Where unfathomable begins

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I show any theory assuming state of an object, or even object's existence, will be at odds with empirical evidence. I discuss QM relation with special relativity (SR). I argue all paradoxes are artifacts of factitious assumptions

A *dogmatic realist* [1] would believe, at least on subconscious level, that information extracted by the measurement pertains to an entity extraneous to that information, i.e., to some measured object, which exists "out there", beyond the tip of our noses, whether we measure it or not. Such line of thought can only be a belief, since any attempt to prove the existence of extraneous entity would have to attribute obtained information to that extraneous entity, i.e., the proof would involve circular reasoning. Here I show such beliefs would also contradict some experiments[1]. Generally, for any belief or theory, not equivalent to already existing objective facts, one can obtain empirical evidence contrary to that belief. This principle is demonstrated in a double-slit experiment.

The measured by device $\boldsymbol{X}$ expectation value of observable is given by Born rule:

$$\langle X \rangle = Tr(\boldsymbol{X} \cdot \boldsymbol{\rho}) \tag{1}$$

, where density matrix $\boldsymbol{\rho}$ represents information about *state*; $\boldsymbol{X}$ is the operator matrix of observable the device measures. The *objectivity* [2], signified by independence of objective facts on observer [basis], dictates the classical information, such as event probabilities, is conserved upon observer basis transformation. The unitarity, imposed [2] by objectivity, leads to conservation of quantum information[2], as manifested by *no-hiding theorem* [3]. Thus, without new measurement, quantum and classical information are separately conserved. With measurement, the conserved property can only be the sum of quantum and classical information, as measurement transforms quantum information into classical[3].

Consider a case when $\boldsymbol{X}$ is the only device which performs measurement. If we theorize about state of the object, the outcome of the theory may be an additional information, beyond what is produced by device $\boldsymbol{X}$. This additional information is accounted for by density matrix $\boldsymbol{\rho'} \neq \boldsymbol{\rho}$. It would lead to a different expectation value (1), i.e., the theory would generally contradict experiment where device $\boldsymbol{X}$ is the only source of information.

Consider a measurement in cardinality $M = 2$ basis, i.e., a measurement of a qubit. The measured by device $\boldsymbol{X}$ expectation value is:

$$\langle X \rangle = Tr(\boldsymbol{X} \cdot \boldsymbol{\rho}) = \langle \boldsymbol{0}|\boldsymbol{X}|\boldsymbol{0} \rangle \rho_{00} + \langle \boldsymbol{0}|\boldsymbol{X}|\boldsymbol{1} \rangle \rho_{10} + \langle \boldsymbol{1}|\boldsymbol{X}|\boldsymbol{0} \rangle \rho_{01} + \langle \boldsymbol{1}|\boldsymbol{X}|\boldsymbol{1} \rangle \rho_{11} \tag{2}$$

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[1] It was shown, e.g., that the assumption about radiation existing "out there", in the open space, does not allow self-consistent derivation of Planck's radiation formula [31]. It also leads to zero-point energy paradox [33]: the gravity from all zero-point energy modes would exceed the observed gravity by at least 58 orders of magnitude [32]

[2] The term "quantum information" is widely used [35, 15, 3], but with no clear definition in sight. It appears a common practice to write papers mentioning the term dozens of times, and not to bother defining it. I define quantum information as the *potential information*, which can be converted into real, i.e., classical information, by the measurement; the measurement being defined [5] as extraction of classical information

[3] The distinction between quantum and classical information is the base of Bohr's *complementarity principle* [30]. The wave-like behavior, associated with unitary transformation of density matrix, is said to complement the particle-like outcomes of measurement events, delineating the boundary between quantum and classical physics [18, 2]

