The 2022 Nobel prize in Physics

And why it rules out hidden variables in quantum mechanics!

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Synopsis

What is classical mechanics?

What is Quantum mechanics?

Uncertainty in classical and quantum mechanics

What are hidden variables?

Entanglement and classical correlations

What do EPR experiments say?

What do Bell type inequalities and their extensions really say?

"Simulating physics with computers"

there's no real problem. It has not yet become obvious to me that there's no real problem. I cannot define the real problem, therefore I suspect there's no real problem, but I'm note sure there's no real problem. So that's why I like

An inspiration: S.Coleman
https://youtu.be/EtyNMlXN-sw
2011.12671 And also comments from Peter Morgan (eg 2201.04667)

A coincise definition of Classical mechanics

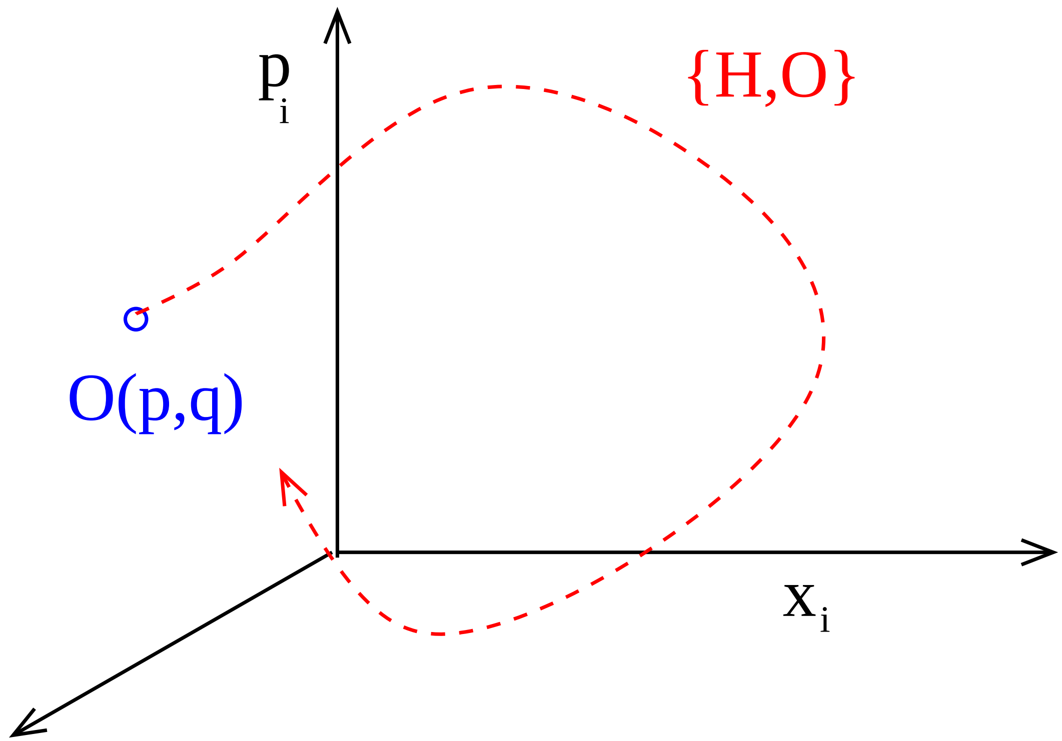
Observables are functions $f(q_i, p_i)$ generally of two variables per degree of freedom (position and momentum)

$$\{p_i, x_i\} = \delta_{ij} \quad , \quad \{p_i, p_j\} = \{x_i, x_j\} = 0$$

$$\{A, B\} = \sum_i \left(\frac{\partial A}{\partial x_i}\frac{\partial B}{\partial p_i} - \frac{\partial B}{\partial x_i}\frac{\partial A}{\partial p_i} \right)$$

Dynamics is given by the Hamiltonian $H(x, p)$. For any function $O(x, p)$ and $\partial H/\partial t = 0$

$$\dot{O} = \{H, O\}$$



The picture: A configuration of a system, and any observable O can be thought of as a point in a 3N-dimensional space (N is the number of DoFs) which “is transported” via a flow-type equation. For non-integrable systems this equation is highly aperiodic

Uncertainty of generic O codified in a Probability density function $\rho(x,p)$

$$\dot{\rho}(x,p) = \{H, \rho(x,p)\} \quad , \quad O = \int O(x,p)\rho(x,p)dxdp$$

Propagation of uncertainty generally non-linear, for bounded chaotic systems $\rho(x,p,t)$ becomes more "fractal" with time, until until "ergodic" limit where

$$\langle O \rangle_{time} \simeq \int O(x,p)\rho_{eq}(x,p)dxdp \quad , \quad \int_t^{t+\Delta t} \dot{\rho}_{eq}(x,p) = 0$$

And statistical mechanics follows . Hypothetical $\rho(x,p) = \delta(x - x_0, p - p_0)$ deterministic Laplace's demon!

All well and good until quantum mechanics

Quantization of energy levels and incompatiblity between electron-photon scattering (width of energy levels,"event by event" violation of conservation laws

Photoelectric effect,black body and ambiguity of wave particle picture

Eventually, via many models (Bohr's semiclassical Quantization, Heisenberg Matrices,Schrodinger wave mechanics) forced us to adapt a radically different paradigm: Observables are not always best represented by numbers, and their evolution by number-valued functions

The basics: Quantum mechanics (Heisenberg)

Observables represented by operators that do not necessarily commute

$$A, B \to \hat{A}, \hat{B} \quad , \quad \left[\hat{A}, \hat{B}\right] = \hat{A}\hat{B} - \hat{B}\hat{A} \neq 0$$

So measuring A after B not the same as measuring B after A !

In particular $[\hat{q}, \hat{p}] = i$

The Hamiltonian continues to exist and dictate dynamics but is now an Operator

$$\frac{d}{dt}\hat{A} = i\left[\hat{A}, \hat{H}\right]$$

What does this mean?!?!?!

