Space and Time: Back to Aristotle!

Gerold Gründler [1]

In modern physics, space and time are introduced as basic notions, while they had been secondary, derived notions in the physics of Aristotle. In this essay the big advantages are outlined, which make a regress to the Aristotelian notions of space and time very attractive for (both quantum and classical!) modern physics.

1. The notion of space in Newtonian and Aristotelian physics

If we want to define a notion, then in that definition we must make use of other notions. To define those other notions, we must make use of again other notions. To sidestep an infinite regress, we unavoidably must have besides the defined, secondary notions a set of undefined primary notions, usually called basic notions, the meanings of which we must know without definitions.

Newton considered space a basic notion. In the "Scholium", which he appended to the "Definitiones" of secondary notions at the beginning of the "Principia Mathematica" [1], he remarks:

> "Absolute space [Latin: spatium], which according to it's nature is not related to anything external, remains always similar and immovable. Relative space is an indefinite variable measure or dimension of that absolute space, which is defined by our senses according to it's position [Latin: situs] relative to bodies [...]. (1)

[1] email: gerold.gruendler@astrophys-neunhof.de

> Place [Latin: locus] is a part of space which a body takes up [...]. I emphasize: a part of space; not the position of the body, nor the surface of it's surroundings." [2]

Thus Newton makes a clear distinction between absolute space, which is a basic notion, and relative space, which is merely a "measure or dimension" of space.

Relative space is defined by coordinates, which may be aligned e. g. to far-distant stars, or whatever other objects. Note that the far-distant stars or other objects are not creating the space. Instead the space is there first (i. e. a basic notion), and by chance within the space there is some content, like stars or other objects, relative to which coordinate systems can be aligned.

When Newton emphasizes that his space concept doesn't refer to "the position of the body" nor to "the surface of it's surroundings", then he is rejecting an older space concept, which had dominated science in Europe for two thousand years, and was still popular in Newton's days. That older concept can be traced to ancient Greece, and in particular to the writings of Aristotle. In βίβλος Δ (= book 4) of the "Physics", Aristotle defines the position of a body as follows:

> "The position [Greek: τόπος] [... of a body] is the surface of the surrounding body." [3] (2)

Here *body*, *surface*, and *surrounding* are basic, undefined notions, while *position* — and consequently *space*, being the entirety of the

[2] "Spatium absolutum, natura sua sine relatione ad externum quodvis, semper manet similare & immobile: Relativum est spatii hujus mensura seu dimensio quaelibet mobilis, quae a sensibus nostris per situm suum ad corpora definitur [...]. Locus est pars spatii quam corpus occupat [...]. Pars, inquam, spatii; non situs corporis, vel superficies ambiens." [1, 3rd ed., page 6]

[3] «τὸν τόπον εἶναι [...] τὸ πέρας τοῦ περιέχοντος σώματος.» [2, 212a5+6] Aristotles writings are conventionally cited by the page (in this case 212), column (in this case a for left column), and lines (in this case 5 and 6) of the 1831 – 1870 Bekker edition, see https://en.wikipedia.org/wiki/Bekker_numbering.

positions of all bodies[4] — are secondary notions. With Aristotle's concept, there can be no space, unless it contains bodies which are surrounded by other bodies. With Newton's concept, there can be no bodies, unless they are located within space.

2. The notion of time in Newtonian and Aristotelian physics

In the "Principia" [1, 3rd ed., page 6], Newton explains:

> "The absolute, true, and mathematical time [Latin: tempus] is flowing evenly, by itself and by it's nature without relation to anything external; it is also called duration [Latin: duratio]: The relative, apparent, and common [time] is some (either accurate or only rough) sensible and external measure of duration due to motion [Latin: motum], which commonly is used instead of the true time; like hour, day, month, year." [5] (3)

Newton emphasizes that time is not created by motion; instead time is there first, i. e. a basic notion. If by chance some motion is happening in the course of time, then from that motion an "external measure" of time can be derived. Thereby Newton is rejecting the older time concept, which Aristotle explicates in the "Physics":

> "We measure not only the movement [Greek: κίνησις] by the time [Greek: χρόνος], but also the time by the move- (4a)

[4] This is a modern extrapolation. Aristotle stopped at the definition of position, and obviously felt no need to consider the totality of all positions.

[5] "Tempus absolutum, verum, & mathematicum, in se & natura sua sine relatione ad externum quodvis, aequabiliter fluit, alioque nomine dicitur duratio: Relativum, apparens, & vulgare est sensibilis & externa quaevis durationis per motum mensura (seu accurata seu inaequabilis) qua vulgus vice veri temporis utitur; ut hora, dies, mensis, annus." [1, 3rd ed., page 6]

> ment, they are determined by each other. [...] As time is the measure [Greek: μέτρον] of movement, it is consequently as well the measure of rest; [...] for time is not movement, but the number [Greek: ἀριθμὸς] of movement; in the number of movement, the rest is comprised as well." [6]

The first sentence seems to be a circular definition. But with the second sentence, Aristotle clarifies the issue: Time is a numeric value, which is derived from movement, but applies as well to rest: If e. g. somebody sits without moving in a chair, while the sun moves 1/12 of a full rotation around the earth, then from that movement the number "2 hours" is derived, which is the time that person spent at rest in the chair.

