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Conditions for Entanglement

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Abstract
Whereas entanglement and nonlocality belong to the fundamental findings of quantum theory, possible extensions to macroscopic systems outside the quantum laboratory are scarcely studied. This paper analyses conditions for entanglement to occur on a macrophysical level. An empirical basis is given by historic episodes and modern quantitative data. Theoretical understanding can start from the concept of perspective notions; the crucial new term is *"common prearranged context",* which characterizes the preparation to be made in advance (or naturally given conditions) in order to enable entanglement. A mathematical formalization is possible and gives some insight about how to handle perspective notions.

1. Entanglement in Quantum Theory and on a Macrophysical Level

Entanglement and nonlocality belong to the eminent findings of modern quantum theory, [1 2] confirmed experimentally beyond any doubt, and also by the functioning of quantum communication. Some years after the famous experiments by Aspect *et al.,* [3] the idea was sketched that EPR correlatedness could be generalized beyond the original domain. [4] Along this line, series of fascinating experiments were performed inside the quantum laboratories. [5]

In a modern view, there is no strict dichotomy between a "realm of quantum theory" and a "macrophysical range" [5] Quite the contrary, there are macrophysical effects originating in quantum phenomena, e.g., a utilization of quantum phenomena by living organisms [6 7].

The purpose of this paper is:
- To present an ordered overview of classes of nonlocal phenomena (as far as known in this moment), both on the microphysical and on the macrophysical level,
- To propose a unified description of these phenomena and of the underlying conditions,
- To advance a mathematical formalism which is suitable to represent these underlying conditions and the influence of entanglement on the system behavior.

Entanglement is understood as a *concrete, measurable (observable)* correlatedness between two spatially separated entities (persons, objects or processes). *Spatially separated* means that one partner cannot reach the other by signalling, taking into account the velocity of light as the ultimate limit.

2. Various Manifestations of Nonlocal Correlatedness
2.1. Quantum Entanglement

The standard EPR experiment involves two spatially separated particles emitted from the same source; measuring on one of them immediately influences properties of the other. More recently, Elitzur and Dolev [8] describe an experiment in which two atoms are entangled by a "future interaction": "Unlike the ordinary EPR, where the two particles interacted earlier, here their common event lies in their *future*." ([8], p. 301)

2.2. Clues Suggestive for Entanglement on the Macroscopic Level
2.2.1. Historic Episodes

For historical reasons and for the sake of completeness, a strange phenomenon must be mentioned: *Synchronicity* denotes the occurrence of *acausal meaningful* coincidences; e.g., suddenly encountering an old friend, unseen for many years, or running across a book or a reference, without conscious search, that exactly matches a current information requirement. From the abundant literature we only quote an article by C. G. Jung, [9] which was influenced by Jung's cooperation with the physicist Wolfgang Pauli. The bulk of printed paper, with masses of anecdotal stuff, can be considered a collection of material, typical of the early phase of some new branches of research; the attempts of a theory are not convincing, and the argument of mere chance cannot be refuted.

2.2.2. Modern Quantitative Material

Based on careful experiments with pairs of spatially separated human subjects, several authors (see e.g. [10] [11]) found significant correlations between the two subjects' brain functional states. Due to the automated registration of electrophysiological observables and the computerized evaluation, some points of criticism voiced against earlier experiments are no more valid here.

A *pathogenetic trial* is a test of a specific substance (expected to be of medical importance) by registering the symptoms experienced by healthy volunteers. Some recent studies [12] [13] used a meticulous experimental design. The studies were randomised and double-blind; the "provers", the researchers, and the persons who handed the substance were uninformed ("blinded"). The provers neither knew nor met each other. In one study [12] even the substance to be tested was blindly chosen from a list of 12 candidates by a neutral person, who did not inform any other participant before the end of the study. What is of interest here is the fact that typical symptoms were also found in those provers who had only received an undistinguishable fake.

