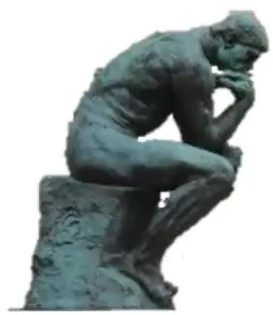

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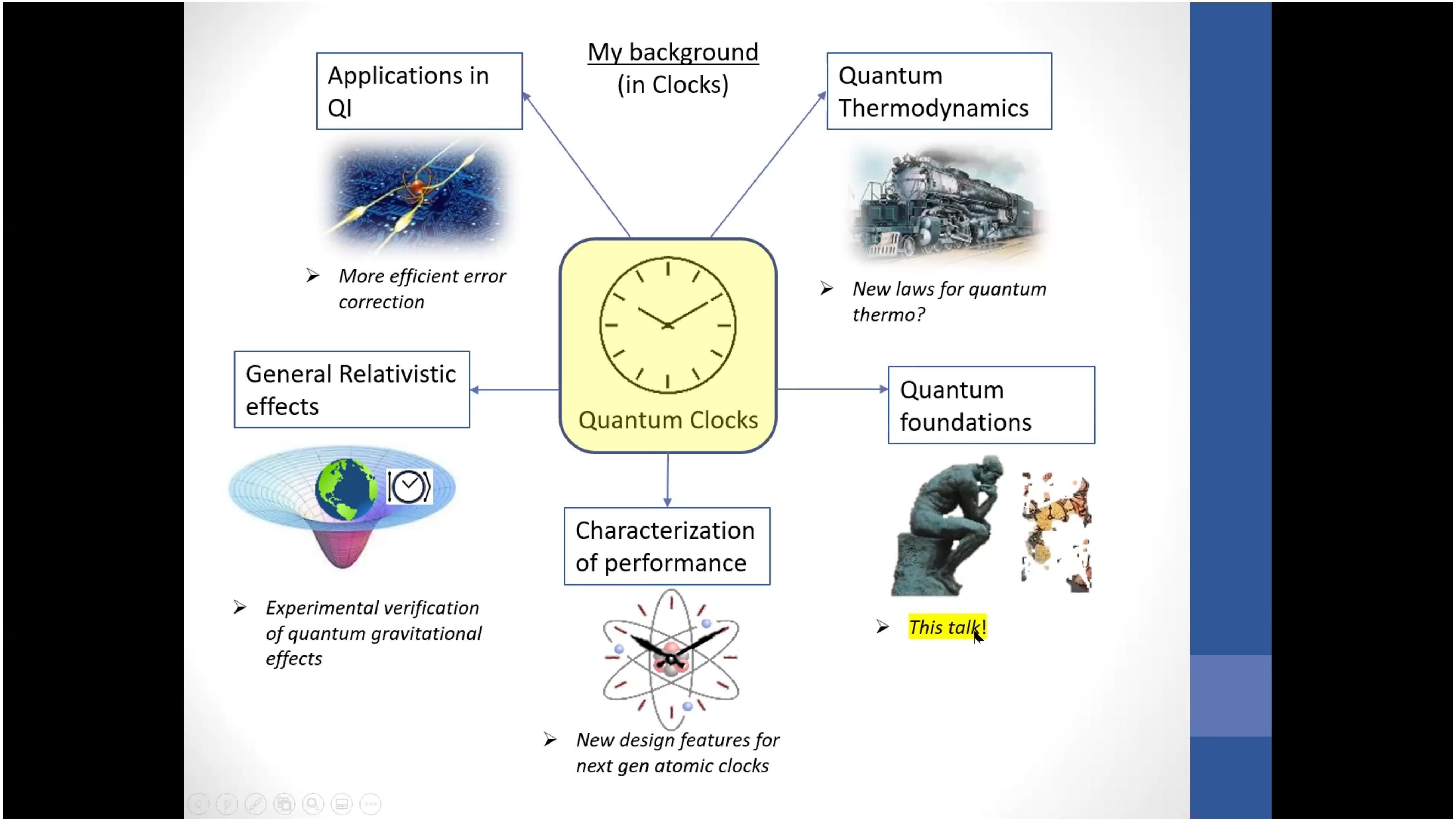

