Students Learn to Derive Nonlocality from Fundamental Physics

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Abstract

In everyday life, in smartphones, we use electromagnetic waves for telecommunication. These waves propagate at the velocity of light. Is telecommunication at superluminal velocity (at $v > c$) possible? Einstein (1907) wrote that no action can travel faster than light, as such action would imply a causality violation.

However, quantum physics includes actions that travel faster than light, see e. g. Einstein, Podolski and Rosen (1935). Accordingly, Einstein (1948) named such actions (at $v > c$) 'spukhafte Fernwirkung' or 'spooky action at a distance'. But Aspect, Grangier and Roger (1982) provided such action at $v > c$ in experiments with pairs of entangled photons. While this experiment demonstrates the seeming transfer of information at $v > c$, delayed-choice experiments do additionally demonstrate the seeming transport of energy and matter at $v > c$, see Jaques (2008) and Manning et al. (2015). Do these actions at $v > c$ violate the principle of causality? Does quantum gravity escape causality violation, as Hobson, Efstathiou and Lasenby hope (2006, p. 346)? Can such action at $v > c$ be used in telecommunications and quantum computers?

These questions are answered with help of the dynamics of volume in nature, the volume dynamics, VD, see Carmesin (2023a). The VD bridge general relativity and quantum physics. For these results, we provide a learning process, so that you can directly use the concept in your courses. The learning process has been tested in various learning groups, and experiences are reported.

1. Introduction

1.1. On Einstein's causality violation at $v > c$

Einstein (1905) proposed that the velocity of light is an invariant and universal constant, irrespective of the velocity of the object that emits the electromagnetic radiation. Indeed, this invariance can even be derived from the principle of superposition, see Carmesin (2022 a, section 7.8).

Moreover, Einstein (1907, p. 381) analysed how a velocity $w > c$ could imply causality violation, see Fig. (1):

Relative to a first system in Fig (1), there moves a second system with a velocity v. In that system, there moves an object or signal with a velocity w. As a consequence, the object moves with a velocity u relative to the first system. Thereby, u is the following function of v and w, see e. g. Einstein (1905, p. 906) or Burisch et al. (2022, p. 482):

$$u = \frac{v+w}{1+\frac{v\cdot w}{c^2}} \qquad \{1\}$$

As a consequence, in order to travel a distance dL from a point A to a point B relative to the first system, the object requires the following time dt:

$$dt = \frac{dL}{u} = dL \cdot \frac{1+\frac{v\cdot w}{c^2}}{v+w} \qquad \{2\}$$

If the velocity w is positive, and if the velocity v is negative with an absolute value $\bar{v} = |v|$, then the required time is as follows:

$$dt = dL \cdot \frac{1-\frac{\bar{v}\cdot w}{c^2}}{w-\bar{v}} \qquad \{3\}$$

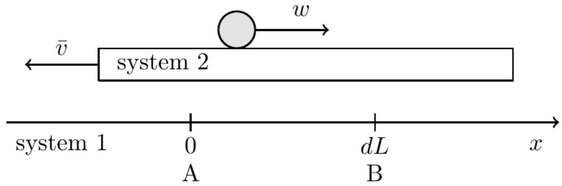

Fig. 1: Einstein (1907, p. 381) proposed the following situation: In a system 1, a system 2 moves at a velocity $\bar{v}$ to the left. In system 2, an object or signal moves at a velocity w to the right. Thus, in system 1, the object moves at a velocity u. The time dt is analysed, that the object requires for a motion from a Point A at $x = 0$ to a point B at $x = dL$.

Einstein (1907, p. 381) argues, that the time dt can become negative at appropriate values of the velocity v, and that negative times indicate causality violation. We analyse the velocity u and the required time dt as a function of the absolute velocity $\bar{\boldsymbol{v}}$, see Fig. (2):

As an example, we use $w = 2c$ and $dL = 10$ m, without loss of generality in principle. There occur three qualitatively different cases, see Fig. (2):

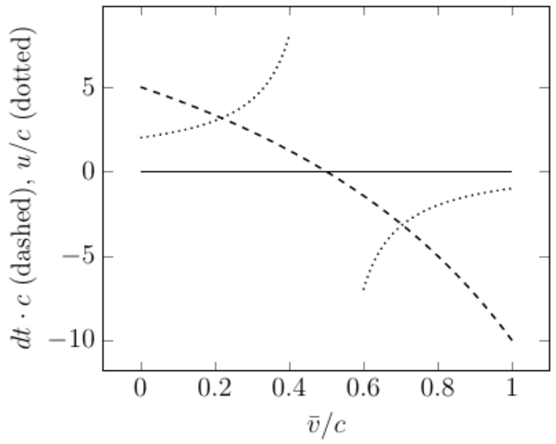

Fig. 2: Required time $dt \cdot c$ (dashed) and velocity $\frac{u}{c}$ (dotted) as a function of the velocity $\frac{\bar{v}}{c}$ in the example proposed by Einstein (1907, p. 381). Hereby, for instance, $w = 2c$ and $dL = 10$ m have been chosen. At $\frac{\bar{v}}{c} = \frac{1}{2}$, the velocity $\frac{u}{c}$ diverges, and the time dt becomes zero. At $\frac{\bar{v}}{c} > \frac{1}{2}$, the velocity $\frac{u}{c}$ as well as the time dt become negative: We interpret that case as follows: The object moves to the left and might have been at the point B in the past, accordingly, $dt < 0$.