According to Newton, movement merely defines the measure of time (i. e. relative time), but not (absolute) time itself, while with Aristotle's concept (4a), time itself is a secondary notion, derived from the two basic notions *movement* and *counting*. Sloppily we may state Aristotle's concept by "time is, what clocks display." Note that this fits remarkably well to Einsteins theories of relativity.

Aristotle furthermore states — in contrast to Newton and Einstein! — that time has by itself (but not only due to statistical thermodynamic effects) a built-in definite direction from past towards future:

> "[Everything] suffers from time, as is well-known, just as we usually say that time destroys [everything], and that everything grows old through time, and get's forgotten due to time, but not becomes known or new or pretty [due (4b)

[6] «ὀυ μόνον δὲ τὴν κίνησιν τῷ χρόνῳ μετροῦμεν, ἀλλὰ καὶ τῇ κινήσει τὸν χρόνον διὰ τὸ ὁρίζεσθαι ὑπ' ἀλλήλων· [...] ἐπεὶ δ' ἐσὶν ὁ χρόνος μέτρον κινήσεως, ἔσαι καὶ ἠρεμὶας μέτρον κατὰ συμβεβηκός· [...] ὀυ γὰρ κίνησις ὁ χρόνος, ἀλλ' ἀριθμὸς κινήσεως· ἐν ἀριθμῷ δὲ κινήσεως ἐνδέχεται εἶναι καὶ τὸ ἠρεμοῦν .» [2, 220b14–16, 221b7–8,11–12]

to time]." [7]

For any natural number n, it's predecessor $n-1$ and it's successor $n+1$ are uniquely defined. Predecessor and successor can not be interchanged. Thus the basic notion *counting* has — by the sequence of natural numbers — a build-in direction from small towards large. Due to the definition (4a), the secondary notion *time* inherits that build-in direction, which in this context becomes a unique direction from past towards future.

3. Adopting Aristotle's concepts of space and time

In the sequel I will outline the big advantages, which make a regress to Aristotle's concepts (2) and (4) of space and time very attractive for (both quantum and classical!) modern physics. But of course these concepts need updated formulations: Instead of referring to "the surface of the surrounding body", the notion *position* becomes much more general due to reference to the interaction(s) between the object and it's environment. Thus we define this secondary notion:

The *position* of a (classical or quantum) object is defined by the interactions between that object and it's environment. (5a)

Space is the entirety of the positions of all objects in the universe. (5b)

Aristotle's definition of time needs almost no changes. For use in modern physics, this formulation is adequate:

Time is, what clocks display. Clocks are devices, which count the periods of periodic motions. (6a)

[7] «καὶ πάσχειν δή τι ὑπὸ τοῦ χρόνου, καθάπερ καὶ λέγειν εἰώθαμεν ὅτι κατατήκει ὁ χρόνος, καὶ γηράσκει πάνθ' ὑπὸ τοῦ χρόνου, καὶ ἐπιλανθάνεται διὰ τὸν χρόνον, ἀλλ' ὀυ μεμάθηκεν, ὀυδὲ νέον γέγονεν ὀυδὲ καλόν.» [2, 221a30–b1]

As "counting" is part of the definition (6a), time has a built-in unique direction from past towards future, because natural numbers have a unique direction from small towards large. (6b)

Object and *interaction* are basic notions, from which the secondary notions *position* and *space* are derived in (5). *Motion* and *counting* are basic notions, from which the secondary notion *time* is derived in (6).

4. Localization of a C_{70} molecule

In a beautiful experiment, Hackermüller et. al. [3] observed the one-particle near-field interference of C_{70} molecules, which crossed three identical gratings. Before a molecule crossed the first grating, it was heated by laser radiation with 0 W, 3 W, 6 W, or 10.5 W. With molecules which had been heated with 0 W or 3 W, a clearly visible interference structure could be observed as a function of lateral shift of the third grating. With 6 W heating the fringe visibility was strongly reduced, and with 10.5 W heating it disappeared completely.

The heating does not significantly change the de Broglie wavelength of the C_{70} molecule, this is not the reason why the single-particle interference disappears. Instead the experimenters offered the plausible explanation, that the molecule is emitting on it's way through the gratings the more thermal photons, the higher it's temperature is. The emitted photons may be absorbed by some solids in the environment, or they may bounce off some air molecules, or whatever. Thus due to the emitted photons, the C_{70} molecule gets entangled with the environment.

According to the space concept (5), the interactions (due to emission of thermal photons) between the C_{70} molecule and the environment contribute to the definition of the molecule's trajectory (which is just the sequence of it's positions in the course of time). We could in principle observe the emitted photons, and analyze from which direction they are coming. Thus the trajectory becomes more and more narrow, if more and more photons are emitted. When the diameter of the trajectory becomes as small as one grid period, the interference structure at the third grating disappears.

Note that the diameter of each molecule's trajectory "really" shrinks due to entanglement with the environment. This is an *objective* fact, happening "out there", not only on the paper of the theorist. Even though the photons were not observed and not analyzed by a physicist in the experiment of Hackermüller et. al. , the interference structure disappeared when the rate of photon emission was sufficiently high. While in some interpretations of quantum theory a human observer must take note to make objective facts happen, such strange assumptions become superfluous with the secondary space concept (5).