An obvious consequence: inherent probabilistic dynamics

$$\frac{d}{dt}\hat{A}^n = i\left[\hat{A}^n,\hat{H}\right] \neq \left(i\left[\hat{A},\hat{H}\right]\right)^n \equiv \left(\frac{d}{dt}\hat{A}\right)^n$$

Way to make sense of the above: apply to ensemble of identical measurements $\langle ... \rangle$

$$\frac{d}{dt}\left\langle \hat{A}^n \right\rangle = i\left\langle \left[\hat{A}^n,\hat{H}\right]\right\rangle$$

Since for probabilistic systems generally $\langle A^n \rangle \neq \langle A \rangle^n$ this simply means non-commutativity implies measurements always probabilistic unless $\left[\hat{A},\hat{H}\right] = 0 \Rightarrow \frac{d}{dt}\left\langle \hat{A}^n \right\rangle = 0$ (and $\hat{B}$, $\left[\hat{A},\hat{B}\right] \neq 0$ unmeasured)

But how to accommodate this with some common-sense observations?

All measurements can be performed in any sequence

All measurements will give some answer event by event?

All repeated measurements give same answer

All measurements are real . Where does "i" go?

The "trick" is to specify $\hat{O}$ of observable quantities to be hermitian (if system is closed) Hermitianness has quite a few consequences.... (Real Eigenvalues,completeness,...)

There exists a density operator $\hat{\rho}$

$$\langle O \rangle = \mathrm{Tr}\left(\hat{O}\hat{\rho}\right) \quad , \quad \mathrm{Tr}\left[\hat{\rho}\right] = 1$$

The Eigenbasis of any operator $\hat{O}_1$ has a complete set of Eigenvectors in any other operator $\hat{O}_2$. There exists a density operator

$$\hat{\rho} = c_j^* c_i \left| j \right\rangle \left\langle i \right| \quad , \quad \forall \left| A \right\rangle_{O_1} \exists c_i \quad , \quad \left| A \right\rangle_{O_1} = \sum_i c_i \left| i \right\rangle_{O_2}$$

And Eigenvalues of Hermitian operators real

So assuming that at observation of the eigenvalue of $\left| j \right\rangle$ density matrix becomes $\hat{\rho} \to \left| j \right\rangle \left\langle j \right|$ gives "recipe" for sampling probability. Gleason's theorem: Hermiticity implies that

$$\left| j \right\rangle = \sum_i c_{ij} \left| i \right\rangle \quad , \quad P\left(i | j \right) = \left| c_{ij} \right|^2$$

The good news (SHO) Provided coordinates $\hat{X}, \hat{P}$ s.t.

$$\hat{H} = \frac{1}{2}\left(\hat{X}^2 + \hat{P}^2\right) \quad , \quad \left[\hat{X}, \hat{P}\right] = i$$

$$\hat{\rho} = \hat{a}^{+n} \left|0\right\rangle \left\langle 0\right| \hat{a}^m \quad , \quad \hat{a} = \hat{X} + i\hat{P} \quad , \quad \left|0\right\rangle \sim e^{-X^2}$$

Any initial sensible PDF of any observable integrable.

The great news all features motivating QM emerge naturally

hydrogen atom "hidden" SHO because of Laplace-Runge-Lenz

Also photon gas/free fields - ∞ SHOs why we study them so much!

The bad news Groenwold-Van Hove thm: no systematic way to do this for most systems That's why we do SHOs and perturbation theory!

Summarizing, Classical Uncertainity comes from lack of knowledge hence it is Bayesian-probabilistic. Always possible to construct f, ρ, O

$$f(O_{1,2}, t) = \int dx dp \rho(x,p,t) O_{1,2}(x,p,t) \quad , \quad \begin{array}{c} \dot{O} = \{O, H\} \\ \dot{\rho} = \{\rho, H\} \end{array}$$

Quantum uncertainity comes from non-commutativity

$$\langle O_{1,2} \rangle = \mathrm{Tr}\left[\hat{\rho}\hat{O}_{1,2}\right] \quad , \quad \begin{array}{c} \frac{d}{dt}\hat{O}_{1,2} = \left[\hat{O}_{1,2}, \hat{H}\right] \\ \frac{d}{dt}\hat{\rho} = \left[\hat{\rho}, \hat{H}\right] \end{array}$$

NB open quantum systems have both uncertainities!

Big difference If $\left[\hat{O}_1, \hat{O}_2\right] \neq 0$ a decomposition of the type

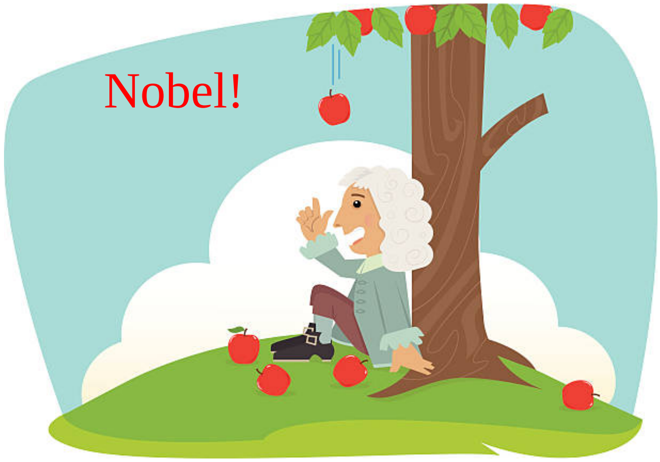
$$f(O_{1,2}, t) = \int dx dp \rho(x, p, t) O_{1,2}(x, p, t)$$

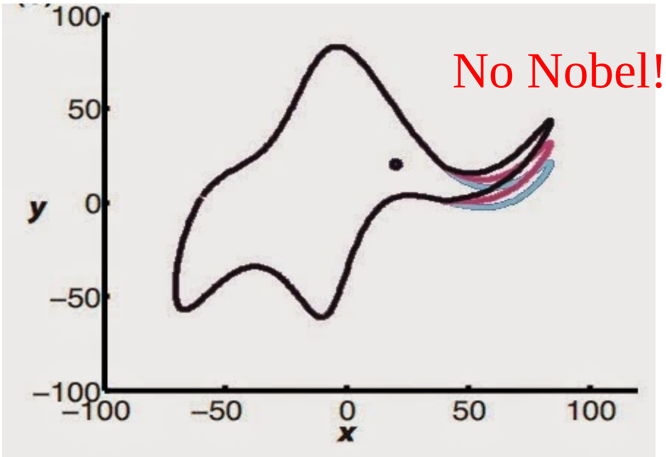
impossible because measuring O_1 changes O_2

Unless (Hidden variables) What if one adds variables

$$f(O_{1,2}, t) = \int dx dp d\lambda_{1,...,N} \rho\left(x, p, t, \lambda_{1,...,N}\right) O_{1,2}\left(x, p, t, \lambda_{1,...,N}\right)$$

for some new unknown $\lambda_{1...N}$ manages to mimic quantum mechanics? Is this possible? What exactly do Aspect,Clauser and Zeilinger say?





