Quantum Physics of Chronology Protection

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Why is chronology even an issue?

Observation:

- The Einstein equations are local:

$$G^{\mu\nu} = 8\pi \, G_{\text{Newton}} \, T^{\mu\nu}.$$

- These equations do not constrain global features — such as topology.

- In particular, they do not constrain *temporal topology*.

Consequence:

- General relativity (Einstein gravity) *seems* to be infested with time machines.

An infestation of dischronal spacetimes:

- Goedel's universe.

- van Stockum time machines.
  (Tipler cylinders/Spinning cosmic strings.)

- Gott time machines.

- Kerr and Kerr–Newman geometries.

- Wormholes — quantum.
  (Wheeler's Spacetime foam.)
  [Spatial topology change $\Rightarrow$ time travel.]

- Wormholes — classical.
  (Morris–Thorne traversable wormholes.)

So what?

- Time travel is problematic, if not downright repugnant, from a physics point of view.

- One can either learn to live with it or do something about it —

  1. Radical re-write conjecture.

  2. Novikov: consistency conjecture.
     "You can't change recorded history".

  3. Hawking:
     chronology protection conjecture.

  4. Boring physics conjecture;
     (canonical gravity on steroids).

- I'll concentrate on explaining chronology protection.

Closed chronological curves (CCCs):

- Definition: any closed timelike curve (CTC) is a time machine.

- A closed null curve (CNC) is almost as bad.

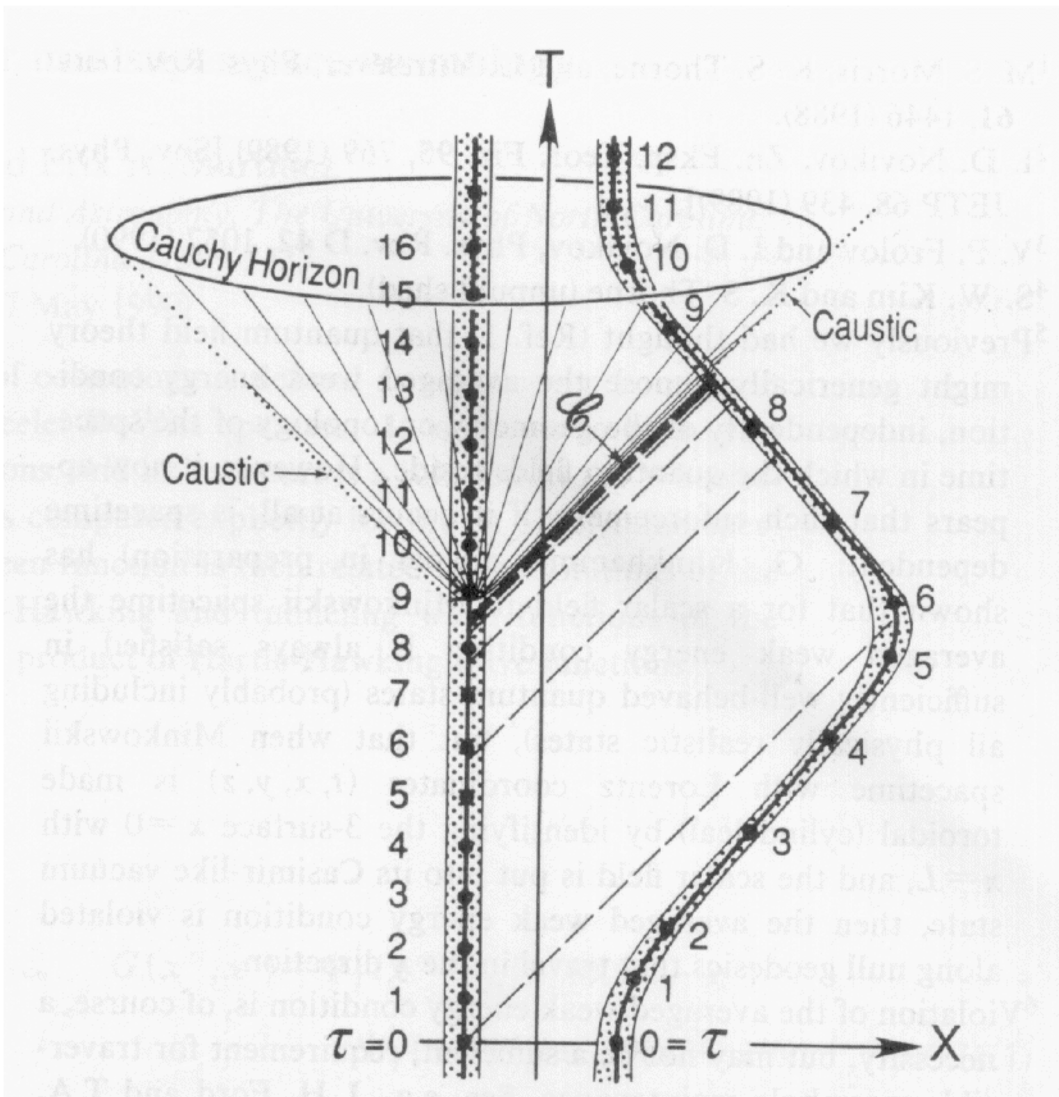
- If the closed chronological curves are cosmological, completely permeating the space-time, apply the GIGO principle.
  (garbage in — garbage out.)