The entanglement due to emitted photons may be ignored in good approximation as long as the C_{70} molecule is sufficiently cold. Then the only interaction with the environment, which defines the molecule's position according to the space concept (5), is the interaction with the source apparatus from which the C_{70} molecule is emitted. In this case the molecule can be described by the state vector

$$|C_{70}\rangle = \sum_j a_j |\text{path}_j\rangle \ . \tag{7a}$$

The sum is over all the different paths the molecule could follow if it's trajectory had a diameter which was smaller than the grid period of the gratings. But the observed interference structure proves that actually the interaction with the source apparatus created a trajectory with a much larger diameter, which extends over many grid periods.

With Newton's basic space notion (1) we would say that the small molecule crosses only one slit of each grating, we merely don't know which one. But in the framework of the secondary space concept (5), we must state that the position of each single molecule *really* extends over several grid periods, because there are no interactions with the environment, which *define* — i. e. which *create* — a more narrow trajectory. Consequently the single molecule *really* crosses several different slits of each grating, i. e. several amplitudes a_j in (7a) are different from zero. The probability $P(x)$ that the molecule crosses the third grid (the detection grid) at some position x, is according to Borns rule

$$P(x) = |\langle x|\mathrm{C}_{70}\rangle|^2 \overset{(7a)}{=} \sum_j \sum_i a_j^* a_i \langle \mathrm{path}_j|x\rangle\langle x|\mathrm{path}_i\rangle \ . \tag{7b}$$

The mixed terms with $j \neq i$ in this expression correspond to the observed interference structure.

If the entanglement between the molecule and the environment gets strong due to a large number of emitted photons, then the state vector (7a) isn't a good approximation any more. Instead now quantum theory assigns to the entangled overall system the state vector

$$|\mathrm{C}_{70}\,\&\,\mathrm{environment}\rangle = \sum_j a_j |\mathrm{path}_j\rangle |j\rangle_{\mathrm{env}} \tag{8a}$$

$$\text{with} \quad |j\rangle_{\mathrm{env}} = |\text{the environment absorbed photons which were emitted from the molecule moving on path}\,_j\rangle \ .$$

Thereby the probability (7b) is replaced by

$$P(x) = \sum_j \sum_i a_j^* a_i \,{}_{\mathrm{env}}\langle j|\langle \mathrm{path}_j|x\rangle\langle x|\mathrm{path}_i\rangle|i\rangle_{\mathrm{env}} \ ,$$

which due to ${}_{\text{env}}\langle j|i\rangle_{\text{env}} = \delta_{ji}$ reduces to

$$P(x) = \sum_j |a_j|^2 \, |\langle \text{path}_j | x \rangle|^2 \; . \tag{8b}$$

The mixed terms with $j \neq i$ have vanished in (8b), correlating with the fact that the interference fringes at the third grating have disappeared.

In (8) several amplitudes a_j are different from zero only because of incomplete information on side of the physicist. There is no reason to doubt that the environment "knows" more than we know, and actually has confined the trajectory of each single molecule to just one certain path$_k$. If we knew what the environment knows, then we would set $a_j = \delta_{jk}$ in (8):

$$\begin{aligned} &|\text{C}_{70}\,\&\,\text{environment}\rangle = |\text{path}_k\rangle |k\rangle_{\text{env}} \\ &\quad \text{with} \quad |k\rangle_{\text{env}} = |\text{the environment absorbed photons which} \\ &\qquad\qquad \text{were emitted from the molecule moving on path}_k\rangle \end{aligned} \tag{9}$$

Actually we could find out what the environment knows, by placing lots of photon detectors around the experiment, and analyzing precisely the directions of flight of the photons emitted by the C_{70} molecule.

Thus the probabilities (8b) are merely classical probabilities, reflecting our lack of knowledge. In contrast, the probabilities (7b), with several a_j being different from zero, are true quantum probabilities. The diameter of the trajectory of each single sufficiently cold C_{70} molecule extended in the experiment of Hackermüller et. al. objectively over several grid periods, as proved by the observed interference fringes.

5. Single photons at beam splitters

If an optical beam splitter transmits 50% of the intensity of a light beam, and reflects the other 50% , what then will happen if single photons impinge one by one onto the beam splitter? This question has been evaluated in the experiments sketched in fig. 1 and fig. 2 . Pairs of correlated photons were produced due to spontaneous parametric down conversion (SPDC) in a β-Bariumborat (BBO) crystal. Photon$_1$ was observed by the gate detector D_G , while photon$_2$ reached a beam splitter.

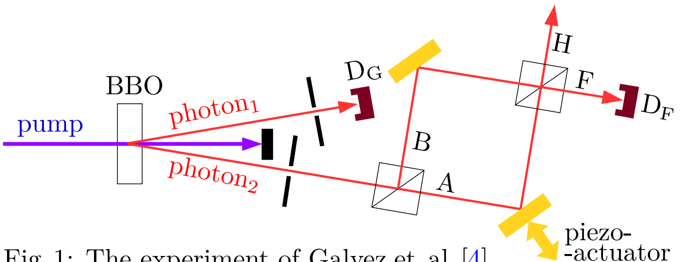

Fig. 1: The experiment of Galvez et. al. [4]

In the experiment of Galvez et. al. [4], sketched in fig. 1 , photon$_2$ was reflected by two mirrors towards a second beam splitter. One of the mirrors could be shifted some few micrometers due to a piezoelectric actuator. With different actuator voltages, the experimenters counted the coincidences of photon$_1$ being registered by detector D_G and photon$_2$ being registered by detector D_F within a 4 ns time window.