What distinguishes great (Nobel-worthy) from ordinary since is a general,crisp path between axiom,theory and experiment!
What we described in the beginning reduces to very crisp axiom difference.

$$f(O_{1,2},t) = \int dx dp d\lambda_i \rho\left(x,p,t,\lambda_i\right) O_{1,2}\left(x,p,t,\lambda_i\right) \quad \text{vs} \quad \left[\hat{O}_1,\hat{O}_2\right] \neq 0$$

Can it be translated into data? first, let us elaborate on what is at stake!

How do we "interpret" quantum mechanics?

Copenhagen/Bayesian Wavefunction is "epistemic"/"statistical", represents our knowledge of the system

Many worlds/Relative state Wavefunction continues to exist, observer also "a wavefunction", but we see subsystem so projections non-linear

Relational Operators represent object's relation to other objects

Hidden variables world "classical", invisible DoFs mimic quantumness

- fixes discomfort with quantum world (operators,complex numbers,uncertainity,collapse,...), no measurement problem
- Restores primacy of configuration space
- beyond QM? Ghirardi Rimini Weber,objective reduction,gravity...

de Broglie-Bohm theory Schrodinger's equation decomposed into continuity

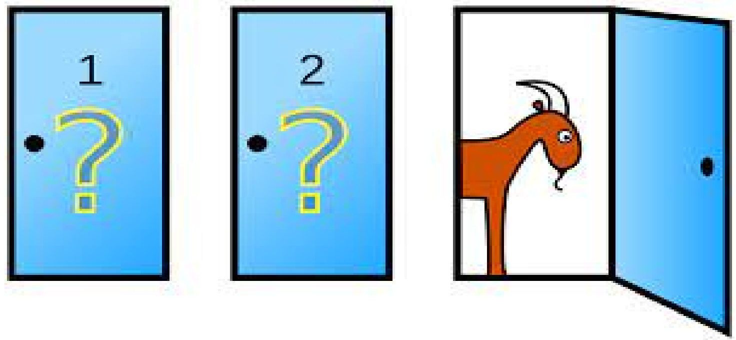
$$\psi = Re^{iS} \quad , \qquad \underbrace{\dot{\rho}}_{R^2} + \nabla(\underbrace{\rho}_{m^{-1}\nabla S} v) = 0$$

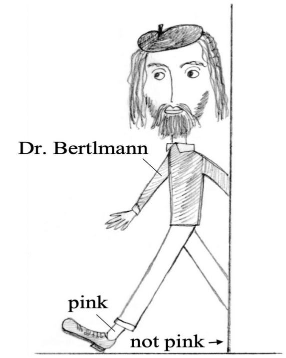
and classical type energy conservation with "extra" quantum potential

$$-\dot{S} = \frac{(\nabla S)^2}{2m} + V(x) - \underbrace{\frac{\nabla^2 R}{2mR}}_{Quantum \quad potential}$$

Motivates search of "hidden DoFs" from which QM emerges

Loses "symmetry" between observable bases
"Collapse" non-linear. Stimulated a lot of interest in hidden variables
(Bohm is the closest "Brazilian" to winning the Nobel prize, for this!)





IMHO (Bayesian/relational/relative state)

- Operators Makes sense from a <u>relational</u> point of view
  Asking "what's a system's state" independently from "how I interact with it" as silly as asking "where's the real 0 on the cartesian plane"?
  Equivalently (?) measurement $\equiv$ interaction $\equiv$ disturbance?
  And Common sense requirements lead to hermiticity

- "Wave function collapse" is the same as Monty Hall problem , "many worlds" is the same as frequentism?

What do you know 2x + 7 is equal to 15," he says

"and youre trying to find out what x is."

I says, "you mean 4." He says,

"Yeah, but you did it with arithmetic, you have to do it by algebra,"

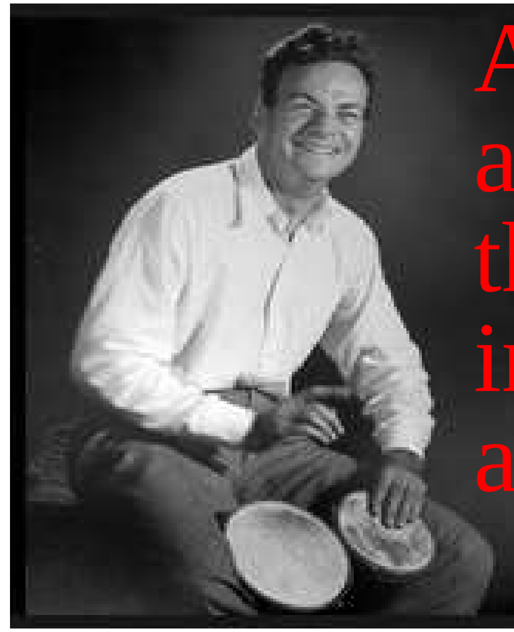
and thats why my cousin was never able to do algebra,

I learnt algebra fortunately ... knowing the

whole idea was to find out what x was and it didnt make any difference

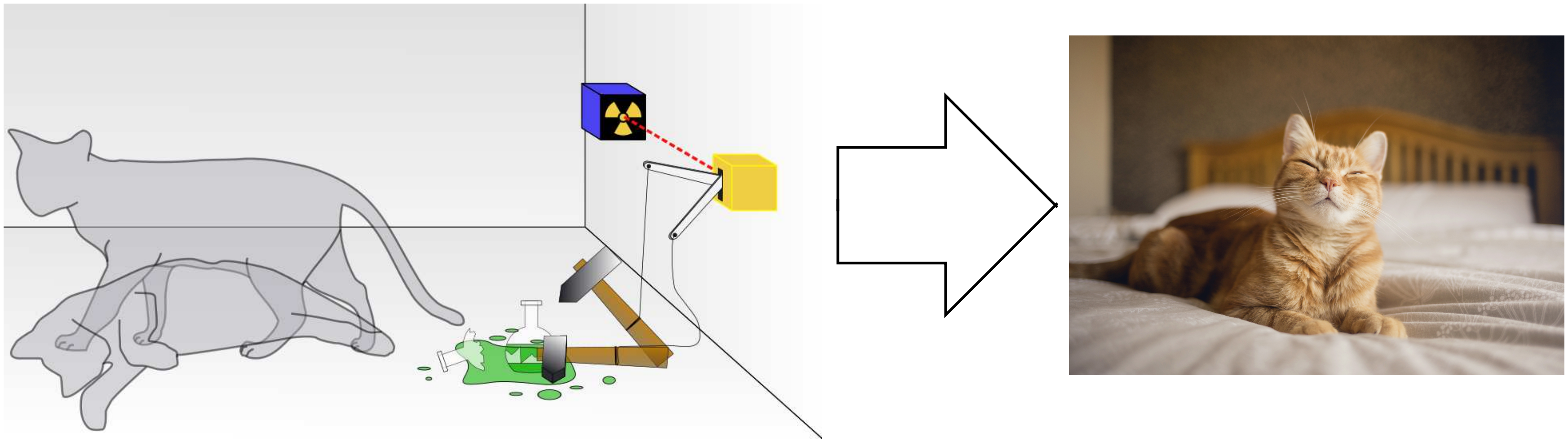
how you did it theres no such thing as you know, you do it by