- If the closed chronological curves are "confined" to some region we can begin to say something interesting.

- This situation corresponds to a "locally constructed" time machine.

Locally constructed time machines:

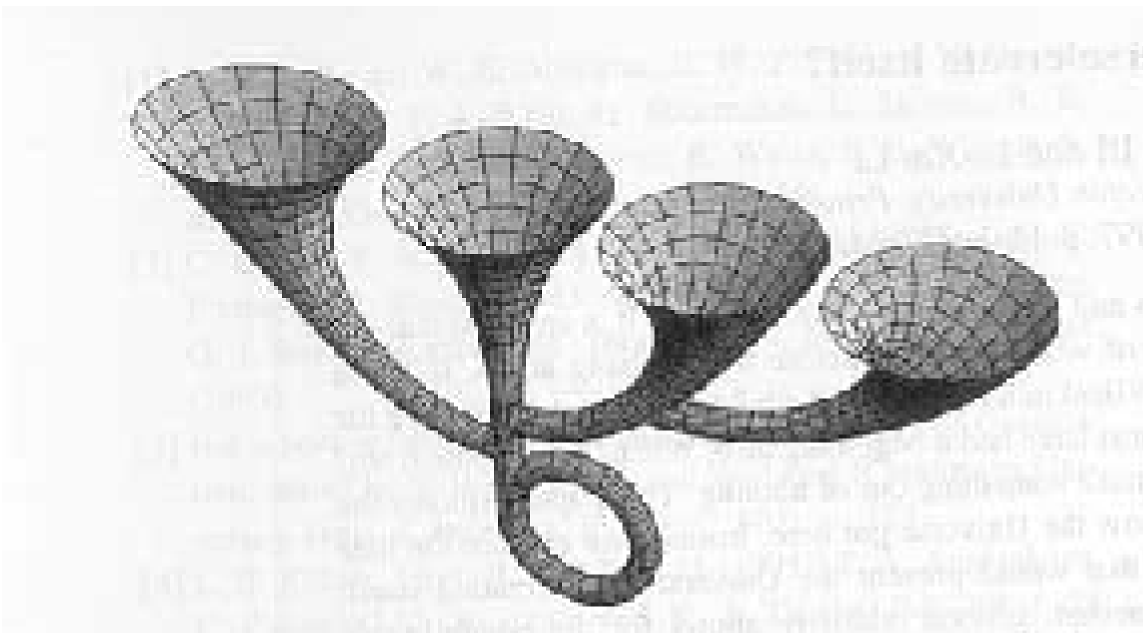
Example 1:



Morris–Thorne traversable wormholes...

Locally constructed time machines:

Example 2:



Gott–Li bootstrap universe...

Lorentzian signature "no boundary" proposal...

[PRD 58 (1998) 023501]

Having your cake and eating it too:

- Stephen's chronology protection permits a rich structure of strange and interesting objects without indulging in a free-for-all.