My background
(in Clocks)
Applications in QI
More efficient error correction
Quantum Thermodynamics
New laws for quantum thermo?
Quantum Clocks
General Relativistic effects
Experimental verification of quantum gravitational effects
Quantum foundations
This talk!
Characterization of performance
New design features for next gen atomic clocks

Overview:

- Philosophy of time: two competing viewpoints
- Interaction-free measurements
- Introduce counterfactual clocks
- Implications for the debate on time

The nature of time:

- Two competing theories:

  - Substantival theory:

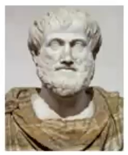
    Time exists independently of motion; it forms an invisible contain in which matter lives.

  - Relative theory:

    Time is merely a consequence of motion; it is a result of the relationships between events of physical things.

History (highlights):

- Greek atomists: substantivalists? (no written account has survived)
- Aristotle: proponent of relative theory



"But neither does time exist without change; ..."

[Aristotle, 350 BC]

Leibniz vs Newton

- Newton: on the Substantival camp
- Leibniz: on the Relative camp

- Ernst Mach: attached Newtons views
- Einstein credits Ernst Mach as a source of his inspiration for relativity
- Alive today: Paul Davies (Relative theory), Tim Maudlin (Substantival theory). Carlo Rovelli, Lee Smolin, Julian Barbour, Fay Dowker.

History (highlights):

- Why is there no consensus after more than 2 millennia of debate?
  - Our theories appear to allow both a substantival and relative interpretation of time

- Natural experiment:
  - Try to measure time with a stationary clock
    - ➢ If time is substantival, time should be measurable!
    - ➢ If time is relative, clock won't record anything!

History (highlights):

- Why is there no consensus after more than 2 millennia of debate?
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- Natural experiment:
  - Try to measure time with a stationary clock
    - If time is substantival, time should be measurable!
    - If time is relative, clock won't record anything!
  - Problem: clocks appear to need dynamics to function

Interaction-free measurements:

- Invented by A. Elitzur and L. Vaidman (E.-V. bomb tester):
- Have a bomb but not sure if its live or a dud:
  - If live:

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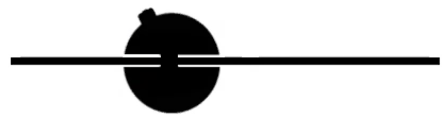
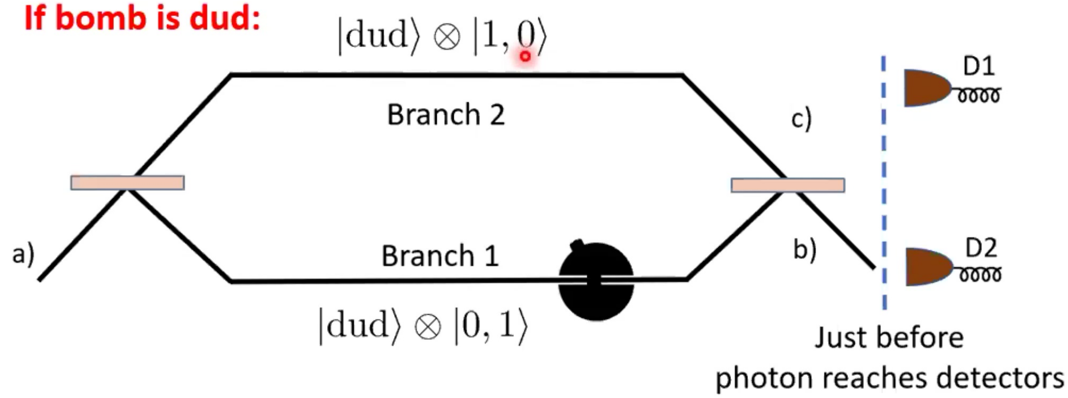
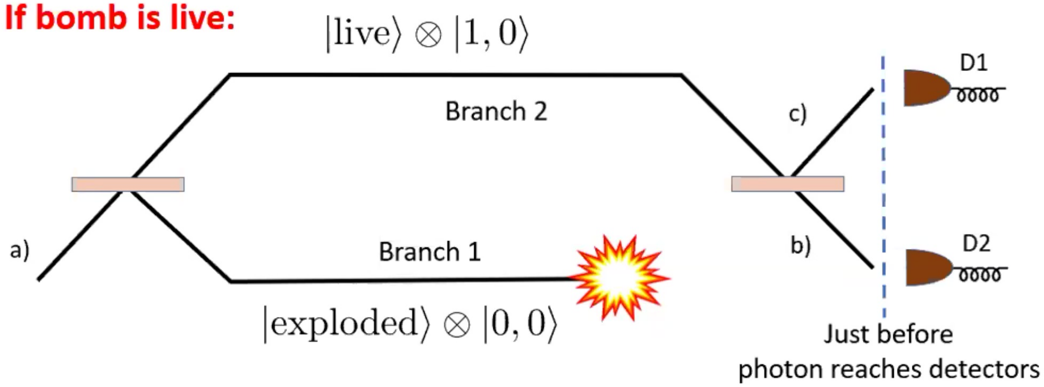
  - If bomb is dud: 
- Classically, no way to distinguish live and dud bombs without exploding live bombs