arithmetic, you do it by algebra



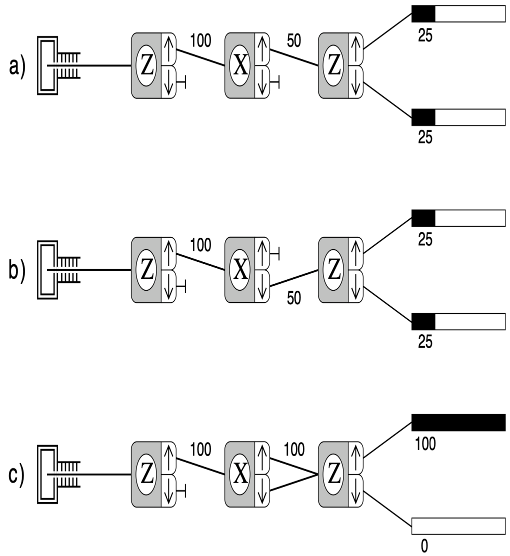
Algebra is a false thing they invented at school

The key is not confusing physics (lack of commutation,probability) with formalism (wavefunctions,operators,eigenstates etc only exist in our heads! $\langle X^n \rangle$ exist in the lab!)



The puzzle is to make a “fundamentally quantum world appear classical”, not the other way around ! In other words the measurement problem is why do quantum descriptions of “detectors” (big objects with $N \gg 1$) coincide with classical ones? Not fully clear,but mixture of Gronwold-Van Hove and opennes!

but many people disagree so hidden variables very popular! What can we say about this without knowing anything about these λ s.



Stern Gerlach
Quantum measurements
"add" and "destroy"
uncertainty

The “dynamical” nature of uncertainity tested thoroughly with stern-Gerlach setups, taking advantage of the simple commutation rules of spin

$$[\hat{s}_i, \hat{s}_j] = i\epsilon_{ijk}\hat{s}_k \quad , \quad e.g. [\hat{s}_x, \hat{s}_y] = i\hat{s}_z$$

Can such uncertainities be encoded in hidden variables?

It turns out we can say something very general:entanglement

Key insight we can separate a system T into subsystems $1, 2$

Classical mechanics: Just use $X, x = x_1 \pm x_2, Q, q = q_1 \pm q_2$ but quantum

$$\hat{O}_T = \hat{O}_1 + \hat{O}_2 \quad , \quad \hat{\rho}_T = \hat{\rho}_1 \otimes \hat{\rho}_2$$

EPR : "We take two particles with momentum conservation, measure position in one and momentum in the other... But by momentum conservation means we know position of the first particle, so we violated the uncertainity principle. Or "something" tells particle 1 at arbitrary distance what the momentum of particle 2 is? Action at a distance?

Bartlemann's socks Bartlemann always wears socks of different color! If you see one sock as "red" you know the other sock is "blue". Is this similar?

A bit more technical: What if

$$\hat{O}_T = \hat{O}_1 + \hat{O}_2 \quad , \quad \hat{\rho}_T = \hat{\rho}_1 \otimes \hat{\rho}_2 \quad , \quad \langle O^n \rangle_{T,1,2} = \underbrace{\mathrm{Tr}\left[\hat{\rho}_T \times \hat{O}^n_{1,2,T}\right]}_{\mathrm{Matrix\ \ product+Trace}}$$

$$\left[\hat{O}_T, \hat{H}\right] = 0 \quad , \quad \left[\hat{O}_{1,2}, \hat{H}\right] \neq 0$$

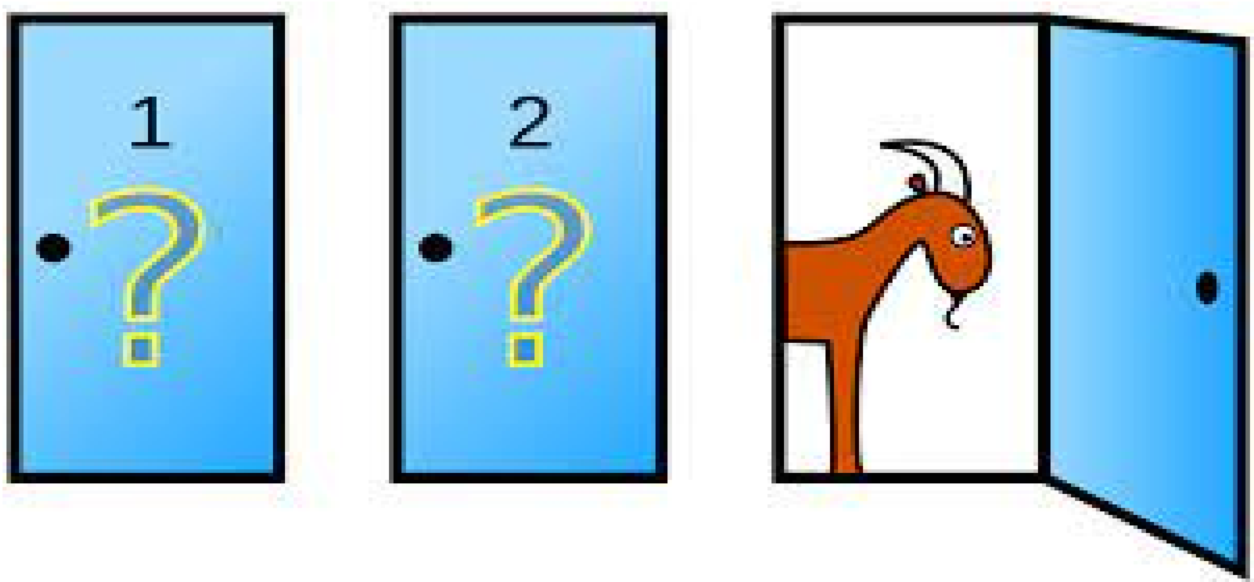
We can reduce uncertainity of $\hat{O}_T$ arbitrarily without affecting the uncertainity of $\hat{O}_{1,2}$. This is generally incompatible with "classical" Bayesian probability where

