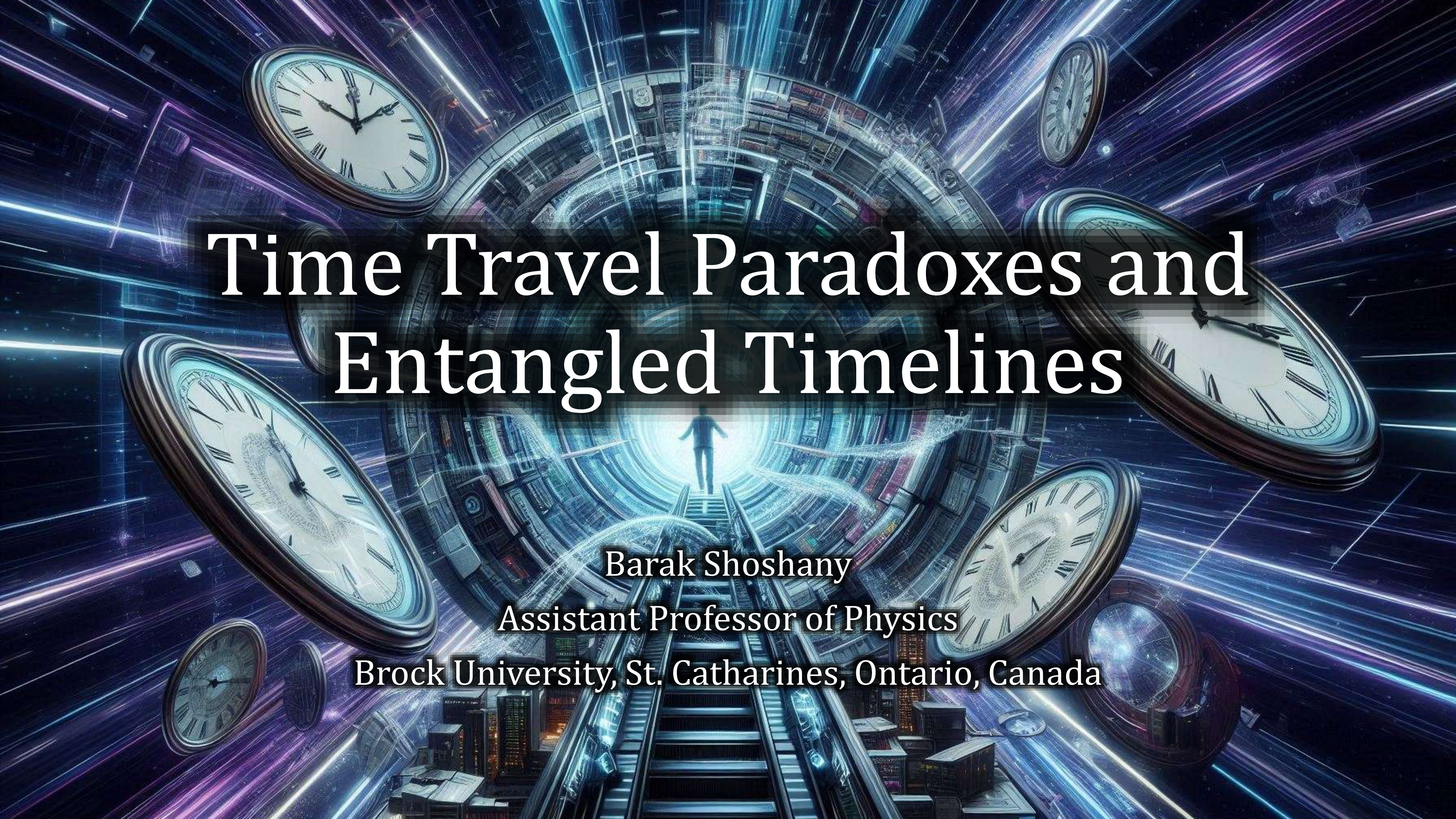

Time Travel Paradoxes and Entangled Timelines

Barak Shoshany
Assistant Professor of Physics
Brock University, St. Catharines, Ontario, Canada

Motivation

- Time travel may be possible
  - GR solutions with CTCs/CCCs
  - FTL: wormholes/warp drives → time travel?
- If possible: paradoxes?
  - Consistency: grandfather
  - Bootstrap: time loops
  - Inconsistent with known physics
- Proposed solutions
  - Hawking chronology protection: boring
  - Novikov self-consistency: problematic
  - **Parallel timelines: solve all paradoxes, but no concrete models**