In order to have a room for conjecture, we deliberately choose device' basis so it does not resolve input states $\{\mathbf{0},\mathbf{1}\}$, i.e., $\langle\mathbf{0}|\boldsymbol{X}|\mathbf{1}\rangle \neq 0$. If we theorize that input states $\mathbf{0},\mathbf{1}$ correlate respectively with states $\boldsymbol{u}$, $\boldsymbol{v}$ of the object[4], the predicted expectation value [4, 5] is different from (2):

$$\langle X\rangle = \langle\mathbf{0}|\boldsymbol{X}|\mathbf{0}\rangle\rho_{00} + \langle\mathbf{0}|\boldsymbol{X}|\mathbf{1}\rangle\langle\boldsymbol{u}|\boldsymbol{v}\rangle\rho_{10} + \langle\mathbf{1}|\boldsymbol{X}|\mathbf{0}\rangle\langle\boldsymbol{v}|\boldsymbol{u}\rangle\rho_{01} + \langle\mathbf{1}|\boldsymbol{X}|\mathbf{1}\rangle\rho_{11} \tag{3}$$

The difference between (2) and (3) is especially pronounced if conjectured object states are orthogonal: $\langle\boldsymbol{u}|\boldsymbol{v}\rangle = 0$. This is the case when, e.g., input basis states $\{\mathbf{0},\mathbf{1}\}$ are chosen to correlate respectively with the state of object's existence $\boldsymbol{u}$, and non-existence $\boldsymbol{v}$.

The expectation value (3) would be correct if $\boldsymbol{u}$ and $\boldsymbol{v}$ were not just conjectured object states, but outcomes of an actual measurement[5], performed in addition to the measurement by device $\boldsymbol{X}$.

The double-slit experiment is the canonical setup to confirm the above conclusion. Double-slit generates a spatial qubit [6]. The device $\boldsymbol{X}$ is the screen behind the slits. The input basis state $\mathbf{0}$ is that of a particle passing through left slit, and basis state $\mathbf{1}$ is that of a particle passing through right slit. In the absence of additional measurement, device $\boldsymbol{X}$ measures expectation value (2). It exhibits characteristic interference pattern due to $\langle\mathbf{0}|\boldsymbol{X}|\mathbf{1}\rangle\rho_{10} + \langle\mathbf{1}|\boldsymbol{X}|\mathbf{0}\rangle\rho_{01}$ term. The expectation (2) would contradict any theory ascertaining the slit particle passed through, and, generally, any theory whose predictions extend beyond information obtained[6] by device $\boldsymbol{X}$.

If, however, an additional measurement is performed, whose output $\boldsymbol{u}$ correlates with state $\mathbf{0}$, and output $\boldsymbol{v}$ correlates with state $\mathbf{1}$, the measured expectation value at the screen is given by (3). The interference pattern is affected by term $\langle\boldsymbol{u}|\boldsymbol{v}\rangle$. A textbook example of a double-slit experiment would include an additional measurement at the slits, to determine which slit particle passed through. If measurement at the slits is accurate, the output states are orthogonal: $\langle\boldsymbol{u}|\boldsymbol{v}\rangle = 0$, and no interference pattern at the screen is observed [7, 8].

The expression (3) goes beyond the case of interference decay. It may also involve a shift in interference pattern, given $\langle\boldsymbol{u}|\boldsymbol{v}\rangle = |\langle\boldsymbol{u}|\boldsymbol{v}\rangle| \cdot exp(i\varphi)$, by φ; combined with decay, if $|\langle\boldsymbol{u}|\boldsymbol{v}\rangle| < 1$. If $|\langle\boldsymbol{u}|\boldsymbol{v}\rangle| = 1$, no information is extracted. In this case $\boldsymbol{\rho}$ just undergoes unitary transformation[7].

The amount of quantum information, contained in state $\boldsymbol{\rho}$, which *can be* extracted per single measurement event, in a limit of infinite size event sample, is evaluated using Von Neumann entropy H [9] as [10, 2]:

$$\mathcal{L} = H_{max} - H = \ln M + Tr(\boldsymbol{\rho}\ln\boldsymbol{\rho}) \;\; (nats/event) \tag{4}$$

, where M is the cardinality of measurement basis. The entropy H of $\boldsymbol{\rho}$ is, therefore, the amount of *already extracted* information, per event. A known density matrix means the measurement has been performed, either by preparation or by measuring device. For the finite size event sample, the amount of extracted information is Boltzmann's entropy $H_\Omega = \ln\Omega\ (nats)$, where Ω is the statistical weight of the sample [11].