(1) At $\bar{v} < 0.5\,c$, the object has a positive velocity u. Thus, it reaches the point B after a positive time $dt > 0$. This motion is in accordance with causality.

(2) At $\bar{v} = 0.5\,c$, the velocity u diverges and is not defined by Einstein's (1907) relation in Eq. {1}. In spite of the undefined velocity, the time dt that converges to zero and is zero according to Eq. {3}. Thus, in the limiting case $\bar{v} = 0.5\,c$, the required time is zero, $dt = 0$.

(3) At $\bar{v} > 0.5\,c$, the velocity u is negative. A negative u describes a motion of the object to the left, with respect to the system 1. In such a motion, an object starting at the point A does never reach the point B in Fig. (1). More generally, in such a motion, the object could have been at the point B in the past, described by $dt < 0$. Thus, the case 3), the velocity $u < 0$ with the time $dt < 0$ describe a causal motion, as the product of the velocity and the time is positive, see Fig. (2). More generally, in all cases 1) and 3), at which u is defined by Eq. {1}, the product of the velocity and the time is positive, see Fig. (2), so that a causal motion is described.

(4) In spite of that fact, Einstein stated that the negative time dt would imply causality violation (1907, p. 381-382): ‘Dies Resultat besagt, dass wir einen Übertragunsmechanismus für möglich halten müssten, bei dessen Benutzung die erzielte Wirkung der Ursache vorangeht.‘ In English: , This result states, that we must accept a mechanism of transmission, that provides an effect before the cause has taken place.’

(5) Additionally, Einstein (1907, p. 381-382) stated the impossibility of $w > c$: ‘…, dass durch dasselbe die Unmöglichkeit der Annahme $w > c$ zu Genüge erwiesen ist.‘ In English: ,…, that by this the impossibility of the assumption $w > c$ is sufficiently proven.’

What can we learn from Einstein's (1907, p. 381-382) example?

(1) If an effect occurs before its cause has taken place, then causality is violated.

(2) Einstein's example can be interpreted with a causal motion in all cases with a defined value of the velocity u, see Fig. (2) and the cases (1), $\bar{v} < 0.5\,c$, and (2), $\bar{v} = 0.5\,c$.

(3) In the addition of velocities in Einstein's example, an assumed velocity $w > c$ can give rise to $dt < 0$. This could be interpreted as a causality violation, if the interpretation with causal motions in 1) and 3) is not discussed. Indeed, Einstein did not discuss these motions in (1), $\bar{v} < 0.5\,c$, and 3), $\bar{v} > 0.5\,c$, and he proposed the interpretation of causality violation. However, as a consequence, his analysis is incomplete. Thus, his interpretation in the above item (4) of his example as a causality violation is hardly convincing.

(4) At this point, we apply the contraposition: A velocity u that is well-defined by Eq. {1} implies the impossibility of $w > c$. In this sense, we agree with Einstein's statement in the above item 5) that the impossibility of $w > c$ is proven (if u has to be well-defined by Eq. {1}).

(5) In the sense of the above item (4), velocities $w > c$ appear not realistic or ‘spooky’ in relativity.

(6) In the case 2), the required time dt is zero, see Fig. (2). Thus, an object with $w > c$ can reach each location at zero required time, with help of the addition of velocities. Accordingly, such a system can be named nonlocal.

(7) Accordingly, the following criterion for quantum nonlocality can be formulated: Objects that are not fully separated (or consisting of stochastic dependent components alias entangled components) or that propagate at superluminal velocity, $w > c$, have the property of quantum nonlocality.

Can quantum nonlocality be observed, and how are results obtained?

1.2. Epistemology

Kircher, Girwidz und Häußler (2001, section 4.1.2) describe the hypothetic deductive method. In the epistemological literature, this method is also called hypothetico-deductive testing (Niiniluoto, Sintonen, Wolenski 2004, S. 214). The method consists of three steps: In the hypothetic step, a thesis or hypothesis is suggested for testing. In the deductive step, implications are derived. In the third step, the implications are compared with observation. Hereby, in principle, a falsification should be possible. This method is used here as well as in Carmesin (2024a-g, 2017, 2018a-b, 2019a-b, 2020a-c, 2021a-d, 2022a-c, 2023a-f).

