Title: Witnesses of non-classicality beyond quantum theory

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Series: Quantum Gravity

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Abstract: I discuss general argument to show that if a physical system can mediate locally the generation of entanglement between two quantum systems, then it itself must be non-classical. Remarkably, the argument does not assume any classical or quantum formalism to describe the mediating physical system: the result follows from general information-theoretic principles. This argument provides a robust and general theoretical basis for recently proposed tests of non-classicality in gravity, based on witnessing gravitationally-induced entanglement in quantum probes.

Witnessing non-classicality beyond quantum theory

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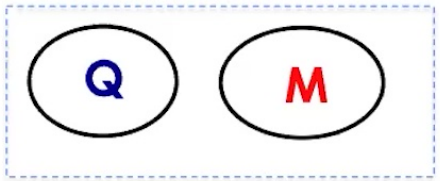
A problem:

how does one make predictions about hybrid systems?

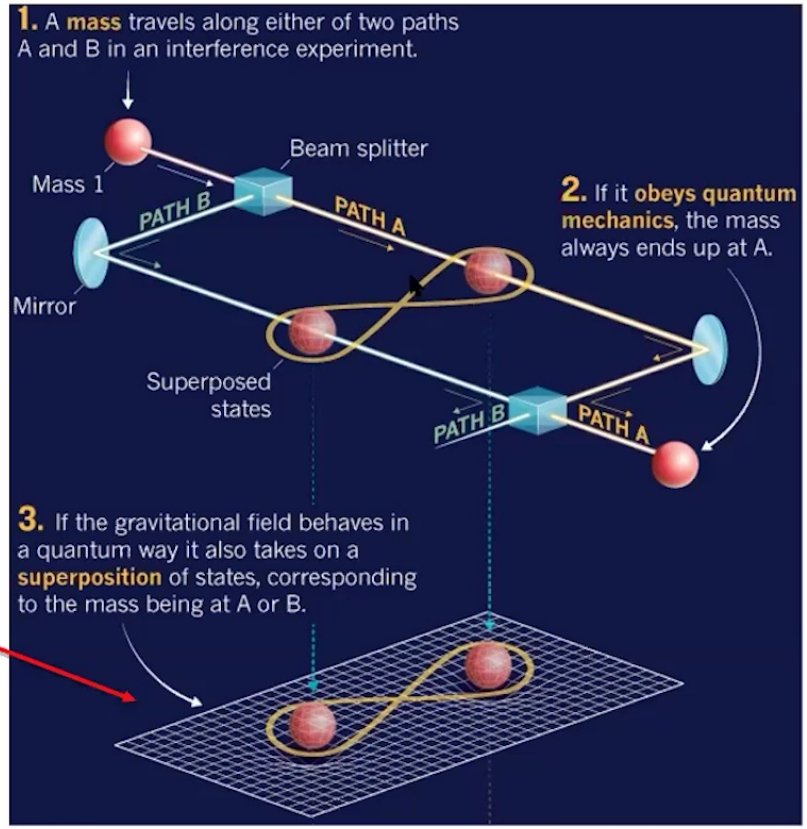
A quantum system (e.g. a qubit)



Another system whose dynamical evolution is intractable or imperfectly known (e.g. a macroscopic biomolecule; or even gravity)

An example: how can we tell that **M** is 'quantum'?

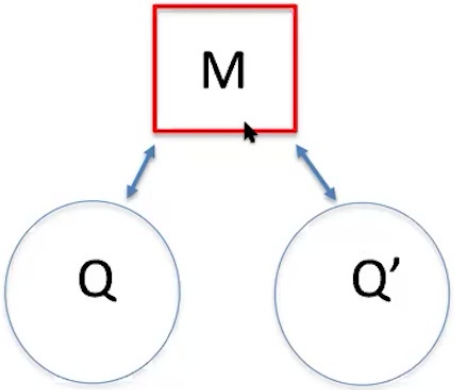
Feynman's problem



How does one confirm that the gravitational field is quantum?

