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**Non-local Building Blocks of Spacetime**

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**Abstract**

*Non-locality in the sense of non-separability is an experimental fact of quantum mechanics that seems to contradict the postulates of relativity. We aim to show that there is no real contradiction between quantum mechanics and relativity. Instead, they simply describe different levels of physical reality. We extrapolate from Schrodinger’s original proposal that a particle could be assimilated to a cloud-like entity, by suggesting that the particle is not an entity located in space-time, but an extended field-like entity that is an integral part of spacetime itself. Furthermore, we propose to describe the particle in terms of proper time rather than ordinary time. In fact the particle can be associated with a slice within a light cone in such a way that all its points are related to the same proper time. We will show that these extended entities are intrinsically non-local and that they are the substantival building blocks of ordinary spacetime. In this case locality in spacetime becomes an emergent property. It emerges from the combination of the various non-local entities. Quantum mechanics is mainly concerned with the intrinsically non-local structure of space-time, while the theory of relativity is concerned with the resultant or emergent spacetime. It should be emphasised that this paper does not propose a new theory, but simply a different way of looking at the structure of spacetime.*

Keywords: spacetime; substantivalism; proper time; non-locality; configuration space.

1. **Introduction**

Over the centuries, philosophers and scientists have tried to understand what space is and what time is. Two opposing visions have emerged: "substantivalism" and "relationism", discussed in detail by Dainton [1].A very short introduction on the nature of space and time is given by Wallace [2].

The main proponent of substantivalism was Newton, who regarded space and time as real entities. For Newton, time and space are absolute in the sense that they are unaffected by the presence or absence of material objects. Absolute space acts as a container in which everything is embedded and provides the only true frame of reference for defining the rest or motion of an object.

In contrast, the main proponents of relationism were Leibniz and Mach, who held that space and time have no real existence in themselves. It is only a relationship between objects, such that if all of these objects were to be removed, there would be no more space and no more time. For Leibniz, the universe consists only of material objects with spatial and temporal relations between them. Space and time are only conceptual terms for describing the relationships between objects.

Descartes had a view that can be seen as intermediate between those of Newton and Leibnitz. Like Leibnitz, he believed that ‘empty space’ could not have an existence of its own, but like Newton, he believed that ‘non-empty space’ was a real entity in itself and not a mere relation between objects. In fact, Descartes saw the universe as a ‘material plenum’ in which space is a tangible fluid.

Mach and Leibniz were major influences on Einstein. This is evident in the special theory of relativity, which rejects any absolute notion of space and time. In particular, simultaneity has no meaning in special relativity, independent of any frame of reference, and there should be no preferred frame of reference [3] [4]; thus absolute simultaneity, absolute space and absolute time have no meaning. In a sense, absolute space and time have been replaced by an absolute speed of light.

In general relativity, however, space interacts with material objects, and in particular the geometry of space or space-time is affected by the presence of objects. This would seem to imply, in contrast to special relativity, that space is a real entity, thus supporting the view of substantivism. However, some philosophers and scientists argue that the geometry or curvature of space can be thought of as a physical field. A flat space with a gravitational field is equivalent to a curved space, and both give the same predictions, again supporting the view of relationism. In particular, Poincaré claimed that one could start from geometrical notions and end up with physical laws, or equivalently, start from physics and end up with geometry. Both approaches lead to the same results. However, even if we replace the geometry of space by fields, this means that space is not empty and is filled with fields. Rovelli [5] [6] provided a conceptual analysis of space and time with deep critical insight.

Whether space is real or not, special and general relativity undoubtedly conclude that interactions in space are local and that there can be no action at a distance. That is to say, interactions take place between objects that have almost the same location in space, or through intermediaries such as fields or variations in the geometry of space that travel at the speed of light.

However, a quantum system consisting of a pair of entangled particles behaves in such a way that the quantum state of one particle cannot be described independently of that of the other [7]. Standard quantum mechanics postulates that neither particle has a definite state until it is measured. Since both particles are correlated, it is necessary that when the state of one particle is measured, the second particle should 'instantaneously' acquire a determinate state. The non-locality problem can be resumed by Einstein's argument that, if quantum mechanics is complete, then the ‘collapse’ of the wave function is a dynamical process that violates relativistic locality. This quantum phenomenon was first introduced as a thought experiment in the EPR paper [7], and it was later discovered to be experimentally testable using Bell's Inequality [8]. Numerous experiments, such as Aspect's experiment [9], proved the validity of quantum entanglement and thus a certain notion of non-local connections. The notions of non-locality and simultaneity are thus inferred by quantum mechanics, while they are forbidden by the postulates of relativity.

Non-locality has been widely discussed in various interpretations and candidate theories of quantum mechanics, including the Copenhagen interpretation [10], the Everett many-world theory [11], the de Broglie-Bohm pilot wave theory [12] [13], and the GRW spontaneous collapse theory [14].