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[4] Such correlation has earned a popular, albeit not informative name: entanglement

[5] This expounds the falsehood of so-called *Wigner's friend paradox* [28]. According to (3), the measurement performed by Wigner's friend, i.e., the measurement of $\langle\boldsymbol{u}|\boldsymbol{v}\rangle$, affects Wigner's measurement of $\langle X\rangle$. The information extracted by Wigner's friend reduces the amount of information available for extraction by Wigner

[6] The proof is rather trivial, as prediction of the theory can be mapped into $\boldsymbol{u}$,$\boldsymbol{v}$ outcomes, leading to expectation (3)

[7] The shift in interference pattern here is a type of Aharonov-Bohm effect [29, 27]

For cardinality $M=2$ basis, (4) is expressed in terms of the length of Bloch vector $\boldsymbol{\alpha}$ as [12]:

$$\mathcal{L}=\frac{1-|\boldsymbol{\alpha}|}{2}\ln(1-|\boldsymbol{\alpha}|)+\frac{1+|\boldsymbol{\alpha}|}{2}\ln(1+|\boldsymbol{\alpha}|)\ \ (nats/event) \tag{5}$$

, where

$$\boldsymbol{\alpha}^2=1-4\cdot det(\boldsymbol{\rho})=2\cdot Tr(\boldsymbol{\rho}^2)-1 \tag{6}$$

From (5),(6), it follows, $det(\boldsymbol{\rho})$, or $Tr(\boldsymbol{\rho}^2)$ are single parameters defining the amount of quantum information in qubit. With measurement having output states $(\boldsymbol{u},\boldsymbol{v})$, $det(\boldsymbol{\rho})$ changes as

$$det(\boldsymbol{\rho}')=det(\boldsymbol{\rho})+\rho_{01}\rho_{10}\sin^2\theta\quad;\quad\cos^2\theta=\langle\boldsymbol{u}|\boldsymbol{v}\rangle\langle\boldsymbol{v}|\boldsymbol{u}\rangle \tag{7}$$

The parameter $0\le(R^2=\sin^2\theta)\le 1$ equates to a coefficient of determination R^2 in statistics, as a measure of how much the measurement of $\langle\boldsymbol{u}|\boldsymbol{v}\rangle$ predetermines the measurement of $\langle X\rangle$.

The dependence of (3) on product $\langle\boldsymbol{u}|\boldsymbol{v}\rangle$ of entangled ancilla states creates an impression the remote ancilla instantaneously affects the results of local measurement by device $\boldsymbol{X}$. There is nothing in expression (3) that prohibits instantaneous effect of the measurement of $\langle\boldsymbol{u}|\boldsymbol{v}\rangle$ on the measurement of $\langle X\rangle$. In varying forms, the expression (3) is the root of continuing claims of QM non-locality [13], and part of the problem reconciling QM with special relativity[8]. I reproduce the issue in a thought experiment below.

Consider an experiment in which pairs $(\boldsymbol{A},\boldsymbol{B})$ of left (L), and right (R) circular polarization-entangled photons [14] are generated, by passing *UV* laser beam through SPDC crystal (Figure 1). The polarizing beam splitters (PBS) separate vertical (V) and horizontal (H) polarizations down two paths: $\boldsymbol{A}_V,\boldsymbol{A}_H$ for photon $\boldsymbol{A}$, and $\boldsymbol{B}_V,\boldsymbol{B}_H$ for photon $\boldsymbol{B}$. The paths $\boldsymbol{A}_V,\boldsymbol{A}_H$ are registered by separate detectors, which I summarily reference as device $\boldsymbol{A}$. Path $\boldsymbol{B}_H$ passes through $\lambda/2$ plate which makes polarization of $\boldsymbol{B}_H$ same as $\boldsymbol{B}_V$. The paths $\boldsymbol{B}_V,\boldsymbol{B}_H$ converge on screen $\boldsymbol{X}$ to form interference pattern.