R. Feynman, Chapel Hill Conference, 1957.

Witnessing non-classicality of gravity using gravity-induced entanglement between two quantum probes



Key Idea:

If M can entangle Q and Q' by pairwise, local interactions, then it has to be non-classical (i.e., it must have at least two non-commuting observables)

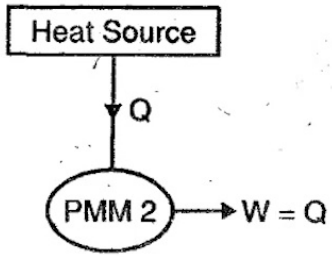
Bose et al. (2017), Marletto&Vedral (2017)
Variants:
Marletto, Vedral & Deutsch (2018)
Christodoulou&Rovelli (2018)
Krisnanda et al. (2019)
Marletto&Vedral (2020)
Howl et al. (2020)

BUT: how general is this idea?

We want to avoid assuming that **M** obeys quantum theory, as that is the very thing the witness is supposed to check out!

Beyond dynamics: physical principles

Impossible (by the Conservation of Energy)



Impossible (by the 2nd Law)

Possible (Computability of Nature)

Can the principle-based mode of explanation be used to express laws and derive predictions about hybrid systems?

Constructor Theory's Programme

*Laws of physics are expressed as scale-independent principles about which **tasks** are **possible**, which are **impossible** and why*

Specific dynamics is not assumed; dynamics and supplementary conditions are to be derived from the principles as emergent consequences.

NOTE: CT supplements existing principles, so it's not just a 'framework'

*Deutsch, D. "Constructor theory". Synthese. **190** (18): 4331–4359. 2011.*

A principle-based mode of explanation

Tasks are sets of ordered pairs of attributes, specifying a general physical transformation.

$$\text{Input Attributes of Substrates} \Rightarrow \text{Output Attributes of Substrates}$$

A task is impossible if there is a law of physics forbidding its being performed to arbitrarily high accuracy, possible otherwise

Note the fundamental difference between dynamically allowed transformations and possible tasks!

A constructor for a task T is a system that is capable of performing the task T while retaining its ability to do so again

Constructor

Input Attributes of **Substrates** ⇒ Output Attributes of **Substrates**

(the name is inspired by von Neumann's universal constructor – but constructor theory is not about constructors. It's about possible/impossible tasks.)

An example :
an application of CT to information theory

Information Media

Information medium: a system with a set of attributes X that it is possible to permute and copy.

NOTE: if X={0, 1, 2,…,n}, the 'copy' task on X looks like this:

{(0,b)→(0,0); (1,b)→(1,1);…(n,b)→(n,n)}

X is called an 'information variable'.

EXAMPLE: a set of n orthogonal quantum states.

Principles About Information Media

Interoperability Principle

The combination of two information media with information variables X_1 and X_2 is an information medium with information variable $X_1 \times X_2$.

〔Informally: 'Information variables can be copied from any information medium to any other'〕