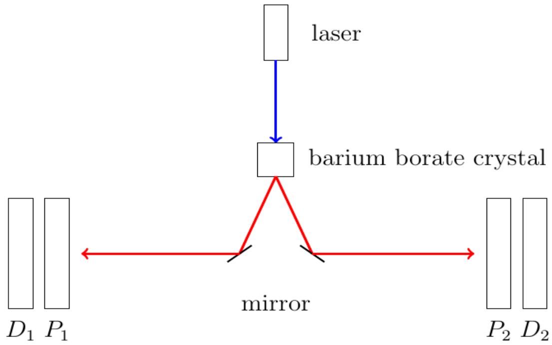

Fig. 3: Pairs of entangled photons are generated in a barium borate crystal. These photons are directed to two observers with polarizers P_1 and P_2 and detectors D_1 and D_2.

1.3. A pair of photons shows action at $v > c$

A pair of entangled photons are generated, see Fig. (3). Hereby, the polarization of one of the two photons at detector D_1 is correlated with the polarization of the other photon at D_2. Thereby, the two polarizations are different, for instance vertical and horizontal. Hereby, the measurement includes the polarizer and the detector. For instance, observer 1 polarizes the photon with P_1 and then measures with D_1.

However, if the photon at P_1 is polarized with P_1, then the state of the entangled pair is changed at the same time. Consequently, the state of the other photon is changed without loss of time. These instant changes of the polarization state of the other photon at a distance have been checked in many experiments, see e. g. Aspect, Grangier and Roger (1982). For a detailed analysis, see Carmesin (2023a). These changes take place at a velocity above the velocity of light. Consequently, this experiment shows nonlocality.

1.4. A delayed-choice experiment

Jaques et al. (2008) performed the delayed-choice experiment in Fig. (4). It is based on a Mach-Zehnder Interferometer, MZI. Single photons enter the MZI. The second beam splitter operates in one of two modes:

Mode 1: If the second beam splitter has the reflectivity 0.5, then the photon exhibits interference:

In detector D_1, the wave at the solid line accumulates the phase shift π at the right mirror. Moreover, the wave at the dashed line accumulates the phase shift π at the left mirror plus two phase shifts of $\pi/2$ at each beam splitter. Altogether, the phases of the two paths differ by π. Thus, there occurs destructive interference at D_1.

In detector D_2, the wave at the solid line accumulates the phase shift π at the mirror plus the phase shift $\pi/2$ at the second beam splitter. Moreover, the wave at the dashed line accumulates the phase shift π at the mirror plus the phase shift of $\pi/2$ at the first beam splitter. Altogether, the phases of each path is $3\pi/2$. Thus, there occurs constructive interference at D_2. Hence, the photon occurs at D_2. In the experiment, the interference showed a visibility of 94 %.

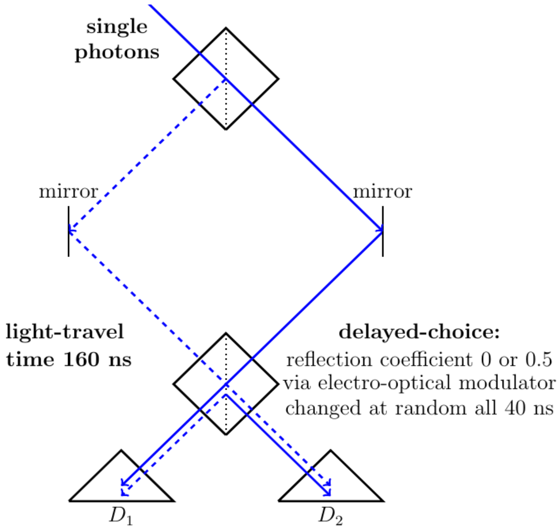

Fig. 4: Mach-Zehnder Interferometer: The second beam splitter is switched at random from reflectivity 0 to 0.5 and vice versa.

Mode 2: If the second beam splitter has the reflectivity 0., then the photon is transmitted, and there occurs no interference:

The wave function Ψ splits at the first beam splitter into $\Psi/\sqrt{2}$ in the solid path and $\Psi/\sqrt{2}$ in the dashed path. Thus, there occurs the probability $0.5\Psi^2 = 0.5$ at each detector. As the photon is quantized, it occurs in one detector, and it does not occur in the other detector. Consequently, the detection of the photons is anticorrelated. In the experiment, the anticorrelation parameter $\alpha = 0.12$ is observed.

Altogether, the second beam splitter operates in the delayed-choice mode, as a new choice is generated at random every 40 ns. Thereby, the light-travel time of a photon from the first beam splitter to the second one is 160 ns. Consequently, the wave function passed the first beam splitter, when the choice is generated.

Interpretation:

Particle interpretation: In a classical particle interpretation, one might assume that the photon uses one of the two paths after the first beam splitter.

That interpretation describes the experiment in the mode (2) with reflectivity 0.

