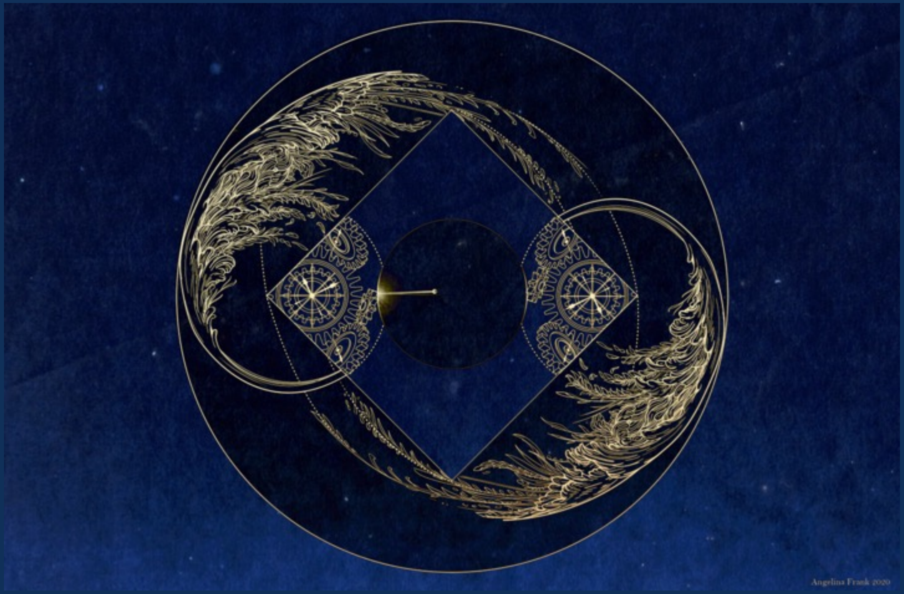
Beyond quantum computing:

The physics of can and can't



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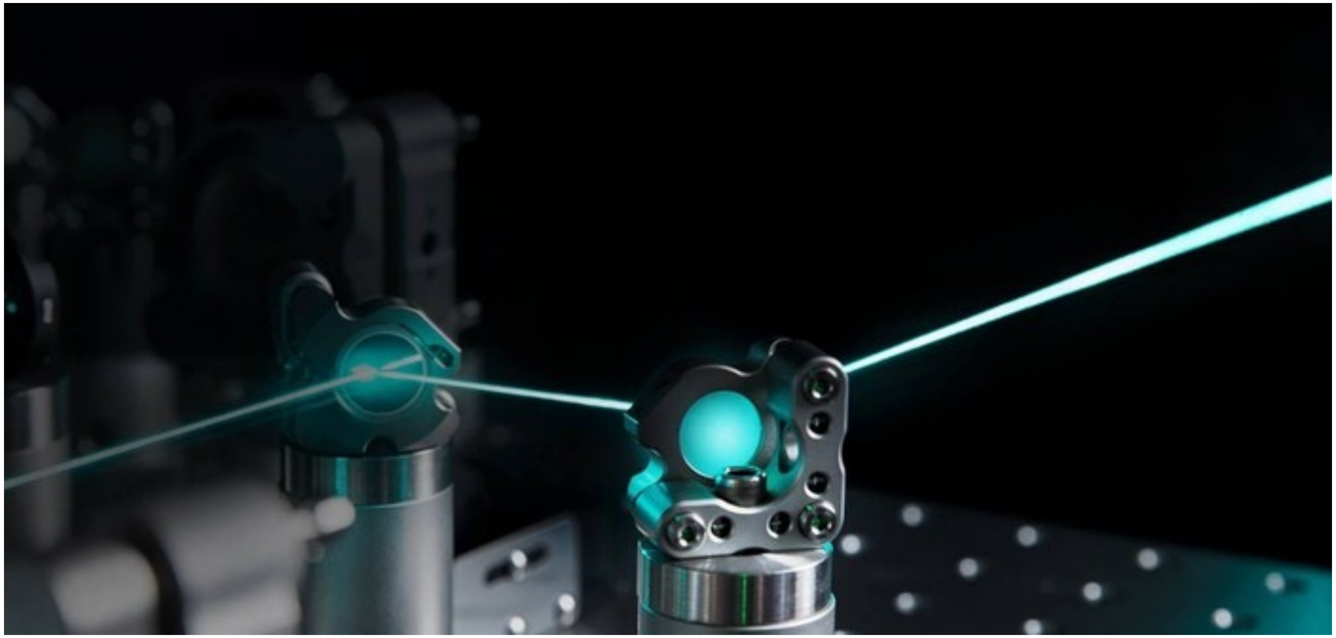
Quantum Computation: an unfinished revolution