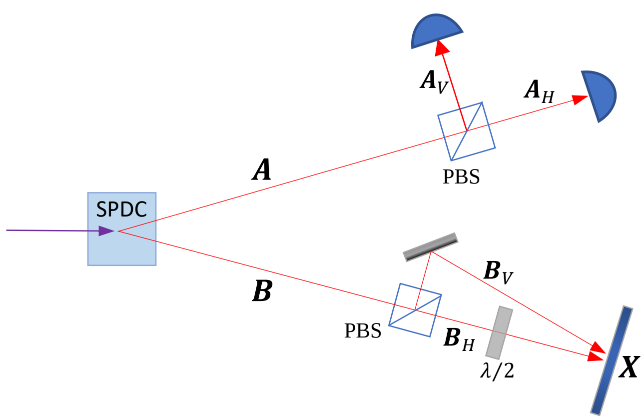

Figure 1

[8] Another part is the "*infinitely sharp boundary between the region of simultaneousness, in which no action could be transmitted, and other regions, in which direct action from event to event could take place. Since an infinitely sharp boundary means an infinite accuracy with respect to position in space and time, the momenta or energies must be completely undetermined, or in fact arbitrarily high momenta and energies must occur with overwhelming probability. Therefore, any theory which tries to fulfill the requirements of both special relativity and quantum theory will lead to mathematical inconsistencies, to divergencies in the region of very high energies and momenta*" [1]

By virtue of entanglement, a photon registered at $\boldsymbol{A}_V$ or $\boldsymbol{A}_H$ points to the photon $\boldsymbol{B}$ being in a reciprocal $\boldsymbol{B}_V$ or $\boldsymbol{B}_H$ path, akin to detecting the slit particle passed through in a double-slit experiment. The accurate detection of entangled photon at $\boldsymbol{A}_V, \boldsymbol{A}_H$ would lead to disappearance of interference pattern at the screen $\boldsymbol{X}$. By modulating PBS in path $\boldsymbol{A}$, the experimenter can communicate with observer $\boldsymbol{X}$, seemingly in violation of no-signaling theorem [15, 16], and in violation of special relativity, since the distance between $\boldsymbol{X}$ and device $\boldsymbol{A}$ can be arbitrary large. Even more paradoxical is the situation when length $\boldsymbol{A}$ is longer than $\boldsymbol{B}$. In this case, the photon $\boldsymbol{A}$ is detected after photon $\boldsymbol{B}$ has been registered by $\boldsymbol{X}$. Yet, the detection of photon at $\boldsymbol{A}_V, \boldsymbol{A}_H$ would affect the interference pattern at $\boldsymbol{X}$, i.e., the measurement in the future would affect the measurement in the past. Thus, in one thought experiment we find at least three paradoxes:

1. violation of special relativity
2. violation of causality [17]
3. violation of no-signaling theorem [15]

And yet, as I show below, none of these paradoxes is real. As all paradoxes, they are artifacts of factitious assumptions. Let's disassemble them.

One obvious assumption we made was that there are photons traveling[9] from SPDC down two paths $(\boldsymbol{A}, \boldsymbol{B})$. Anyone who understands the base QM principles would know the photon comes into being only as a measurement event [18, 19]. Until measurement there is no photon. A way to describe the situation before measurement, i.e., to describe the *measurement setup*, is by representing it as superposition of correlated radiation modes; with *mode* defined as *possibility* of certain measurement outcome. Such superposition is what is referred to as *quantum state*. The setup on Figure 1 is described, in two measurement eigenbases, as

$$\boldsymbol{\psi} = (\boldsymbol{A}_R\boldsymbol{B}_L + \boldsymbol{A}_L\boldsymbol{B}_R)/\sqrt{2} = (\boldsymbol{A}_H\boldsymbol{B}_H + \boldsymbol{A}_V\boldsymbol{B}_V)/\sqrt{2} \tag{8}$$