Interaction-free measurements:

- **If bomb is dud:**



- **If bomb is live:**



- **Possible outcomes:** **1)** D1 clicks. **2)** D2 clicks. **3)** no clicks

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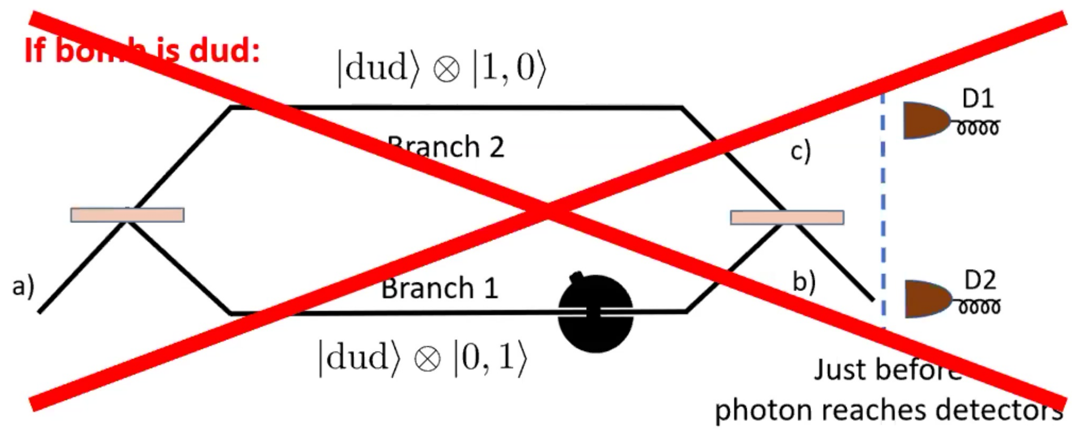

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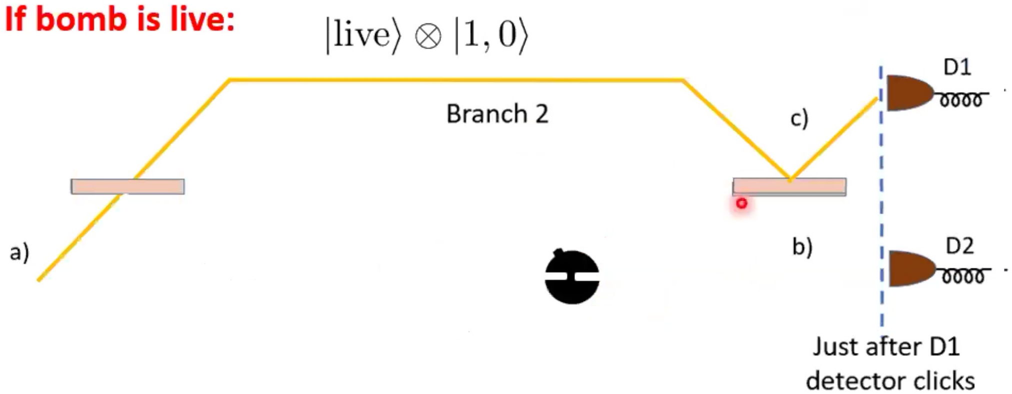