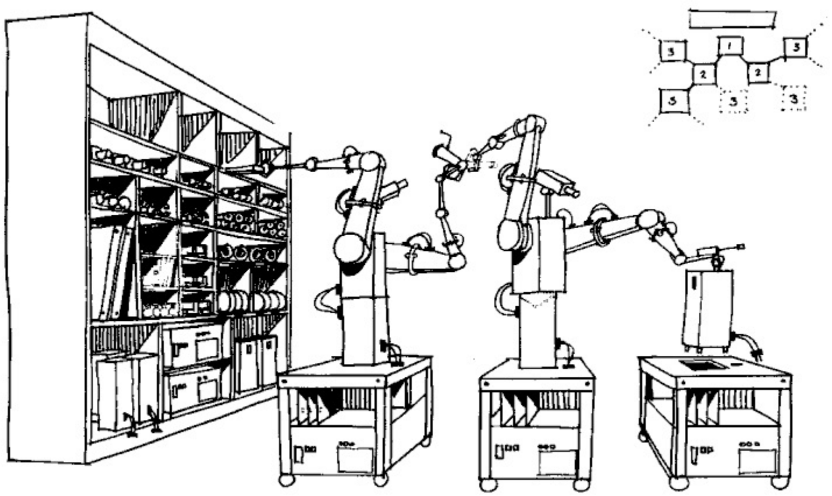
Quantum computation fully relies on quantum theory...but quantum theory may have to be modified (e.g. to incorporate gravity.)

Can we have a "quantum theory of information without quantum theory"?

A universal computer is not the most universal machine

Universal computer: a programmable computer whose repertoire includes all physically possible *computations*.
(A. Turing, D. Deutsch)

But there are tasks that a universal computer cannot perform (e.g. constructing a copy of itself from raw materials)



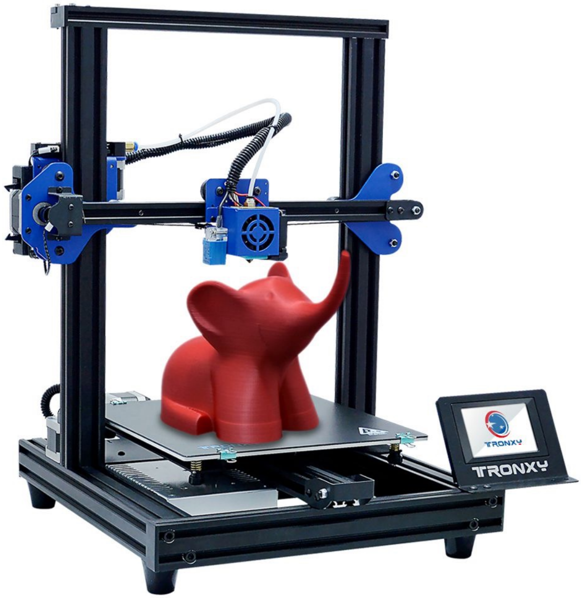
Beyond the universal computer

Universal constructor:

A programmable machine that can perform any task that is physically allowed. (J. von Neumann)

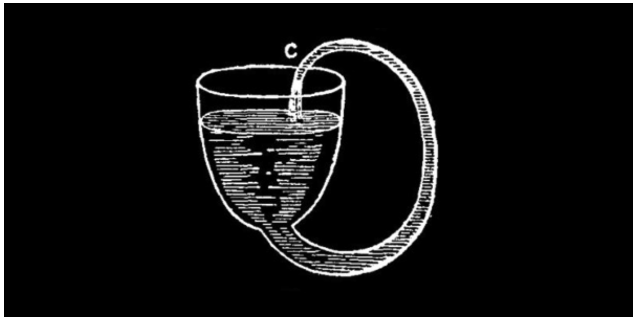
It's a bit like a universal 3d printer.

And it can also reliably create a replica of itself.

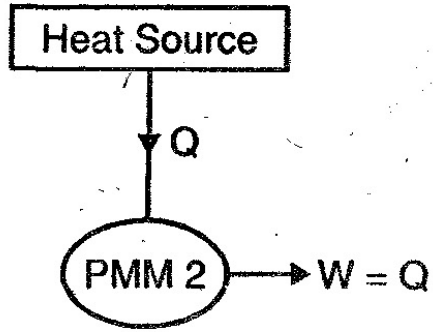


How does one generalise the quantum theory of computation to a theory for the universal (quantum) constructor?

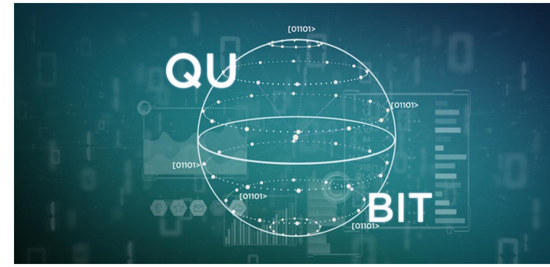
Counterfactual physical principles



Conservation of Energy: a perpetual motion machine is impossible.



2nd Law: it's impossible to convert all heat into useful work.



Heisenberg's uncertainty principle: it's impossible to copy reliably all states of a qubit.

Principles are about what is possible or impossible (counterfactuals) and they are more general than particular laws of motion.

Can this "can/can't" approach provide the foundation for a scale-independent, dynamics-independent extension of quantum information theory?

Constructor Theory's Programme

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

Dynamics and 'initial' conditions are emergent consequences of the principles.

D. Deutsch, Synthese. 190 (18): 4331–4359, 2011.

Constructor Theory plays two roles

- It is a candidate to expand on the theory of quantum computation, and ultimately to deliver the theory of the universal constructor.
- It also provides novel physical principles to understand systems that go beyond current dynamical laws – e.g. by unifying quantum and classical information.