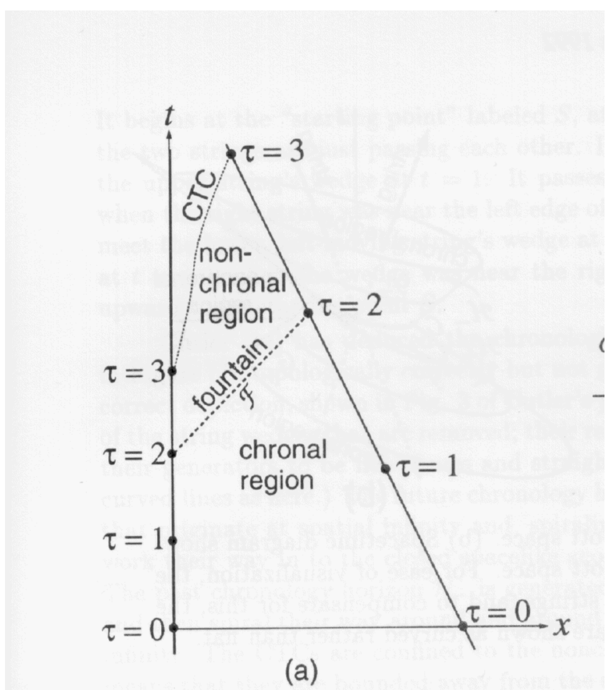
- GR community hoped to be able to settle this issue using classical, or at worst semi-classical, methods...

Stephen: [PRD 46 (1992) 603-611]

> "It seems that there is a Chronology Protection Agency which prevents the appearance of closed timelike curves and so makes the universe safe for historians."
>
> "There is also strong experimental evidence in favour of the conjecture — from the fact that we have not been invaded by hordes of tourists from the future."
>
> "The laws of physics do not allow the appearance of closed timelike curves."

Definitions:

- Chronology violating region.
- Chronology horizon.
- Compactly generated chronology horizon.
- “First” CNC: “fountain”.



Classical chronology protection:

- Consider a photon that travels round the fountain.

- On every trip its energy is boosted:

$$E \to h\,E \to h^2\,E \to h^3\,E\ \dots$$

$$\text{with} \qquad h \geq 1.$$

  Simple cases:

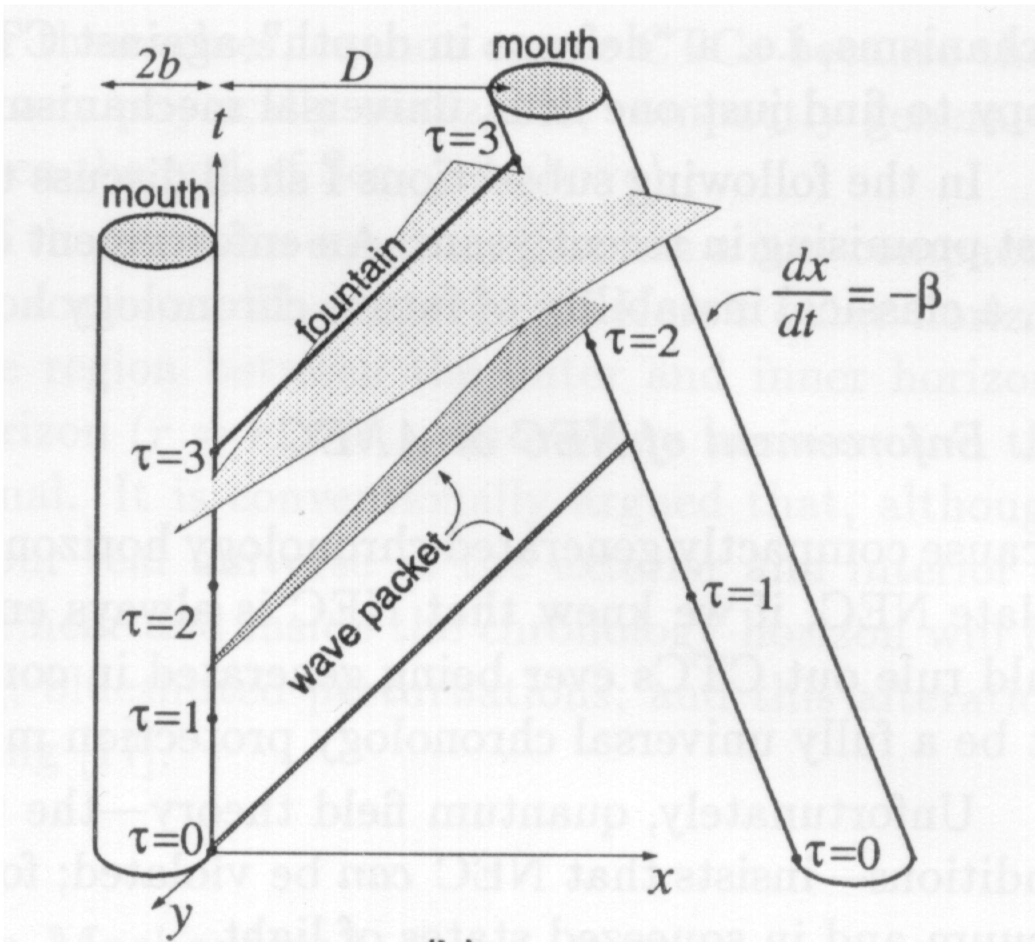
$$h = \sqrt{\frac{1+\beta}{1-\beta}}$$

Questions:

- Will this classical effect destabilize the chronology horizon?

- Will quantum physics amplify or ameliorate the effect?

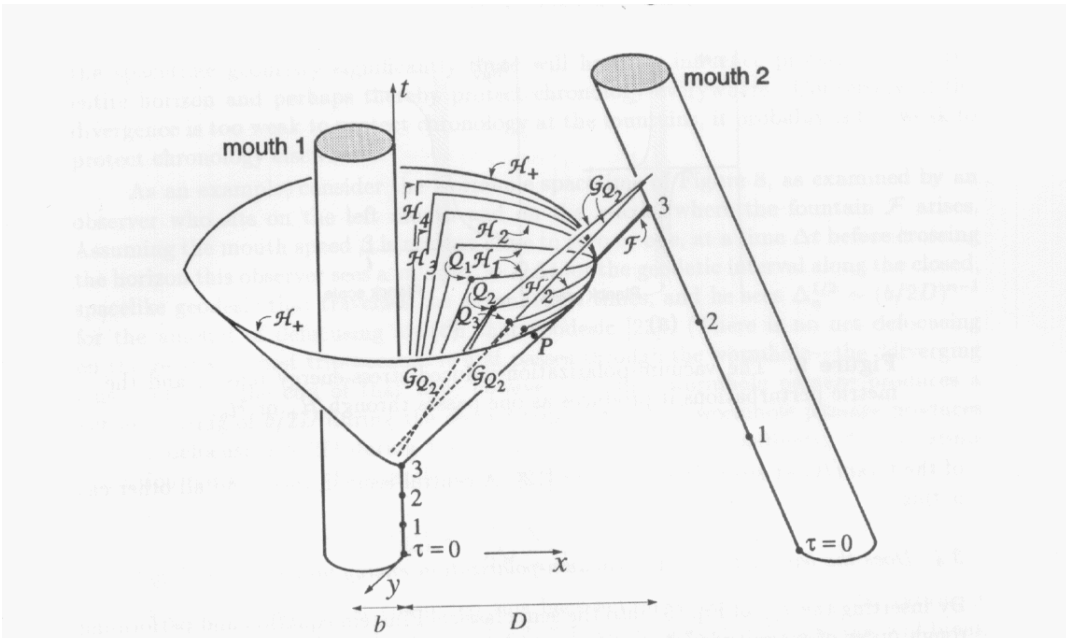
Wave packet defocussing:



- Question: Will this defocussing effect stabilize the chronology horizon?

- This would be *bad*.

Quantum chronology protection:



Polarized hypersurfaces:

- There is an entire nested structure of self-intersecting null curves that wrap through the wormhole N times.

- $N \to \infty$ approaches the chronology horizon.

Renormalized stress energy tensor:

$$\langle 0|T_{\mu\nu}(x)|0\rangle = \lim_{y\to x}\langle 0|T_{\mu\nu}(x,y)|0\rangle.$$

$$\langle 0|T_{\mu\nu}(x,y)|0\rangle = D_{\mu\nu}(x,y)\{G_R(x,y)\}.$$

- G_R — renormalized Green function.
- $D_{\mu\nu}$ — second–order differential operator.
- Adiabatic approximation:

$$\langle 0|T_{\mu\nu}(x)|0\rangle = \hbar \sum_{\gamma}{}' \frac{\Delta_\gamma(x,x)^{1/2}}{\pi^2 s_\gamma(x,x)^4}\, t_{\mu\nu}(x;\gamma) + O(s_\gamma(x,x)^{-3}).$$

- $t_{\mu\nu}(x;\gamma)$ function of metric and tangent vectors.

Blowups happen?

- $\langle T_{\mu\nu} \rangle \to \infty$ as $s[\gamma] \to 0^+$.

