Problems and possibilities for semi-classical gravity theories

Adrian Kent
Centre for Quantum Information and Foundations,
DAMTP, University of Cambridge
and
Perimeter Institute for Theoretical Physics

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UNIVERSITY OF CAMBRIDGE

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Some problems (*) with quantum gravity

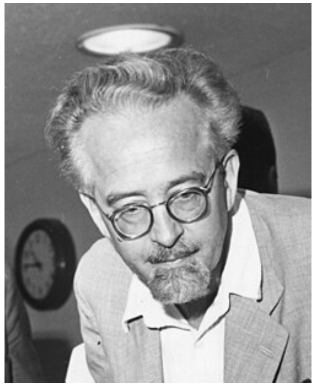
- The measurement problem: neither Everettian quantum gravity nor quantum gravity with fundamental measurements are well-defined.
- The problem of time
- The notion of events and indefinite causality
- The existence of a Hilbert space of suitable Lorentzian metrics
- Renormalisability
- The tension between Einstein's equivalence principle and quantum theory
- The quantum hole argument
- String theory's inability to predict the observed dimensionality of space-time or particle spectrum.
- The black hole information paradox

(*) Not everyone (incl. me) would agree these are all unsolved problems.

Møller-Rosenfeld semi-classical gravity

- Matter is quantum, state ρ
- Space-time is classical, Einstein tensor G_{ab}
- Renormalised stress-energy tensor $\hat{T}_{ab}^{ren}(x)$

$$G_{ab}(x) = \kappa\, Tr\left[\rho\, \hat{T}_{ab}^{ren}(x)\right]$$
$$\nabla^a \widehat{\langle T_{ab}^{ren} \rangle} = 0$$
$$\nabla^a G_{ab}(x) = 0$$



Christian Møller

Leon Rosenfeld

Some problems with semi-classical gravity

- Inconsistent with observation (astronomy; Page-Geilker experiment) if no measurement/collapse postulate.
- Renormalisability
- Nonlinear equation for quantum matter, which implies:
  - Superluminal signalling? (Gisin, Polchinski)
  - Violation of second law of thermodynamics? (von Neumann, Peres)
  - Violation of quantum uncertainty relations
  - Violation of the quantum "mixture equivalence principle" (mixtures with same ρ become distinguishable; proper and improper mixtures become distinguishable

- Violates stress-energy conservation if we add a measurement/collapse postulate
- Hence violates the Bianchi identities:

$$\nabla^a \langle \widehat{T_{ab}^{ren}} \rangle \neq 0 \quad \Rightarrow \quad \nabla^a G_{ab}(x) \neq 0 \quad \text{(inconsistent)}$$

Page-Geilker's account of their experiment

VOLUME 47, NUMBER 14 PHYSICAL REVIEW LETTERS 5 OCTOBER 1981

Indirect Evidence for Quantum Gravity

Don N. Page
Department of Physics, The Pennsylvania State University, University Park, Pennsylvania 16802

and

C. D. Geilker
Department of Physics, William Jewell College, Liberty, Missouri 64068

(Received 9 June 1981)

An experiment gave results inconsistent with the simplest alternative to quantum gravity, the semiclassical Einstein equations. This evidence supports (but does not prove) the hypothesis that a consistent theory of gravity coupled to quantized matter should also have the gravitational field quantized.

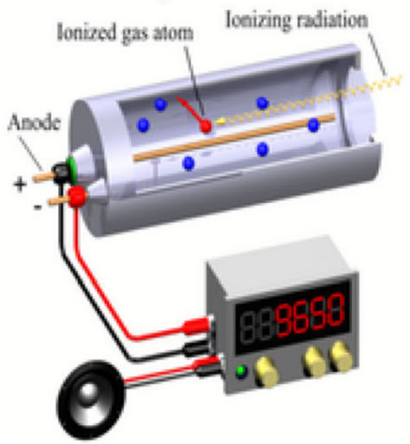
- Violates stress-energy conservation if we add a measurement/collapse postulate
- Hence violates the Bianchi identities:

$$\nabla^a \langle \widehat{T^{ren}_{ab}} \rangle \neq 0 \quad \Rightarrow \quad \nabla^a G_{ab}(x) \neq 0 \quad \text{(inconsistent)}$$

"..our theoretical arguments show that the semiclassical Einstein equations are mathematically inconsistent if the matter wave function collapses arbitrarily during a measurement, and our experimental results show that these equations are inconsistent with nature (to a high confidence level) if the wave function does not collapse"