Digression: basics of constructor theory

Assume a theory endowed with a structure including a set of allowed states and a partition into subsystems.

Define an attribute as a set of states, and a task as a set of ordered pairs of input/output attributes:

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

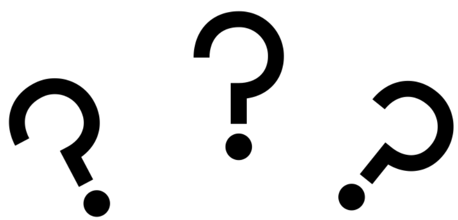
A constructor for a task is a system that, whenever presented with the substrates in one of the input attributes, delivers them in (one of) the corresponding output attributes, and retains the property of doing this again.

$$\text{Input Attributes of } \textbf{Substrates} \overset{\textbf{Constructor}}{\Rightarrow} \text{Output Attributes of } \textbf{Substrates}$$

(Takes its name from von Neumann's universal constructor; cf. catalyst -- any object that can work in a cycle.)

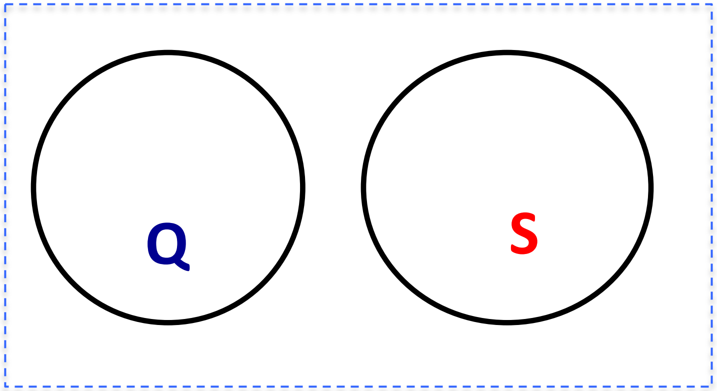
A task is **impossible** if there is a law of physics forbidding its being performed to arbitrarily high accuracy, possible otherwise

Can this new approach have testable consequences?



Application 1: Predictions when a specific dynamics cannot be assumed

Hybrid Systems: a problem beyond dynamics



Questioning the universality of unitary quantum theory:

Is it possible to have a hybrid system composed of a quantum system interacting with one that is fully classical?

‘Totalitarian’ property of quantum theory

“…the quantization of a given system implies also the quantization of any other system to which it can be coupled [...] Quantum theory must immediately be extended to all physical systems, including the gravitational field.”

B. S. DeWitt, in: Gravitation: an introduction to current research, edited by L. Witten (Wiley, New York, 1962)..

Can DeWitt's argument be improved?

- It assumes many dynamics-specific features
- It's desirable to extend it to a more general set of assumptions, holding for quantum theory, but also for other classical theories, and possibly quantum theory's successor.

One can use the Constructor Theory of Information to tackle this problem.

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

Information Media

Information medium: a system with a set X of disjoint attributes on which these tasks are possible: 1) all permutation tasks; and 2) the copy task.

Example: $X = \{0,1\}$

{0 → 1, 1 → 0}
{0 → 0, 1 → 1}

Permutation tasks

{00 → 00, 10 → 11} 'Copy' task

X with these properties is called an 'information variable'

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 information medium of at least the same capacity'〕