The Copenhagen interpretation regards standard quantum mechanics as merely a tool to determine the effects of microscopic objects belonging to an unknowable quantum realm on macroscopic instruments.

Everett's Many-Worlds Theory [15] [16] claims that when a measurement is made on a particle in a superposition state, a deterministic bifurcation occurs, where on one branch a first detector detects the particle while a second detector does not, and at the 'same moment' but on the other branch (i.e. another world) the first detector does not detect the particle while the second detector does. Unfortunately, there seems to be no clear meaning of 'same moment' for a variety of unconnected worlds. Nevertheless, Everett’s quantum mechanics, as advocated by Wallace [15], is considered to be a literal interpretation of the world.

The de Broglie-Bohm theory suggests that a particle, such as an electron, always has a well-defined position on a particular trajectory through physical space. However, its motion is influenced by an associated wave function, giving rise to wave-like properties. For a multi-particle system, the theory explicitly formulates the non-local dependence of the evolution of a particle at a given moment on the positions of all other particles at the same moment. This would be acceptable if the de Broglie-Bohm theory were Lorentz invariant, but unfortunately it is not [17].

The GRW theory of spontaneous collapse [14] modifies Schrodinger's equation with stochastic terms that cause a wavefunction to obey Schrodinger's equation most of the time, except for extremely rare and random instants when it undergoes spontaneous collapse. The collapse instantaneously modifies all the spatial arguments of the wavefunction. However, an instantaneous collapse in one Lorentz frame may not be instantaneous in another.

The fundamental problem that remains is the inconsistency [18] of almost all of the above models with the notion of locality [8] posited by special and general relativity. The predictions of quantum mechanics concerning entanglement are incompatible with the relative simultaneity and locality postulated by special relativity.

Another problem concerns the fact that, for more than one particle, the wavefunction is defined on a high-dimensional configuration space rather than a physical space, and thus cannot represent a physically real field. It is not clear how the high-dimensional configuration space of a wavefunction representing more than one particle can be related to the three-dimensional physical space.

The aim of this paper is to show that there is no contradiction between quantum mechanics and relativity. Instead, spacetime has an atomistic structure consisting of non-local substantival constituents. Quantum mechanics applies to the intrinsic structure of spacetime, while relativity applies to the global structure of spacetime. In section 2 we review the formalism of Minkowski spacetime. In section 3 we define the substantival constituents or building blocks of spacetime. In Sections 4, 5 and 6 we consider the state vector, which represents a building block of spacetime, and its dynamics with respect to proper time. The intrinsic non-locality of the building blocks and the relation between the configuration space and ordinary spacetime are illustrated in Sections 7 and 8.

It should be noted that this paper proposes a literal reading of standard quantum mechanics in terms of proper time rather than ordinary time. It is in no way a new theory of quantum mechanics.

**2.** **Minkowski spacetime**

We propose to use the formalism of Minkowski spacetime [19] as defined in a geometrical way by Gourgoulhon [20]. The Minkowski spacetime is an affine space of four dimensions on R endowed with a bilinear metric tensor defined in an underlying vector space E of signature . In the vector space E, a set C consisting of all null vectors forms a light cone C.

Given the spacetime defined above and an arbitrary origin , a family of affine subspaces is defined such that each subspace corresponds to the set of points of the vector space E that can be connected to the origin O by a time-like vector of modulus , where :

|  |  |  |
| --- | --- | --- |
|  |  | (1) |

Let be the coordinates of in the affine frame defined by origin O and an appropriate basis. Then, can be expressed as follows:

|  |  |  |
| --- | --- | --- |
|  |  | (2) |

Referring to a two-dimensional orthonormal reference frame , the light cone is composed of two lines within which a family of simple hyperbolas is stacked. Each point of the slice is represented by a hyperbolic coordinate which is a vector whose modulus is constant, and whose direction is the orientation of a straight line or a ray passing through the origin and is related to the velocity at that point. All points on the same slice share the same invariant proper time coordinate and the position of each point is the intersection of the corresponding ray and slice .

In particular, the hyperbolic slice can be parameterised by a bijective function from the points on the real axis into the points on that slice (i.e. ) such that each point on the slice is given by , where is the standard space coordinate. In fact, each point on the slice can be simply defined by the standard space coordinate and the proper time . Each slice can thus, be defined by a set of points as follows:

|  |  |  |
| --- | --- | --- |
|  |  | (3) |

Note that the position is a vector representing a point on the corresponding slice and the direction of the ray passing through the point, represents the velocity at that point.

On the other hand, each slice is considered to represent a basis , which can be associated with a corresponding Hilbert space with elements labelled by a continuous variable normalised using the Dirac -function:

|  |  |  |
| --- | --- | --- |
|  |  | (4) |

Since each slice is associated with a corresponding proper time , the passage from one slice into a subsequent slice represents the “transition” from a first proper time to a subsequent proper time . Proper time provides an invariant temporal ordering of the set of slices.