- This happens at every "polarized hypersurface".

- Unless there is an "accidental" zero in the Van Vleck determinant — $\Delta_\gamma(x, x)$.

- Unfortunately, there are special configurations (e.g., "Roman ring") where this happens.

- So generically $\langle T_{\mu\nu} \rangle \to \infty$;
  But for exceptional situations $\langle T_{\mu\nu} \rangle \to$ *finite*.

- Need a better argument to guarantee chronology protection.

Breakdown of semiclassical quantum gravity:

- Theorem: The two-point function is not of Hadamard form at the chronology horizon. [Kay, Radzikowski, Wald; CMP 183 (1997) 533-556.]

- That is: At the chronology horizon

$$G_{\mu\nu} \neq 8\pi \, G_{\text{Newton}} \, \langle T_{\mu\nu} \rangle,$$

  simply because $\langle T_{\mu\nu} \rangle$ does not exist...

- This does not necessarily mean $\langle T_{\mu\nu} \rangle \to \infty$.

- More prosaically $\langle T_{\mu\nu} \rangle \to undefined$.

- Need to go beyond semi-classical quantum gravity (scqg).

Green function:

The adiabatic approximation gives —

$$G_R(x,y) = \hbar \frac{\Delta_{\gamma_0}(x,y)^{1/2} \varpi_{\gamma_0}(x,y)}{4\pi^2} + \hbar \sum_{\gamma}{}' \frac{\Delta_\gamma(x,y)^{1/2}}{4\pi^2} \times \left[\frac{1}{\sigma_\gamma(x,y)} + \upsilon_\gamma(x,y) \ln|\sigma_\gamma(x,y)| + \varpi_\gamma(x,y) \right].$$

- The sum runs over nontrivial geodesics.
- $\sigma_\gamma(x,y) = \pm\frac{1}{2}s[\gamma(x,y)]^2$ is the geodetic interval.
- $\Delta_\gamma(x,y)$ is the Van Vleck determinant.
- $\upsilon_\gamma(x,y)$ and $\varpi_\gamma(x,y)$ are smooth as $x \to y$.

Retaining only the most singular terms as $\sigma \to 0^+$:

$$G_R(x,y) = \hbar \sum_{\gamma}{}' \frac{\Delta_\gamma(x,x)^{1/2}}{2\pi^2 s_\gamma(x,x)^2} + O\left[\ln(s_\gamma(x,x))\right].$$

Reliability of csqft:

- Near the chronology horizon $\exists$ arbitrarily short self-intersecting spacelike geodesics
$$\mathrm{d}s^2 = \mathrm{d}z^2 + g_{ab}^{(2+1)}\,\mathrm{d}x^a\,\mathrm{d}x^b.$$
(Not necessarily smooth.)

- $\Phi(z+s) = \Phi(z)$.

- $s < L_{\mathrm{Planck}} \Rightarrow$
modes with $p_z > P_{\mathrm{Planck}}$ excited.

- That is: Close enough to the chronology horizon $\exists$ Planck scale physics.

- Region invariantly defined by looking at length of self-intersecting spacelike geodesics.

Quantum physics wins:

- $g_{ab}(z + s) = g_{ab}(z)$.
- Close enough to the chronology horizon $\exists$ Planck scale metric fluctuations.
- Should not trust semi-classical quantum gravity there.
- Generically, csqft (curved-space qft) is not enough to guarantee chronology protection.
- Full quantum gravity is unavoidable. (strings/branes, quantum geometry, Lorentzian lattice qg, canonical qg, whatever...)

Quantum gravity:

- Canonical quantum gravity (on steroids) and Lorentzian lattice quantum gravity both satisfy chronology protection by fiat. (Impose global hyperbolicity $\Rightarrow$ stable causality $\Rightarrow$ cosmic time.)

- Quantum geometry and string/brane models do not (yet) seem to be able to address these issues.

  – Quantum geometry (currently) has enough troubles getting a "continuum limit".

  – String/brane models (currently) address chronology protection only within the low-energy limit — where they are a special case of csqft.

Conclusions:

- Chronology protection is a useful organizing principle.

- Chronology protection keeps life "interesting", without letting things get *too* "interesting".

- Chronology protection forces us to think about full-fledged quantum gravity.

- Chronology protection forces us to think about the quantum gravity/ semiclassical gravity interface.

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