The Page-Geilker experiment

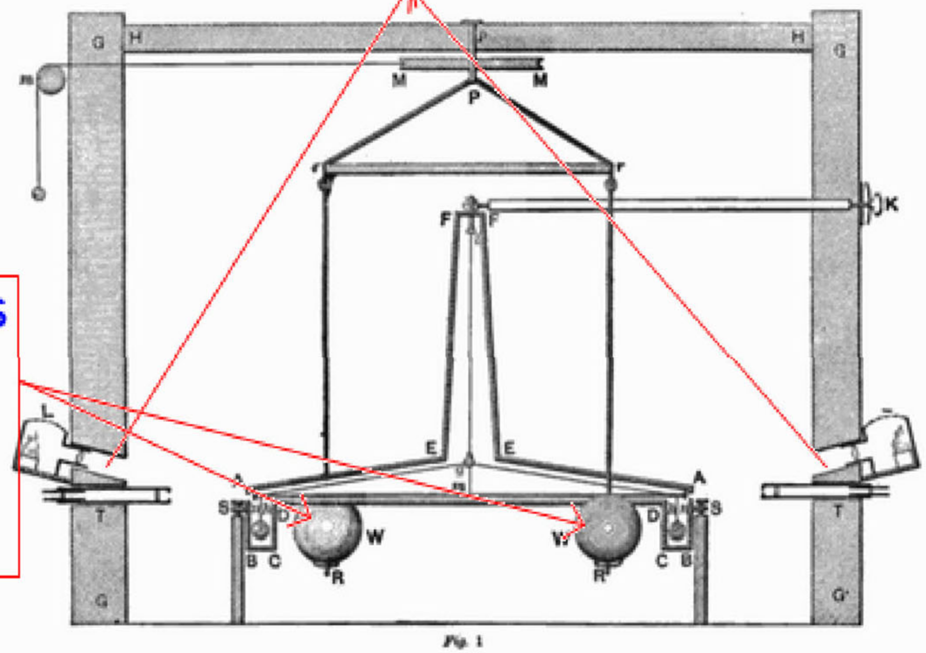
Geiger counter read by Don Page



Don Page

Larger masses moved depending on count

Displacement of smaller masses observed to depend on larger masses' locations.



Page-Geilker's account of their experiment

Because of the enormous complexity of the full wave function of the universe, it does seem highly likely that it may have significant components in which the earth, moon, sun, and other astronomical bodies are in positions greatly different from those in our component, the relative state[9] corresponding to our nongravitational observations. This would lead to a semiclassical gravitational field quite in conflict with gravitational observations.[10] However, it is plausible (though perhaps intrinsically unlikely) that ψ has all astronomical bodies at macroscopically well-defined positions. A quick calculation then shows that the quantum-mechanical uncertainty of their positions could remain observationally negligible during their lifetimes. Hence to make a more definite test of semiclassical gravity, one needs to make certain that the wave function does have components that would give measurably different gravitational fields.

In conclusion, our theoretical arguments show that the semiclassical Einstein equations (1) are mathematically inconsistent if the matter wave function collapses arbitrarily during a measurement, and our experimental results show that these equations are inconsistent with nature (to a high confidence level) if the wave function does not collapse. (An analogous argument and experiment could easily be used to rule out the semiclassical Maxwell equations, but we already know the electromagnetic field is quantized.) Because there are presumably more complicated schemes for coupling a classical gravitational field to matter that we know is quantized, this does not prove that gravity is quantized, but it may be interpreted as indirect evidence supporting the hypothesis of quantum gravity by ruling out what is probably the simplest plausible alternative.

Possible responses to Page-Geilker

- Semi-classical gravity with pure unitary (Everettian) quantum evolution is indeed inconsistent with observation and experiment
- Semi-classical gravity as an effective theory in some regime – for example, small masses, weak fields – is **not** ruled out and should be tested.
- Semi-classical gravity together with a measurement/collapse postulate certainly has consistency issues as a fundamental theory, but there are possible resolutions:
  - Consider modifications of the Einstein field equations that recover Einstein theory in some limit. For example, f(R,Q,T) gravity (which has higher-order Ricci terms, non-zero metricity and/or torsion) with nonminimal coupling can have $\nabla^a \langle \widehat{T_{ab}^{ren}} \rangle \neq 0$
  - Semiclassical field equations hold only "sufficiently far away" from quantum measurements, with modified field equations close to measurement.
  - Semiclassical field equations hold in patches. Measurements induce discontinuities in space-time, with different space-times "glued" together (Sudarsky et al. 2012, 2025).
- Other ideas being explored (not covered in this talk).