However, that interpretation does not describe the experiment in the mode 1 with reflectivity 0.5. In this mode, interference is observed. This falsifies the particle interpretation.

Wave interpretation: In a classical wave interpretation, one might assume that the wave functions $\Psi/\sqrt{2}$ propagate in each path.

That interpretation describes the experiment in the mode (1) with reflectivity 0.5, as interference is observed.

However, that interpretation does not describe the experiment in the mode 2 with reflectivity 0. In the wave interpretation, in each detector, there should occur 50 % of all photons, without any anticorrelation. This interpretation is falsified by the observed anticorrelation.

Moreover, in each detector, there would be insufficient energy for the detection of a complete photon. However, in the wave interpretation, only one half of the squared wave function arrives at each detector.

Is it possible that each interpretation explains one of the modes? For it, the quantum object must make its choice at the first beam splitter in accordance with the choice made at the second beam splitter at a time t_2. For it, the object must start at the first beam splitter at the time t_2, then the object must propagate at superluminal velocity, in order to arrive in time at the detectors. In this sense, the delayed-choice experiment is an example of nonlocality. Moreover, similar delayed-choice experiments have been performed with atoms, see Manning et al. (2015).

1.5. **Organization of the paper**

A didactic analysis including a professional analysis is provided in section 2. The learning process including experiences with learning groups are shown in part 3. We discuss our findings in section 4. Many useful and insightful related results are presented in my parallel papers in the report about the DPG conference in March 2024 in Greifswald, see Carmesin (2024a-g).

2. **Didactic analysis**

2.1. **Universal nonlocal quantization**

2.1.1. **Physical analysis**

(1) Derivation of a universal quantization:

If monochromatic light with a circular frequency ω falls down towards a mass M, then a minimal portion of energy E_{min} has the momentum $p_{min} \cdot c$, according to special relativity.

Moreover, the minimal portion has the wave number $k = \omega/c$. As a consequence, wave theory and special relativity imply the following relation:

$$\frac{E_{min}}{p_{min}} = c = \frac{\omega}{k} \qquad \{4\}$$

This relation is solved for $\frac{E_{min}}{\omega}$:

$$\frac{E_{min}}{\omega} = \frac{p_{min}}{k} = K(\omega) \qquad \{5\}$$

The above two ratios are equal, and they are named $K(\omega)$. Using gravity caused by the mass M and general relativity, it has been shown in Carmesin (2023a-b), that this ratio $K(\omega)$ is the same for each ω. Thus, that ratio is a universal constant of quantization.

(2) Value of the universal constant of quantization: Based on the wave theory of light and on special relativity, that universal constant of quantization could have the value zero, in principle. In that case, the minimal energy portion would have the energy zero. Such a quantization would not differ from classical physics. $K > 0$ is derived in Carmesin (2024g). In fact, the value of the universal constant K is measured. Its value is the Planck constant divided by 2π:

$$K = \frac{h}{2\pi} \;\&\; h = 6.626\,070\,15 \cdot 10^{-34}\ \text{Js} \qquad \{6\}$$

(3) Derivation of universal nonlocality:

The nonlocal delayed-choice experiment in Fig. (4) can be used in the vicinity of the mass M, so that all derived results about the universal quantization apply (of course, these results would also apply without M):

a) At each circular frequency ω, there occurs a minimal energy portion E_{min}.

b) Consequently, a detector can measure either one or zero minimal energy portions E_{min}, irrespective of the value of the universal constant of quantization K.

c) As a consequence, the observations in the delayed-choice experiment in Fig. (4) are fully implied by the wave property of light combined with special & general relativity.

These results are summarized:

Theorem: Law of the derived universal quantization and universal nonlocality:

Special & general relativity combined with the wave property of light imply the following:

(1) Light with a circular frequency ω forms minimal portions of energy $E_{min}(\omega)$ and of momentum $p_{min}(\omega)$ with a quantization constant K as follows:

$$\frac{E_{min}}{\omega} = \frac{p_{min}}{k} = K \qquad \{7\}$$

The quantization constant is the same for all ω. In this sense, K is universal.

(2) The value of K in SI units is measured, shown in Eq. {6} and named reduced Planck constant $K = \hbar$.

(3) The implied quantization in parts (1) and (2) implies quantum nonlocality in the delayed-choice experiment in Fig. (4), irrespective of the value of the quantization constant.

Similarly, the implied quantization in parts (1) and (2) implies quantum nonlocality in all experiments and systems in nature, in which light exhibits quantum nonlocality in a manner not depending on the value of the quantization constant. In this sense, quantum nonlocality is universal.

Comments:

(1) It can be shown that the constant K of quantization must be nonzero, see Carmesin (2024g).

(2) It is insightful that universal quantum nonlocality is inherent to special & general relativity combined with the wave property of light.

(3) However, an essential question remains: How can objects achieve quantum nonlocality as described in the criterion in section (1.1)?

