Our Current Concept of Locality may be Incomplete

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Our Standard Notion of Locality

No Energy, matter, influence, signal etc. can travel faster than the speed of light in space

More formally: let L be the set of all spacetimes events local with respect to spacetime event a. Then $b \in L$ *iff*

$$\int_{r(a)}^{r(b)} dr \leq \int_{t(a)}^{t(b)} cdt \qquad (1)$$

$\Rightarrow$ Definition of spacetime interval is behind locality constraint
But experiments on entangled particles show that there appears to be some kind of connection which violates this constraint: Non-locality?

Central Claim of this Talk

These specific phenomena may only appear non-local to us because our current concept of locality may be incomplete due to the tacit assumption that spacetime is the repository of everything that exists

Why does questioning that spacetime is the repository of everything that exists render our current concept of locality incomplete?

If it was true that pre-measurement quantum objects are due to entities that exist “outside spacetime”, then these could satisfy a relation analogous to equation (1) in their own repository and still give rise to spacelike separated correlated events in spacetime after measurements if distance relations that govern them are independent of spacetime intervals

Maybe not such a crazy idea?

Gisin: "...quantum correlations somehow arise from outside spacetime, in the sense that no story in space and time can describe them"[2]

[2] N Gisin, as quoted in science news *Looking beyond space and time to cope with quantum theory*, Oct 28, 2012

Do Photons exist in Spacetime?

4 simple arguments which suggest that they do not

1. The Ontological Argument: The duration of existence in spacetime of a photon in its proper frame is zero
2. The Linear Dependence Argument: In a photon frame, spacetime has redundant dimensionality
3. The Four-Volume argument: Photons cannot be associated with four-volumes in the absence of matter
4. The limit argument: At $\mathbf{v} = \mathbf{c}$, the Lorentz transformations may take a vector outside spacetime

1. The Ontological Argument

- Zero proper time means that moment a photon is observed to come into existence (emitted) and moment it is observed to go out of existence (absorbed) are the *same* moment in its proper frame: It "observes" itself to have a zero duration of existence in spacetime.
- Strange fact about SR and photons under our current worldview, but if photons do not exist in spacetime, it would make perfect sense!
- **But** (1) "existence" is not a physics concept and (2) argument assumes that one can coherently talk about photon frames

2. The Linear Dependence Argument

- When two frames moving relative to each other coincide at the origin, time and space axes associated with moving frame are observed to be contracted by 2α, where $\alpha = \tan^{-1} v/c$
- when moving at c, unit vectors along both axes point in the lightlike direction $\Rightarrow$ in this sense, they become “parallel”
- the set becomes linearly dependent $\Rightarrow$ spacetime has redundant dimensionality in photon frame
- **But** (1) argument also assumes one can speak of photon frames (2) couldn't one apply this argument to us? Asymmetry (3) Vectors of zero magnitude are also orthogonal to each other

3. The Four-Volume Argument

- 4-volume element in Minkowski spacetime: $\sqrt{| g |} dx^0 dx^1 dx^2 dx^3$, where $g \equiv det[\eta_{ij}]$
- if $ds^2 = \eta_{ij} dx^i dx^j = 0$, then cannot create 4-volume out of the dx^i because one can always be expressed in term of the other 3
- 4-volumes which include absorption/emission events are associated with massive objects, rather than photons
- 4-volumes which do not include absorption/emission events cannot be claimed to "contain" photons:
  - pointing to a location of a photon implies attributing a rest frame to it, but photons do not have rest frames
  - photons do not have definite trajectories

But, intuition is that we can talk about photons "in" space, e.g "photon gas", laser beam etc.

4. The limit Argument

- $\lim_{v \to c} \gamma$ *DNE*
- $\lim_{v \to c} \left[ct' = \gamma \left(ct - \frac{vx}{c} \right), x' = \gamma \left(x - vt \right), y' = y, z' = z \right]$ *DNE*
- Two possible interpretations, either
  - *LT* at $v = c$ has no meaning, or
  - *LT* at $v = c$ means that the resultant vector would have been transformed to be outside spacetime
- If we had not known about photons, we might have given first interpretation as reason for their non-existence
- existence of photons discourages first interpretation but does not preclude it

How Strong are these arguments?