For about 200 years, homeopathy has been controversially debated. A comprehensive overview of its history, principles, facts and interpretations is given by Walach. [14] As a conclusion derived from their meta-analysis, [15] the authors state that the results "are not compatible with the hypothesis that the clinical effects of homeopathy are completely due to placebo". Trivial explanations, like the "shaping" of water molecules, must be regarded as irrelevant at least in the case of highly diluted substances.

3. Outline of a Unified Theoretical Basis
3.1. Common Prearranged Context

Now a "generic term" is required which includes both microscopic and macroscopic nonlocal correlatedness, and which is suited to cover the variety of its manifestations (as far as currently known). Here the term *common prearranged context* is proposed. Two persons, objects or processes can be comprised by such a common context, which may have been generated by nature or by human persons or institutions. The principal appearances can be characterized as follows:

- *Common historical context*: e.g., two photons generated by the same process, as in the standard EPR experiments,
- *Common future:* e.g., two atoms entangled by future interaction (see Section 2.1)
- *Common biographic context:* e.g., two persons familiar with each other for some time,
- *Common organizational context:* both partners are involved in the same organized process, e.g., the same action, project, experiment, test, etc., both have a role or a function in it; this also holds for relations between persons and objects (e.g., patient and remedy in the case of extreme dilutions, see Section 2.2.2).

3.2. Perspective Notions and the Necessary Preceding Steps

As can be taken from these characteristic patterns, a *preceding step* is always required, which may possibly be provided by nature; this also holds for entanglement by future interaction, where a suitable laboratory setting is a precondition for the future encounter. This feature, the *necessary preceding step* for short, can be associated to some other topics having just this feature in common; altogether this will supply a key to mathematical modelling (Section 4).

Any measurement is a *two-step process*: first the purpose of the measurement and some details must be fixed, then the measurement can be performed; this property of being a two-step process is often obscured by a tacit consensus among the persons involved.

Perspective notions are terms that – beyond the trivial context-dependence of any word meaning – require the context to be disclosed. The most eminent perspective notions are *meaning* and *interpretation*. A prearrangement of context, as considered here, includes an assignment of meaning or a previously fixed interpretation. [16]

Next, *similarity* and *dissimilarity*, also relevant here, must be named. An example is given by chemical elements, which can be regarded as "similar" depending on their atomic weights, electrochemical or radioactive properties, etc. Similarity plays a role in synchronistic phenomena (Section 2.2.1), where there are striking cases of similarity between two synchronistically coupled events, and also in the hypotheses underlying homeopathy. [14] The intuitive concept of "affinity" (between two persons or two processes) can also be expressed by similarity; the latter term offers a path to a mathematical handling of the necessary preceding step and its role within the conditions for entanglement (Sections 4.2 and 4.3).

4. First Steps towards Mathematical Modelling

4.1. Quantification of Similarity

There are three characteristic features of entanglement which entail the requirements on a mathematical tool:

- *Selectivity, exclusivity*: In principle, entanglement concerns *two* entities (persons, objects, processes); an extension to a greater (finite) number of persons or particles under specific conditions is not excluded.
- *Nonlocality* indeed has a dual character: Entanglement is immune against bounds imposed by distance or maximal velocity (Section 1), but conversely, a third party, geometrically very near to one of two entangled partners, even need not be aware of the fact that something is going on.
- *Condition-dependence:* Entanglement does not happen at random, but requires a precondition to be fulfilled.

Therefore, the next task will be to formulate a mathematical tool to express the similarity between two given structures. In a second step (Section 4.2), these similarity characteristics will enter into a matrix formalism which describes the system behaviour.