Note that the notion of proper time emerges from the combination of space and time and captures the fundamental concepts of relativity. It allows us to decompose spacetime into space and proper time by transforming the coordinates from to .

It is also possible to represent the slices within the light cone in a Cartesian coordinate system . The slices then become parallel to the spatial coordinates in the Cartesian coordinate system . The set of points constituting each slice can be connected to the origin by a vector whose modulus is the ordinary time , which is defined by a Euclidean distance:

|  |  |  |
| --- | --- | --- |
|  |  | (5) |

From this point of view it follows that, first, proper time is lower bounded by zero, which implies that there is an ultimate speed limit c. Second, the rate of proper time (i.e. the rate of ageing) of all inertial objects is invariant, which implies that it is ordinary time that is modified with respect to speed.

In the following, however, we will continue to use the coordinates with respect to the slices formed within the light cone in the standard coordinate system .

**3. Elemental substantival blocks**

In this section, we apply the above framework of hyperbolas to a particle, using Schrodinger’s original proposal that an unobserved particle could be assimilated to an extended cloud-like entity [21]. In the following, we will give a name to this extended entity. We will call it an ‘elemental substantival block’ or ‘elemental block’ for short.

The elemental block should be thought of as an integral part of spacetime itself, rather than as an entity located in spacetime. The points of the elemental block, which we will call “elemental points” can be defined with respect to a coordinate system materialised by a light cone of origin O, within which a family of slices is defined.

The elemental block can be mapped in a continuous way by a bijective application onto a subset of a corresponding slice within the light cone. That is, for any elemental point of the elemental substantival block, there exists a unique image belonging to the corresponding slice . The image represents the coordinates of the elemental point . Note that different elemental substantival blocks can have common coordinates within the same slice, and so we denote the coordinates of a given elemental point by (although sometimes, for simplicity, we drop the .) The elemental points of an elemental block can thus be represented by a set of coordinates belonging to the slice , as follows:

|  |  |  |
| --- | --- | --- |
|  |  | (6) |

Moreover, the particle has a certain velocity, energy/mass and may have a spin, charge, etc. All these attributes should be taken into account and so the elemental substantival block should be represented by a set of weighted elemental points. A velocity , a mass/energy density , and possibly other weights such as spin or charge density should be assigned to each elemental point. An elemental substantival block can thus, be defined, as follows:

|  |  |  |
| --- | --- | --- |
|  |  | (7) |

Each argument of the elemental block is defined by a position , a velocity , a density as well as other attributes at this position. In particular, the mass/energy density is the substantival structure of the elemental block.

It follows that ordinary spacetime - more generally, the universe - is made up of a combination and/or juxtaposition of the elemental substantival blocks that form a global four-dimensional spacetime. Any ordinary point (i.e. event) in spacetime can be common to a set of elemental blocks, each of which has its own proper time. That is, the position of an ordinary point in a light cone coordinate system can coincide with the positions of a set of elemental points belonging to the set of elemental blocks, even though the coordinates may be different because each elemental block can refer to a corresponding light cone. This implies that the density at the ordinary point results from the combination of the densities associated with the set of corresponding elemental points.

As we will see in Section 6, each elemental block is intrinsically non-local in the sense that all its elemental points are interconnected, i.e. the relation between any two elemental points within the elemental block is non-local. However, its evolution (or ageing) as a block with respect to its environment is local. In a sense, an elemental block can be regarded as an 'intrinsically proper-time event', regardless of its extension.

Thus, the relation between any two events (i.e. ordinary points) in ordinary spacetime is subject to a variety of relations between different sets of elemental blocks with different proper times, so that it is highly improbable that the relation between the two events is non-local, even though each block is intrinsically non-local.

Suppose a first event A in ordinary spacetime is shared by a set of first blocks b11….b1n, i.e. the event A is a combination of elemental points p11, p12,….p1n belonging respectively to the first blocks b11….b1n. Similarly, suppose a second event B is shared by a set of second blocks b21….b2m, i.e. the event B is a combination of elemental points p21, p22,….p2m belonging respectively to the second blocks b21….b2m,. Then, in order to have a non-local relation between events A and B, all first blocks b11….b1n as well as all second blocks b21….b2m, should be entangled and the set of the first blocks b11….b1n should be identical to or entangled with the set of second blocks b21….b2m. This is very unlikely, and the greater the distance between A and B, the less likely it becomes. This points to the fact that locality in global spacetime is created by the combination of the various non-local blocks.

In order to take into account the individuality of each elemental substantival block, ordinary spacetime can be represented by an abstract space equal to the tensorial product of all elemental blocks, where we drop the subscript from for simplicity of notation:

|  |  |  |
| --- | --- | --- |
|  |  | (8) |

The framework of relativity is the global 4d-spacetime, while that of quantum mechanics is the individual elemental substantival blocks as defined by the abstract space which, as we shall see, is related to the configuration space of a wavefunction.