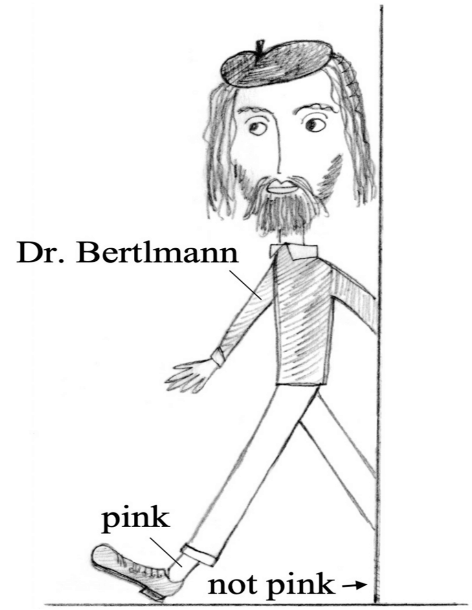
$$P(O) = \int dO_1 dO_2 P(O_1, O_2) \delta\left(O_1 + O_2 - O\right)$$

so

$$P(O) \to \delta(O) \quad , \quad \exists X_{1,2}(O_1, O_2) \;\; P(X_{1,2}) \to \delta(X_{1,2})$$

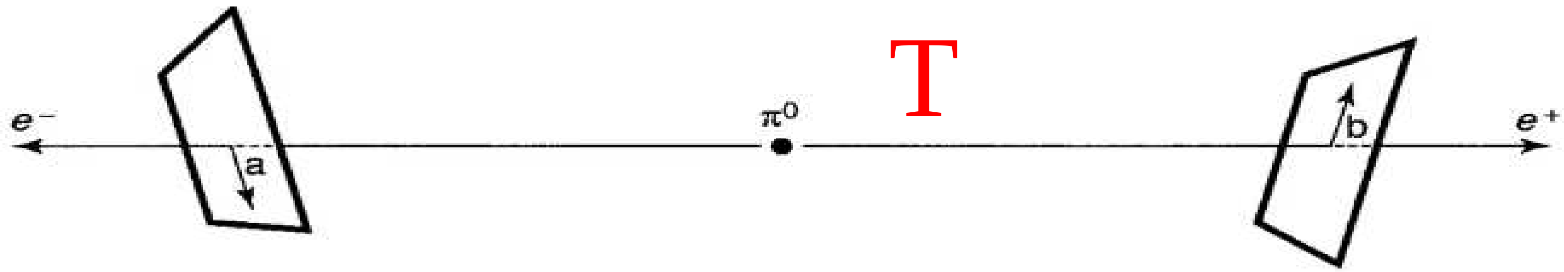
Entanglement vs Bartlemann's socks





Classical correlations are lost when you destroy information. Quantum correlations persist while separate ensembles prepared using non-commuting operators are probed.

A particularly simple realization

1  2

$$\hat{O} = \hat{S}^{x,y,z}_{T,1,2} \quad , \quad \left\langle \hat{S}^z_1 \right\rangle = -\left\langle \hat{S}^z_2 \right\rangle \quad , \quad But \ \left\langle \left(\hat{S}^z_1 \hat{S}^y_2 \right)^2 \right\rangle \sim \frac{1}{2}$$

since

$$\left[S^{1,2,T}_x , S^{1,2,T}_y \right] = S^{1,2,T}_z \quad , \quad \left[S^1_x , S^2_y \right] = \left[S^T_{x,y,z} , \hat{H} \right] = 0$$

What if "z" chosen <u>after</u> T particle decays?

$$\Delta = 2\left(\left\langle \hat{S}^1_z \hat{S}^2_z \right\rangle + \left\langle \hat{S}^1_z \hat{S}^2_x \right\rangle + \left\langle \hat{S}^1_x \hat{S}^2_z \right\rangle - \left\langle \hat{S}^1_x \hat{S}^2_x \right\rangle\right)$$

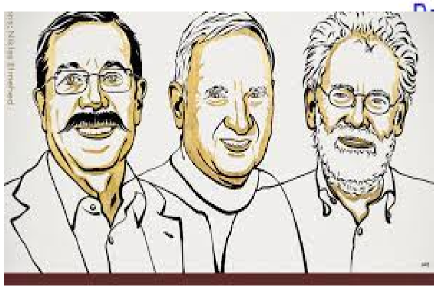
Any local hidden variable theory predicts $\Delta \leq 2$
Provided decision of whether $S_{x,z}$ are measured made at spacelike separations. Because $\left\langle \hat{S}_1 \hat{S}_2 \right\rangle \to \langle s_1 \rangle \langle s_2 \rangle$ and

$$\left(\underbrace{s^1_x + s^1_z}_{=0 \quad if \quad s_x = -s_z} \right) s^2_x + \left(\underbrace{s^2_x - s^2_z}_{=0 \quad if \quad s_x = s_z} \right) s^1_z$$

Can decide if to measure s_x or s_z electronically and instantaneusly!
NB: Classical statistical independence violations are correlations, here extra quantum term increases fluctuations to $\Delta = 2\sqrt{2}$

Ultra-bright source of polarization-entangled photons

1998



aul G. Kwiat (1), Edo Waks (1 and 2), Andrew G. White (1), Ian Appelbaum (1 and 3), Philippe H. Eberhard (4) ((1) Physics Division, P-23, Los amos National Laboratory, (2) Ginzton Laboratory, Stanford University, (3) Physics Dept., M.I.T., (4) Lawrence Berkeley Laboratory)

Using the process of spontaneous parametric down conversion in a novel two-crystal geometry, one can generate a source of polarization-entangled photon pairs which is orders of magnitude brighter than previous sources. We have measured a high level of entanglement between photons emitted over a relatively large collection angle, and over a 10-nm bandwidth. As a demonstration of the source intensity, we obtained a 242-σ violation of Bell's inequalities in less than three minutes.

