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THE EPR-EXPERIMENT AND FREE PROCESS THEORY

ABSTRACT. As part of the 'creation-discovery' interpretation of quantum mechanics Diederik Aerts presented a setting with macroscopical coincidence experiments designed to exhibit significant conceptual analogies between portions of stuff and quantum compound entities in a singlet state in Einstein–Podolsky–Rosen/Bell-experiments (EPR-experiments). One important claim of the creation-discovery view is that the singlet state describes an entity that does not have a definite position in space and thus 'does not exist in space'. 'Free Process Theory' is a recent proposal by Johanna Seibt of an integrated ontology, i.e., of an ontology suitable for the interpretation of theories of the macrophysical and microphysical domain (quantum field theory). The framework of free process theory allows us to show systematically the relevant analogies and disanalogies between Aerts' experiment and EPR-experiments. From free process ontology it also follows quite naturally that the quantum compound entity described by the singlet state 'does not exist in space.'

1. INTRODUCTION

Louis de Broglie reports Einstein as saying: "It should be possible, aside from all calculations, to illustrate physical theories, with images of such simplicity, that a child should be able to understand them".[1] One can distinguish two kinds of such simple examples of a theory T: ones that bring out what is distinctly different about T, and examples that make T more familiar and transparent. In the case of quantum theories, the first kind of illustrative purpose is easily fulfilled, while the second is not. It is not that hard to find illustrations that bring out what is distinctly different about quantum theories.[2] In contrast, it is notoriously difficult to come up with examples that would bring quantum theory close to our common understanding of physical reality. It is well known that quantum mechanics (QM) violates Bell-inequalities and that the experiments support the quantum-mechanical predictions. If a theory confirms a Bell-inequality it is local, otherwise the theory is non-local. There have been a number of experiments confirming the quantum mechanical predictions, the most famous one being the experiments by Alain Aspect and his collaborators in Paris in 1982.[3] In such experiments ensembles of pairs of quantum entities are considered. These compound entities are prepared in a uniform way

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(they are produced by a source in a singlet state), which leads us to expect statistical correlations between the measurements results performed on each of the entities in a pair. But the measurements are performed in apparatuses that are widely separated in space. (Henceforth we will refer to these experiments as EPR-experiments.) In this paper we will proceed from the commonly accepted view that the cause of the violation of Bell-inequalities is the violation of *outcome independence*.[4] Usually we tend to believe that when there is a correlation between kinds of event, if the events have a common cause, the common cause makes the events statistically independent (they are screened off from each other by the common cause). Outcome independence identifies the uniformly prepared states coming from the source as the common (stochastic) causes of the measurement results performed on each of the components in of one of the compound entities (Redhead (1987, p. 102)). A violation would mean, first, that the state coming form the source is not the common cause of the measurement results in both wings, secondly, that there is a direct stochastic causal link between the two particles. But then we are not taking into account the following fact: "Definite correlations are there if I do not poke or disturb the system in any way, but they are too delicate ... to reflect a causal connection" (Redhead (1989, p. 440)). So basically the violation of outcome independence only tells us that probability distributions of properties possessed by the one particle would depend essentially on the property possessed by the other particle. QM is non-local in the sense of violating outcome independence. In the eighties Diederik Aerts presented a simple macroscopical thought experiment with coincidence measurements on communicating vessels of water, which he claims to be strongly analogous ('identical') to EPR-experiments (Aerts 1981; Aerts 1982; Aerts 1983b).[5] It is clear that Aerts' experiment (hereafter: the Aerts-experiment) belongs to the second kind of illustration: it describes a macrophysical scenario with familiar entities that aims to give us a simple image of what is actually happening in an EPR-experiment. The Aerts-experiment is part of the creation-discovery view on quantum mechanics, developed by Aerts and his co-workers. According to the creation-discovery view on quantum mechanics, the entity described by the singlet state in EPR-experiments acts as the common cause of the measurement results in both wings, however without making the measurement results statistically independent. Part and parcel of the creation-discovery view is the following assumption:[6]

> CD: The entity described by the singlet state has no definite position in space, i.e. it 'does not exist in space', which explains why it is able to act in two spatially separated regions of space and why it does not make its separate effects statistically independent.

Our focus here will be on what might be considered the crucial *lacuna* in Aerts' attempt to provide a macrophysical illustration of the EPR-paradox. Aerts does not state this explicitly but he operates on the assumption that water and quantum entities are sufficiently analogous in ontological respects. The main aim of this paper is to show that this assumption is justified and this leads to a confirmation of CD.