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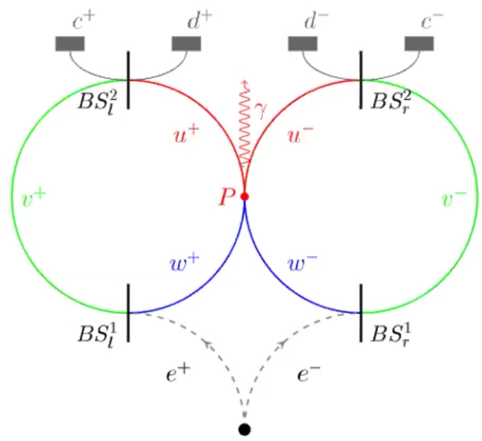
Elementary timekeeping systems

- Objections: system has certainly been in a superposition exploded and live bomb *before* measurement
- But: outcome "D1 ticks" can only be observed if we collapse to a branch of the wave function orthogonal to exploded bomb
- Interpretation uses *retrodiction*: measurement collapse determines past events

$$|\text{alive}\rangle \longrightarrow \frac{1}{\sqrt{2}}\big(\,|\text{alive}\rangle + |\text{dead}\rangle\,\big)$$

Interaction-free measurements:

- Other examples:
  - The Penrose bomb-testing device: [R. Penrose, Phys. Rev. Lett. (1994)]
  - Interaction-free imaging: [A. White et. al. (1998)]
  - Counterfactual computing: [G. Mitchison and R. Jozsa, Proc. Roy. Soc. (1992)]
  - The Hardy paradox: [Lucien Hardy, Phys. Rev. Lett. (1992)]



  - Many experimental realizations: e.g. [O. Hosten et. al., Nature (2006)]

Elementary timekeeping systems

- Setup

$$|\psi(t)\rangle \in \mathcal{H}, \qquad \dim(\mathcal{H}) = N_T + 1$$

$|\tau_0\rangle, |\tau_1\rangle, \ldots, |\tau_{N_T}\rangle$ at times $\tau_0, \tau_1, \ldots, \tau_{N_T}$

- Two external events separated by elapsed time t

$$t \in \{\tau_0, \tau_1, \tau_2, \ldots, \tau_{N_T}\}$$

- What is t ?

- Protocol:
  - ➢ At 1st event prepare $|\psi(0)\rangle$
  - ➢ At 2nd event measure in basis $|\tau_0\rangle, |\tau_1\rangle, \ldots, |\tau_{N_T}\rangle$
  - ➢ Measurement outcome determines t

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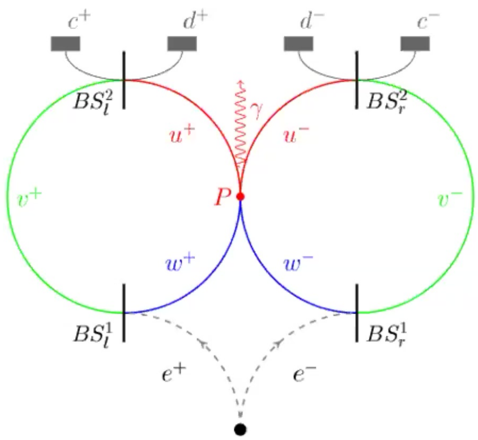

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Elementary timekeeping systems

- Using it to tell the time when off

  - New protocol using interaction-free measurement ($N_T = 1$): $t \in \{\tau_0, \tau_1\}$

    $$|\tau_0\rangle,\ |\tau_1\rangle,\ \underbrace{|E\rangle\,, |A\rangle}_{\text{Add energy eigenstate and stationary ancilla state}}$$

    - Start in $|E\rangle$
    - At 1st event apply U:

$$\begin{tikzcd}[column sep=small, row sep=small] & c\,|E\rangle \\ |E\rangle \arrow[ur, dash] \arrow[dr, dash] & \\ & s\,|\psi\rangle \end{tikzcd}$$