(4) Moreover, an important question remains: Is quantum nonlocality a causality violation?

2.1.2. Didactic analysis

In a first didactic step, the universal quantization is derived from the wave property of light and from special & general relativity. Hereby, a very direct, clarifying and insightful way to general relativity is used, see Carmesin (2023a, 2024f). As a consequence, this step has no special learning barrier.

In a didactic step (2), the Planck constant is measured, see e. g. Carmesin (2020a, c). This step has no special learning barrier.

In a didactic step (3), the universal nonlocality is derived from the wave property of light and from the derived universal quantization in step (1). Thereby, the intuitive and clear delayed-choice experiment in Fig. (4) is used. As a consequence, this step has no special learning barrier.

2.2. No substantial transport

2.2.1. Physical analysis

In quantum physics, the propagating object is the wave function. In the VD, it is equal to the time derivative $\Psi = t_n \cdot \dot{\varepsilon}_L$ of the relative additional volume ε_L, multiplied by a normalization factor, see Carmesin (2022a-b, 2023a, 2024a). The wave function must be related to the relative additional volume, as in this manner, it provides the Schrödinger equation, see Carmesin (2022a-b, 2023a, 2024a). Moreover, the wave function must be proportional to the time derivative of ε_L, as in this manner, it provides the correct probabilities proportional to $|\Psi^2|$, as the generalized kinetic energy density is proportional to $\dot{\varepsilon}_L^2$, and that energy density is proportional to the probability, see Carmesin (2022a-b, 2023a, 2024a). As a consequence, the propagating object, the wave function, is not substantial like the relative additional volume ε_L, as Ψ represents the derivative only. Furthermore, the relative additional volume has a generalized field, which is an exact version of the gravitational field with an energy density $u_{gr.f.}$, see Carmesin (2021a-b, 2022a-b, 2023a, 2024a). Moreover, each harmonic solution of the DEQ of the volume-dynamics, VD, has a generalized kinetic energy density $u_{gen,kin}$, see Carmesin (2021a-b, 2022a-b, 2023a, 2024a). Thereby, $u_{gr.f.}$ and $u_{gen,kin}$ compensate each other, $u = u_{gr.f.} + u_{gen,kin}$. Thus, the complete energy density of a harmonic solution, corresponding to a harmonic wave function, vanishes. According to the Fourier analysis, a general wave can be described as a linear combination of harmonic solutions, in the form of a Fourier integral, see e. g. Schiff (1991).

As a consequence, a nonlocal transport by a wave function does not necessarily cause a transport of a physical entity, such as ε_L, or of a complete energy density u.

Of course, observables are represented by self-adjoint operators, such as the momentum operator $-i\hbar\partial_x$, or the energy operator $i\hbar\partial_\tau$. These provide the values that can be measured by a corresponding measurement device, the eigenvalues with corresponding probabilities. In principle, such a process can be provided by the VD, for instance, a stationary local quantum can form at the detector, see Carmesin (2023a, d).

Altogether, the above discussed facts show that in the VD, in general, an object does not travel at a path taken by the wave function.

2.2.2. Didactic analysis

In one didactic step, it is summarized, how the VD describes the correct observable eigenvalues and the corresponding probabilities, without describing the propagation of any substance. This step has an intermediate mental learning barrier, as in everyday life, many objects appear to be transported at paths. However, also in everyday life, there are other examples. For instance, the optimal visual acuity can be understood with help of the Heisenberg uncertainty relation, see Carmesin (2020c). Such examples are used in order to overcome that mental barrier. With it, there is no special remaining learning barrier in this step.

2.3. Explanation of nonlocality by the dynamics of volume in nature

2.3.1. Physical analysis

(1) How objects achieve quantum nonlocality:

a) Propagation:

The law of propagation of relative additional volume shows that volume-portions, VPs $\varepsilon_L(\tau, \vec{L})$, propagate according to the following DEQ, see Carmesin (2023a, 2024a):

The relative additional volume $\varepsilon_L(\tau, \vec{L})$ fulfils the following differential equation, DEQ:

$$\frac{\partial}{\partial \tau}\, \varepsilon_L = -v \cdot \vec{e}_v \cdot \frac{\partial}{\partial \vec{L}}\, \varepsilon_L \quad \text{with} \quad v = c \quad \{8\}$$

The law of the derived Schrödinger equation, SEQ, in Carmesin (2024a) shows that the wave function is the product of the time derivative $\dot{\varepsilon}_L$ of the relative additional volume ε_L and a normalization factor t_n, thus: $\Psi = t_n \cdot \dot{\varepsilon}_L$. And the normalization factor is t_n.

b) Subspace:

Thus, the solutions ε_L of Eq. {8} form a vector space. Similarly, the time derivatives $\dot{\varepsilon}_L$ thereof and the wave functions Ψ form a vector space. It is the Hilbert space H in quantum physics. Note that these are solutions of a generalized Schrödinger equation, GSEQ, see Carmesin (2024a). In a particular physical system, the solutions of the GSEQ form a subspace of H_1.