, where $\boldsymbol{A}_R, \boldsymbol{A}_L, \boldsymbol{B}_R, \boldsymbol{B}_L$ are circular left and right polarization modes; $\boldsymbol{A}_R = (\boldsymbol{A}_H + i\boldsymbol{A}_V)/\sqrt{2}$; $\boldsymbol{A}_L = (\boldsymbol{A}_H - i\boldsymbol{A}_V)/\sqrt{2}$; $\boldsymbol{B}_R = (\boldsymbol{B}_H + i\boldsymbol{B}_V)/\sqrt{2}$; $\boldsymbol{B}_L = (\boldsymbol{B}_H - i\boldsymbol{B}_V)/\sqrt{2}$. The expectation at the screen $\boldsymbol{X}$ is:

$$\langle X\rangle = \langle\boldsymbol{\psi}|\boldsymbol{X}|\boldsymbol{\psi}\rangle = \frac{1}{2}[\langle\boldsymbol{B}_H|\boldsymbol{X}|\boldsymbol{B}_H\rangle + \langle\boldsymbol{A}_H|\boldsymbol{A}_V\rangle\langle\boldsymbol{B}_H|\boldsymbol{X}|\boldsymbol{B}_V\rangle + \langle\boldsymbol{A}_V|\boldsymbol{A}_H\rangle\langle\boldsymbol{B}_V|\boldsymbol{X}|\boldsymbol{B}_H\rangle + \langle\boldsymbol{B}_V|\boldsymbol{X}|\boldsymbol{B}_V\rangle] \tag{9}$$

, where $R^2 = \sin^2\theta = 1 - \langle\boldsymbol{A}_H|\boldsymbol{A}_V\rangle\langle\boldsymbol{A}_V|\boldsymbol{A}_H\rangle$ characterizes PBS efficiency. Eq. (9) is same as (3), where $\rho_{00} = \rho_{01} = \rho_{10} = \rho_{11} = 1/2$, and $\langle\boldsymbol{u}|\boldsymbol{v}\rangle = \langle\boldsymbol{A}_H|\boldsymbol{A}_V\rangle$.

While QM formalism above accurately predicts expectation value, it is seemingly at odds with special relativity (SR), with an illusion of instantaneous effect of the measurement by detectors $\boldsymbol{A}_V, \boldsymbol{A}_H$ on $\boldsymbol{X}$. Since SR is entirely in classical domain, for resolution, we should look at classical information produced by the measurement.

A single measurement event is one of eigenstates of measuring device. The associated eigenvalue is the device reading. In a limit of infinite number of measurement events, the event sample is described by projection of quantum state on eigenspace of measuring device:

$$\boldsymbol{P}_X = \boldsymbol{X}\boldsymbol{\psi}_X \tag{10}$$

, where subscript X indicates, the measurement basis is that of device $\boldsymbol{X}$.

[9] The very word *traveling* implies intermediate measurement events, i.e., a *trajectory*

Since device readings are real-valued classical parameters, the eigenvalues of device operator $\boldsymbol{X}$ are real, i.e., operator $\boldsymbol{X}$ is Hermitian. Below I show, the hermiticity condition is sufficient for the measurements to comply with SR. In order to ascertain this in experiment on Figure 1, we transform measurement basis from that of device $\boldsymbol{X}$ to that of device $\boldsymbol{A}$. I designate this transformation as $\boldsymbol{V}$: $\boldsymbol{\psi}_X = \boldsymbol{V}\boldsymbol{\psi}_A$; $\boldsymbol{P}_X = \boldsymbol{V}\boldsymbol{P}_A$. The existence of such transformation indicates, devices $\boldsymbol{X}$, $\boldsymbol{A}$ belong to the same measurement context. In new basis, (10) becomes: $\boldsymbol{V}\boldsymbol{P}_A = \boldsymbol{X}\boldsymbol{V}\boldsymbol{\psi}_A$. Therefore, device $\boldsymbol{A}$ operator *intertwines* with operator $\boldsymbol{X}$ as

$$\boldsymbol{V}\boldsymbol{A} = \boldsymbol{X}\boldsymbol{V} \tag{11}$$

The irreducible representation of Hermitian operators $\boldsymbol{X}$, $\boldsymbol{A}$ is [20]:

$$\boldsymbol{X} = t_0 \cdot \boldsymbol{I} + (\boldsymbol{r}_0, \boldsymbol{\sigma}) \tag{12}$$

$$\boldsymbol{A} = t_1 \cdot \boldsymbol{I} + (\boldsymbol{r}_1, \boldsymbol{\sigma}) \tag{13}$$