    - At time of 2nd event apply U_{m} and measure in basis

      $$|\tau_0\rangle,\ |\tau_1\rangle,\ |E\rangle\,, |A\rangle$$

Elementary timekeeping systems

- Using it to tell the time when off
  - Analyze protocol:

- If $t = \tau_0$.

$$|E\rangle \to \begin{cases} c\,|E\rangle \overset{\tau_0}{\rightsquigarrow} c\,|E\rangle \xrightarrow{U_{\mathrm{m}}} cA_1^0\,|E\rangle + cA_2^0\,|A\rangle + cA_3^0\,|\tau_0\rangle + cA_4^0\,|\tau_1\rangle \\ \qquad t=\tau_0 \\ s\,|\psi\rangle \overset{\tau_0}{\rightsquigarrow} s\,|\tau_0\rangle \xrightarrow{U_{\mathrm{m}}} -cA_2^0\,|A\rangle + sA_3^1\,|\tau_0\rangle + sA_4^1\,|\tau_1\rangle \end{cases}$$

- If $t = \tau_1$.

$$|E\rangle \to \begin{cases} c\,|E\rangle \overset{\tau_1}{\rightsquigarrow} c\,|E\rangle \xrightarrow{U_{\mathrm{m}}} cA_1^0\,|E\rangle + cA_2^0\,|A\rangle + cA_3^0\,|\tau_0\rangle + cA_4^0\,|\tau_1\rangle \\ \qquad t=\tau_1 \\ s\,|\psi\rangle \overset{\tau_1}{\rightsquigarrow} s\,|\tau_1\rangle \xrightarrow{U_{\mathrm{m}}} -cA_1^0\,|E\rangle + sA_3^{1\prime}\,|\tau_0\rangle + sA_4^{1\prime}\,|\tau_1\rangle \end{cases}$$

- If $|E\rangle$ outcome:
  - If $t = \tau_0$. Clock was off
  - If $t = \tau_1$. No outcome

Elementary timekeeping systems

- Using it to tell the time when off
  - Analyze protocol:

- If $t=\tau_0$.

$$|E\rangle \to c\,|E\rangle \overset{\tau_0}{\rightsquigarrow} c\,|E\rangle \xrightarrow{U_{\mathrm{m}}} cA_1^0\,|E\rangle + cA_2^0\,|A\rangle + cA_3^0\,|\tau_0\rangle + cA_4^0\,|\tau_1\rangle$$

$$t=\tau_0$$

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- If $t=\tau_1$.

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$$t=\tau_1$$

$$|E\rangle \to s\,|\psi\rangle \overset{\tau_1}{\rightsquigarrow} s\,|\tau_1\rangle \xrightarrow{U_{\mathrm{m}}} -cA_1^0\,|E\rangle + sA_3^{1'}\,|\tau_0\rangle + sA_4^{1'}\,|\tau_1\rangle$$

- If $|E\rangle$ outcome:
  - If $t=\tau_0$. Clock was off
  - If $t=\tau_1$. No outcome

- If $|A\rangle$ outcome:
  - If $t=\tau_0$. No outcome
  - If $t=\tau_1$. Clock was off

Elementary timekeeping systems

- Using it to tell the time when off
  - Analyze protocol:

- If $t = \tau_0$.

$$|E\rangle \begin{cases} c\,|E\rangle \overset{\tau_0}{\rightsquigarrow} c\,|E\rangle \xrightarrow{U_\mathrm{m}} cA_1^0\,|E\rangle + cA_2^0\,|A\rangle + cA_3^0\,|\tau_0\rangle + cA_4^0\,|\tau_1\rangle \\ \qquad t = \tau_0 \\ s\,|\psi\rangle \overset{\tau_0}{\rightsquigarrow} s\,|\tau_0\rangle \xrightarrow{U_\mathrm{m}} \qquad -cA_2^0\,|A\rangle + sA_3^1\,|\tau_0\rangle + sA_4^1\,|\tau_1\rangle \end{cases}$$