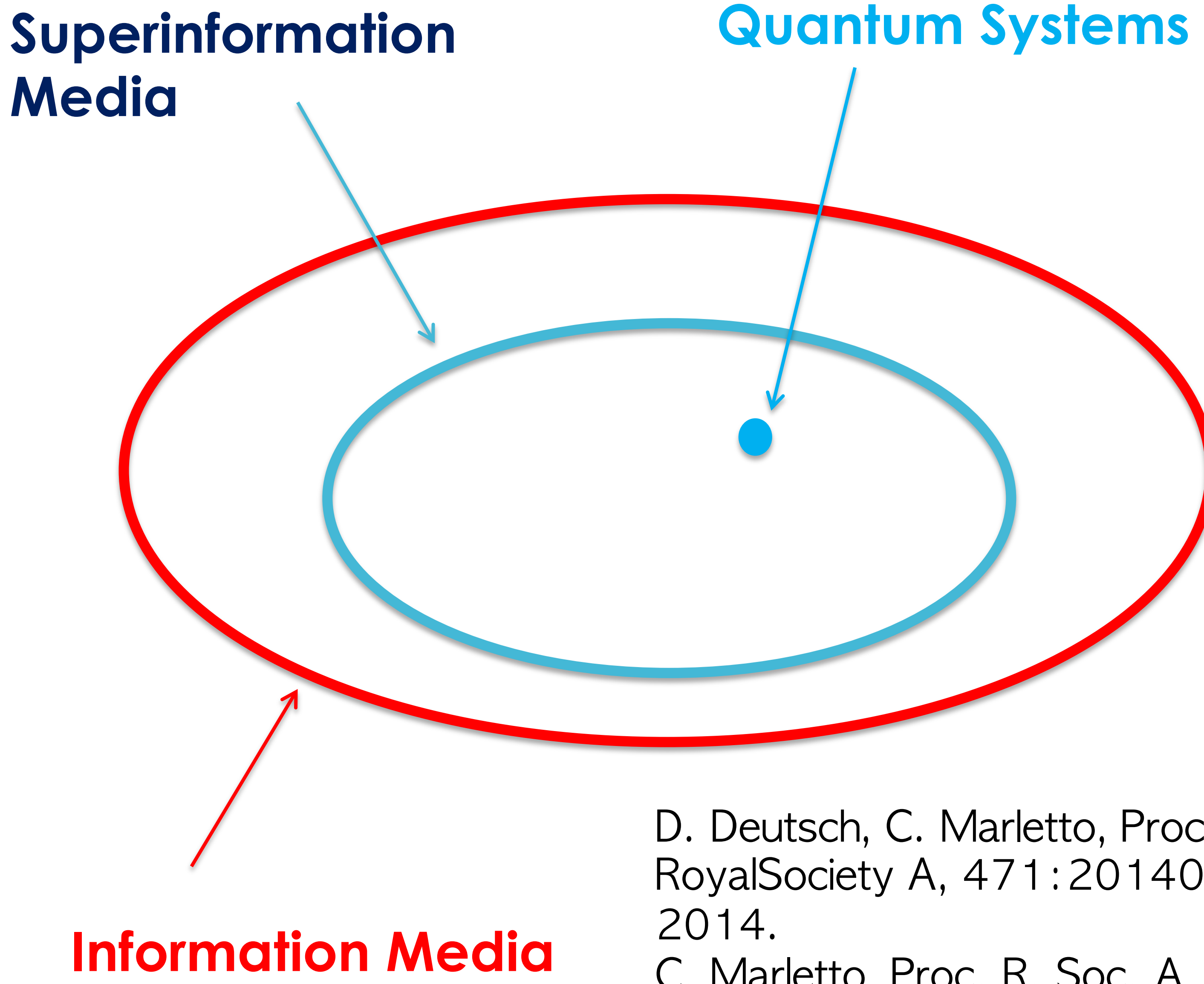
Superinformation Media

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

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

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

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



D. Deutsch, C. Marletto, Proceedings of RoyalSociety A, 471:20140540, 2014.
C. Marletto, Proc. R. Soc. A 472:20150883, 2016.

Defining 'non-classicality' within the superinformation framework

A system is 'non-classical' if it has at least two incompatible variables X and Z, one of which is an information variable.

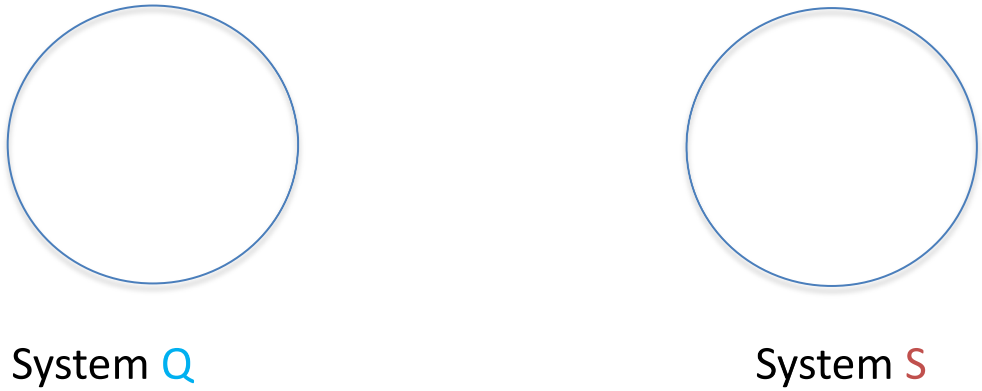
'Incompatible' means that it is impossible that X and Z are copied simultaneously to perfect accuracy (generalises the idea of non-commutativity)

An information-theoretic argument for the totalitarian property of QT

Assume three general principles:

1. Locality (no action at a distance)
2. Interoperability of information
3. 1:1 dynamics

An information-theoretic argument for the totalitarian property of QT

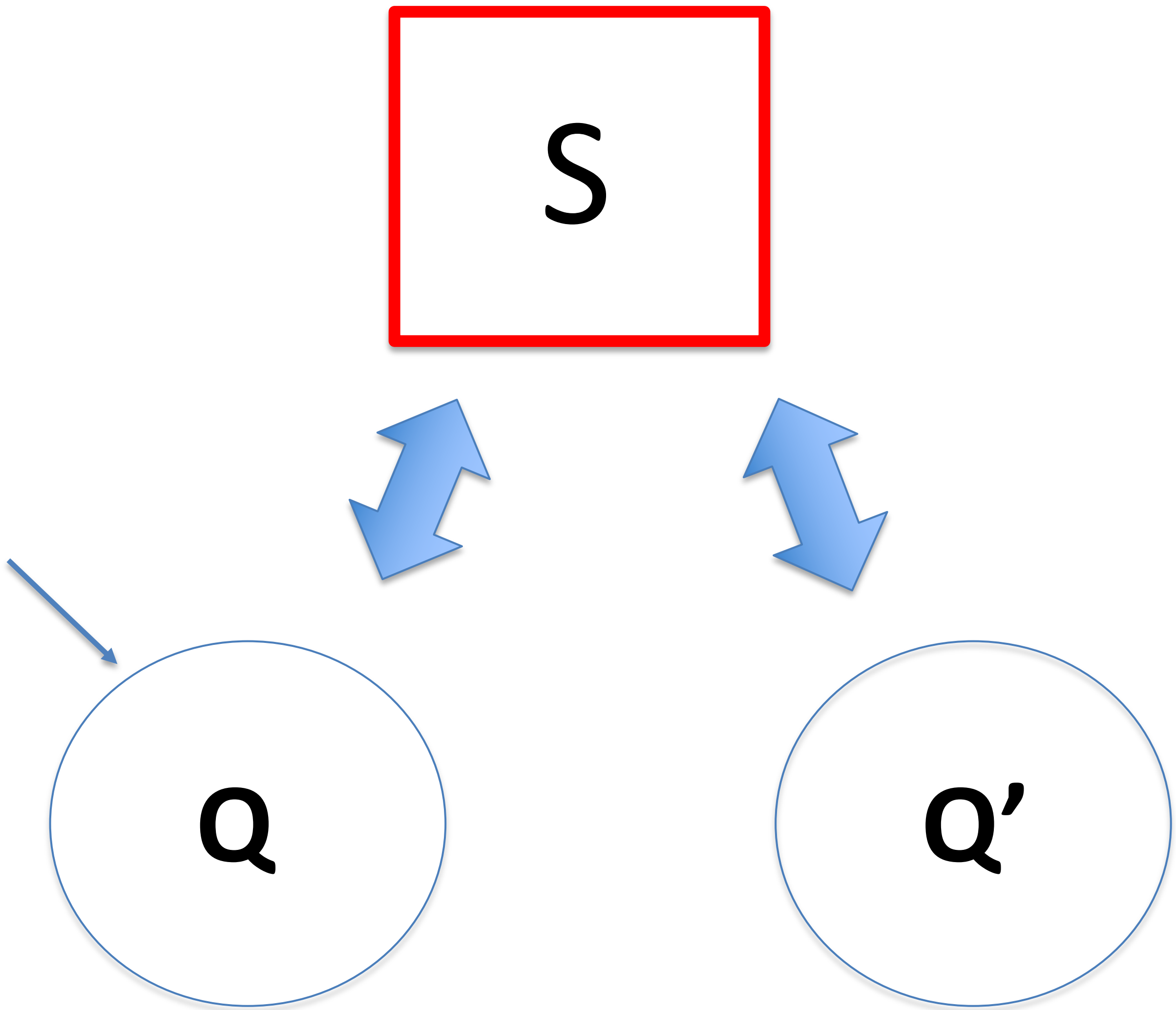


Theorem 1 (Generalisation of DeWitt's theorem): if it is possible to couple a superinformation medium Q with an information medium S via a copy-like interaction, then S must be non-classical.

C. Marletto, V. Vedral, npj Quantum Information 3, 41, 2017.
C. Marletto, V. Vedral, npj Quantum Information 3, 29, 2017.

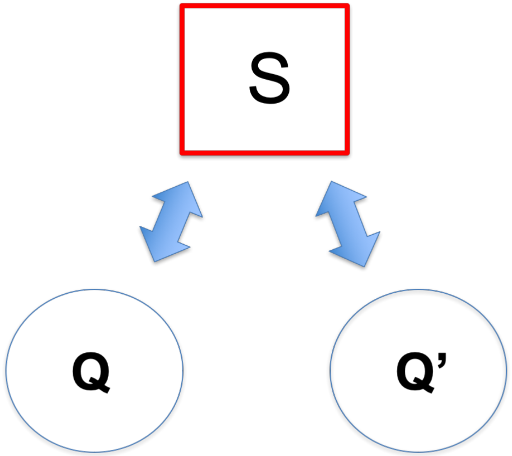
Step two: the totalitarian property suggests a robust witness of non-classicality for system S

Use two 'superinformation media' to extract S's non-classical features !



Assume:

1. Locality
2. Interoperability of information

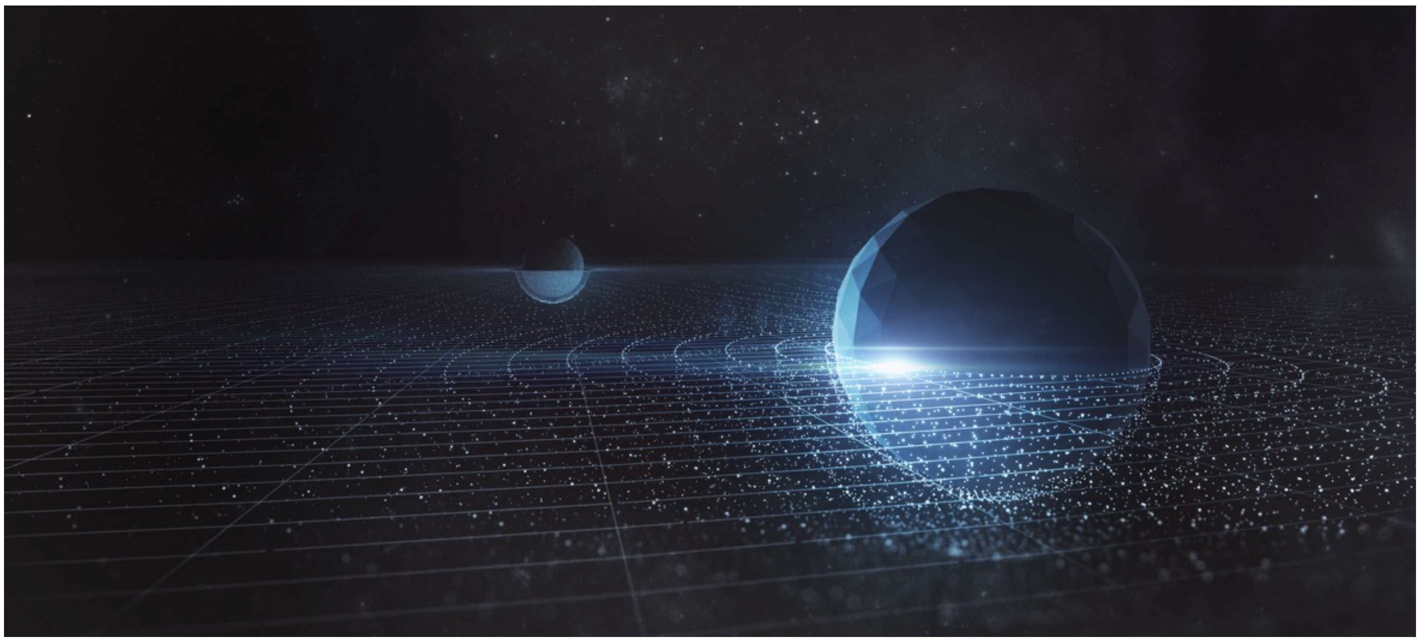


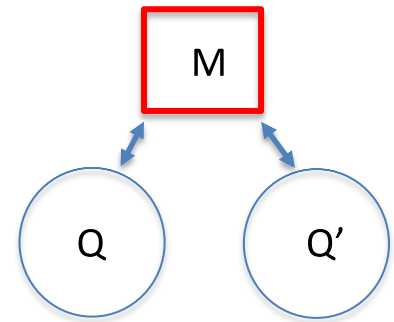
Theorem 2
(Witness of non-classicality)

If **S** can locally mediate entanglement between two superinformation media **Q** and **Q'**, then **S** is non-classical.

C. Marletto, V. Vedral , Phys. Rev. Lett. 119, 2017.
C. Marletto, V. Vedral, *Phys. Rev. D 102, 086012 (2020).*

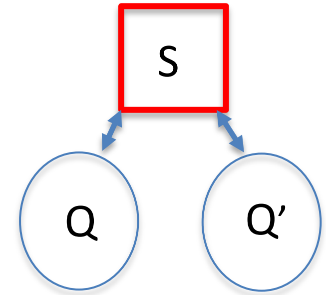
Gravitational Entanglement
as a test of quantum gravity





If gravity can entangle two masses, then gravity must be non-classical.