Semi-classical gravity is nonlinear

- The non-relativistic limit of semi-classical gravity for an N-particle system is the Schrödinger-Newton equation:

$$\nabla^2 \Phi(t, x) = 4\,\pi\, G\, mN \int \ldots \int |\, \psi(x, x_2, \ldots, x_n)|^2 \, d^3\, x_2 \ldots d^3 x_n.$$

$$i\,\hbar\,\partial_t\, \Psi_N(t, x_1, \ldots, x_N) \;\; = (\sum_{k=1}^{N} \;(-\left(\frac{\hbar^2}{2m}\right)\nabla^2_{x_k} \; + \; m\,\Phi(t, x_k)\,)) \;\; \Psi(t, x_1, \ldots, x_N)$$

- Nonlinear equation for quantum matter, which implies:
  - Superluminal signalling? (Gisin, Polchinski)
  - Violates 2nd law of thermodynamics? (von Neumann, Peres)
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  - Superluminal signalling? (Gisin, Polchinski) NO! (If defined carefully.)
  - Violates 2nd law of thermodynamics? (von Neumann, Peres) NO! (If defined carefully.)
  - Violates quantum "mixture equivalence principle" (mixtures with same ρ become distinguishable; proper and improper mixtures become distinguishable).

    FEATURE, NOT A BUG. INTERESTING TO TEST EXPERIMENTALLY.
  -

Semi-classical gravity allows classical readout of quantum states

The non-relativistic limit of semi-classical gravity for an 1-particle system is the Schrödinger-Newton equation:

$$\nabla^2 \Phi(t, x) = 4\,\pi\, G\, m\, |\,\psi(\,x)|^2$$

$$i\,\hbar\,\partial_t\,\Psi(t,x) \;=\; (-\left(\frac{\hbar^2}{2m}\right)\nabla_x^2 \;+\; m\,\Phi(t,x)\,))\;\;\Psi(t,x)$$

If $|\psi\rangle = a_0\,|x\_0\rangle + a_1|\,x_1\rangle$ then

$$\Phi(\mathbf{y}) = -Gm\left(\frac{|a_0|^2}{|\mathbf{x}_0-\mathbf{y}|} + \frac{|a_1|^2}{|\mathbf{x}_1-\mathbf{y}|}\right).$$

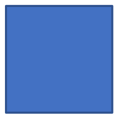
We can learn $|a_0|^2$, $|a_1|^2$ by measuring the gravitational field Φ , without disturbing $|\psi\rangle$.

By repeatedly applying unitaries and remeasuring, we can learn a_0, a_1.

So we obtain a classical description of $|\psi\rangle$ without disturbing it: we have a **classical state readout device.**

A hypothetical state readout machine

A hypothetical device extending NR QM: acts on a single pure qubit state
and outputs the state together with a classical description.
(We assume infinite precision and ignore classical memory space issues.)

$|\psi\rangle \rightarrow$  $\rightarrow |\psi\rangle,\quad$ "$|\psi\rangle = a|0\rangle + b|1\rangle$"

Assuming, to idealise for simplicity, infinite precision and infinite memory,
we obtain all information about a state without any disturbance.
Is that a problem or just a feature of semi-classical gravity?

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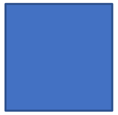
$|\psi\rangle \rightarrow$  $\rightarrow |\psi\rangle$, "$|\psi\rangle = a|0\rangle + b|1\rangle$"

Let A and B share an entangled state $\frac{1}{\sqrt{2}}(|0\rangle_A |1\rangle_B - |1\rangle_A |0\rangle_B)$
Suppose that B carries out a measurement in the $|0\rangle, |1\rangle$ basis.
According the projection postulate, A then has either $|0\rangle$ or $|1\rangle$.
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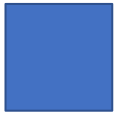
$|\psi\rangle \rightarrow$  $\rightarrow |\psi\rangle$, "$|\psi\rangle = a|0\rangle + b|1\rangle$"

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She learns the state value, and hence B's measurement choice.

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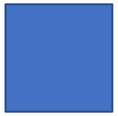
$|\psi\rangle \rightarrow$  $\rightarrow |\psi\rangle$, "$|\psi\rangle = a|0\rangle + b|1\rangle$"

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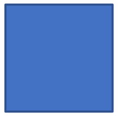
So, **if** this standard argument is watertight, readout machines allow superluminal signalling.

Is a Quantum State Readout Device Model Necessarily Superluminal?

If measuring one entangled subsystem B instantaneously alters the state of a distant other A, then a cloning or readout device at A could produce outputs that depend on the measurement choice. Hence superluminal signalling.