c) Preparation or measurement:

Each measurement provides a preparation of the state. Each such preparation switches from a subspace H_1 of solutions of the GSEQ to subspace H_2 of the subspace H_1 of solutions of the GSEQ. Such a change of solutions represents a transient phenomenon in the theory of solutions of linear differential equations, whereby that transient phenomenon can be described with help of the Laplace transform, see Schiff (1991).

d) Transient phenomenon:

Einstein's (1907, p. 381-382) example in section (1.1) shows that a local signal of object cannot move or propagate faster than the velocity of light.
However, a harmonic solution of the DEQ {8} of the VD does not represent such a local signal or object, as a harmonic solution can be represented by a sine function and a cosine function, both ranging from minus infinity to plus infinity, mathematically. At least these solutions range from one point of the light horizon to the opposite point of the light horizon, as long as observable states are causally related.
Thus, such a harmonic function could in principle propagate at a velocity $v > c$, in accordance with the example proposed by Einstein (1907) in section (1.1). For it, the DEQ {8} is generalized to the case of a velocity v that is not restricted to c, for the case of such harmonic functions. This generalization is adequate and possible, as the development of the DEQ {8} in Carmesin (2024a) can be performed for any velocity v. This shows, that the propagation of a VP can be described by a generalized version of DEQ {8}, at which the only difference to DEQ {8} is the fact that the velocity v can take any value:

$$\frac{\partial \varepsilon_L}{\partial \tau} = -v\vec{e}_v \frac{\partial \varepsilon_L}{\partial \vec{L}}, \text{for harmonic } \varepsilon_L(\tau, \vec{L}) \quad \{9\}$$

That generalized DEQ is applicable to these harmonic functions.
The transient phenomenon can be achieved by a linear combination of such harmonic solutions of the DEQ, see Schiff (1991) or Carmesin (2023a).

Based on such harmonic functions, the change of the subspace H_1 to a subspace H_2 thereof, caused by a measurement, could take place without restriction by c. Of course, this includes one-dimensional subspaces of H. In this manner, quantum nonlocality caused by measurements or preparations at a quantum system could be explained by harmonic solutions of the DEQ of the VD with $\boldsymbol{v} > \boldsymbol{c}$, see Eq. {9}. The mathematical details of the Laplace transform and of the transient phenomenon are elaborated in Carmesin (2023, chapter 16).

e) Applicability:

i) In the experiment in Fig. (3), the measurement at a detector causes the nonlocal change of the state. It is explained by the rapid transient phenomenon provided by the harmonic solutions of the DEQ {9}.

ii) In the experiment in Fig. (4), there are mode 1 and mode 2 with reflectivity 0.5 or 0, respectively:

In mode 1, the wave function Ψ of the photon propagates in both paths of the MZI, as shown by the interference pattern. Thus Ψ is separated into two stochastic dependent components. Thus, according to the criterion of quantum nonlocality in section (1.1), the photon is nonlocal in mode 1.

In mode 2, the photon is detected by one of the detectors, for instance by D_1, and not by D_2. This is shown by the observed anticorrelation, within the experimental accuracy. Thus, at the moment of the detection by D_1, the subspace of H with the wave function at both detectors switches to a subspace with the wave function at D_1 and not at D_2. That change is achieved by the superluminal transient phenomenon provided by the harmonic solutions of the DEQ {9}. Thence, the photon is nonlocal in mode 2 as well.

iii) In general, there are two possible sources of quantum nonlocality, see the criterion in section (1.1):

Entanglement: The wave function propagates in the form of stochastic dependent (alias entangled) components of the object.

Transient phenomenon: A measurement or preparation of the object causes the superluminal change of the subspace of H via the superluminal transient phenomenon provided by the harmonic solutions of the DEQ {9}.

In both cases, the quantum nonlocality is explained by the dynamics of volume in nature, as described by the DEQs {8} and {9}.

(2) Is quantum nonlocality a causality violation?

a) The argument proposed by Einstein (1907, p. 381-382) is a good argument for the fact that local signals or objects cannot move at $w > c$. However, the statement that $w > c$ would imply causality violation is not fully convincing, see section (1.1). Nevertheless, we analyse the possibility of causality violation. There are two sources of quantum nonlocality, see section (1.1):

b) Entanglement: The wave function propagates in the form of stochastic dependent (alias entangled) components of the object.

That propagation takes place at velocities w that do not exceed the velocity of light, $w \leq c$. Consequently, that source of quantum nonlocality does not violate causality as discussed by Einstein, as $w \leq c$.

c) Transient phenomenon: A measurement or preparation of the object causes the superluminal change of the subspace of H via the superluminal transient phenomenon provided by the harmonic solutions of the DEQ {9}.