The result: The coincidence rate had a maximum (minimum) when the length difference between path A and path B was an even (odd) integer multiple of half the photon wavelength. This result proves, that each (or at least almost each) single photon$_2$ had seen both arms of the interferometer, and interfered with itself in the second beam splitter accordingly.

While Galvez et. al. used "normal" beam splitters in their ex-

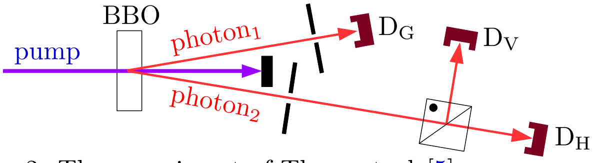

Fig. 2: The experiment of Thorn et. al. [5]

periment fig. 1 , Thorn et. al. [5] used instead in their experiment, sketched in fig. 2 , a polarizing beam splitter, which was rotated 45° versus the polarization plane of photon$_2$. The rates of coincidences (within a 2.5 ns time window) of detectors D_G and D_H, or of D_G and D_V, or of all 3 detectors, were measured. The result: Photon$_2$ was observed — with a significance of 398 standard deviations — in strict anti-correlation by either D_H EXOR D_V .

If we try to interpret the results of these two experiments within Newton's concept of space as a basic notion, then we are facing a mind-boggling paradox: It seems as if photon$_2$ is somehow upfront informed whether behind a beam splitter detectors are lurking or an interference experiment is set up, and decides accordingly either for one single path, or splits onto two paths. In contrast, within

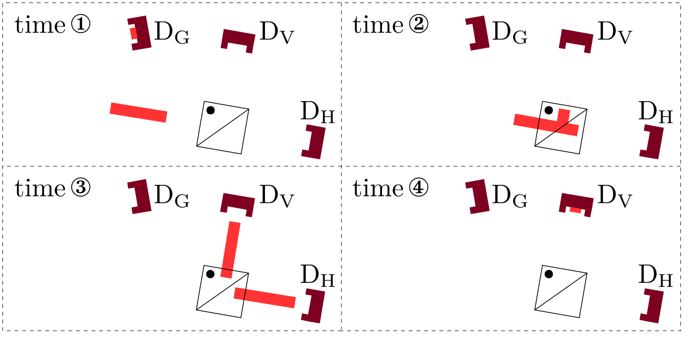

Fig. 3: The position of photon$_2$ at four different points of time

the framework (5) of space as a derived secondary notion these results seem perfectly natural, and are exactly what was to be expected:

In the four sketches of fig. 3 on the previous page, the photon positions in the experiment of Thorn et. al. are indicated in red color for 4 different points of time. At time ① photon_1 has just triggered detector D_G. It's position has thereby shrunk onto to active surface of D_G.

The position of photon_2 got due to interactions with the environment the form of a cylinder. As photon_2 is correlated with photon_1 due to their common creation in the SPDC process, the cylinders length is defined by the time resolution of detector D_G, and it's diameter is defined by the apertures in the diaphragms which the photons had to cross. Let's assume that the time resolution of D_G is 0.1 ns. Then the length of the cylindric position of photon_2 is 0.03 m.

With Newton's framework of space as a basic notion, we would say that photon_2 must be at some certain point within the red cylinder, we just don't know that exact point due to lack of experimental accuracy. But according to the secondary space notion (5), the 0.03 m long cylinder really *is* the position of photon_2. And this position really spreads into both paths in the beam splitter at time ②, and at time ③ even splits! The photon does not split, but it's position does, if we consistently apply the space notion (5).

When eventually at time ④ one of the detectors registers photon_2, it's position — which just before had been split onto two different paths — shrinks onto the active surface of the detector. This shrinking of position needs absolutely no time! There is no conflict with relativity theory, as will now be explained by analysis of a further experiment.

6. Space-like correlation over 400 m distance

Weihs et. al. [6] performed the experiment, which is sketched in fig. 4 . Pairs of photons were produced by SPDC in a BBO crystal in the entangled state

$$|\text{photon}_1\&\text{photon}_2\rangle = \sqrt{\frac{1}{2}}\Big(|H\rangle_1|V\rangle_2 - |V\rangle_1|H\rangle_2\Big)\ . \qquad (10)$$

Here $|H\rangle_{\text{x}}$ resp. $|V\rangle_{\text{x}}$ indicate that photon_{x} is horizontally resp. vertically polarized in some arbitrarily chosen reference system. Note that (10) can not be factorized, i. e. quantum theory assigns neither to photon_1 nor to photon_2 a state vector, but only to the entangled overall system $\text{photon}_1\&\text{photon}_2$.

Detector stations for photon_1 and photon_2 were set up in about 400 m distance. Each detector station consisted of an electro-optical

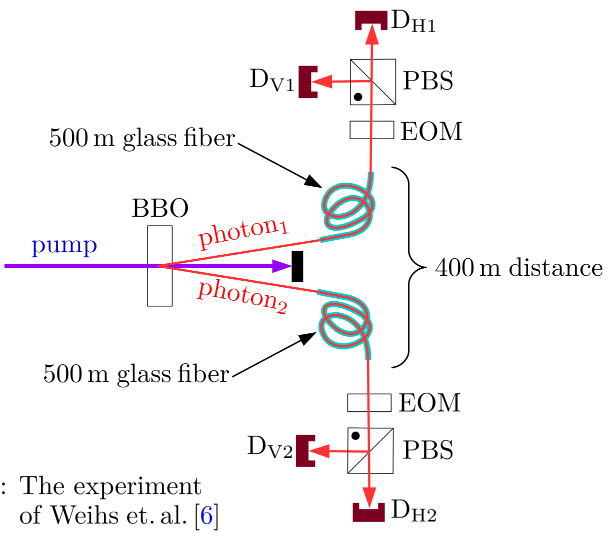

Fig. 4: The experiment of Weihs et. al. [6]

modulator (EOM) which rotated the photon's polarization plane, a polarizing beam splitter (PBS), and detectors D_H and D_V which registered horizontally or vertically polarized photons, respectively.