Quantum mechanics predicts $\Delta = 2\sqrt{2} > 2$
Because for singlet state

$$\sqrt{2}\left(\underbrace{\left\langle \hat{S}^1_z \hat{S}^2_z \right\rangle}_{=1} + \underbrace{\left\langle \hat{S}^1_z \hat{S}^2_x \right\rangle}_{=1} + \underbrace{\left\langle \hat{S}^1_x \hat{S}^2_z \right\rangle}_{=1} - \underbrace{\left\langle \hat{S}^1_x \hat{S}^2_x \right\rangle}_{=-1}\right) = 2\sqrt{2}$$

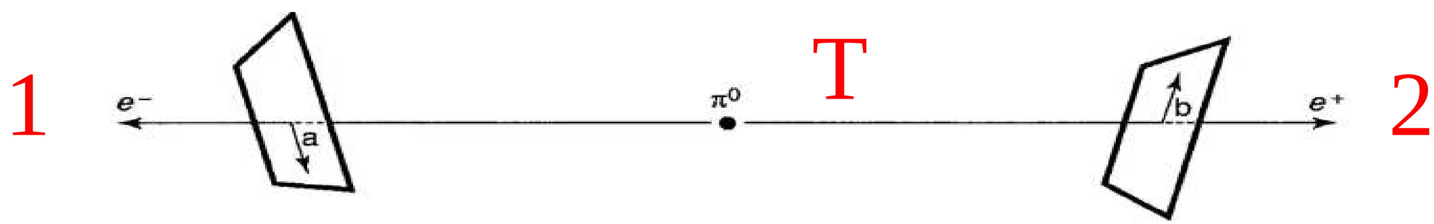
Experiment confirms, <u>242σ</u>, multiple setups

Way out: Non-local hidden variables?

$$f(O_{1,2},t) = \int dxdpd\lambda_{1,\ldots,N} f\left(x,p,t,\lambda_{1,\ldots,N}\right) O_{1,2}\left(x,p,t,\lambda_{1,\ldots,N}\right)$$

$$\langle \lambda_1(x,t)\lambda_2(x,t-\pm\delta)\rangle - \langle \lambda_1(x,t)\rangle \langle \lambda_2(x,t\pm\delta)\rangle \neq 0 \quad , \quad -\infty < \delta < \infty$$

Correlations can travel instantaneously, backward in time etc.



1,2 choice influences T instantaneusly

A parenthesis

Quantum mechanics is "non-local" but causal

$$\sqrt{2}\left(\underbrace{\left\langle \hat{S}_z^1 \hat{S}_z^2 \right\rangle}_{=1} + \underbrace{\left\langle \hat{S}_z^1 \hat{S}_x^2 \right\rangle}_{=1} + \underbrace{\left\langle \hat{S}_x^1 \hat{S}_z^2 \right\rangle}_{=1} - \underbrace{\left\langle \hat{S}_x^1 \hat{S}_x^2 \right\rangle}_{=-1}\right) = 2\sqrt{2}$$

But each $\langle S_1 S_2 \rangle$ are random correlators. They can not be used to send signals.

$$\langle [S_i(t1, x1), S_j(t2, x2)] \rangle \neq 0 \quad , \quad Iff(t^2 - x^2) \geq 0$$

Copenhagen/Bayesian view: You get a non-local answer when you ask a non-local question! correlations need to be compared, which happens "after the time required by relativity" ,so what's the problem?

If you do QFT this is really awkward!

$$[\phi(x), \phi(y)] = \int \frac{d^3p}{(2\pi)^3} \frac{1}{\sqrt{2E_{\mathbf{p}}}} \int \frac{d^3q}{(2\pi)^3} \frac{1}{\sqrt{2E_{\mathbf{q}}}} \times \left[\left(a_{\mathbf{p}} e^{-ip\cdot x} + a_{\mathbf{p}}^\dagger e^{ip\cdot x} \right), \left(a_{\mathbf{q}} e^{-iq\cdot y} + a_{\mathbf{q}}^\dagger e^{iq\cdot y} \right) \right]$$

$$= \int \frac{d^3p}{(2\pi)^3} \frac{1}{2E_{\mathbf{p}}} \left(e^{-ip\cdot(x-y)} - e^{ip\cdot(x-y)} \right)$$

$$= D(x-y) - D(y-x). \tag{2.53}$$

Peskin
and Schroeder

When $(x-y)^2 < 0$, we can perform a Lorentz transformation on the second term (since each term is separately Lorentz invariant), taking $(x-y) \to -(x-y)$, as shown in Fig. 2.4. The two terms are therefore equal and cancel to give zero; causality is preserved. Note that if $(x-y)^2 > 0$ there is no continuous Lorentz transformation that takes $(x-y) \longrightarrow -(x-y)$. In this case, by Eq. (2.51), the amplitude is (fortunately) nonzero, roughly $(e^{-imt} - e^{imt})$

In fact in QFT every spacetime point is entangled with every other and causality is rigorously built into the theory! but for true believers...

This is probably why Aspect and Clauser faced so much opposition

- Experiment from scavanged equipment
- Lots of criticism from collegues like Feynman "who cares?"
- Tenure denial,warnings

In the context of the success of quantum field theory ($g - 2$ to 10 decimal places!) it was thought "testing quantum mechanics" was a waste of resources.

Perhaps the renewed interest in this subject is a reflection of the crisis of "fundamental physics"... But it triggered a deeped examination of the foundations of quantum mechanics that led to new insights

"How the hippies saved physics", David Kaiser

So... non-locality is enough? probabilities must...

Be $0 \leq P_i \leq 1$
Because of how they are defined!

Sum up to unity $\sum_i P_i = 1$
(*Something* must happen!)