$|\psi\rangle \rightarrow$  $\rightarrow |\psi\rangle,$ "$|\psi\rangle = a|0\rangle + b|1\rangle$"

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Related to this, the action of our devices on general states was defined on pure states, but not on states of an entangled subsystem.

$|\psi\rangle \rightarrow$  $\rightarrow |\psi\rangle$, "$|\psi\rangle = a|0\rangle + b|1\rangle$"

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It *does* make sense to allow physical effects to propagate at light speed in a relativistic model.

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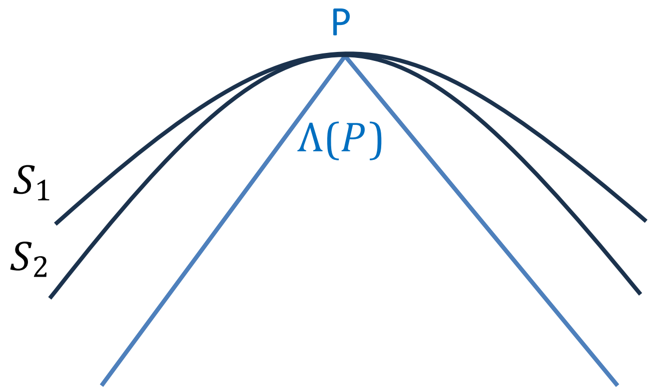

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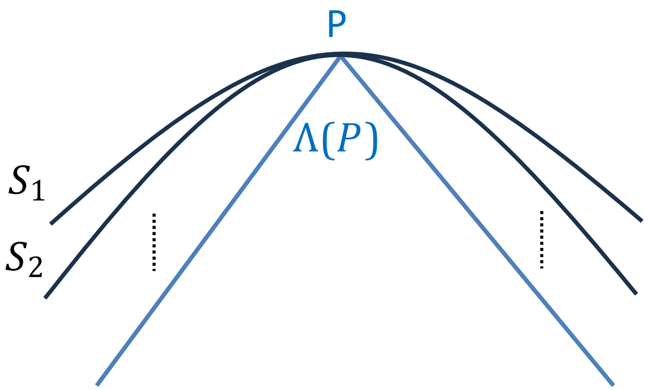

$$\rho_P = \lim_{\rightarrow} Tr_{S_n \backslash P} \left(|\psi_{S_n}\rangle \langle \psi_{S_n}| \right)$$

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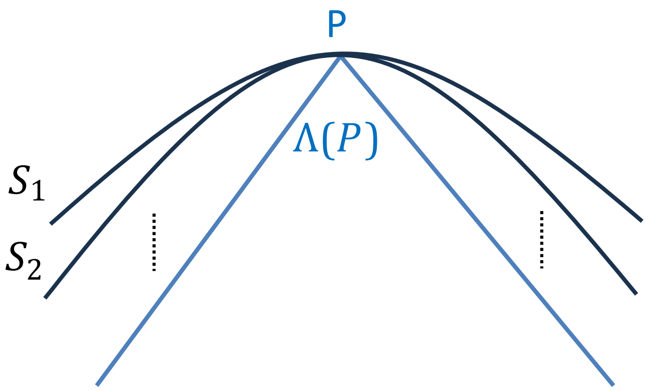
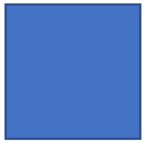


$$\rho_{\mathrm{P}} = \lim_{\to} Tr_{\mathrm{S_n}\backslash \mathrm{P}} \left(|\psi_{\mathrm{S_n}}\rangle \langle \psi_{\mathrm{S_n}}| \right)$$

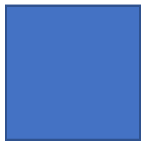
Local quantum state at P is the local density matrix ρ_{P} obtained by evolving the initial quantum state, taking account of (only) measurements that took place in the past light cone $\Lambda(P)$

Action of the better state readout machine on separated subsystems.

Given a single pure qudit state $\psi \in C^d$ it outputs the state **together with its classical description.**
(For now we assume infinite precision and ignore memory space issues.)