It is easier to formulate the following definition in terms of dissimilarity – if a dissimilarity function is known, then the transition to similarity is elementary. A dissimilarity function *d(x,y)* is a function of two variables with the usual properties of a metric, as specified by the well-known system of axioms (here only the symmetric case is relevant):

M1: *non-negativity:* $d(x,y) \geq 0$
M2: $d(x,y) = 0$ *if and only if x and y are identical*
M3: *symmetry:* $d(x,y) = d(y,x)$
M4: *triangle inequality*: $d(x,y) \leq d(x,z) + d(z,y)$

Now a finite set of structures $S = \{S_1, S_2, \dots, S_n\}$ is presupposed. To start with, these S_i may be finite connected graphs – possible extensions will be addressed later. The tool for finding a function $d(S_i,S_k)$ is supplied by graph grammars. A *graph grammar* is given by a startgraph and a finite number of production rules. Each production rule permits the generation of a new graph from one of the already existing ones. This is done by graph rewriting: replacing a subgraph of the given graph – where the subgraph must obey a condition specified in the production rule – by another graph. For the present purpose, a graph grammar Γ is required that will generate at least all graphs in the given set S. For a fixed graph grammar Γ the requested dissimilarity function is defined by

$$d(S_i,S_k) = \min L(S_i,S_k), \qquad (1)$$

where $L(S_i,S_k)$ denotes the length of a "path" that leads from S_i to S_k by following the lines "upward" and "downward" which represent the generation of these two structures in a "pedigree-like" diagram depicting Γ; each such step upward or downward contributes 1 to *L*.

This procedure can be generalized to graphs with edge- and/or vertex-labels, and to hierarchical graphs. For these extensions, as well as for the technical details of graph grammars, diagrams, and references see [17].

For a given set S of structures, it is always possible to find a graph grammar Γ such that at least all structure in S are generated by Γ. But, apart from trivial cases, a graph grammar specified in this way cannot be unique. Rather, there is a great variety of graph grammars, each of which will be suited to represent the desired dissimilarity function on S. The reason behind lies in the fact that similarity and dissimilarity are perspective notions (Section 3.2), and no quantification is possible without a reference to the purpose (and the entire context) of such an assessment. Similarity between structures is never a property of the structures themselves; rather, it is defined by an observer, and different similarity functions mirror the different subjective views of different observers.

In summation, similarity can be quantified in a manner that takes the context into account. By analogy with the two-step character of every measurement, first a graph grammar must be formulated, and then the similarity can be measured. By further sophistication, e.g., by the use of hierarchical graph grammars, also a greater complexity in the interior of the two structures under comparison can be adequately handled.

4.2. The Effect of Entanglement Expressed by Connector Matrices

The system behaviour is characterized here by the system state and by operators specifying the transition from one state to the subsequent one. For the sake of simplicity, the state is written as a vector (from an *n*-dimensional vector space), and the operators are represented by square matrices of the appropriate size. (The matrix elements are nonnegative real numbers.)

First, the "unconnected" system behavior – that is in absence of entanglement between subsystems – must be described. In view of the following demonstration it is presupposed that the system consists of exactly three subsystems, which are pairwise independent in the "unconnected" case. Then, with a block-structured matrix and a correspondingly structured vector, a transition step can be written as

$$\begin{pmatrix} \mathbf{A} & \mathbf{O} & \mathbf{O} \\ \mathbf{O} & \mathbf{B} & \mathbf{O} \\ \mathbf{O} & \mathbf{O} & \mathbf{C} \end{pmatrix} \begin{pmatrix} \mathbf{x} \\ \mathbf{y} \\ \mathbf{z} \end{pmatrix} = \begin{pmatrix} \mathbf{x'} \\ \mathbf{y'} \\ \mathbf{z'} \end{pmatrix} \tag{2}$$