, where $\boldsymbol{r} = (x, y, z)$; $\boldsymbol{\sigma} = (\sigma_x, \sigma_y, \sigma_z)$ are Pauli matrices. Representation (12),(13) indicates the measurement has an associated spacetime 4-vector[10]. The non-trivial *intertwist* $\boldsymbol{V}$ between devices $\boldsymbol{X}$, $\boldsymbol{A}$ is possible only if matrix determinant of (11) is zero. With (12),(13), this condition is

$$det\begin{pmatrix} 0 & -x_0 - iy_0 & x_1 - iy_1 & t_1 - t_0 - z_1 + z_0 \\ -x_0 - iy_0 & 0 & t_1 - t_0 + z_1 + z_0 & x_1 + iy_1 \\ x_1 - iy_1 & t_1 - t_0 - z_1 - z_0 & 0 & -x_0 + iy_0 \\ t_1 - t_0 + z_1 - z_0 & x_1 + iy_1 & -x_0 + iy_0 & 0 \end{pmatrix} = 0 \tag{14}$$

The above equates to:

$$((t_1 - t_0)^2 - \boldsymbol{r}_0^2 - \boldsymbol{r}_1^2)^2 = 4\boldsymbol{r}_0^2\boldsymbol{r}_1^2 \tag{15}$$

Eq. (15) splits into four relations between 4-vector components $(t_0, \boldsymbol{r}_0)$, $(t_1, \boldsymbol{r}_1)$ signifying different causal possibilities, as illustrated on Figure 2, where arrow base is the potential cause, and arrow head is the possible effect; $r_0 = |\boldsymbol{r}_0|$; $r_1 = |\boldsymbol{r}_1|$. The causal possibilities, as seen by observer $\boldsymbol{O}$, are indicated by positive values of parameters Δt, Δr under $\boldsymbol{O}(\quad)$. Since 4-vectors $(t_0, \boldsymbol{r}_0)$, $(t_1, \boldsymbol{r}_1)$ are relative to observer, the observer is a key element of causal relationships.

$$\boldsymbol{A}(t_1, \boldsymbol{r}_1) \longrightarrow \boldsymbol{O}(t_0 - t_1, r_1 - r_0) \longleftarrow \boldsymbol{X}(t_0, \boldsymbol{r}_0)$$

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$$\boldsymbol{A}(t_1, \boldsymbol{r}_1) \longrightarrow \boldsymbol{O}(t_0 - t_1, r_0 + r_1) \longrightarrow \boldsymbol{X}(t_0, \boldsymbol{r}_0)$$

$$\boldsymbol{A}(t_1, \boldsymbol{r}_1) \longleftarrow \boldsymbol{O}(t_1 - t_0, r_0 + r_1) \longleftarrow \boldsymbol{X}(t_0, \boldsymbol{r}_0)$$

Figure 2

With observer at device $\boldsymbol{X}$, $\boldsymbol{r}_0 = 0$. In this case (15) becomes $(t_1 - t_0)^2 = \boldsymbol{r}_1^2$. Hence, relative to device $\boldsymbol{X}$, the measurement by device $\boldsymbol{A}$ is separated by time interval $|t_1 - t_0|$ equal to distance r_1 between $\boldsymbol{X}$ and $\boldsymbol{A}$; with associated speed limit $c = 1$. Not only QM is not at odds with SR, in fact, SR is imposed by classicality of measurement results, which is one of QM base concepts.