$|\psi\rangle \rightarrow$  $\rightarrow |\psi\rangle$, $\quad$ "$|\psi\rangle = \sum_{i=1}^{d} c_i \; |i\rangle$"

Given a single pure state $\psi \in C^{d_1} \otimes \cdots \otimes C^{d_n}$, applied to system 1, it outputs ψ together with **a classical description of the system 1 reduced density matrix**

$|\psi\rangle \rightarrow$  $\rightarrow |\psi\rangle$, $\quad$ "$\rho_1 = Tr_{2\ldots n}(\,|\psi\rangle\langle\psi|)$ "

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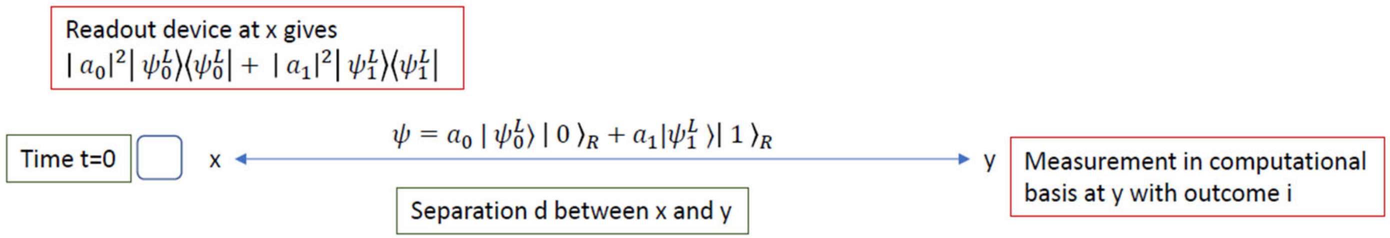
A relativistic qubit state readout device

We assume infinite precision and neglect issues arising from this for now.

We also assume that "measurement" is a primitive and well-defined concept.
In particular, measurements take place at definite points in space-time.



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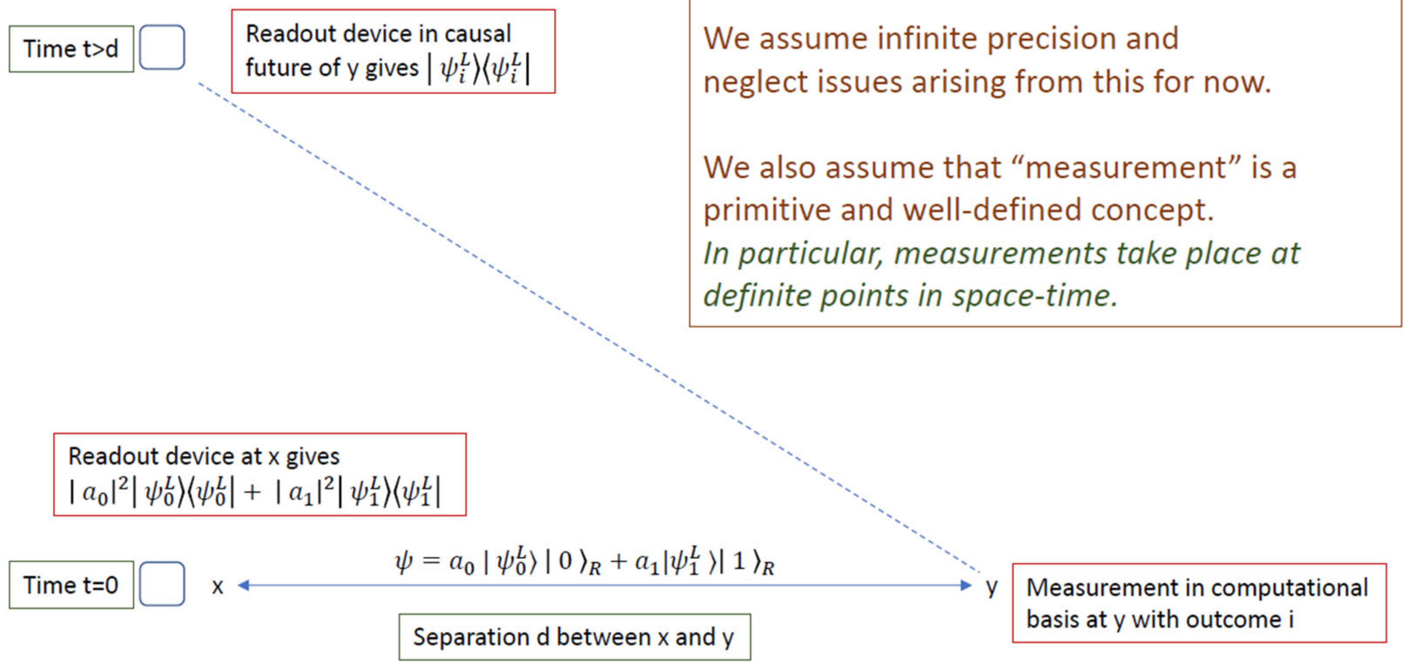

Is the Quantum State Readout Device Model Consistent?