Not strong enough to be conclusive, but strong enough to consider investigating the question of whether photons exist in spacetime a legitimate research subject.

Where could photons exist, if not in spacetime?

- May consider interior of a lightcone a submanifold
- For a submanifold S, its topological boundary ∂S has 1 spatial dimension fewer
- photons only exist in the boundary of lightcones
- If boundary of a lightcone is topological, then this suggests that photons exist in a $2+1$ analog of spacetime (not rigorous!)

What do we gain if we accept that photons exist in a $2+1$ analog of spacetime?

Understanding intrinsic nature of photons more deeply allows us to understand its properties more deeply

- Photons intrinsically 2-dimensional $\Rightarrow$ completely length-contracted in every spacetime frame
- If given relation $\gamma^{-2}+\beta^2=1$, $\Rightarrow$ invariance of speed of light
- "explains" fewer degrees of freedom of polarization state than massive particles

How does all this relate to quantum theory?

Central Principle of quantum mechanics (in my view):
The Absence of an explicit specification entails all possible default specifications

Actually a fundamental mathematical principle we use all the time but rarely articulate

- trivial example: $(a + b) \times (c + d) = ac + ad + bc + bd$
- $x = 3$ is represented in R^1 as a single point, in R^2 as an infinite line, and in R^3 as an infinite plane.

Application of Principle to Quantum Theory

- if a quantum object does not *have* a physical property (Energy, momentum, position etc.) pre-measurement, then it must be described by spacetime observers as if it had all possible values for that property at the same time $\Rightarrow$ Quantum Superposition!
- Why would it not have a particular physical property?
- Physical properties belong to spacetime objects, but if we assume that the pre-measurement quantum object is not in spacetime, then we cannot assign to it the property of a spacetime object

A Theory based on this Principle already exists!

- Dimensional Theory
- Can derive free-particle path integral from it
- Presented last year here in Växjö [3]

[3] A Nikkhah Shirazi *A Novel Approach for'Making Sense' Out of the Copenhagen Interpretation*,AIP Conf. Proc. 1508, pp. 422-427
Also, recording of talk available at http://youtu.be/GurBISsM308

Dimensional Theory: 2-minute version

- Assume that there exists a limit in which Spacetime reduces to Areatime
- Areatime objects vs. spacetime objects: Distinct metric intervals ⇒ Distinct proper times ⇒ Distinct worldlines
- Application of principle to this situation implies description by spacetime observers in terms of superposition of all possible spacetime worldlines of objects into which areatime object can emerge ⇒ "Sum over Histories"

Dimensional Theory: 2-minute version (cont.)

- Need a mechanism for comparing passage of time along areatime worldline to each individual spacetime worldline which keeps time dimensions distinct
- Postulate a symmetry: 'Superposition' of two rotations in opposite directions in an abstract plane composed of the two proper time dimensions
- More symmetric than a simple rotation:
  - Invariance under reflection
  - invariance under angular displacement for any angle
- Point of mechanism:
  - *Process* allows comparison of passage of time
  - *Outcome* allows proper times to remain distinct

Dimensional Theory: 2-minute version (cont.)

- Can mathematically transform symmetry into two complex conjugate phases $e^{\frac{\tau}{\tau_A}}$ where τ_A is the proper time associated with the areatime object (imaginary), and τ is the proper time of the spacetime worldline to which the areatime object's proper time is compared
- Appropriate substitution yields $e^{\pm i\frac{S}{\hbar}}$ (free particle: $\tau_A \Rightarrow \pm i\frac{\hbar}{mc^2}$)
- Since mechanism applies to each spacetime worldline, must associate phase factor with each $\Rightarrow$ Feynman Path Integral

Actual vs. Actualizable Mass

- **But** We started off with photons as lower-dimensional objects but this the theory is meant to apply to objects with mass.
- to preserve consistency, must introduce a novel distinction in concept of mass[4]

Actualizable mass	**Actual mass**
$\eta_{ij}x^i x^j, \; i,j = 0,1,2$	$\eta_{ij}x^i x^j, \; i,j = 0,1,2,3$
Superposition	No Superposition

A "Measurement" can then be thought of as any process that brings about the transformation from actualizable to actual mass.