If $det(\boldsymbol{V}) \neq 0$ in (11), we have additional conditions:

[10] Spacetime as an entity emerges as encoding structure for classical information extracted by the measurement [2]

$$det(\boldsymbol{A}) = det(\boldsymbol{X}) \quad \Rightarrow \quad t_1^2 - \boldsymbol{r}_1^2 = t_0^2 - \boldsymbol{r}_0^2 \tag{16}$$

, and

$$tr(\boldsymbol{A}) = tr(\boldsymbol{X}) \quad \Rightarrow \quad t_1 = t_0 \tag{17}$$

, from where it follows, $\boldsymbol{r}_1^2 = \boldsymbol{r}_0^2$. Therefore, if $det(\boldsymbol{V}) \neq 0$, transformation $\boldsymbol{V}$ has to be unitary, i.e., a transformation of observer basis. Unitary transformations conserve information (4) and trivially comply with SR by (16). Consequently, Schrödinger equation, being an expression of parameter-driven unitary transformation [2], also complies with SR, namely with unitary subgroup of Lorentz transformations. Generally, however, Lorentz transformations, specifically *boosts*, do not conserve quantum information. In one form or another, they imply measurement, i.e., extraction of information. The boost involves acceleration from $\boldsymbol{v}_0$ to $\boldsymbol{v}_1$. It is done through the action of a classical force, always accompanied by decoherence [21]. An assumption that one can reconcile extraction of information, implied by the boost transformation, with unitarity, leads to a collection of paradoxes, see, e.g., Lecture IV in [22].

As for the causality violation paradox, note, that we can remove device $\boldsymbol{A}$ from measurement setup on Figure 1 by increasing length $\boldsymbol{A}$ to infinity. In this case, the interference pattern at the screen $\boldsymbol{X}$ would re-appear. The interference pattern re-appears when difference in lengths $\boldsymbol{A}$ and $\boldsymbol{B}$ increases above *coherence length*, corresponding to [de]coherence time [23], i.e., the time it takes to perform measurement[11]. If devices $\boldsymbol{A}$ and $\boldsymbol{X}$ are within coherence region, one cannot predict which detector clicks first: $\boldsymbol{X}$ or one of $\boldsymbol{A}_V, \boldsymbol{A}_H$. There is no causal order in coherence region, reflected by the fact that t_1, t_0 are interchangeable in (15). A causal order would mandate additional information beyond what is implanted in quantum state (8). The amount of information extracted by single measurement event, equals Boltzmann's entropy of event sample $H_\Omega = \ln \Omega = \ln(1!/1!\,0!) = 0$. It means, a single event in either device would not change the amount of information available for extraction by another device. Thus, there is no causality violation as there is no causal order in measurement events to begin with. It can be proven experimentally by placing separate detectors in paths $\boldsymbol{B}_V, \boldsymbol{B}_H$. These detectors would register random events with $1/2$ probability each. There is no way to tell from these events if there is any measurement done by detectors $\boldsymbol{A}_V, \boldsymbol{A}_H$[12]. This is the essence of no-signaling theorem [15].

The causality arises when amount of classical information extracted by one device reduces the amount of information available for extraction by another device. From above paragraph, it follows, the causal relationship can only be between event samples, not between individual events.

The change in amount of information available for extraction by device $\boldsymbol{X}$ due to the measurement by device $\boldsymbol{A}$ can be used for communication between experimenter controlling device $\boldsymbol{A}$, and observer of device $\boldsymbol{X}$. The experimenter at device $\boldsymbol{A}$ can modulate the amount of

[11] Taking $length(\boldsymbol{A}) = |\boldsymbol{r}_0|$ and $length(\boldsymbol{B}) = |\boldsymbol{r}_1|$, from (15) we obtain: $(t_1 - t_0)^2 = (|\boldsymbol{r}_1| - |\boldsymbol{r}_0|)^2$