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- If $|E\rangle$ outcome:
  - If $t = \tau_0$. Clock was off
  - If $t = \tau_1$. No outcome

Interaction-free measurement! ✓

- If $|A\rangle$ outcome:
  - If $t = \tau_0$. No outcome
  - If $t = \tau_1$. Clock was off

Timing of unitaries: no external clock needed ✓

Elementary timekeeping systems

- Properties:
  - Theorem: One Ancilla $|A\rangle$ is necessary and sufficient in one tick case.
  - Optimal prob. is 1/6

$$c = s = \frac{1}{\sqrt{2}}$$

$$U_{\mathrm{m}}: \quad \begin{array}{c|cccc} & |E\rangle & |\tau_1\rangle & |\tau_0\rangle & |A\rangle \\ \hline |E\rangle & \sqrt{1/3} & \sqrt{1/3} & \sqrt{1/3} & 0 \\ |\tau_1\rangle & 0 & -\sqrt{1/3} & \sqrt{1/3} & -\sqrt{1/3} \\ |\tau_0\rangle & -\sqrt{1/3} & 0 & \sqrt{1/3} & \sqrt{1/3} \\ |A\rangle & \sqrt{1/3} & -\sqrt{1/3} & 0 & \sqrt{1/3} \end{array}$$

Elementary timekeeping systems

- Multiple ticks: $|\tau_0\rangle, |\tau_1\rangle, \ldots, |\tau_{N_T}\rangle$

$$|E\rangle \quad \nearrow \; c\,|E\rangle \overset{\tau_l}{\rightsquigarrow} c\,|E\rangle \xrightarrow{U_{\rm m}} cA_0^0\,|E\rangle + \sum_{j=1}^{N_T} cA_j^0\,|\tau_j\rangle + cA_{N_T+1}^0(\tau_l)\,|\tau_0\rangle + \sum_{k=1}^{m} cB_{-1,k}\,|A_k\rangle$$

$$|E\rangle \quad \searrow \; s\,|\psi\rangle \overset{\tau_l}{\rightsquigarrow} s\,|\tau_l\rangle \xrightarrow{U_{\rm m}} sA_0^1(\tau_l)\,|E\rangle + \sum_{j=1}^{N_T} sA_j^1(\tau_l)\,|\tau_j\rangle + sA_{N_T+1}^1(\tau_l)\,|\tau_0\rangle + \sum_{k=1}^{m} sB_{l,k}\,|A_k\rangle$$

- Unitary $U_{\rm m}$:

	$\lvert E\rangle$	$\lvert\tau_1\rangle$	$\lvert\tau_2\rangle$	$\lvert\tau_3\rangle$	$\ldots$	$\lvert\tau_{N_T}\rangle$	$\lvert\tau_0\rangle$	$\lvert A_1\rangle$	$\ldots$	$\lvert A_m\rangle$
$\lvert E\rangle$	A_0^0	A_1^0	A_2^0	A_3^0	$\ldots$	$A_{N_T}^0$	γ_0	$B_{-1,1}$	$\ldots$	$B_{-1,m}$
$\lvert\tau_1\rangle$	0	$-A_1^0\,r$	$-A_2^0\,r$	$-A_3^0\,r$	$\ldots$	$-A_{N_T}^0\,r$	γ_1	$B_{1,1}$	$\ldots$	$B_{1,m}$
$\lvert\tau_2\rangle$	$-A_0^0\,r$	0	$-A_2^0\,r$	$-A_3^0\,r$	$\ldots$	$-A_{N_T}^0\,r$	γ_2	$B_{2,1}$	$\ldots$	$B_{2,m}$
$\lvert\tau_3\rangle$	$-A_0^0\,r$	$-A_1^0\,r$	0	$-A_3^0\,r$	$\ldots$	$-A_{N_T}^0\,r$	γ_3	$B_{3,1}$	$\ldots$	$B_{3,m}$
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$		$\vdots$	$\vdots$	$\vdots$		$\vdots$
$\lvert\tau_{N_T}\rangle$	$-A_0^0\,r$	$-A_1^0\,r$	$-A_2^0\,r$	$-A_3^0\,r$	$\ldots$	$-A_{N_T}^0\,r$	γ_{N_T}	$B_{N_T,1}$	$\ldots$	$B_{N_T,m}$
$\lvert\tau_0\rangle$	$-A_0^0\,r$	$-A_1^0\,r$	$-A_2^0\,r$	$-A_3^0\,r$	$\ldots$	0	γ_{N_T+1}	$B_{N_T+1,1}$	$\ldots$	$B_{N_T+1,m}$
$\lvert A_1\rangle$	$B_{N_T+2,0}$	$B_{N_T+2,1}$	$B_{N_T+2,2}$	$B_{N_T+2,3}$	$\ldots$	B_{N_T+2,N_T}	B_{N_T+2,N_T+1}	B_{N_T+2,N_T+2}	$\ldots$	B_{N_T+2,N_T+m+1}
$\vdots$	$\vdots$	$\vdots$	$\vdots$	$\vdots$		$\vdots$	$\vdots$	$\vdots$		$\vdots$
$\lvert A_m\rangle$	$B_{N_T+m+1,0}$	$B_{N_T+m+1,1}$	$B_{N_T+m+1,2}$	$B_{N_T+m+1,3}$	$\ldots$	B_{N_T+m+1,N_T}	B_{N_T+m+1,N_T+1}	B_{N_T+m+1,N_T+2}	$\ldots$	B_{N_T+m+1,N_T+m+1}