A quantum state readout device at P only produces information that is in principle calculable at P, given

- (a) knowledge of the initial state on the intersection of a hypersurface with the past light cone $\Lambda(P)$ of P
- (b) knowledge of the unitary evolution law in $\Lambda(P)$
- (c) knowledge of any collapse/measurement events in $\Lambda(P)$

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We may never know (a) or (c) (or maybe even (b) ☹).
But there is *no logical inconsistency* in a universe
in which local agents have all this information and use it.

Such agents could use it to simulate the action of quantum state readout devices.

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But there is *no logical inconsistency* in a universe in which local agents have all this information and use it.

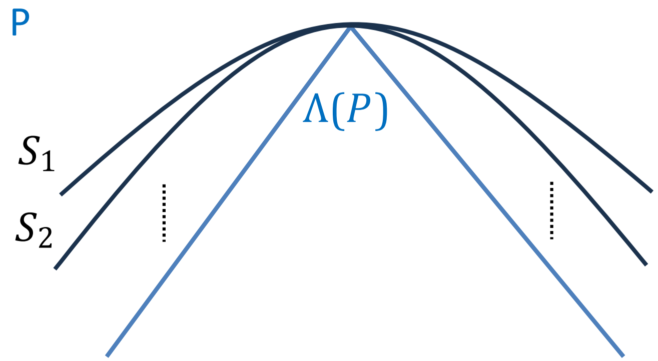
Such agents could use it to simulate the action of quantum state readout devices. *Hence quantum theory with readout devices is an internally consistent model.*

Does Semi-classical gravity necessarily allow superluminal signalling?

It makes no sense to consider a relativistic model in which physical effects propagate instantaneously.

It *does* make sense to allow physical effects (gravitational field sourcing, effects of measurements/collapses) to propagate at light speed in a relativistic model.

If semi-classical gravity is sourced causally (i.e. with standard retarded propagators) by the local quantum state, we have no superluminality.



Semi-classical gravity and consistent thermodynamics

Thermodynamics of readout devices and semiclassical gravity

Samuel Fedida[1] and Adrian Kent[1,2]

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Samuel Fedida

In *Mathematical Foundations of Quantum Mechanics* (1932), von Neumann argued
that the ability to distinguish non-orthogonal states would violate the second law of thermodynamics.

Arguments later extended by Peres (1993), Hanggi-Wehner (2013).

Nonlinear theories generically allow non-orthogonal state discrimination.

So is **this** a reason to reject them?

John von Neumann

von Neumann's Cycle with Non-orthogonal States: the argument

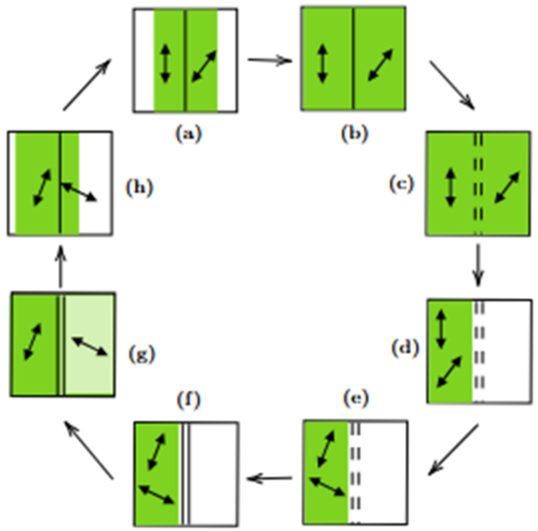


Figure 1: Cycle extracting heat from an isothermal reservoir and converting it into work using a semi-permeable non-quantum membrane that separates a specific pair of non-orthogonal states as well as a semi-permeable quantum membrane that separates a specific pair of orthogonal states. The quantum membranes, which let through one of two orthogonal states, are depicted as solid double lines, while the semi-permeable membranes, which can be implemented by readout devices and let through one of two non-orthogonal states, are shown in dashed double lines. Walls, which do not let any states through, are depicted with single lines.

Schematic of von Neumann's thermodynamic cycle with semipermeable walls for non-orthogonal states.

(a) Work $W^{+} = Nk_B T log(2)$ extracted by expanding chambers

(c) Semi-permeable membrane, using non-orthogonal state discrimination, allows states to pass from R to L but not vice versa.

(e) Equal mixture of non-orthogonal states has the same ρ as unequal mixture of orthogonal eigenstates of ρ.