Thus, the difference between relativity and quantum mechanics is that the former deals with global spacetime without considering its internal structure, while quantum mechanics deals with its intrinsic building blocks. Locality in relativity is a property that emerges from the statistical ensemble of elemental substantival blocks.

**4. State Vector**

Each elemental block at a given proper time can be represented by a “State Tensor” defining all the attributes associated with each elemental point of the elemental block , as follows:

|  |  |  |
| --- | --- | --- |
|  |  | (9) |

Different state vectors can be constructed from the state tensor by hypothetically summing the elements or weights of interest.

For example, if we are interested in the spin with respect to a given direction Z in a Bloch sphere, then all elemental points whose spin points to the upper hemisphere are assigned a spin Up, while all other elemental points are assigned a Spin Down. The frequencies of the Up and Down spins represent the squares of the probability amplitudes associated with the Up and Down spins, respectively.

This hypothetical construction is only meant to illustrate that a state vector representing the spin of a particle - if unobserved - can be considered as the resultant of a binary representation of all the ‘elementary spins’ of the elemental points composing the elemental block. The probability of a spin Up is related to the frequency of the elemental points of the block pointing to the upper hemisphere of the chosen axis.

Another example, is the restriction of the state tensor to the mass/energy density associated with the different positions of the elemental block, as follows:

|  |  |  |
| --- | --- | --- |
|  |  | (10) |

The elemental block can be represented by an ‘elementary’ state vector in a Hilbert space . The elementary state vector (or state vector for short) can be expanded as an integral function of the basis elements as follows:

|  |  |  |
| --- | --- | --- |
|  |  | (11) |

where is the wavefunction of the particle defined at each elemental point .

Note that the mass/energy density is a scalar function which is invariant under Lorentz transformations.

As noted in Section 1, the position is a vector representing an elemental point on the corresponding slice and has the direction of the ray passing through that point. Furthermore, is the value of the mass/energy density at the position . The value of the density at each corresponding position is the square of the probability amplitude (or square of the wavefunction) associated with that position. This means that the wavefunction should be related to the mass/energy density at each elemental point as well as to the direction of the ray passing through that point.

In other words, the wavefunction should represent the distribution and configuration of the mass/energy density of the elemental block, as originally proposed by Schrodinger. In fact, Schrodinger originally proposed that a particle is a cloud-like object that continuously fills all space, and whose density is given by the square of the wavefunction.

Furthermore, as Tim Maudlin explains in [22], the wavefunction faithfully accounts for the interference pattern (e.g. in a two-slit experiment), and it is reasonable to assume that it represents some real physical properties of a physical system. The properties and behaviour of the wave function should reflect those of the physical system.

We note that Schrodinger’s original idea has been reintroduced in GRW theory [14]. In the following, we adopt this concept in relation to the wavefunction and consider that the amplitude should depend on the mass/energy density.

Here we consider that the wavefunction is an exact representation of the elemental block. If the density of the block is concentrated in an infinitesimal zone, even if it is not zero elsewhere, it behaves as a particle. If the density is dispersed, it behaves like a wave.

**5. Evolution with respect to proper time**

The wavefunction depends on proper time , and so its evolution should also be defined with respect to proper time instead of ordinary time .

In other words, the evolution of the wavefunction (denoted as for short) should be defined with respect to subsequent hyperboloidal slices. This can be achieved by associating the relativistic energy of the particle.

In particular, the relativistic energy of a particle with a given momentum (or velocity ) with respect to an inertial frame of reference (Lorentz coordinate system) is defined as follows:

|  |  |  |
| --- | --- | --- |
|  |  | (12) |

The differential quantum operator associated with the energy E is given by the formula:

|  |  |  |
| --- | --- | --- |
|  |  | (13) |

To define the energy operator for a particle with respect to proper time, we use Equation (2) to express the differential of proper time as a function of the differentials of ordinary time and space as follows:

|  |  |  |
| --- | --- | --- |
|  |  | (14) |

The ‘+/-’ signs denote vectors within the upper/lower light cones with respect to the origin O. In the upper light cone, , whereas in the lower light cone, .

Using relation (14), the differential can be expressed as follows:

|  |  |  |
| --- | --- | --- |
|  |  | (15) |

where .

Substituting equation (12) into equation (15) we obtain:

|  |  |  |
| --- | --- | --- |
|  |  | (16) |

Substitution of equation (16) into equation (13) yields the energy operator with respect to proper time:

|  |  |  |
| --- | --- | --- |
|  |  | (17) |

To describe the evolution of the wavefunction with respect to proper time, we apply Equation (17) to the wavefunctions , as follows:

|  |  |  |
| --- | --- | --- |
|  |  | (18) |

By expanding the expression in Equation (18) into a system of two equations, using the relativistic energy E from equation (12), we obtain

|  |  |  |
| --- | --- | --- |
|  |  | (19) |
|  |  | (20) |

Equations (19) and (20) describe the evolution of the wavefunction according to two different dynamics: Equation (19) corresponds to the future-directed dynamics taking place within a future-light cone, while Equation (20) corresponds to the past-directed dynamics taking place within a past-light cone. The system of equations as a whole can be regarded as time-reversal invariant in the sense that if we reverse the direction of proper time in any one of the two equations, we directly obtain the other equation. This is discussed in more detail in [23].