Parallel timeline models

- General relativity: branching spacetimes
  - Non-Hausdorff manifold? (Hausdorff = distinct points have disjoint neighborhoods)
  - Non-locally-Euclidean? (Locally Euclidean = every point has a neighborhood homeomorphic to $\mathbb{R}^n$)
  - Mathematically intractable, no branching mechanism
- Quantum mechanics
  - Deutsch D-CTCs: Everett / “many-worlds” interpretation (MWI)
  - Uses reduced/mixed states, destroys information about timelines
  - **Our new model (with Zipora Stober): “entangled timelines” (E-CTCs)**

The generic paradox

- Independent of geometry/topology or specific physical system
- Time machine $\mathcal{H}_{\mathrm{CTC}}$: occupation number
  - $|0\rangle =$ empty (time travel has not occurred)
  - $|1\rangle =$ not empty (time travel has occurred)
- External system $\mathcal{H}_{\mathrm{ex}}$ (human, billiard ball, particle): control bit
  - $|0\rangle =$ won't go in (time travel will not occur)
  - $|1\rangle =$ will go in (time travel will occur)
- Logical, not physical states

The generic paradox

- $|\Psi(t)\rangle = \mathcal{H}_{\mathrm{CTC}} \otimes \mathcal{H}_{\mathrm{ex}}$
- True consistency paradox: time travel iff no time travel
- Cyclic
- Novikov does not apply; no way to make this consistent

Time	State/Event
$t = 0$	$\|0\rangle \otimes \|1\rangle$
	Nothing happens
$t = 1$	$\|0\rangle \otimes \|1\rangle$
	Time travel occurs
$t = 0$	$\|1\rangle \otimes \|1\rangle$
	Time travel is prevented
$t = 1$	$\|1\rangle \otimes \|0\rangle$
	Time travel does not occur
$t = 0$	$\|0\rangle \otimes \|1\rangle$

Alice and the bomb

- At $t = 1$, Alice puts bomb inside time machine, sends to $t = 0$
- At $t = 0$, Alice opens the time machine door and is killed
- Now Alice cannot send bomb at $t = 1$, so she's alive at $t = 0$
- Classic consistency paradox
- Macroscopic: cannot be precise, issues of free will, etc…
- Treat Alice's states as equivalence classes of states with same macroscopic behavior

Alice and the bomb

- Formulate using generic paradox.
- For $\mathcal{H}_{\text{CTC}}$: (time machine)
  - $|0\rangle \equiv |\text{empty}\rangle$
  - $|1\rangle \equiv |\text{bomb}\rangle$
- For $\mathcal{H}_{\text{ex}}$: (Alice)
  - $|0\rangle \equiv |\text{dead}\rangle$
  - $|1\rangle \equiv |\text{alive}\rangle$

Time	State/Event
$t = 0$	$\|\text{empty}\rangle \otimes \|\text{alive}\rangle$
	Nothing happens
$t = 1$	$\|\text{empty}\rangle \otimes \|\text{alive}\rangle$
	Alice sends a bomb back in time
$t = 0$	$\|\text{bomb}\rangle \otimes \|\text{alive}\rangle$
	Bomb explodes, Alice dies
$t = 1$	$\|\text{bomb}\rangle \otimes \|\text{dead}\rangle$
	Dead Alice cannot send a bomb
$t = 0$	$\|\text{empty}\rangle \otimes \|\text{alive}\rangle$

Particle annihilation

- Microscopic (simpler)
- For $\mathcal{H}_{\text{CTC}}$: (time machine)
  - $|0\rangle \equiv |\text{empty}\rangle$
  - $|1\rangle \equiv |\text{particle}\rangle$
- For $\mathcal{H}_{\text{ex}}$: (particle)
  - $|0\rangle \equiv |\text{annihilated}\rangle$
  - $|1\rangle \equiv |\text{not annihilated}\rangle$