$$r := c/s$$

Theorem: For all $N_T \in \mathbb{N}$, there exists a solution

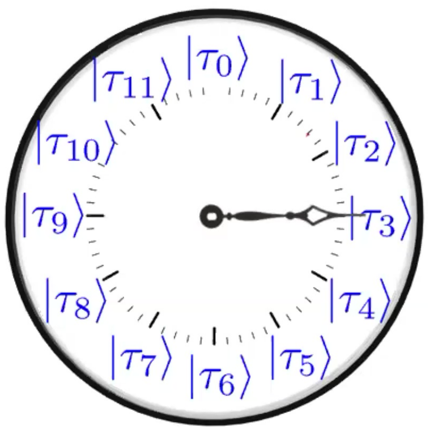
Engineered clocks

- Recall: $|\tau_0\rangle, |\tau_1\rangle, \dots, |\tau_{N_T}\rangle$ at times $\tau_0, \tau_1, \dots, \tau_{N_T}$

$$t \in \{\tau_0, \tau_1, \tau_2, \dots, \tau_{N_T}\}$$

- Improvement: $|\tau_0\rangle$ for $t \in [0, t_1)$, $|\tau_1\rangle$ for $t \in [t_1, 2t_1)$, ...
  $|\tau_{N_T}\rangle$ for $t \in [N_T t_1, (N_T+1)t_1)$.

$t \in [3t_1, 4t_1)$



$$t \in \cancel{\{\tau_0, \tau_1, \tau_2, \dots, \tau_{N_T}\}}$$

$$t \in [0, (N_T+1)t_1)$$

- Price: Small probability of error

Is time Sustantival or Relative?

- Assumptions:

  (A) Interaction-free measurements exist

  (B) If a clock can measure time while switched off, then time is substantival

- Theorem: if (A) and (B) hold, then time is substantival

- Alternative interpretations:

  - Many worlds interpretation: in the world we inhabit, the clock was never on, but it was on in another world

    - Implications for substantival theory of time: for time to be of a substantival nature in our world, we need dynamics in another world

Conclusions and open questions: arXiv:2106.07684

- Philosophy of time:
  - Aristotle to present
- Interaction-free measurements:
  - Bomb tester (Elitzur & Vaidman 93, Penrose 94, Kwit et al 95, Hosten et al 06)
  - Counterfactual computation (R. Jozsa 99, G. Mitchilson & R. Jozsa 01)
- Introduced counterfactual clocks:
  - Elementary clocks
  - Type engineered clocks
- Implications for the debate on time: Substantival theory vs Relative theory
  - Our results led support for the substantival theory
- Experimental implementations?
  - Harmonic oscillator?