The first Equation (19) is analogous to Schrodinger’s, except that ordinary time is replaced by proper time and a constant is added to the right-hand side. The mathematical methods for solving the above equation are therefore similar to those used to solve Schrodinger’s equation.

The energy for a free particle in the non-relativistic limit can be expressed as follows:

|  |  |  |
| --- | --- | --- |
|  |  | (21) |
|  |  | (22) |

Using and substituting the approximation from Equation (22) into the first equation, we obtain:

|  |  |  |
| --- | --- | --- |
|  |  | (23) |

Thus, in the non-relativistic limit, we obtain Schrodinger’s equation. The term is a constant corresponding to the rest energy, which has no effect on the evolution of the physical system and can be omitted.

The system of Equations (23) and (24) can be expressed as a single equation. In fact, the relationcan also be expressed as a product of two terms:

|  |  |  |
| --- | --- | --- |
|  |  | (24) |

Applying the above operator to the wavefunction with respect to the proper time, we get

|  |  |  |
| --- | --- | --- |
|  |  | (25) |

Developing Equation (25), we obtain an equation of motion equivalent to the system of Equations (19) and (20), as follows:

|  |  |  |
| --- | --- | --- |
|  |  | (26) |

Note that the above equations of motion are equivalent to the standard relativistic equations of motion, except that they are expressed in proper time rather rhan ordinary time.

In fact, Equation (26) is equivalent to the Klein–Gordon equation. By squaring expression (16), we obtain:

|  |  |  |
| --- | --- | --- |
|  |  | (27) |

By introducing the above relation into the operator of equation (26) before applying it to the standard wavefunction with respect to ordinary time, we obtain:

|  |  |  |
| --- | --- | --- |
|  |  | (28) |

Introducing the identity of the relativistic energy (21) into equation (28), the latter becomes

|  |  |  |
| --- | --- | --- |
|  |  | (29) |

Finally, by expressing the momentum according to its corresponding operator, equation (29) becomes the Klein-Gordon equation:

|  |  |  |
| --- | --- | --- |
|  |  | (30) |

The above analysis shows that the dynamics of the wavefunction with respect to proper time is, on the one hand, equivalent to the Klein–Gordon equation, and on the other hand gives Schrodinger’s equation in the non-relativistic limit. This clearly confirms that the definition of the wavefunction in terms of proper time is reasonable.

**6. Non-locality**

The wavefunction is a complex function that can be defined as follows:

|  |  |  |
| --- | --- | --- |
|  |  | (31) |

where is the phase and is the amplitude.

In [24], the following continuity equation has been derived from the equation of motion (19):

|  |  |  |
| --- | --- | --- |
|  |  | (32) |

where the current is given by:

|  |  |  |
| --- | --- | --- |
|  |  | (33) |

The current can be expressed as the density multiplied by the velocity . This implies that the velocity should be related to the phase while the density should be related to the amplitude. That is the phase should depend on the direction of the ray (or velocity ) at each elemental point of the elemental block, and where the amplitudeshould depend on the mass/energy density at that elemental point.

The wavefunction can thus be expressed as follows:

|  |  |  |
| --- | --- | --- |
|  |  | (34) |

It has also been shown in [24], that the evolution of the wavefunction through proper time is unitary; that is, its global density is conserved at each proper time instant . So the sum of the squares of the amplitudes should be normalised:

|  |  |  |
| --- | --- | --- |
|  |  | (35) |

It follows that the amplitude of the wavefunction at a given elemental point can be defined as the square root of the mass/energy density at that point divided by the square root of the total mass/energy of the particle:

|  |  |  |
| --- | --- | --- |
|  |  | (36) |

On the other hand, using the same formalism as in Bohmian mechanics for a particle of mass , the velocity at each elemental point of the corresponding elemental block can be expressed as being proportional to the gradient of the phase,as follows:

|  |  |  |
| --- | --- | --- |
|  |  | (37) |

To highlight the non-locality in an elemental block associated with a given slice within an elementary light cone, we propose to decompose the slice into non-overlapping discrete elements as follows:

|  |  |  |
| --- | --- | --- |
|  | and | (38) |

All the discrete elements refer to the same parameter , so for simplicity, we express the slice , as follows:

|  |  |  |
| --- | --- | --- |
|  |  | (39) |

Let and be the velocity and density associated with the discrete element . The velocity can be considered as the average velocity of all the elemental points associated with the positions belonging to the discrete element .