The transient phenomenon is achieved by harmonic solutions propagating at $w > c$. However, these do not provide a local motion of energy, as a harmonic solution does not even define a local position of energy. Thus, these harmonic solutions do not violate causality. Correspondingly, such solutions are not included in Einstein's (1907, p. 381-382) analysis of causality violation.

Moreover, the effect of the transient phenomenon does not enable the emission of an object in the form of an information or energy E or mass $m = \frac{E}{c^2}$ at a point A and the arrival of that object at a point B according to a superluminal velocity. Thus, the effect of the transient phenomenon does not violate causality violation.

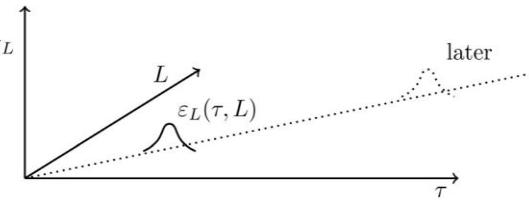

Fig. 5: A portion of relative additional volume ε_L propagates in space. The relative additional volume is analysed as a function of τ and $\vec{L}$.

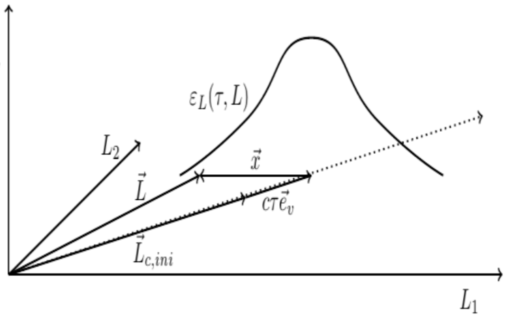

Fig. 6: A volume-portion with an initial position of the centre at $\vec{L}_{c,ini}$. The VP moves, e. g. during a time τ, the centre moves to $\vec{L}_{c,ini} + c\tau\,\vec{e}_v$. The VP has a form (similar to an orbital in an atom). For instance, a part is shifted by a vector $\vec{x}$ from the centre, so the part is at a coordinate $\vec{L}$, in an external frame. In particular, these relations hold in an incremental manner.

These results are summarized:

Theorem: Law of the mechanisms underlying quantum nonlocality:

(1) A measurement or preparation at a quantum object or quantum system can change the subspace H_{sub} of Hilbert space H, that describes the state of the object or system. In particular, that H_{sub} can be a one-dimensional subspace of H. Such a change of H_{sub} represents a transient phenomenon in the space of solutions of the DEQ {9}. Such a transient phenomenon can be achieved by harmonic solutions, see Schiff (1991) of the respective DEQ {9}. The velocity of propagation of harmonic solutions of DEQ {9} is not restricted by the velocity of light. Thus, the transient phenomenon can cause superluminal changes of H_{sub}. This explains the mechanism of the observed and observable superluminal changes of states in quantum objects, quantum systems and quantum nonlocality by the dynamics of volume in nature, the volume-dynamics, VD, see Eqs. {8} and {9}. Thus, the VD explain the measurement based source of quantum nonlocality.

For the case of localized VPs, the VD is represented by the DEQ {8}. For the case of harmonic functions, the VD is represented by the DEQ {9}. Both DEQs {8} and {9} describe the same process of propagation, formation and evolving form of VPs, see Figs. (5) and (6), see Carmesin (2023a, 2024a-b).

(2) The DEQ {8}, describing the VD, can cause a separation of a wave function into stochastic dependent (alias entangled) parts. Thus, the VD explains the propagation based source of quantum nonlocality.

(3) There is no unequivocal empirical or theoretical proof of a causality violation provided by quantum nonlocality.

2.3.2. Didactic analysis

In a first didactic step (1), the following question is answered: How objects achieve quantum nonlocality?

For it, the transient phenomenon is identified and applied. This didactic step has an intermediate learning barrier, as several facts about the solutions of linear differential equations are combined.

This learning barrier is overcome as follows: For the case of harmonic functions, the DEQ {8} with $v = c$ is generalized to the DEQ {9}. A measurement can provide an change of subspace H_{sub} of Hilbert space H at a superluminal rate. That change is explained by the DEQ {9}. Thereby, the DEQ {8} and {9} describe the same process of propagation, formation and evolution of form of VPs. On that basis, this didactic step has no remaining special learning barrier.

In a didactic step (2), the following question is answered: Is quantum nonlocality a causality violation?

For it, the criterion of quantum nonlocality in section (1.1) is used and the results of step (1) are applied.

On that basis, this didactic step has no remaining special learning barrier.

3. Experience: learning process and learners

The experiences with learning groups have been documented in terms of photographs of the blackboard and with help of additional reports. These are summarized as follows.