S. Bose et al., Phys. Rev. Lett. 119, 2017.
C. Marletto, V. Vedral , Phys. Rev. Lett. 119, 2017.



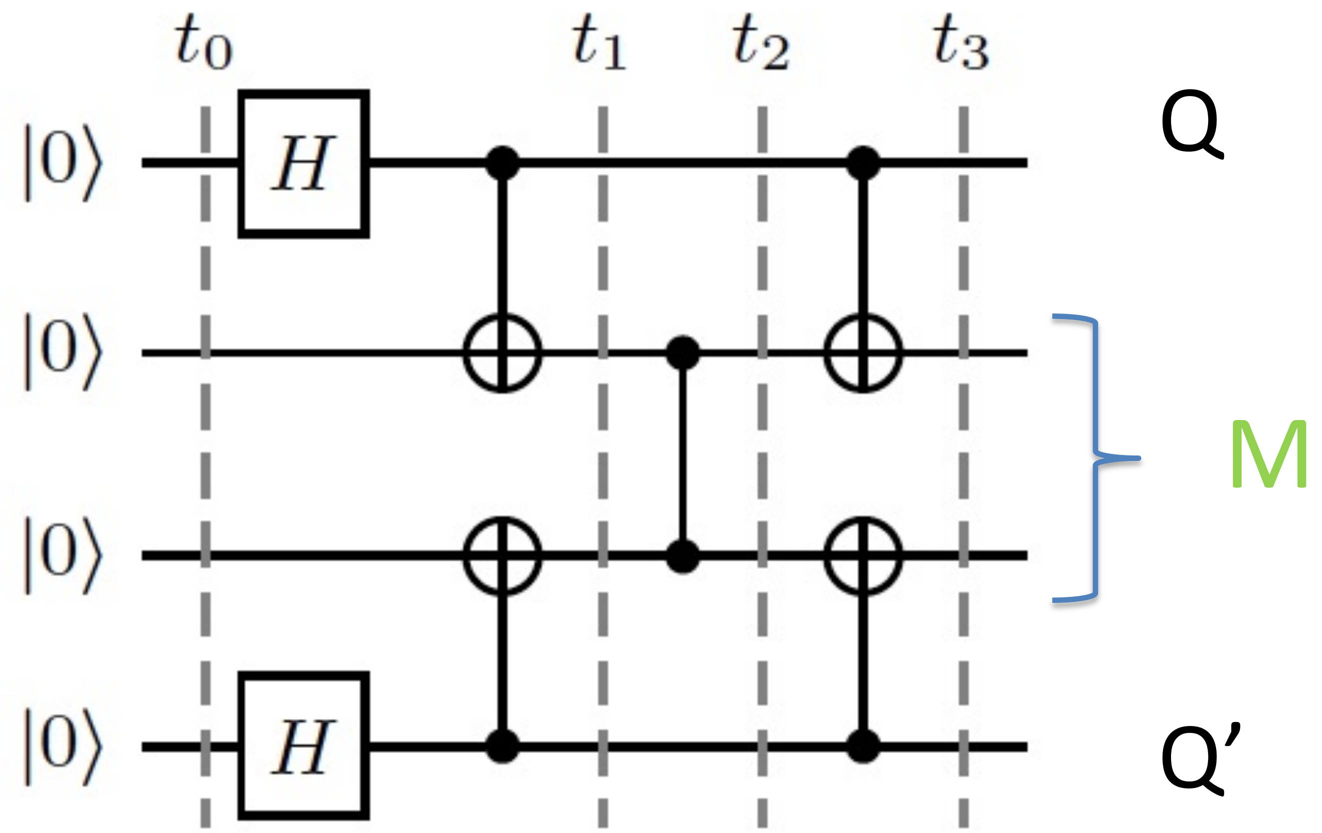
In summary:

1) The principles underlying both theorems are expressed independently of dynamics and scale.

2) The second theorem suggests a class of experiments which, upon observing entanglement, rule out all classical models (known and yet to be known) for **S**, that obey the two general principles of interoperability of information and locality.

Cf. Bell’s inequalities violation, which does not imply that the system is quantum-mechanical, only that it cannot be described by local hidden variables (real-valued) models.

A simulation with NMR qubits



G. Bhole, et al., J. Phys. Commun. 4 (2020).

...and further applications.

- Applications of the non-classicality witnesses to quantum-biology systems

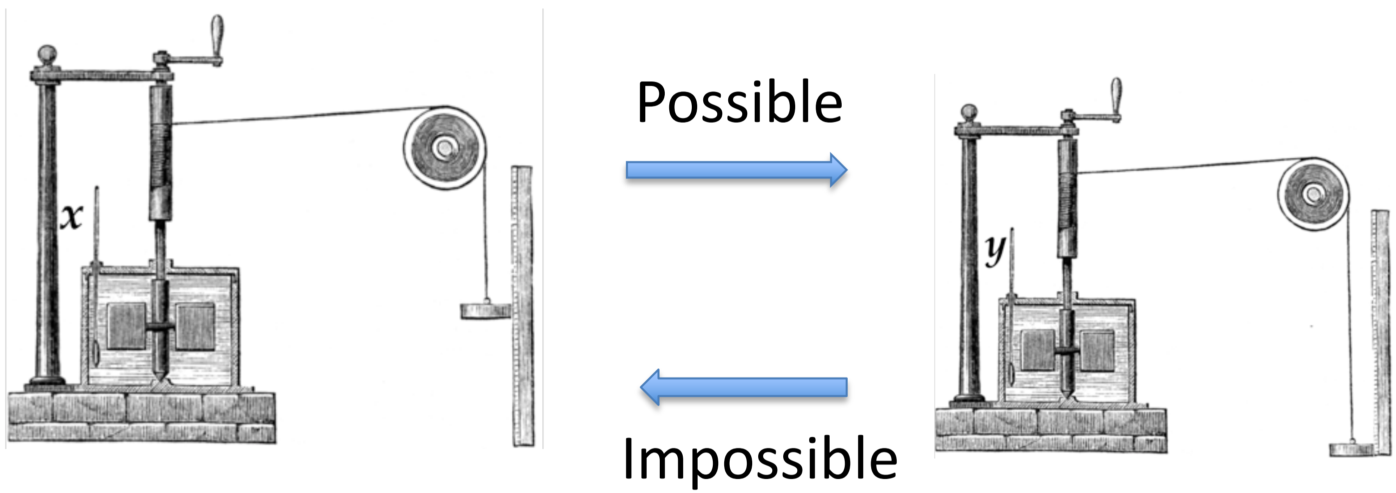
T. Krisnanda et al., npj Quantum Information, 4, 60, 2018.

- Design of experiments/simulations to test non-classicality in general hybrid systems

C. Marletto *et al.*, Nature Communications, 10, **182**, 2019.
C. Marletto *et al.*, to appear in Science Advances, 2021.