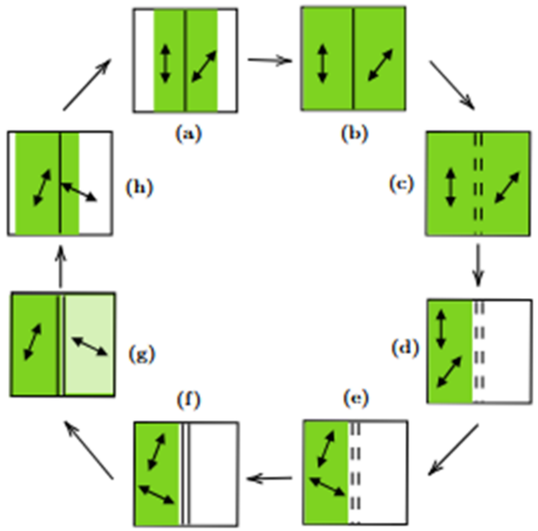
(g) Semi-permeable membrane, using standard orthogonal state discrimination, allows one eigenstate to pass from L to R, retaining the other in L.

(h) Isothermal compression reduces volume in proportion to number of states in each chamber, to original volume. This requires work $W^{-} = Nk_B T\, S(\rho) < W^{+}$.

(a) Boundaries are returned to original using standard orthogonal state discrimination, then unitaries applied on each chamber to restore states to original.

This returns us to (a) having extracted net work.

von Neumann's Cycle with Non-orthogonal States: the argument



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This step assumes that the von Neumann entropy $S(\rho)$ is the correct definition for any ensemble with density matrix ρ and hence that this standard quantum measurement does not alter the entropy. Not true in readout device world: the ensemble entropy $S(\{ p_i \})$ is correct. Calculation inapplicable (also because the quantum measurement alters $S(\{ p_i \})$).

Relevance to quantum + gravity models

- An alternative to standard quantum gravity ideas is that in some regimes, the gravitational effect of quantum matter may be modelled classically.

- For example a position space superposition of mesoscopic masses could produce a classical gravitational field determined by semi-classical gravity, $G_{\mu\nu} = \langle T_{\mu\nu} \rangle$, applied to the mesoscopic subsystem.

- **There are serious problems with this idea.** Semi-classical gravity certainly doesn't hold for Everettian macroscopic superpositions. It's not clear that it's a consistent theory in any interesting regime for any sensible version of quantum theory.

- **But the common objection that it implies superluminal signalling is not compelling**, as we've seen.

- **In semi-classical gravity and related models, the gravitational field is effectively some form of post-quantum readout device.**

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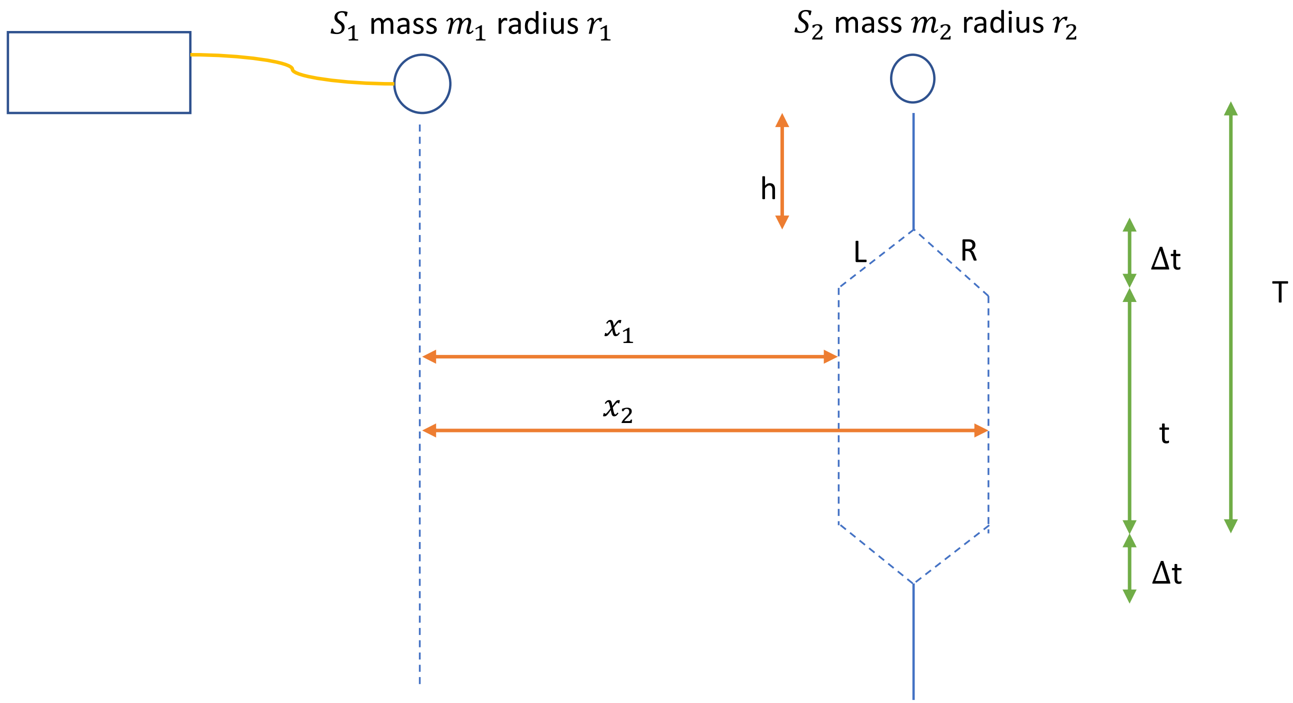
- **There are serious problems with this idea.** Semi-classical gravity certainly doesn't hold for Everettian macroscopic superpositions. (If it did we would see a mixture of gravitational fields from other cosmologies.)