Time	State/Event
$t = 0$	$\|\text{empty}\rangle \otimes \|\text{not annihilated}\rangle$
	Nothing happens
$t = 1$	$\|\text{empty}\rangle \otimes \|\text{not annihilated}\rangle$
	Particle goes into time machine
$t = 0$	$\|\text{particle}\rangle \otimes \|\text{not annihilated}\rangle$
	Past and future particles annihilate
$t = 1$	$\|\text{particle}\rangle \otimes \|\text{annihilated}\rangle$
	Particle doesn't go into time machine
$t = 0$	$\|\text{empty}\rangle \otimes \|\text{not annihilated}\rangle$

Note: This means a particle has traveled through, not that it still exists

Classical timelines: generic

Time	Timeline $h = 0$	Timeline $h = 1$
$t = 0$	$\|0\rangle \otimes \|1\rangle$	$\|1\rangle \otimes \|1\rangle$
	Nothing happens	Time travel is prevented
$t = 1$	$\|0\rangle \otimes \|1\rangle$	$\|1\rangle \otimes \|0\rangle$
	Time travel occurs	Time travel does not occur

Note: $\mathcal{H}_{\mathrm{CTC}}$ state $|0\rangle$ or $|1\rangle$ indicates the timeline

Classical timelines: macroscopic

Time	Timeline $h = 0$	Timeline $h = 1$
$t = 0$	$\lvert\text{empty}\rangle \otimes \lvert\text{alive}\rangle$	$\lvert\text{bomb}\rangle \otimes \lvert\text{alive}\rangle$
	Nothing happens	Bomb explodes, Alice dies
$t = 1$	$\lvert\text{empty}\rangle \otimes \lvert\text{alive}\rangle$	$\lvert\text{bomb}\rangle \otimes \lvert\text{dead}\rangle$
	Alice sends a bomb back in time	Dead Alice cannot send a bomb

Classical timelines: microscopic

Time	Timeline $h = 0$	Timeline $h = 1$
$t = 0$	$\lvert\text{empty}\rangle \otimes \lvert\text{not annihilated}\rangle$	$\lvert\text{particle}\rangle \otimes \lvert\text{not annihilated}\rangle$
	**Nothing happens**	**Past and future particles annihilate**
$t = 1$	$\lvert\text{empty}\rangle \otimes \lvert\text{not annihilated}\rangle$	$\lvert\text{particle}\rangle \otimes \lvert\text{annihilated}\rangle$
	**Particle goes into time machine**	**Particle doesn't go into time machine**

Quantum superposition

- $\mathcal{H}_{\text{ex}}$ always has initial condition $|1\rangle$, so no superposition at $t = 0$
- But $\mathcal{H}_{\text{CTC}}$ can be in superposition:
$$|\Psi(0)\rangle = (\alpha|0\rangle + \beta|1\rangle) \otimes |1\rangle, \qquad |\alpha|^2 + |\beta|^2 = 1$$
- Unitary evolution operator U from $t = 0$ to $t = 1$:
$$U(|0\rangle \otimes |1\rangle) = |0\rangle \otimes |1\rangle, \qquad U(|1\rangle \otimes |1\rangle) = |1\rangle \otimes |0\rangle$$
- Just CNOT gate:
$$U(|x\rangle \otimes |y\rangle) = |x\rangle \otimes |x \dotplus y\rangle$$

($x, y \in \mathbb{Z}_2$ and $\dotplus$ is addition mod 2)
$$|\Psi(1)\rangle = U|\Psi(0)\rangle = \alpha|0\rangle \otimes |1\rangle + \beta|1\rangle \otimes |0\rangle$$
- State became entangled!

Quantum superposition

- Define timeline correlation operator T between $t = 1$ and $t = 0$ at different h:
$$T(|x\rangle \otimes |y\rangle) = |y\rangle \otimes |1\rangle$$
- Not unitary; loses info about $|x\rangle$, as it does not affect time travel
- Not evolution; just correlation
$$T|\Psi(1)\rangle = \alpha|1\rangle \otimes |1\rangle + \beta|0\rangle \otimes |1\rangle$$
- Compare to initial state:
$$|\Psi(0)\rangle = \alpha|0\rangle \otimes |1\rangle + \beta|1\rangle \otimes |1\rangle$$
- So $\alpha = \beta = 1/\sqrt{2}$ (up to phase)

Collapse interpretation

- State at $t = 1$:

$$|\Psi(1)\rangle = \frac{1}{\sqrt{2}}(|0\rangle \otimes |1\rangle + |1\rangle \otimes |0\rangle)$$

- Collapses to $|0\rangle \otimes |1\rangle$ or $|1\rangle \otimes |0\rangle$ with 50% probability
- Correlates with either $|1\rangle \otimes |1\rangle$ or $|0\rangle \otimes |1\rangle$ at $t = 0$
- Collapse will destroy superposition, so paradox reappears
- Quantum superposition solution doesn't work in collapse models!