The settings of the electro-optical modulators (EOM) were controlled by physical random number generators. Generation of a new random number, setting of the EOM, and photon detection were accomplished within time intervals, which were significantly shorter than the time needed to transmit these informations by whatever unknown mechanism, working at a speed $\leq$ the speed of light in vacuum, to the other detector station. Thus the two stations were strictly "causally separated".

At both stations the times of detector clicks as measured by synchronized atomic clocks were stored independently, together with the actual EOM settings. Only after the end of the measurements, the results from both detector stations were compared. Whenever both stations registered a photon each within the same 6 ns time window, these photons were considered the partners photon_1 and photon_2 of the same entangled photon pair (10).

The experiment confirmed that the correlation of polarizations of both photons is as strong as predicted by quantum theory, i. e. significantly stronger than compatible with the assumption that the polarization of each photon is determined already at the time of photon creation in the BBO crystal. Instead the strength of correlation proves (as explicated e. g. in [7]), that Nature decides only in the very moment of photon registration by one of the four detectors D_{Hx} or D_{Vx} — but not earlier! — for some polarizations of photon_1 and photon_2 .

How does Nature bring about the correlation of polarizations over space-like distance? If we apply Newton's concept of space as a basic notion, then we must conclude that these correlations are non-local. With space as a secondary notion as defined in (5), on the other hand, there is nothing happening non-locally:

As long as no separate objects photon_1 and photon_2 with separate positions are created due to detection of a photon by one of the four detectors D_{Vx} or D_{Hx}, the pair $\text{photon}_1\&\text{photon}_2$ is just *one* quantum object with just *one* (possibly split) position. In his answer to the 1935 EPR article [8], Bohr explains [9]:

> "The impossibility of a closer analysis of the reactions between the particle and the measuring instrument is [...] an essential property of any arrangement suited to the study of the phenomena of the type concerned [i. e. systems of entangled quantum objects like the pair $\text{photon}_1\&\text{photon}_2$], where we have to do with a feature of *individuality* completely foreign to classical physics." (11)

To emphasize the word, Bohr had *individuality* printed in italics, and he left nowhere in his writings any doubt that he meant that word literally: (Latin) dividere = to divide, hence individuality = indivisibility. Quantum phenomena require a holistic description in Bohr's point of view. This is just the approach of quantum theory: It assigns the well defined state vector (10) to the *individual* system $\text{photon}_1\&\text{photon}_2$, but it assigns no state vectors to the system's constituent particles photon_1 and photon_2.

It is a peculiar consequence of the space notion as defined in (5), that the position of an *individual* object can be split, even though the object is not split. Like in the experiment of Thorn et. al. the *one* quantum object photon_2 has *one* position, even though this position is split onto two arms of the apparatus depicted in fig. 3 at time ③, now in the experiment fig. 4 there is — in the time interval between creation of the photon pair and the first registration of a photon by one of the four detectors — *one* position of the *one* pair $\text{photon}_1\&\text{photon}_2$, even though this *one* position is split onto the two arms of the apparatus. Hence Nature doesn't need to bridge a gap between different positions. Instead she arranges for appropriately correlated photon polarizations at that *one* single (though split) position.

Thus the issue of non-locality of quantum phenomena vanishes, once consistently the space notion (5) is applied. This holds as well for the experiment fig. 3 . The strict anti-correlation of photon detections at the detectors D_V and D_H can be explained without the assumption of whatever non-locality. At time ③ the *one* (though split) position of $photon_2$ is approaching both detectors. Then Nature decides, and arranges within this *one* position — hence locally! — , whether D_V detects the photon AND D_H does NOT detect the photon, EXOR whether D_H detects the photon AND D_V does NOT detect the photon.

While the secondary space notion (5) cures much of the weirdness of quantum phenomena, we might ask whether the price isn't to high. Is the split position of an indivisible particle really less counterintuitive than the paradoxes from which that space notion does free us? I think that much of the discomfort we feel in view of the secondary notion (5) and it's consequences is merely caused by the fact that Newton's space concept has dominated physics since his times, and therefore by today the primacy of space over it's content seems almost self-evident to most of us, and is deeply ingrained in our brains.

But until Newton, the older, Aristotelian space concept was widespread used, and seemed to many contemporaries as self-evident, as Newton's concept seems to us by today. In the Aristotelian concept, *body* was a basic notion, and *position* — being a part of space — was defined as the volume filled by a body. Consequently in that conceptual framework there couldn't be space unless it was filled by a body, and the idea of "empty" space seemed abstruse nonsense; a logical contradiction within itself. Therefore still Descartes allegedly mocked at the vacuum which Torricelli had first demonstrated in 1644: "If there should exist a vacuum somewhere, then in Torricelli's head!" [8]

If a scientist and philosopher as intelligent as Descartes had no problem to adopt a secondary space notion and it's logical consequences, then — I think — we should be able to do that as well, after some time of habituation. The really tremendous advantages for our interpretation of quantum phenomena are worth the effort!