If the subsystems described by **A** and **C** are correlated (and no other ones), this will be symbolized by a connector matrix: the unit matrix plus two additional blocks **S** and **T** representing exactly that correlatedness. The product matrix **P**

$$\mathbf{P} = \begin{pmatrix} \mathbf{I} & \mathbf{O} & \mathbf{S} \\ \mathbf{O} & \mathbf{I} & \mathbf{O} \\ \mathbf{T} & \mathbf{O} & \mathbf{I} \end{pmatrix} \begin{pmatrix} \mathbf{A} & \mathbf{O} & \mathbf{O} \\ \mathbf{O} & \mathbf{B} & \mathbf{O} \\ \mathbf{O} & \mathbf{O} & \mathbf{C} \end{pmatrix} = \begin{pmatrix} \mathbf{A} & \mathbf{O} & \mathbf{SC} \\ \mathbf{O} & \mathbf{B} & \mathbf{O} \\ \mathbf{TA} & \mathbf{O} & \mathbf{C} \end{pmatrix} \tag{3}$$

multiplied with the original state vector leads to a different transformed vector with

$$\mathbf{x''} \neq \mathbf{x'}, \quad \mathbf{y''} = \mathbf{y'}, \quad \mathbf{z''} \neq \mathbf{z'}, \tag{4}$$

where the two cases with inequality show the alteration due to entanglement. In the general case, the simple matrix multiplication, which brings about **SC** and **TA** in (3), can be replaced by a more sophisticated procedure taking a deep structure into account (see Section 4.3), and the connector matrix is replaced by an operator. Strictly speaking, all matrix elements can be influenced by the process and hence vary in time; for the sake of simplicity this was not noted in the formulas.

4.3. Common Prearranged Context and the Mathematics of Similarity

Any action which assigns entities (from a given finite set) to different subsets will define a measure of similarity between these entities. (In this moment it is still a draft – two elements of the same subset are more similar than two elements of different subsets.) This definition will be as momentous or as sloppy as the underlying action. Here we have a first hint that a common prearranged context is connected with a measure of similarity. Other acts of fixing that are essential for a prearranged context – e.g., a regulation binding certain individuals to a role or a cooperation – can be considered in the same manner. So *context determines similarity,* and *similarity modifies the system behaviour.*

The mathematics of similarity can also be hidden behind the easy notations **SC** and **TA** in (3). For the sake of easiness, consider just two opposite cases: depending on a better or worse "fitting" between two factors (e.g., **S** and **C**), the product matrix can take on significant numerical values or collapse into a quagmire of numbers close to zero.

For simple cases the usual matrix multiplication can suffice, but for more complicated cases that notation may symbolize a combination of the two matrices which takes their internal structure into account more rigorously (block-structured matrices or hierarchically structured matrices). A possible tool is a specific operation called "matrix weaving", which includes some known combinations of matrices as special cases. [18]

5. A Proposal of a Macrophysical Experiment

The following proposal starts from the fact that entanglement by common future is experimentally proved on the quantum level ([8], see Section 2.1), and consequently aims at a related experiment on the macrophysical scale. Let there be N test tubes (N is an even number), all filled with the same pure chemical substance, called A, either a liquid or in form of a solution. These test tubes are given numbers from 1 to N, and by a random number generator each is assigned to one of two subsets, named X and Y, where each subset consists of $N/2$ tubes. In the near future, the contents of each X-tube (apart from a little rest) is to be brought into a chemical reaction with a previously arranged substance called X', and correspondingly for each Y-tube and a different stuff named Y'. The substances A, X' and Y' must be selected in such a way that reactions of the types (A,X') and (A,Y') really do occur and generate new stable compounds, different for X' and Y'.

Now it is supposed that the predestined future can have an impact on the substances, clearly distinguished for members of the subsets X and Y, after fixing the assignment to the subsets, but before starting the chemical reactions. This impact can be understood as an adaptation to the future chemical reaction. Hence a substance is required for A which – independently from this experiment – spontaneously oscillates between two states, e.g., between two stereochemical conformations (stereoisomers). If necessary, energy can be supplied by heat, radiation or shaking (for all test tubes in the same way). The substance must be carefully selected. For example, it is known that chirality is a "classical variable", and hence an experiment on this basis would fail.