- **In semi-classical gravity and related models, the gravitational field is effectively some form of post-quantum readout device.**

- **In any plausible model we would expect it to give noisy, incomplete information about the quantum state – a finite precision readout device.**

Measurement-like interaction
(on small enough scale that by hypothesis there is no collapse).

Testing semiclassical gravity in mesoscopic regimes



Schematic description of experiment (not to scale). A quantum process is amplified by a small electrical pulse to an apparatus that (for example by switching a magnetic field) either holds or releases the sphere S1 at time t = 0. At the same time, S2 is released, falling under gravity through a Stern-Gerlach interferometer. Distances are represented by orange arrows, times of fall by green arrows. Paths with amplitude 1 are represented by solid blue lines; paths with smaller amplitudes by dotted blue lines

(from Tests of Quantum Gravity near Measurement Events, AK, Phys. Rev. D 103, 064038 (2021))

The (gravitational) mixture equivalence principle

Quantum theory tells us that proper and improper mixtures with the same density matrix are indistinguishable.

Nonlinear versions of quantum theory violate this **mixture equivalence principle**.

For example, a state readout device reads out the actual state "ψ_i" (probabilistically chosen from the ensemble) in a proper mixture $\rho = \sum_i p_i \ \psi_i$.

Given a subsystem of an entangled system whose reduced density matrix is ρ, it reads out "ρ".

The (gravitational) mixture equivalence principle

- Quantum theory tells us that proper and improper mixtures with the same density matrix are indistinguishable.
- Semi-classical gravity violates what we may call the **gravitational mixture equivalence principle**:

For the state $\frac{1}{\sqrt{2}}(\; | \, m \, >_x \; | \; 0 >_y \; + \; |0 >_x \; | \, m \, >_y \;)$

it gives gravitational field near x given by a source of mass $\frac{1}{2}m$.

For the corresponding proper mixture, it gives gravitational field near x as either that given by a source of mass 0 or mass m, each with probability $\frac{1}{2}$.

Gravity models based on other readout devices similarly violate the MEP.
We should test it as carefully as possible.

Not problems. Also problem for quantum gravity. Interesting testable features.
Remain problems, but with some ideas for tackling.

- Inconsistent with observation (astronomy; Page-Geilker experiment) if no measurement/collapse postulate.
- Renormalisability
- Nonlinear equation for quantum matter, which implies:
  - Superluminal signalling? (Gisin, Polchinski)
  - Violation of second law of thermodynamics? (von Neumann, Peres)
  - Violation of quantum uncertainty relations
  - Violation of the quantum “mixture equivalence principle” (mixtures with same ρ become distinguishable; proper and improper mixtures become distinguishable)

- Violates stress-energy conservation if we add a measurement/collapse postulate
- Hence violates the Bianchi identities:

$$\nabla^a \langle \widehat{T_{ab}^{ren}} \rangle \neq 0 \quad \Rightarrow \quad \nabla^a G_{ab}(x) \neq 0 \quad \text{(inconsistent)}$$


tusind tak
ngiyabonga
dziękuję
谢谢
dakujem vám
ありがとう
merci
suksema
danke
thank
baie dankie
धन्यवाद
molte grazie
gracias
takk
you
dank u
teşekkür edire
mahalo
obrigada
obrigado
gràcies
teşekkür ederim
شكرا
tänan
tack så mycket

ありがとう