7. Renormalization in quantum field theory

By end of the nineteenfourties physicists learned to handle the divergences, which are turning up in quantum field theory (QFT), by the method of renormalization. For more than 20 years, renormalization seemed to be nothing than a shady trick, relying on quite dubious mathematics: The infinite results are cured by subtraction of other infinite values, such that the differences give finite results.

Only when Wilson [10] applied the renormalization group to phase transitions and other critical phenomena, it became visible that renormalization is a sound procedure, based on reasonable physical arguments. See e. g. [11, chap. 21] for an elementary introduction to renormalization theory.

For example, the coupling constant λ of QFT actually isn't a constant; instead it depends on the energy $\hbar q$ at which the theory is being tested:

$$\lambda(q_s) = \lambda(q_r) + \int_{q_r}^{q_s} \frac{\mathrm{d}k}{k}\, \beta(k) \tag{12}$$

$\beta > 0$ in case of quantum electrodynamics. $\lambda \approx 1/128$ has been

[8] This quotation might be not authentic. At least I do not know the source. Se non è vero, è ben trovato.[9]

[9] Italian: If it is not true, then it is good invented.

measured at $100\,\mathrm{GeV}/(\hbar c)$, while at low wavenumbers (i. e. at large distance of the interacting particles) $\lambda \approx 1/137$. In case of quantum chromodynamics, $\beta < 0$, and λ furthermore decreases logarithmically for increasing wavenumbers, resulting into "asymptotic freedom" of the quarks in a nucleus.

Infinities turn up in QFT, if the integrals, which have to be solved in second and higher order of perturbative treatment, are extended to arbitrarily large wave numbers, i. e. to arbitrarily small distance $d \approx 1/q$. This problem is a direct consequence of Newton's primary space notion, in which *distance* is just the difference of two points in a coordinate system, which of course can be arbitrarily small. With the secondary space notion (5), *distance* is the difference of two positions, which again are *defined* by the interactions of particles, which are situated at these positions, with their respective environment. Consequently there can be no arbitrarily small distance because no particle is confined by it's environment to an arbitrarily small position.

Actually renormalization is nothing other than a switch to a secondary space notion "through the back-door". Equation (12) stipulates that the coupling constant λ must be derived from the interaction energy $\hbar q$ at which the theory is being tested. Thus the wave number q and the distance $d \approx 1/q$ are *derived* from the interaction strength. The primacy of interaction over position (hence space) is at the core of the secondary space notion (5). If quantum field theory would set out from that space notion, then the divergences and the need for renormalization would never arise in the first place.

8. Are quanta real?

This question may rightly be criticized as ill-posed: It is far from clear what exactly is meant by the word "real". Thus we should better ask: Are the electrons, photons, quarks, and gluons from which atoms are built, and are the atoms, which constitute a macroscopic stone, as real as that macroscopic stone?

Naively we would tend to answer "obviously yes". But the seemingly paradoxical quantum phenomena led influential pioneers of quantum theory to other answers. Heisenberg, for example, repeatedly pointed out that quanta are *not* as real as macroscopic bodies. In a 1958 lecture he explains [12]:

> "In [...] atomic physics, [...] the conception of reality gets lost, [...] that there are objective processes going on, which are well-defined in space and time, no matter whether they are being observed or not. [...] Due to this trait of quantum theory it becomes [...] difficult, [...] to consider the smallest parts of matter, the elementary particles, as the proper reality, because these elementary particles are, if quantum theory is correct, actually not [...] as real as the things of everyday life, the trees or the stones. Instead they appear more as abstractions, which have been concluded from the actually real observed facts." [10] (13)

Thus Heisenberg denies the reality of quanta, because many quantum processes do not allow for objective descriptions in space and time. It is Newton's basic notion of space, which is causing the

[10] "In [...] der Atomphysik geht [...] die Wirklichkeitsvorstellung [verloren ...], daß es objektive Vorgänge gebe, die in Raum und Zeit in einer bestimmten Weise ablaufen, ganz unabhängig davon, ob sie beobachtet werden oder nicht. [...] Dieser Zug der Quantentheorie macht es [...] schwierig, [...] die kleinsten Teilchen der Materie, die Elementarteilchen, als das eigentlich Wirkliche zu bezeichnen. Denn diese Elementarteilchen sind, wenn die Quantentheorie zurecht besteht, eben nicht [...] in dem gleichen Sinne wirklich, wie die Dinge des täglichen Lebens, die Bäume oder die Steine, sondern sie erscheinen eher als Abstraktionen, die aus dem im eigentlichen Sinne wirklichen Beobachtungsmaterial gewonnen sind." [12, S. 142 – 143]

problem: If we believe that a C_{70} molecule has a diameter of about $7 \cdot 10^{-10}$m at any time, no matter whether or not it is localized to this diameter due to interactions with it's environment, then we can in fact not objectively describe in space and time, how the molecule traverses the grids and interferes with itself. Then we may indeed conclude with Heisenberg, that this molecule can impossibly be as real as "the trees or the stones".

In contrast, with the secondary space notion (5) there is no need for ontological assumptions as counterintuitive as those suggested by Heisenberg. With the secondary space concept, we may consistently assume that there is absolutely no ontological difference between macroscopic objects and their microscopic (even elementary) constituents.