Many-worlds interpretation

- Alice has a qubit:
$$|\text{qubit}\rangle = a|0\rangle + b|1\rangle$$
- Measurement: collapses to 0 or 1, **non-unitary** evolution
- Solution: consider Alice's state too
$$|\Psi(0)\rangle = (a|0\rangle + b|1\rangle) \otimes |\text{Alice}\rangle$$
$$|\Psi(1)\rangle = a|0\rangle \otimes |\text{Alice saw 0}\rangle + b|1\rangle \otimes |\text{Alice saw 1}\rangle$$
- Unitary evolution (similar to CNOT gate)
- MWI = "unmodified" (purely unitary) QM

Entangled worlds

- Recall:
  $$|\Psi(1)\rangle = a|0\rangle \otimes |\text{Alice saw } 0\rangle + b|1\rangle \otimes |\text{Alice saw } 1\rangle$$
- Alice and qubit are now entangled; Alice “branches” into two
- Each Alice sees “collapse” from her own perspective
- Superposition $\neq$ measurement outcomes or knowledge
- Interpret as multiplicity of “worlds”
- Not physically distinct universes! Just 2 different terms in universal quantum state

Spreading of branches

- Consider Bob. Before measurement:

$$|\Phi(0)\rangle = (a|0\rangle + b|1\rangle) \otimes |\text{Alice}\rangle \otimes |\text{Bob}\rangle$$

- Alice measures:

$$|\Phi(1)\rangle = (a|0\rangle \otimes |\text{Alice saw } 0\rangle + b|1\rangle \otimes |\text{Alice saw } 1\rangle) \otimes |\text{Bob}\rangle$$

- Alice tells Bob what she measured:

$$\begin{aligned}|\Phi(2)\rangle = a|0\rangle \otimes |\text{Alice saw } 0\rangle \otimes |\text{Bob heard } 0\rangle \\ +b|1\rangle \otimes |\text{Alice saw } 1\rangle) \otimes |\text{Bob heard } 1\rangle\end{aligned}$$

- All 3 systems now entangled; branching spread further
- At $t \to \infty$ branching will spread to the entire universe (causal future)
- Branching is not global; it's local and spreads causally

Common misconceptions

- **Misconception 1:** branching happens upon measurement
- Correction: branching happens upon interaction between any two systems (e.g. Alice tells Bob the result)
- **Misconception 2:** branching instantaneously creates entire new parallel universes from scratch
- Correction: branching is just gradual and causal spreading of entanglement to more systems within a single universe
- Better name for MWI: “entangled worlds” or “entangled histories”?

Entangled timelines

- Back to time travel. At $t = 0$, state is separable:
$$|\Psi(0)\rangle = \frac{1}{\sqrt{2}}(|0\rangle + |1\rangle) \otimes |1\rangle$$
- Time machine ($\mathcal{H}_{\mathrm{CTC}}$) has 2 timelines; external system ($\mathcal{H}_{\mathrm{ex}}$) has only 1 timeline
- At $t = 1$, state is entangled:
$$|\Psi(1)\rangle = \frac{1}{\sqrt{2}}(|0\rangle \otimes |1\rangle + |1\rangle \otimes |0\rangle)$$
- Both systems have 2 timelines
- Systems entangled, so both must share the same timelines

Spreading timelines

- Timelines spread locally like branches in MWI
- Macroscopic: Bob opens door to lab, finds Alice alive or dead
- Microscopic: detector detects products of annihilation or not
- “Parallel timelines” or “parallel universes” are just local branching
- Start by interacting with time machine, then spread out

Conclusions

- QM with the MWI provides a simple and natural way to resolve time travel paradoxes
- The abstract generic paradox qubit model can be mapped onto more complicated macroscopic/microscopic models
- No need to worry about mechanisms for creating new physically distinct universes
- There is only one universe; timelines are emergent structures resulting from entanglement between systems
- Timelines propagate locally, gradually, and causally

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