[4] A Nikkhah Shirazi *Are the Concepts of Mass in Quantum Theory and in General Relativity the same?" Deep Blue:http://hdl.handle.net/2027.42/87999*

Actual vs. Actualizable

- Distinction between concepts of mass carries over to distinction between pre-measurement quantum states and immediate post-measurement states
- To symbolically show it, underline actual states: $\Psi \longrightarrow \underline{\psi}_i$
- Until recently, thought that distinction was a matter of interpretation, but recent argument suggests that it is required for standard quantum mechanics to maintain logical consistency [5]

[5] Asymmetry Due To Quantum Collapse, Deep Blue: http://hdl.handle.net/2027.42/97779, 2013

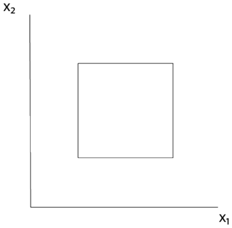
Locality: A Conjecture

Supposing that the metric intervals of spacetime and areatime are independent of each other, if spacetime objects emerge out of areatime objects, then spacelike separated correlated spacetime objects can be made to emerge out of objects in the same region in areatime in the absence of superluminal signaling, energy transfer, information transmission, causal influence.

Cannot prove this, but can attempt to give picture of an analogy

A Euclidean Analogy

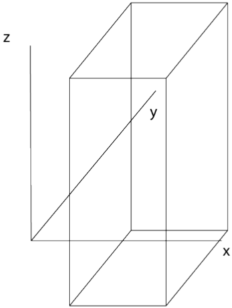
Consider $\int_a^b \int_c^d dx_1 dx_2$ where a,b,c,d are corners of a square



A Square disk in R^2(*Flatland*, anyone?)

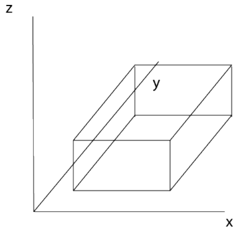
A Euclidean Analogy

In R^3 it must be represented as an infinite square column



A Euclidean Analogy

Attributing an interval $\int_e^f dx_3$ along the third axis-the analog of a "measurement"-collapses the infinite column to 3-dimensional cuboid

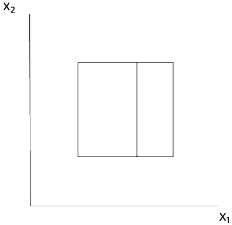


Alice and Bob in Euclidland

Can do the same with a square that consists of two distinct parts:

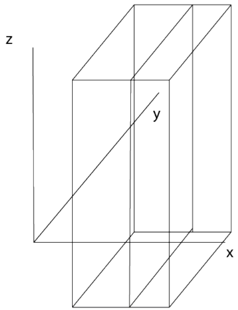
Total disk= Disk1 + Disk 2

Disk 1:$\int_a^b \int_c^{c'} dx_1 dx_2$ and Disk 2: $\int_a^b \int_{c'}^{d} dx_1 dx_2$



Alice and Bob in Euclidland

In R^3 these must be represented as two infinite adjacent columns



Notice what happens if Alice makes a "measurement" on one of the disks *without knowing ahead of time which disk is going to be measured*

Similarities to quantum entanglement

- No influence traveling in 3- space
- Bob Can be arbitrarily far away, correlation still holds
- Bob still needs to make a measurement in order for there to be a correlated object in 3-space

Observation of correlation involves objects distant in 3-space but correlation itself is "local" in 2-space

Conclusion

To understand quantum entanglement, we may need to expand concept of locality to include metric intervals other than that of spacetime. A theory which accommodates this in a natural manner already exists, and it comes closest to the orthodox interpretation.