[12] To confirm or deny the causal order, the experimenter can register the click time of each detector and mark points on the screen $\boldsymbol{X}$, where photon $\boldsymbol{B}$ has hit, with time of the corresponding click of detectors $\boldsymbol{A}_V$, $\boldsymbol{A}_H$. These marked points on screen $\boldsymbol{X}$ can be separated into two groups: one group of points for which detector $\boldsymbol{X}$ clicked first, and second group of points for which one of detectors $\boldsymbol{A}_V, \boldsymbol{A}_H$ clicked first. There is a causal order if group of points for which detector $\boldsymbol{X}$ clicked first exhibits interference pattern, while second group of points shows no interference pattern

extracted information[13] and thus affect the interference pattern at the screen $\boldsymbol{X}$. The measurement by two devices is subject to constraint (15), i.e., there is no superluminal causal relationship. Exactly this type of communication is used in common radio transmission, which also utilizes shared entangled state. Instead of different polarization modes as in (8), radio transmission is based on entanglement between modes of different frequency, with device $\boldsymbol{A}$ the transmitter, and device $\boldsymbol{X}$ the receiver. The interference pattern at device $\boldsymbol{X}$ is by time, instead of spatial coordinate.

The measurement transforms all or part of quantum information, implanted in quantum state, into classical information, thus reducing the quantum state. It is the classical information which is *real*, not the quantum state, which we devised only as a way to describe the measurement setup [5]. In fact, we cannot even describe the measurement setup without measurement, since any such description would require classical information, such as density matrix elements, which can only be obtained through measurement, the preparation of quantum state being a form of measurement.

The conclusions which follow from above discussion:

1. One cannot derive new information from already existing information. New information (knowledge) can only arise from new experience
2. There could be no theory which explains all the existing facts. Having such a theory means being able to obtain new information (explanation), from existing information (facts). A theory can only explain subset of existing facts, by correlating portions of existing information. The correlation logic, i.e., the theory itself, is part of existing information. If theory $\boldsymbol{T}$ explains facts, congruent to information domain $\boldsymbol{Q}$ (questions), the output is information domain $\boldsymbol{A}$ (answers), while theory itself is congruent to information domain $\boldsymbol{T}$ (transformation logic). These domains are parts of existing information $\boldsymbol{R} \ni (\boldsymbol{Q} \cup \boldsymbol{A} \cup \boldsymbol{T})$. This principle is realized in Gödel's Incompleteness Theorem [24], and in Turing's Halting Problem [25]
3. One cannot ascribe any level of reality to an object, even its existence, outside of measurement. Such attribution would mean creating information without measurement, out of nothing. The only thing real is the information extracted by the measurement
4. The information is physical. The extracted information, in amount of $H_\Omega = \log_2 \Omega\ (bits)$, is persisted in some encoded form, i.e., it is physicalized in an encoding structure, such as spacetime [2]. Each qubit of information is specified by a real-valued 4-vector, such as 4-vector of spacetime, or energy-momentum 4-vector, or other equivalent representation. What observer sees and feels are bits of encoded information
5. The information, being synonymous to objective facts, is absolute. In Wigner experiment, the information extracted by Wigner's friend affects the measurement performed by Wigner, even though Wigner and his friend are spacetime-separated. Wigner experiment is a form of double-slit experiment, where measurement at the slits is by friend, and measurement at the screen is by Wigner. It demonstrates the absoluteness of classical information, as information extracted by friend reduces information available for extraction

[13] The experimenter can, e.g., modulate PBS efficiency in path $\boldsymbol{A}$, or modulate length $\boldsymbol{A}$ in and out of coherence region

by Wigner. The information extracted by Wigner and his friend is part of the same spacetime structure

6. All paradoxes are artifacts of false assumptions. I expounded the falsehood of Wigner's friend paradox. Other paradoxes can also be easily disassembled. Perhaps one of the most chewed on paradoxes is the so-called black hole information paradox [26]. The paradoxical here is the apparent loss of information about object falling into black hole, assuming unitary dynamics of the whole system. This "paradox" is the perfect example of a falsehood built into very statement of the problem. The phrase "falling into black hole" implies knowledge of object's coordinates, which, in its turn, implies measurements extracting this information. The very fact of a measurement contradicts the assumption of unitarity. As object falls into black hole, all information about object gets extracted[14] by the time object reaches event horizon. The observer will not see anything actually ending up in black hole

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