A first tentative proposal may be cyclohexane (C_6H_{12}), which alternates (mainly) between the chair conformation and the boat conformation. The marked disparity which is of interest here is the unequal distance between the two pairs of H atoms typical of the two shapes: the two pairs of "flagpole hydrogens" of the boat are less distant than the "up and down" of the chair. ([19], p. 107-116). Therefore, one of the two shapes may better fit the reaction partner X', whereas the other will better match Y'.

If there should be an anticipation of the future chemical reaction, then this can manifest itself by atypical concentrations of two previously adapted shapes (e.g., two stereoisomers) in the time between the arrangement of subset memberships and the reactions; to this purpose, a small sample from each test tube must be saved (unless an unproblematic direct measurement is possible).

6. Concluding Remarks and Outlook

6.1. A Remark on the Data Basis

The material quoted in Section 2.2 requires some critical comments. Most of the authors cited there admit that the empirical basis is not perfectly convincing and advocate further research; some of the authors do not try a theoretical explanation. It would not be justified, however, to stop further endeavor in view of this situation. Rather, here again we are facing the time-honoured vicious circle: as long as there is no fitting and accepted theory, the phenomena are ignored (or misinterpreted), and as long as the phenomena are disregarded, no theory is elaborated. Henry H. Bauer [20] demonstrates, based on an abundant material from the history of science, that science is not always "data-driven", and that the lack of a theory or an opposed predominant theory can block the acceptance of empirical findings. This is exemplified by the delayed acceptance of oscillating chemical reactions and of the continental drift. As a consequence, we should simply dare to sketch theoretical concepts, with all due reservations about their validity and the need for future updating.

6.2. Quantum Theory and Beyond

The fundamental role of quantum theory should always be kept in mind, particularly the fact that quantum indeterminacy has impacts upon the macroscopic level, too. The concept of prearranged context cannot be used in a mechanistic way; it is not possible to enforce macroscopic entanglement, and there are no sufficient conditions to make it occur, but only favorable circumstances.

The proposal developed here is compatible with the state of the art of quantum theory, and particularly with a recent advance to extend quantum theory beyond its original domain (see below). In any such proposal some fundamental properties must be maintained which are typical of nonclassical systems of any kind:

- The system description by system states and operators conveying the transition from one state to the subsequent one
- The noncommutativity of operators [16]
- The noncommutativity of measurements: the temporal sequence of the measurements of two complementary variables makes a difference (e.g., in an interview the temporal order of the questions asked can influence the responses).

Weak Quantum Theory (WQT) [21] is a generalized version of "traditional" quantum theory. It is based on a similar algebraic formalism, but drops some characteristic definitions and restrictions. First of all, there is no Planck constant, and the sum or difference of two operators is undefined. WQT makes a prediction of entanglement, which can be seen in analogy to the classical EPR correlatedness, but is valid for a more comprehensive class of systems.

A particular difficulty comes in when *global* and *local variables* are to be defined for macroscopic entities. Of course, there are global variables, like mass, volume, temperature, etc., and also population, gross national product, etc., but these are not helpful here. So it has been proposed [21 22] to consider the substructure of a macroscopic entity – its composition of sub-systems, sub-sub-systems etc., possibly for a finite number of steps in a hierarchical manner. Yet the substructure of a system is not uniquely defined. It is a perspective notion, too; it depends on the situation and the purpose of such an analysis.

It will not suffice for entanglement to occur that all subsystems of a specified kind share the same property of incompatability or complementarity with respect to the total system. This can be demonstrated by an example. In some country, there were several individuals or groups with the common property that they were not happy with their government. But, as we know from historic examples, such people will not always cooperate, let alone be "entangled". What would be required, in addition, is an agreement between the persons involved, which can be regarded as a *previous arrangement* (Section 3.1).

It is the author's hope that this paper will help to discard misinterpretations of facts (metaphysics where meanwhile physics is possible) and also contribute to a better assessment and understanding of historic material and some intricate empirical findings, where further research is both necessary and promising.

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