Application 2: irreversibility under time-reversal symmetric laws

An instance of the second law is based on the impossibility of certain 'constructors':



(State y has higher temperature than state x)

Constructor-based irreversibility

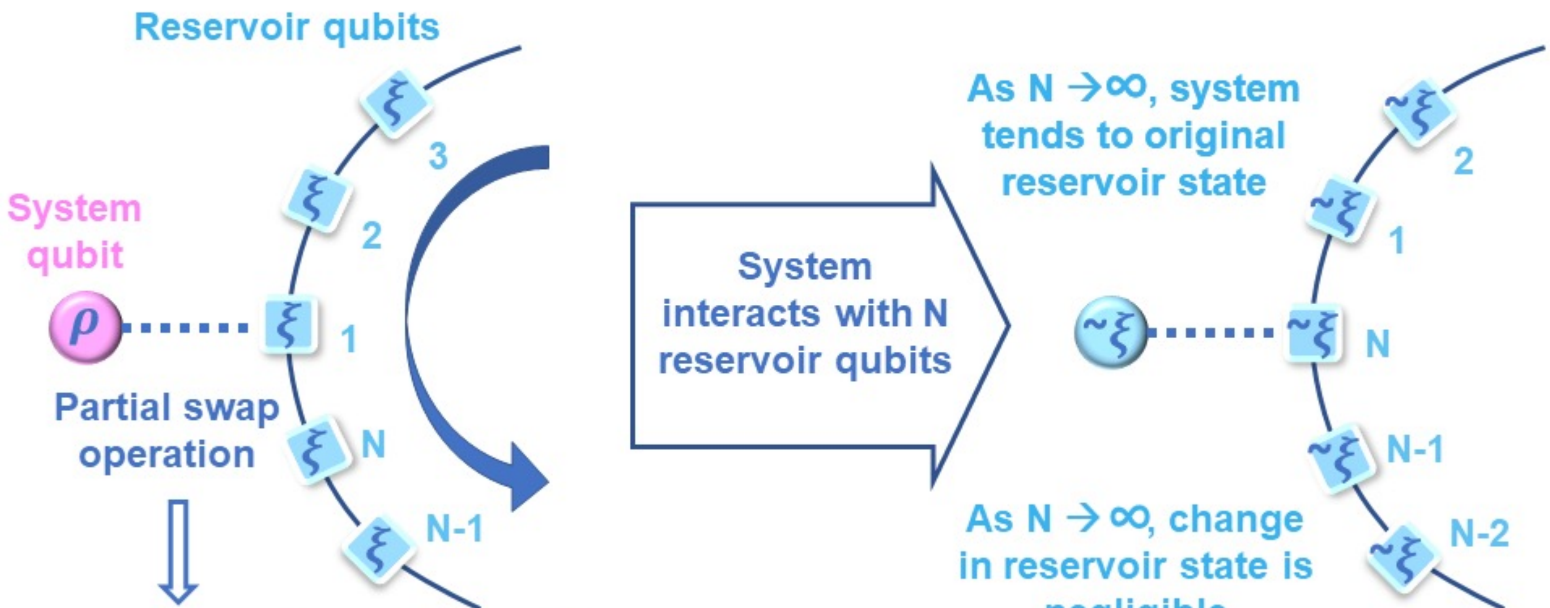
A task {X→Y} is possible, its transpose {Y→X} is not.

Is this 'constructor-based' irreversibility compatible with time-reversal symmetric laws?

C. Marletto, On the relation between cloning and deterministic work extraction, arXiv:2009.04588, 2021.

A toy model: Homogeneization machine

Consider a task defined on a qubit T={ϱ → ξ}



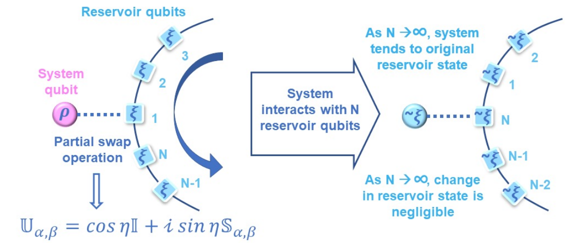
$$\mathbb{U}_{\alpha,\beta} = \cos\eta\,\mathbb{I} + i\,\sin\eta\,\mathbb{S}_{\alpha,\beta}$$

(Image courtesy of M. Violaris)

M. Ziman *et al.* , *Quantum homogeneization*, quant-ph/0110164, 2001.
V. Scarani *et al., Thermalizing quantum machines, Phys. Rev. Lett., 88*, 097905, 2002.

A toy model for constructor-based irreversibility

Consider T={Pure state→ Maximally mixed state}



- 1) The quantum homogeneizer is a constructor for the task T, of transforming a pure state into a maximally mixed state.

(The task T is possible)

- 2) But it is *not a constructor* for the transpose task, of transforming a maximally mixed state into a pure state.

(The transpose task *need not be* possible, even under time-reversal symmetric laws).

C. Marletto, et al. https://arxiv.org/abs/2009.14649, *to appear in PRL, 2022.*

In summary

- the principles of constructor theory (CT) can be useful to make predictions when the dynamics is not fully known/is intractable, because they are more general than any specific dynamics.

- Unlike classical and quantum statistical mechanics, CT's principles are scale-independent.

- CT promises for a unification of the quantum theory of computation, computational biology and thermodynamics in a general theory of the universal constructor.