An elemental block can be represented by the decomposed elements and its wavefunction can be expressed as follows:

|  |  |  |
| --- | --- | --- |
|  |  | (40) |

where

|  |  |  |
| --- | --- | --- |
|  |  | (41) |

The velocity of the slice can be expressed as follows:

|  |  |  |
| --- | --- | --- |
|  |  | (42) |

where each representing the velocity of the discrete elements , is expressed as follows:

|  |  |  |
| --- | --- | --- |
|  |  | (43) |

The gradient of the phase is evaluated at the location of the j-th discrete element .

Any change of the i-th discrete element changes the value of the phase which automatically affects the velocities of the discrete elements.

For example, the velocity of the j-th discrete element according to equation (43) becomes :

|  |  |  |
| --- | --- | --- |
|  |  | (44) |

Consequently changes and, in general, the variation of any discrete element automatically affects all other discrete elements. This variation describes a non-local inherent transformation within the given elemental block .

The above subdivision is only meant to illustrate that all the parts of the elemental block are intrinsically non-separable. In fact, the elemental block is not divisible. Any transformation should always be considered as global or as a single ‘proper time event’.

**7. Measurement**

The wavefunction of an elemental block at a given proper time representing a free particle evolves according to the equation of motion (19). It evolves locally and is consistent with special relativity, although it remains non-local in itself. Here non-locality is used in the sense of non-separability as it is defined by Wallace in [15].

During this evolution, the wavefunction spreads out smoothly as a consequence of its passage from one slice into a subsequent slice . This spreading suggests that the density of the block should be stretched (thus becoming more diluted) as it evolves over proper time.

However, the introduction of an external potential such as a confining potential modifies the equation of motion from (19) to the following one:

|  |  |  |
| --- | --- | --- |
|  |  | (45) |

The above equation is similar to that describing a particle in a potential well, where the wavefunction outside the edges of the potential well tends to zero. Thus, the confining potential imposes boundary conditions on the wavefunction.

The wavefunction is an exact representation of the elemental block. Thus, the action of the confining potential on the elemental block induces its reconfiguration. The density of the elemental block becomes concentrated within the confining potential and tends to zero outside the confining region, while remaining extended and non-separable.

Measurement is actually the contraction of the density of the inherently non-local elemental block in response to the application of an external confining potential . So measurement is not an independent law alongside the equation of motion. It is a literal conformity of the non-separable elemental block to the equation of motion.

The discontinuity in the reconfiguration of the wavefunction is due to the combination of two factors. The first factor is the abrupt introduction of the confining potential, which changes the equation of motion from (19) to (45). The second factor is the non-separable nature of the elemental block, which instantly reacts to conform to the newly introduced potential in the Equation (45).

The illusion of a paradoxical transition from a deterministically evolving spread-out wavefunction to a sudden probabilistic localisation is created by the inherent non-separability of the elemental block. In fact, it is always a deterministic evolution governed by an equation of motion (19) whose potential term is abruptly changed.

The reaction of the elemental block due to its inherent non-separable nature and the abrupt introduction of the confining potential can be formalised by multiplying the wavefunction by a reconfiguration or contraction function , whose form depends on the external potential, as follows:

|  |  |  |
| --- | --- | --- |
|  |  | (46) |

where and represent the subsequent and antecedent wavefunctions.

Equation (46) implies that at a proper time instant , just before the action of the external potential , the wavefunction is in an antecedent state and that at a proper time instant , just after the action of the external potential , the invariant wavefunction is in a subsequent state .

The reconfiguration of the wavefunction representing an elemental block is therefore a consequence of the introduction of an external potential into the equation of motion (19) and the inherent non-separability of the elemental block. It should also be noted that when the elemental block contracts, this does not mean that the elemental block is moving in space. Rather, it is the shrinking of an element of space itself.

In general, the contracting function can be defined by a contracting Gaussian applied to the interaction zone of the wavefunction and whose dispersion depends on the form of the external confining potential. The narrower the confinement potential, the smaller the wavefunction dispersion, and thus, the more concentrated is the density of the elemental block .

In accordance with the uncertainty principle, the density of the elemental block cannot be concentrated beyond an infinitesimally small minimally localised region. In the latter case, the contracting Gaussian becomes a localising Gaussian similar to that in the GRW theory, except that it is not a random spontaneous collapse but rather a deterministic response to the external potential, as described in more detail in [24] [21]. The localising Gaussian has a minimal dispersion consistent with the uncertainty principle and is centred at a point around which the contraction takes place. Thus, unlike the GRW theory, the elemental point is not random and depends on the region of interaction between the wavefunction and the external potential that induces the contraction. On the other hand, the point is not necessarily the centre of density.

**8.** **Configuration space**

As shown above, a particle is considered to be an elemental substantive block whose state can be represented by an elementary wavefunction in a Hilbert space associated with the elemental block.