D. Deutsch, C. Marletto, Proceedings of Royal Society A, 471:20140540, 2014.

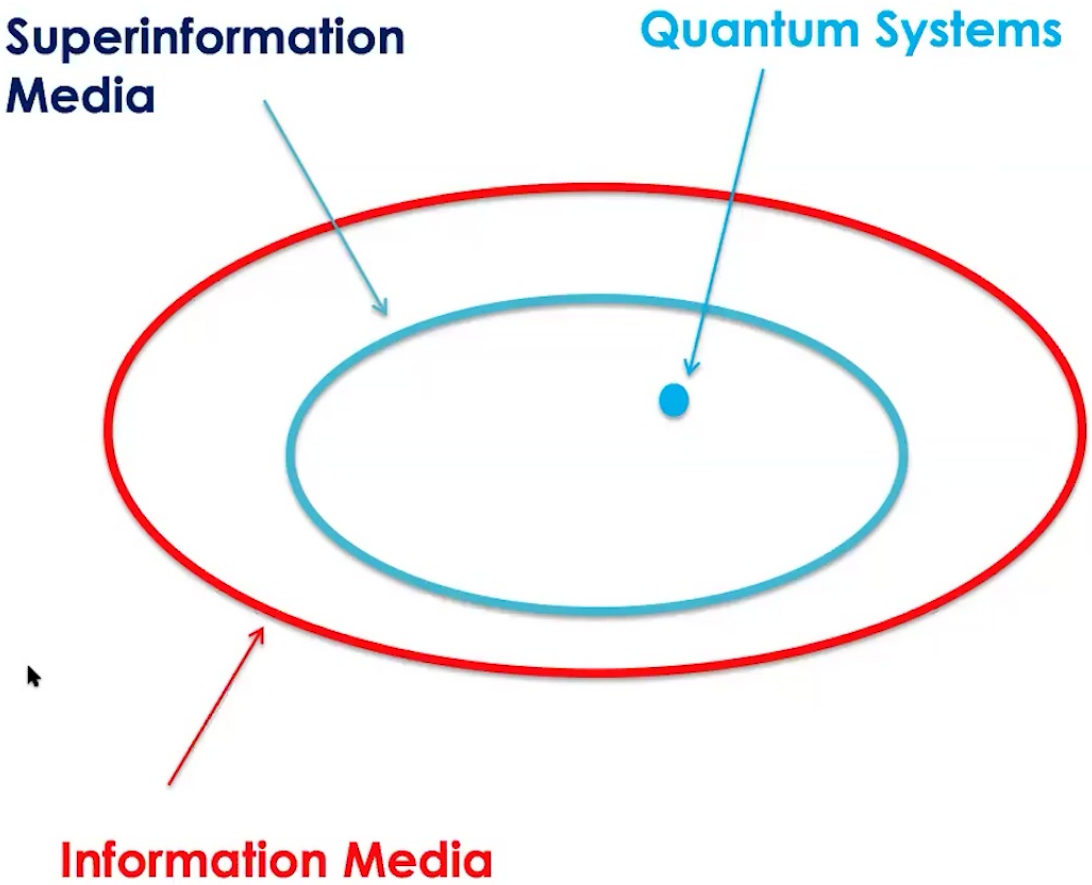
Superinformation Media

Superinformation medium: An information medium with at least two information variables whose union is not an information variable

Example: a qubit with the information variables X and Y :

$$X = \{\{|0\rangle\}, \{|1\rangle\}\}$$

$$Y = \{\{|+\rangle\}, \{|-\rangle\}\}$$


Superinformation Media
Quantum Systems
Information Media

Non-classicality in the superinformation framework

A system is 'non-classical' if it has an information variable Z and another disjoint variable X which *cannot be 'copied'* simultaneously to perfect accuracy.

X and Z we call 'incompatible' and generalise non-commuting variables of quantum theory.

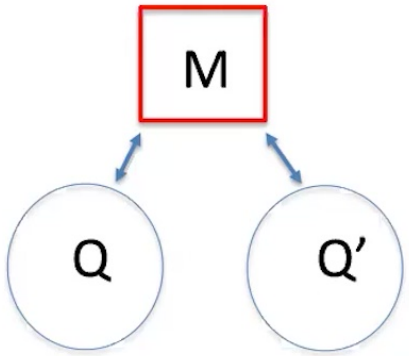
A theory-independent argument for non-classicality

Assume two general principles:

1) Locality (No action at a distance)

2) Interoperability of information

A dynamics-independent argument for non-classicality

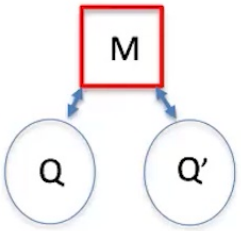


Theorem

If M is an information medium that can locally mediate entanglement between two quantum media Q and Q', then M is non-classical.

C. Marletto, V. Vedral , 2017.
C. Marletto, V. Vedral, 2020.

A dynamics-independent argument for non-classicality



Key traits:

1) The features of the mediator M and the principle underlying the theorem are expressed in the superinformation framework, independently of dynamics and scale.

2) If ANY AMOUNT entanglement is observed and the assumptions are satisfied, this argument allows one to rule out ALL classical models (known and yet to be known) for M that obey the two general principles of interoperability of information and locality.

CF. violating Bell's inequalities, which does not imply that the system is quantum-mechanical, only that it cannot be described by local hidden variables classical models.

Looking ahead

- What constitutes an information variable in GR?
- What are the 'incompatible' variables in spacetime geometry, according to different models of QG?
- Can other existing witnesses of non-classicality in quantum-gravity models be given the same general, robust and dynamics-independent form as the entanglement witness?
- Is there a quantitative version of the general argument (linking e.g. the degree of incompatibility of variables with the degree of entanglement)?