Elementary timekeeping systems

- Using it to tell the time when off
  - Analyze protocol:

- If $t = \tau_0$.

$$|E\rangle \begin{cases} c\,|E\rangle \overset{\tau_0}{\rightsquigarrow} c\,|E\rangle \xrightarrow{U_{\mathrm{m}}} cA_1^0\,|E\rangle + cA_2^0\,|A\rangle + cA_3^0\,|\tau_0\rangle + cA_4^0\,|\tau_1\rangle \\ \qquad\qquad t = \tau_0 \\ s\,|\psi\rangle \overset{\tau_0}{\rightsquigarrow} s\,|\tau_0\rangle \xrightarrow{U_{\mathrm{m}}} \qquad -cA_2^0\,|A\rangle + sA_3^1\,|\tau_0\rangle + sA_4^1\,|\tau_1\rangle \end{cases}$$

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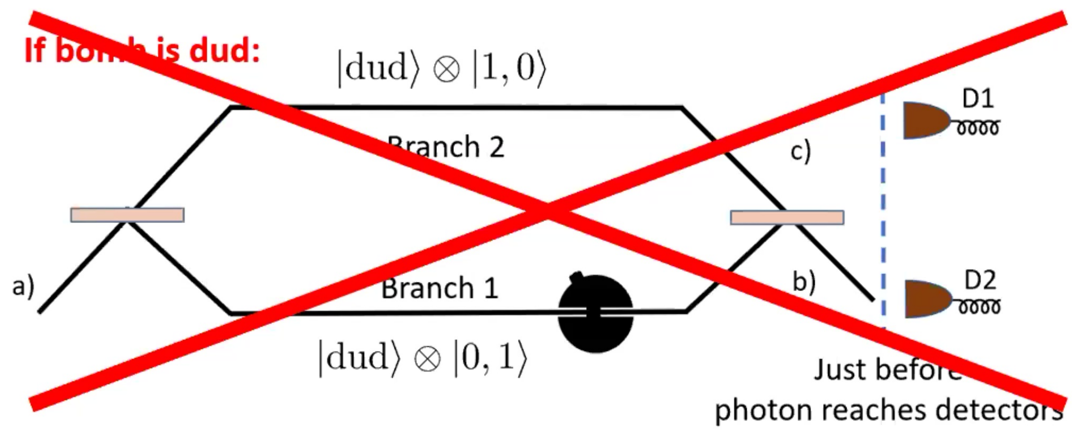
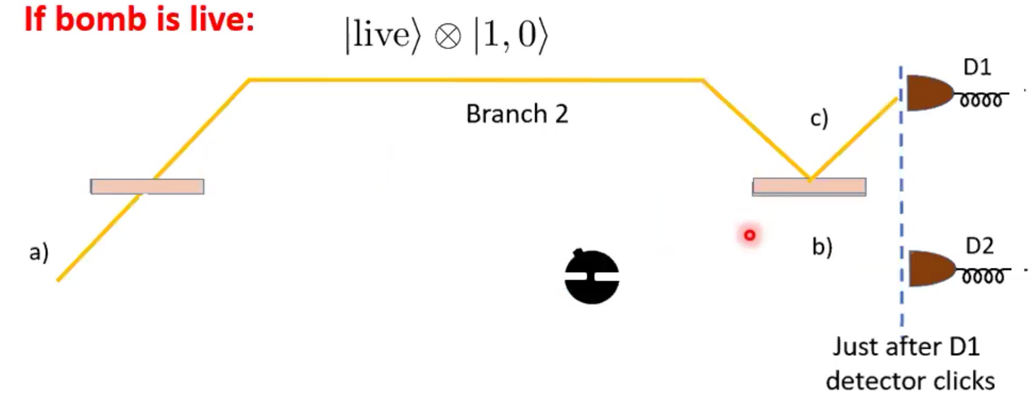
- If $|E\rangle$ outcome: $\begin{cases} \text{- If } t = \tau_0.\ \text{Clock was off} \\ \text{- If } t = \tau_1.\ \text{No outcome} \end{cases}$

Interaction-free measurements:

- ~~**If bomb is dud:**~~



- **If bomb is live:**



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