More generally, a system consisting of N particles is a system of N elemental blocks, which can also be represented by a wavefunction. To take into account the individuality of each elemental block, the system of N elemental blocks is defined in an abstract space equal to the tensorial product of the N elemental blocks:

|  |  |  |
| --- | --- | --- |
|  |  | (47) |

Consequently, the wavefunction of the N-particle system can be represented by a wavefunction in an N-dimensional configuration space defined by the tensorial product of N Hilbert spaces associated to the N elemental blocks. The configuration space in which the state of a system is defined is thus related to the elemental substantival blocks that make up the system of particles.

Consider for example, a system consisting of two particles, i.e. a two-block system. The elemental points of each block can be defined with respect to a corresponding light cone within which a family of corresponding slices is defined. Let the elemental points of the first block be continuously mapped by a first bijective application onto a subset of a first slice in the first light cone (i.e. the block is homoeomorphic to a subset of the slice ). Let also the elemental points of the second block be continuously mapped by a second bijective application onto a subset of a second slice within the second light cone.

Let the image of each elemental point of the first block be and let the image of each elemental point of the second block be . The coordinates of the first and second elemental blocks and are thus defined as follows:

|  |  |  |
| --- | --- | --- |
|  |  | (48) |
|  |  | (49) |

Each slice within the first light cone represents a first basis associated with a first Hilbert space and each slice within the second light cone represents a second basis associated with a second Hilbert space .

The two-block system can be represented by a wavefunction defined in a third Hilbert space corresponding to the tensor product of the first Hilbert space and the second Hilbert space . The tensor product implies that each elemental point of one block is potentially coupled to each elemental point of the other block.

If the two blocks intersect, let be the intersection zone. Each elemental point belonging to the intersection zone has first coordinates in the coordinate system of the first application as well as second coordinates in the coordinate system of the second application .

At the intersection zone , the two blocks have different coordinates and in particular, different proper times. Suppose that the intersection between the two blocks occurs when the proper times of the first and second blocks are and respectively. Then can be considered as an initial condition, so that the evolution of both blocks can then be defined with respect to an arbitrary proper time which represents the proper time increment with respect to the initial condition .

To distinguish between the two blocks, we denote the elemental points of the first block by and the elemental points of the second block by . In the intersection zone , we have .

The mass/energy density of the two-block systemcan be defined as a function of the first and second densities. At each intersection point, the density should be a combination of the densities and relative to the first and second blocks, respectively. At the points that do not intersect, the densities are not combined.

The densities of the first and second blocks at the proper time can thus be defined as follows:

|  |  |  |
| --- | --- | --- |
|  |  | (50) |

It follows that the wavefunction of the two-block system should be the tensorial product of two wavefunctions and depending on the above densities:

|  |  |  |
| --- | --- | --- |
|  |  | (51) |

Taking all possibilities into account, the above equation implies

|  |  |  |
| --- | --- | --- |
|  |  | (52) |

The wavefunction is expressed as the sum of the factorised states *,* , , , , and , the elemental points being defined below.

is any elemental point belonging to the first block that does not intersect with any other elemental point in the second block . Similarly, is any elemental point belonging to the second block which does not intersect with any other elemental point in the first block.

The state represents the coupling or relation between all non-intersecting elemental points and belonging to the first and second elemental block respectively.

is any elemental point belonging to the first block that intersects with a corresponding elemental point belonging to the second elemental block .

The state represents the relationship between all elemental points and belonging to the first and second blocks respectively and having the same coordinates . That is, any elemental point in the first block which is related to the elemental point in the second block that has the same coordinates (i.e. ).

is any elemental point belonging to the first block which intersects with a corresponding elemental point belonging to the second block. The elemental points have the same properties as the elemental points . The different notation is used to highlight the fact that the relationship between the elemental points and is not the same as that between and (or and ). The elemental point in the first block is related to an elemental point in the second block, such that .

The state represents the relationship between all elemental points and belonging to the first and second blocks, respectively which do not have the same coordinates, while each elemental point in the first block has an intersection counterpart in the second block and similarly each elemental point in the second block has an intersection counterpart in the first block.

Similarly, the state represents the relationship between all elemental points and belonging to the first and second blocks, respectively which do not have the same coordinates, while each elemental point in the first block has an intersection counterpart in the second block and similarly each elemental point in the second block has an intersection counterpart in the first block.

In summary, the factorised states *,* , , , , and are defined as follows:

|  |  |  |
| --- | --- | --- |
|  |  | (53) |

The above formulation is only meant to be a very general and schematic one. In particular, the connectivity value between different elemental points belonging to different blocks may vary. Therefore, weights should be assigned to the different connections. For example, the weight can have a value that varies between 0 and 1. The weight is 0 if the elemental points are independent, the weight is 1 if the elemental points are not separable. A weight between 0 and 1 indicates more or less connectivity.