Since 2023, see Carmesin (2023a), the topic has been presented in several general studies courses at the university. The learning process was enriched by a permanent discussion of the achieved results and by exercises about the derived relations. In particular, the learning process took place as follows:

In a first unit, the concepts of causality violation and of quantum nonlocality have been treated, see section (1.1). That unit requires 90 minutes, if the mathematics of the statistical analysis in the experiment in Fig. (3) is elaborated, see Carmesin (2023a, chapter 16). Without that analysis, the unit can be treated in 45 minutes. The students stated that the analysis in section (1.1) is very clear.

In a second unit, the very insightful and valuable universal quantization, see Carmesin (2023a, b, f), and universal nonlocality are derived in a very direct and clarifying manner. As this topic uses very direct and efficient methods only, the unit can be treated in 45 minutes. In discussions, the students appreciate the clarity and efficiency of the derivation. However, students that are already familiar with the dynamics of volume in nature say that they do not need this direct and relatively elementary derivation.

A unit three requires 45 minutes, see section (2.2). In that unit, the fact is summarized that the wave function does not transport any substance, in the VD. The students think that this is quite intuitive.

In a fourth unit, the DEQ {9} is used. With it, the concept of the transient phenomenon is introduced and applied. That unit requires 90 minutes, if the mathematics of the Laplace transform is examined, see Carmesin (2023a, chapter 16). Without that analysis, the unit can be treated in 45 minutes.

In a fifth unit, the results derived in the above units are used in order to discuss and exclude causality violation. That part requires 45 minutes. Depending on the interests of the learning group, quantum cryptography is treated as an innovative and exciting application of quantum nonlocality. This requires additional 45 minutes, see e. g. Carmesin (2020c). Moreover, quantum computing can be treated as an innovative and momentous application of quantum nonlocality, see e. g. Carmesin (2024h). This requires at least additional 90 minutes.

A quantum gravity group of a research club meets 90 minutes each week. Thereby topics such as quantum computers, cosmology, astrophysics or quantum gravity are treated. In that group, essentially the same learning process has been treated in several courses since 2022. Also in this case, all questions have been discussed directly, and exercises have been performed.

Altogether, in all learning groups, the learners asked questions. These have been discussed directly in a fully sufficient manner. Moreover, exercises have been used in order to achieve sufficient training, metacognitive activity and familiarity with the new concepts. In some of the exercises, the students were instructed so that they were able to achieve parts of the derivations on their own. This is an efficient test of the ability of the students, and it provides self-esteem to the students in a convincing manner.

4. Discussion

Telecommunication is an essential tool for our everyday life. Moreover, causality is a fundamental concept for the organization of our everyday life and knowledge. Both concepts are challenged by the observed quantum nonlocality. Moreover, quantum nonlocality is the basis for ground breaking future technologies such as quantum cryptography and quantum computing. Thus, the present topic is very exciting and interesting to students.

In a first unit, the experiments and their challenging implications are analysed. As an important result, a very valuable and insightful criterion for quantum nonlocality is elaborated, see section (1).

On that basis, the universal nature of quantum nonlocality is derived in a second unit.

In a third unit, the underlying mechanisms are elaborated: The volume dynamics, VD, is based on one process of propagation, formation and evolution of form of volume-portions, VPs. That process is described in the DEQs {8} and {9}, see Figs. (5) and (6). That VD explains the quantum nonlocality that is provided by a measurement or preparation. That VD also explains gravity and curvature of space and time. Moreover, that VD solves many problems in physics, see e. g. Carmesin (2023a, 2024a-g).

In a fourth unit, the possibility of causality violation is examined. It is argued that there is no unequivocal empirical or theoretical proof of the idea that quantum nonlocality could provide causality violation. Depending on the learning group, the full mathematical depth can be achieved and innovative applications can be treated. Accordingly, the topic requires between 180 and 450 minutes.

Altogether, we show how the quantum nonlocality and possible causality violations in nature can be treated, analysed and explained in a founded manner. Thereby, we derive the universality as well as the underlying mechanisms of these phenomena. In particular, we show how clarifying criteria for quantum nonlocality and possible causality violation can explain the sources of quantum nonlocality and can exclude that these sources can provide a causality violation.

The learning process is based on the hypothetic deductive method, see the section about the epistemology. Such a testing of a hypothesis and such a deduction from prior knowledge have a high learning efficiency, see Hattie (2006). Moreover, the learning process uses everyday life contexts, so that the learning is meaningful, see Muckenfuß (1995) and achieves an additional high learning efficiency, see Hattie (2006). In the particular case, applications to quantum cryptography and quantum computing are very motivating. For more interesting examples, see Carmesin (2020c).

The learning process has been tested in several learning groups. The learning process includes four units with a minimum of 45 minutes for each unit. Additionally, there are insightful and valuable deepening extensions, so that the time required for the four units adds up to 450 minutes. This has been tested at university courses as well as in research club courses. In all these learning groups, the students were able to perform exercises and to use instructions in order to derive parts of the theory. Thus, the topic provides a large amount of self-esteem to the learners.

5. Literature

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