The point of view, which assigns the identical status of reality to quanta and to macroscopic objects, may appropriately be called *quantum realism*. It has recently been advocated by Hobson [13, 14]. But Hobson stops halfway: He accepts that the position of a quantum *really* extends over several grid openings in the one-particle interference experiment (for this reason he recommends never to name quanta "particles", but to name them "fields" at any time), but he sticks to Newton's basic notion of space. Consequently he must postulate non-local correlations within *individual* quantum phenomena.

Only in combination with the secondary space notion (5), quantum realism becomes a fully consistent and very attractive interpretation of quantum phenomena, truly free of whatever nonlocality. Most (or all? This depends on how sensitive you react on reasonable, but unfamiliar effects.) of the "weirdness" in alternative interpretations of quantum phenomena is sidestepped by this interpretation.

9. Space and time in special relativity theory

In a famous lesson [15], read in 1908, Hermann Minkowski declared:

> "From now on, space on it's own and time on it's own shall completely fade to shadows, and only some sort of union of both shall keep independence." [11] (14)

In this lesson, Minkowski presented special relativity theory (SRT) in an elegant formulation, in which time and space are equally matched components of a four-dimensional space-time continuum. This space-time continuum was (and is) of course a primary, basic notion. Thus we may ask: Is SRT compatible with the secondary notions (5) and (6) of space and time?

Actually it is. This is immediately obvious from Einstein's original formulation of SRT. In his 1905 article [16], Einstein refers nowhere to a space-time continuum.[12] Instead he insists that time intervals must be measured by appropriately synchronized clocks: That is clearly compatible with (6). And he stipulates that space intervals (i. e. distances, or differences of positions) must be measured by counting the number of meter sticks, which must minimum be concatenated to bridge that distance. That fits to (5).

This is not to say that Einstein used a secondary space notion when he invented SRT. He most certainly never abandoned Newton's primary space notion. I merely want to point out that SRT

[11] „Von Stund' an sollen Raum für sich und Zeit für sich völlig zu Schatten herabsinken und nur noch eine Art Union der beiden soll Selbständigkeit bewahren.“ [15]

[12] Allegedly Einstein commented, when he first time became aware of Minkowski's new formulation: "Since the mathematicians have broken into relativity theory, I don't understand it myself any more." [8] But Einstein soon became aware of the power of Minkowski's four-dimensional formalism, and applied it extensively when he developed general relativity theory.

and the notions (5) and (6) of space and time are very well compatible. Minkowski's four-dimensional formalism is elegant, but not necessary for SRT.

10. Space and time in general relativity theory

I am not aware of any formulation of general relativity theory (GRT) without the concept of a four-dimensional space-time continuum, with four equally matched components. And I strongly doubt that GRT could possibly be derived with the secondary space- and time-notions (5) and (6). The definition (6) of time is not the problem; apart from the built-in direction of time, this is essentially identical to the time notion as used by Einstein. The problem comes from the definition of space, which is derived from the interactions of objects. Such construction clearly can not replace the purely geometrical construction of the four-dimensional space-time continuum.

Still I think that the secondary space notion (5) and GRT are "effectively" compatible, because for macroscopic objects the localization due to interaction with the environment is effectively identical to their localization in the framework of Newton's space notion:

Joos and Zeh [17] estimated for different object sizes and different environments, how fast the localization due to interaction with the environment happens. They found that a grain of dust, which has a diameter of $10\,\mu$m with the Newtonian space concept, gets with the secondary space concept (5) localized to this diameter due to interaction with

- air molecules on earth surface within 10^{-30}s
- sun light on earth surface within 10^{-15}s
- the cosmic microwave background within 1 s .

They furthermore demonstrated that the localization speed increases exponentially with increasing object size. Thus for objects larger than, say, 1 mm diameter, the secondary space notion (5) gives effectively at any time the same results as Newton's primary space notion, even in deep intergalactic space where interaction with the cosmic microwave background is the only mechanism of localization.

All objects which can induce significant curvature of space-time (with exception of the hypothetical micro black holes) are *much* larger than 1 mm diameter, and are consequently well localized *passively* by the environment. Micro black holes (if they should exist) would *actively* localize, because they would radiate with intensity inversely proportional to their mass, as asserted by Hawking [18, 19]. This is the same effect as the *active* localization due to emission of thermal photons by C_{70} molecules in the experiment discussed in section 4 .

Hence we may compute the gravitational fields and all other relativistic effects caused by these objects, by means of the four-dimensional space-time continuum usually applied in GRT, even if we consider this four-dimensional continuum merely an excellent approximation to the secondary space- and time-notions (5) and (6).

Of course the secondary space notion (5) must be applied to objects, which do not have sufficient mass to deform space-time significantly, but are moving in the space-time deformed by heavy other objects. This is not a problem, but a welcome and fully satisfying explanation for phenomena like Wheeler's delayed choice experiment [20] with a photon, which interferes with itself after it propagated on several split paths around a galaxy forming a gravitational lens. With the secondary space notion (5) there is absolutely no mystery in this gedanken-experiment: The path of the photon can very well be split to arbitrary distances; and there is no issue with delayed choice, because *there is no choice* — delayed or otherwise — made or required, when the trajectory of the one indivisible photon splits onto various paths.