Be bounded by correlations (Kolmogorov's third axiom)

$$P(A \cup B) = P(A) + P(B) - P(A \cap B) \leq P(A) + P(B)$$

And this becomes a problem for

$$\hat{O}_T = \hat{O}_1 + \hat{O}_2 + \hat{O}_3 \quad , \quad \hat{\rho}_T = \hat{\rho}_1 \otimes \hat{\rho}_2 \otimes \hat{\rho}_3$$

No! Contextuality is also needed!

$$\hat{O}_T = \hat{O}_A + \hat{O}_B + \hat{O}_C \quad , \quad \hat{\rho}_T = \hat{\rho}_A \otimes \hat{\rho}_B \otimes \hat{\rho}_C$$

One can prove Kochen-Specker

$$\exists O_i = \sum_{ABC} \alpha_{Ai}\hat{O}_A + \alpha_{Bi}\hat{O}_B + \alpha_{Ci}\hat{O}_C$$

$$\mathrm{Tr}\left[\hat{\rho}_T \hat{O}_1 \otimes \hat{O}_2 \otimes \hat{O}_3\right] \neq \sum_{i,j} P\left(O_i|\lambda_j\right) P\left(\lambda_j\right)$$

$$\forall 0 < P(...) < 1 \quad , \quad \sum P = 1$$

Proof: find a case and enumerate all alternatives long! Investigated phenomenologically by Zeilinger (Nobel)

A simple example: GHZ state

$$|\psi\rangle = \frac{1}{\sqrt{2}} \left(|\uparrow\uparrow\uparrow\rangle + |\downarrow\downarrow\downarrow\rangle \right)$$

It's a simple exercise to show that

$$\left\langle \hat{\sigma}_x^1 \hat{\sigma}_y^2 \hat{\sigma}_y^3 \right\rangle = \left\langle \hat{\sigma}_y^1 \hat{\sigma}_x^2 \hat{\sigma}_y^3 \right\rangle = \left\langle \hat{\sigma}_y^1 \hat{\sigma}_y^2 \hat{\sigma}_x^3 \right\rangle > 0$$

So any Bayesian inference would disagree with quantum mechanics

$$\left\langle \hat{\sigma}_x^1 \hat{\sigma}_x^2 \hat{\sigma}_x^3 \right\rangle_{Bayes} > 0$$

But it is simple to show that

$$\hat{\sigma}_x^1 \hat{\sigma}_x^2 \hat{\sigma}_x^3 \psi = -\psi$$

$$\left\langle \hat{\sigma}_x^1 \hat{\sigma}_x^2 \hat{\sigma}_x^3 \right\rangle_{Bayes} > 0 \quad , \quad \left\langle \hat{\sigma}_x^1 \hat{\sigma}_x^2 \hat{\sigma}_x^3 \right\rangle_{quantum} = -1 \quad , \quad 100\%$$

Classical and quantum predictions deterministic and opposite

the crux If hidden variables exist, then

$$P_{ijk}(\sigma_{zT}) = \sum_{klm} P(ijk|klm)_{\sigma_k \sigma_l \sigma_m} P_{klm}(\sigma_{zT}) \quad , \quad 1 \mathrm{Iff} \forall P = 1$$

So non-contextual variables are not just hidden, they don't exist! . Variables only exist when operators applied!

Physics doesn't exist, it's all about Gnomes

As we all know, physics is really, really hard. That's because in reality it's all one vast illusion - an extravagant lie carefully constructed just to confuse us. By gnomes. Read on and find out the unsettling cuddly truth you never knew about the whole gnome world . (Unless, of course, you've watched *The Borrowers*. They had it nearly right.)

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Gnome Physics

Electricity

Inside cables there are hundreds of tiny gnomes 'high-fiving' each other and running around swapping messages. This transfer of messages allows things to work, e.g. the gnomes in a plug socket tell the gnomes in the wire, who eventually tell the gnomes in (say) a kettle to fart in the water allowing it to boil.

Atoms

Atoms are in fact minuscule gnomes, all holding hands and feet etc together to form an intricate web from which nearly everything in the universe is comprised. Radioactivity occurs when a rebel gnome is catapulted by his friends from their structure. Should this gnome come into contact with the gnomes from our body, he will offer them beer, thus making the local area either benign or malignant. Either way, just read: *cancerous*.

IMHO if you need contextual non-causal hidden variables why not just have QM with it's mathematical elegance and depth? (Link to representation theory,functional analysis etc.)

What is being proved here is that in general if $[Y_i, Y_j] \neq 0$

$$P(X) \neq \sum_i P\left(X | \{Y_i\}\right) P\left(\{Y_i\}\right)$$

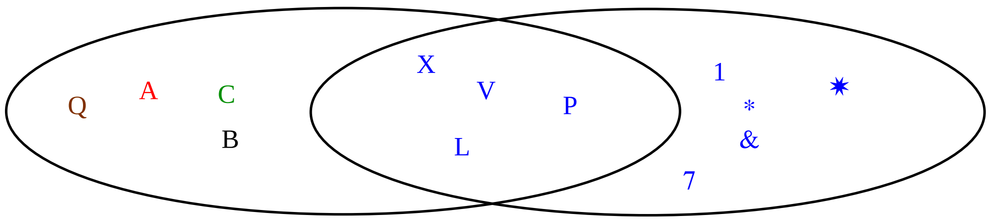
For any $P\left(\{Y_i\}\right)$ precludes statistical independence with "extra fluctuations!" (not correlations!).

CHSH relations (C got Nobel!) explicit demonstration of this!

Hidden variables also need to be contextual, i.e. depend on what is measured. But how is this different from normal quantum mechanics?

Deep reason: Probabilities always $0 \geq P \geq 1$, quantum operators can produce flips, $\sigma_x^1 \sigma_y^2 \sigma_y^3 \psi = -\psi$

$$\mathrm{Tr}\left[\sigma\rho\right] \neq \int f(x) g(x,y) dy$$



My way to see quantum mechanics does not see this as so surprising!

$$[X, Y] \neq 0 \Rightarrow P(X) \neq \sum_Y P(X|Y)P(Y)$$

Conditional probabilities come from set theory where elements of sets are defined by their properties. This is a dubious starting point if reality is relational. Just as with geometry within GR, perhaps we need to rethink set theory to take "relationalism" into account, and fundamental uncertainity arises from this. I believe mathematical logic and methamatematics never addressed this problem, but I am not an expert!

What is probability anyway?

What is a "random" number anyway? What is probability? head oor tail?

$$\lim_{N \to \infty} \frac{P_N(H)}{P_N(T)} = 1 \quad , \quad A \cap B = 0 \Rightarrow P(A \cup B) = P(A) + P(B)$$

and "no other information" about head/tail.

If this sounds vague, it's because it is! Many definitions

Khrennikov,1512.08852 : Kolmogorov (Complexity), Chaitin (Compressibility), Martin-Lof (Typicality),Von Mises (predictability),De Finetti (Exchangeability/Gambling)...