For an elemental block, the connections of each elemental point with every other elemental point can be assigned a connectivity weight of 1, so that the elemental block is completely inseparable.

However, since different blocks can eventually be separated even if they are highly entangled, the connectivity weights between elemental points belonging to different blocks should be strictly less than one.

If the connectivity between elemental points in the intersection zone is high enough to make these elemental points inseparable, then the two-block system automatically becomes non-separable, since all the elemental points belonging to the first block are non-separable and all the elemental points belonging to the second block are also non-separable.

The above equation (53) defines the wavefunction of the two-block system in the general case where the intersection zone can be arbitrary between two limit cases: or . These two limits are discussed below.

In the first limit, the intersection zone is empty (). That is , ; . Then, the wavefunction according to equation (53) is simplified to a single factorised state:

|  |  |  |
| --- | --- | --- |
|  |  | (54) |

The densities of the two blocks are separate and, as would be expected, the description of the combined two-block system is compatible with the descriptions of the two separate blocks, which do not influence each other. The two-block system is thus non-entangled.

The above also applies if the intersecting zone is not empty, but the connection weights are zero.

In the second limit, the two elemental blocks are congruent () as if they formed a single block (andthe connection weights are not equal to zero). Each elemental point of the first block is shared with a corresponding elemental point of the second block, and both blocks have the same proper time . That is, , ; . Then, the wavefunction according to equation (53) becomes:

|  |  |  |
| --- | --- | --- |
|  |  | (55) |

The wavefunction is expressed as the sum of the factorised states , , and . The two-block system is thus entangled.

For an entangled two-particle system, if a measurement is made on the first particle at a proper time instant, the second particle immediately (i.e. at the same proper time instant) acquires a determinate value, irrespective of the spatial separation between the two particles. The hypothesis that non-locality should be considered with respect to proper time and not ordinary time can be tested experimentally.

In view of the above, the wavefunction represents the different elemental substantival blocks that make up the system of particles. These different elemental blocks are defined in a configuration space, while their combination is part of ordinary spacetime.

Lorentz invariance is applicable in ordinary spacetime, while non-local collapse applies in the configuration space, which consists of an elemental block or a set of entangled elemental blocks.

Configuration space takes into account the atomistic nature of spacetime. Atomistic is used here in the sense of fundamental or elementary and not in the sense of microscopic, since the size of each ‘spacetime atom’ (i.e. elemental substantival block) can range from infinitely small to infinitely large. In particular, configuration space takes into account the fact that any elemental block, or system of entangled elemental blocks, is intrinsically non-local, which is not taken into account when spacetime is considered in its globality.

The atomistic nature of spacetime gives a physical sense to configuration space and the ontology of a wavefunction. It also allows a literal interpretation of standard quantum mechanics in terms of proper time rather than ordinary time.

**9.** **Conclusion**

An elemental substantival block can be considered as an elemental “proper time event” whatever is its substantival extension. Within the elemental block, there are no causal connections between its parts because all the parts belong to the same single elemental event. Non-locality is inherent in each elemental block or a set of entangled elemental blocks.

Elemental substantival blocks are the building blocks of ordinary spacetime. A point or event in spacetime may be common to different elemental blocks having different proper times. A classical event can of course be associated to a resultant proper time but, the latter is only a convenient representation of a multitude of elemental proper times. Non-locality has no sense with respect to a plurality of different elemental proper times associated to different non entangled elemental blocks.

The combination of all the elemental blocks wash out the individualities and in particular, the non-local properties of the elemental blocks. Locality in ordinary spacetime becomes emergent.

In fact, the universe as a whole is made up of a combination and/or juxtaposition of elemental substantival blocks wherein the extension of each elemental block can be from infinitesimally small to infinitely big. Each elemental block has a density that can be concentrated or extended. Each particle is an elemental block, which is infinitesimally small when its wavefunction is collapsed or extended when its wavefunction is not collapsed. Spacetime, energy, matter, dark matter, dark energy and everything that exists in the universe is emergent out of all elemental blocks. The difference between matter, energy and spacetime is only a difference in degree, i.e. a difference in the distribution of density. For example, a measured particle is an elemental block that has the bulk of its density concentrated in an infinitely small extension whereas, an unmeasured or unconfined particle is an extended elemental block.

Spacetime is not a recipient that exists in itself outside the objects because all objects as well as spacetime are different forms of elemental substantival blocks. Spacetime is substantival but unlike that of Newton, it is not a container, it is more like the ‘material plenum’ of Descartes.

To sum up quantum mechanics deals with the intrinsic structure of spacetime and applies to the non-local elemental blocks while relativity deals with the resultant or emergent spacetime. Relativity applies to events through spacetime and has no meaning within the elemental block because the latter is not intrinsically composed of different events. There is no contradiction between quantum mechanics and relativity. Their relation to each other is similar to that of statistical physics with respect to thermodynamics.

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