There is one important exception from the effective equivalence of the basic and secondary space notions for heavy objects: If GRT is formulated with Newton's space concept, then black holes inevitably collapse to singularities of zero volume. No such singularities turn up with the secondary space notion (5), because the environment can impossibly localize an object to a radius smaller than it's event horizon (i. e. the Schwarzschild radius in the most simple case). For all non-gravitative types of interactions this is obvious. And it is true for gravitational interaction, because e. g. the gravitational field of a (zero-dimensional) point-singularity is outside the event horizon identical to the field of a sphere with Schwarzschild radius and homogeneous (hence finite) mass density. Therefore the environment's capability to shrink the position of an object ends at the event horizon.

Thus the secondary space concept (5) has the big advantage to free GRT from the annoying singularities. The wish to get rid of those singularities is the most important motivation for the development of a theory of quantum gravity. While the development of that theory is extremely difficult, and had only partial success until today, the solution due to the secondary space concept (5) is simple and completely successful. From this point of view, the singularities of GRT are merely an artifact, caused by the application of an improper (i. e. the Newtonian) space concept.

11. The direction of time

On the occasion of the death of his lifelong friend Michele Besso, Einstein wrote — four weeks before his own death — in a condolence letter to Besso's wife and son [21]:

> "Now he has departed a little ahead of me from this quaint world. This means nothing. For us faithful physicists, the (15)

> separation between past, present, and future has only the meaning of an illusion, though a persistent one." [13]

Indeed, the "flow of time" must be diagnosed a mere illusion, if the findings of general relativity theory are interpreted in a framework of four-dimensional space-time as a basic notion. In his very readable contribution to the 2008 FQXi essay contest, Ken Wharton explains [23]:

> "We live in a block universe. In other words, our universe is best represented as an arrangement of static events in four dimensions — three of space and one of time. Try to picture it: every event that has ever happened or will ever happened, structurally arranged in an unchanging 'block'. [. . .] A block universe has time represented as if it were a spatial coordinate, so it contains information about all times. [. . . The block universe i]s the only picture that's compatible with what we know about space and time." (16)

In the block universe picture, there is no preferred direction of time. If we trace our world line through the block universe in reversed direction, then the course of events which we encounter is as well compatible with the laws of classical physics (including GRT), and the conventional assumption of one preferred direction of time "has only the meaning of an illusion, though a persistent one".

Many (actually almost all) quantum phenomena do *not* fit into the block-universe picture. Consider for example again the experiment fig. 4 . While the pair photon_1 & photon_2 is approaching the detectors, quantum theory assigns to it the entangled state

[13] „Nun ist er mir auch mit dem Abschied von dieser sonderbaren Welt ein wenig vorausgegangen. Dies bedeutet nichts. Für uns gläubige Physiker hat die Scheidung zwischen Vergangenheit, Gegenwart und Zukunft nur die Bedeutung einer wenn auch hartnäckigen Illusion.“ The quotation of the German text, and the English translation, are taken from Jammer [22, page 161]

vector (10), but it does *not* assign a well-defined polarization to photon_1 nor to photon_2. As explained in [7], Nature decides only in the very moment of photon detection for the result $\{H_1$ AND $V_2\}$ EXOR $\{V_1$ AND $H_2\}$. This evolution in time can impossibly be reversed. If we want to describe the time-reversed process, in which one detector each at each detector station emits a photon towards the BBO crystal, which combine in the crystal to a pump photon, then we must decide upfront whether the photons shall be emitted from the detectors $\{D_{H1}$ AND $D_{V2}\}$ EXOR $\{D_{V1}$ AND $D_{H2}\}$. Thus both photons will have on their way from the detectors to the BBO crystal well-defined polarizations, while with the original time direction, the polarizations of the photons are *not* defined.

To save the unity of physics, Wharton [23] suggested to modify quantum theory such, that it fits into the block universe picture. And he offered inspiring suggestions, how to tackle that objective. But the much simpler, and still fully sufficient measure to remove the discrepancies between GRT and quantum theory, is to adopt the time notion (6), in which "the separation between past, present, and future" is not "an illusion", but — by construction — a built-in feature of time, and combine it with the space-notion (5).

These notions of space and time form together the appropriate framework for the description of quantum phenomena. And in the macroscopic limit, these notions converge — as explicated in section 10 — into the four-dimensional space-time conventionally applied in GRT.

12. Conclusions: The unity of physics

Ever since Newton demonstrated that the orbits of planets around the sun, and mechanical processes on earth, are ruled by identical laws of nature, the vision of a universal theory (or at least of a set of formally and logically consistent theories), which should comprise all physical phenomena, has motivated the efforts of theoretical physicists all over the world.

With the advent of quantum theory, this vision got into a deep crisis. Despite of almost a century of intensive work, the formal and logical split between quantum theory and classical theory could not yet be sufficiently bridged.

In this essay, I have argued that we can make a big leap towards the unity of physics, if we adopt the modernized form (5) and (6) of Aristotle's notions of space and time, because this set of notions is perfectly appropriate for both classical and quantum physics: Most quantum paradoxa, the divergences of QFT, and the divergences of ART, vanish once we switch to those notions.

While my arguments concentrated on the physics, the same objective has been approached on a strictly mathematical level in a beautiful recent article [24] by Christian Baumgarten. Under the essential precondition that space is introduced as a secondary, derived notion, Baumgarten demonstrates that a large part of the mathematical formalism of both classical and quantum physics can be derived from a surprisingly small number of basic physical assumptions, which are universally valid for classical and quantum physics. His achievements may be considered an additional, powerful argument for the usefulness of a secondary space notion as a key element on our way towards the unity of physics.

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