Randomness and correlation can be disproven not proven

Randomness, unpredictability, statistical independence

In particular, statistical independence of each event

$$P_N\left(H|\left\{P_1(H),...,P_{N-1}(H)\right\}\right) = P_N(H)$$

nothing you did earlier can predict what the next result can be!
This is obviously "falsifiable but not provable"
Same with statistical independence: If we dont know that $P(A)$ random, we also don't know that $P(A|B) = P(A)$

Kochen,Conway: Free will theorem (quant-ph/0604079)
Bell-type axioms imply that the response of a spin 1 particle to a triple experiment is free—that is to say, is not a function of properties of that part of the universe that is earlier than this response with respect to any given inertial frame. consequence of Kochen-Specker, spin 1+experiments have 3X3X3 combinations

Way out: Superdeterminism? Palmer,Hossenfelder,1912.06462

Perhaps hidden variables inherently correlate observers, detectors and systems and us in a way that statistical independence impossible? "no free will"

Non-computable superdeterminism in principle indistinguishable from quantum mechanics.

Computable look for

$$P_N\left(H|\left\{P_1(H),...,P_{N-1}(H)\right\}\right) \neq P_N(H)$$

in "quantum" events!

Further developments

Quantum encryption generally based on Bell-type correlations. Correlation disappears unless you measure "in right sequence" (protocol)

Quantum computing algorithms such as Shor's heavily based on entanglement between "qubits"

- But "physics vs formalism" can be an issue: Ultimately observable is $\left|_{input}\langle q_1 q_2 ... q_n | q_1 q_2 ... q_m \rangle_{output}\right|^2$. Ensemble size could kill quantum advantage? $n+m$ cumulant needs $\sim \exp(n+m)$ tries!
- Quantum computing experience might shed light on interpretation of QM?

Further developments: Quantum field theory

In QFT every point is entangled with every other point. Or more exactly Reeh–Schlieder theorem , one can "create states" encompassing the whole space by applying operators to arbitrarily small regions. can be used to derive Hawking radiation!

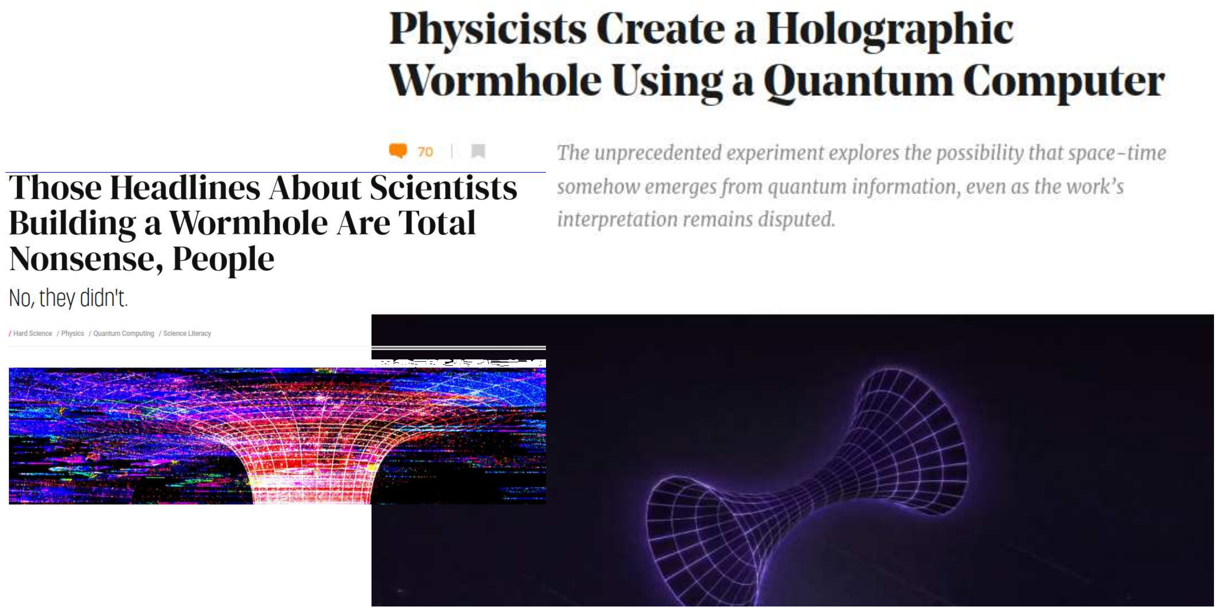
Rewriting QFT using quantum information language is an active research topic, see E. Witten, 1803.04993

Further developments:Why is gravity hard?

$$f(O_{1,2},t) = \mathrm{Tr}\left[\hat{\rho}\hat{O}\right] \neq \int dx dp d\lambda_{1,...,N} f\left(x,p,t,\lambda_{1,...,N}\right) O_{1,2}\left(x,p,t,\lambda_{1,...,N}\right)$$

Assures no action at a distance but entanglement at a distance .
But in gravity $O \equiv$distance,time ,inputs for causality

In Bayesian statistics time privileged ("wave function collapse"), in GR it's just another coordinate to be transformed around!

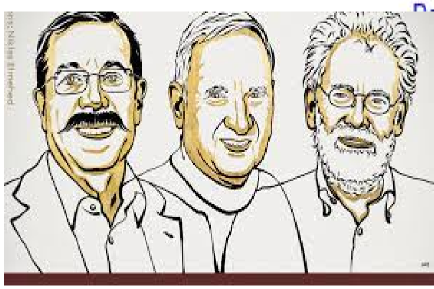


Determining set of <u>hermitian</u> operators preserving <u>locality,causality</u> throghout dynamics when locality,causality <u>result</u> of dynamics hard (?) .

Recent very speculative proposal: ER=EPR ,Maldacena,Susskind, 1306.0533 Controversial test (of what?) with quantum computers.

Some conclusions

Ultra-bright source of polarization-entangled photons 1998



aul G. Kwiat (1), Edo Waks (1 and 2), Andrew G. White (1), Ian Appelbaum (1 and 3), Philippe H. Eberhard (4) ((1) Physics Division, P-23, Los amos National Laboratory, (2) Ginzton Laboratory, Stanford University, (3) Physics Dept., M.I.T., (4) Lawrence Berkeley Laboratory)

Using the process of spontaneous parametric down conversion in a novel two-crystal geometry, one can generate a source of polarization-entangled photon pairs which is orders of magnitude brighter than previous sources. We have measured a high level of entanglement between photons emitted over a relatively large collection angle, and over a 10-nm bandwidth. As a demonstration of the source intensity, we obtained a 242-σ violation of Bell's inequalities in less than three minutes.

Entanglement means quantum .classical probability inherently different, particularly wrt conditional probability/statistical independence

Quantum probability was convincingly experimentally demonstrated. this is the true signifiance of the Nobel prize

Mimicking quantum systems by classical ones inherently problematic