As philosophers of science like to point out, theories are underdetermined by empirical data, and as QM has taught us more than any other physical theory, theories underdetermine their interpretation (an interpretation is here understood as a description of what the theory says there is in the world). Let us very briefly look at this last aspect. There are physicists who have adopted the language of philosophy here, speaking of 'ontologies' for QM (see Herbert (1985) for example). Ontology is traditionally understood as the (or a) theory about what there is. The ontology of a theory T makes explicit and systematizes what there is according to T. But is this not what T already does? In other words, should we not be able to 'read off' the ontology of T from T? Unfortunately that is not always possible, for at least two reasons. First, in order to determine the ontological commitments of a theory T, there should not exist competing formulations of T. Second, within the representative formulation of T it should be clear which parts are to be considered pure 'machinery' or, to use Redhead's term, "theoretical surplus structure." The ontological interpretation of QM confronts both of these obstacles. That QM lacks conceptual transparency is not due solely to the fact that the quantum world is not directly observable and thus cannot be exemplified with an intuitive mental picture close to common sense experience (a characteristic not unique for QM); despite its impressive experimental confirmation it is not clear which of the competing mathematical formalisms should be chosen for interpretation and moreover which parts of the chosen mathematical formalism are ontologically significant. In recent years particular efforts have been spent in interdisciplinary discussion to make some headway on the conceptual clarification and ontological interpretation of theories of the quantum domain.[7] There are a number of descriptive frameworks that are currently discussed as underlying ontologies of quantum theories, based on events, tropes, Tellerian 'quanta,' Whiteheadian occasions, or structures (James Ladyman and Steven French). The theory of free processes is one of the candidate ontologies for the quantum domain; but unlike others its primary application and heuristic origin is the interpretation of macrophysical stuffs and subjectless activities. Thus it suits the purposes of the Aerts-experiments particularly well.[8]

We will show two things: (A) where and how the Aerts-experiment clarifies the EPR-experiments (i.e. specify the relevant analogies and disanalogies) using free process ontology; (B) free process ontology supports CD. In a sense free process ontology completes Aerts' attempts to understand the quantum world on the model of entities familiar from everyday experience. Water and entangled quantum states are ontologically similar and can be considered to be specifications of the same ontological category. With the theoretical embedding in free process theory the Aerts-experiment thus becomes more than just a nice illustrative *metaphor*. Rather, in combination with free process theory the Aerts-experiment can be taken to provide a *literal* illustration: a macrophysical case of 'quantum behavior'. Since free process theory aspires to be an integrated ontology accommodating macrophysical and microphysical entities as cases of the same ontological category, the Aerts-experiments supports, vice versa, free process theory with an additional argument. (Seibt so far only has explored to what extent free process theory could be used for the interpretation of *free* quantum fields, cf. Seibt 2002 and forthcoming.)

2. FREE PROCESS ONTOLOGY

In this section some basic notions of free process ontology are looked at, which will then be applied to the analogy between the Aerts-experiment and EPR-experiments in the next section.

2.1. *Free processes*

Suppose we start from the idea that the world consists of individuals. Although we have a tendency to understand this statement as saying that the world consists of countable things (like billiard balls and stars) or countable events (like collisions and supernovae), we can and should resist this tendency. As Seibt has argued, the features 'individuality,' 'countability,' and 'particularity' are "not an ontological package deal." There are concrete individuals that are neither countable nor particular, i.e., uniquely locatable. While Seibt introduces the notion of a free process via a criticism of substance ontology, for present purposes it suffices to note the differences between the following properties of the axiomatic version of free process theory, the mereological system FPT (cf. Seibt 2002, p. 25):

> FPT(1): x can be *continuously amassed* iff x is of kind K and for any y of kind K, the mereological sum of x and y is again of kind K.
>
> FPT(2): x can be *discretely amassed* or *measured* iff x is of kind K and x is part of S which is coextensive with a sum of non-overlapping P_i of kind K, and for any y and z part of S, the sum of y and z is also part of S.
>
> FPT(3): x can be *aggregated* iff x can be discretely amassed and for any sum S_i of entities of kind K there is exactly one S_k coextensive with S_i and the former is a sum of non-overlapping K-'atoms' (i.e. parts of kind K which do not have parts of kind K).
>
> FPT(4): x can be '*cardinally counted*' iff x is aggregable and there is a function from the K-atoms in x into the natural numbers.
>
> FPT(5): x can be '*ordinally counted*' iff x can be cardinally counted and any two K-atoms in x are distinct from each other.

Let us get clearer on the contrast between FPT(1)–FPT(2) and FPT(5) by looking at some simple examples. Take the referent of a mass term like 'water'. It can be continuously amassed: if one adds water to water, one obtains water. As such it cannot be counted, i.e. it is a non-countable entity. Usually spatio-temporality serves as ultimate 'principium individuationis'; for indistinguishable things for example. In contradistinction to things, a stuff or mass is the same individual even when it appears in two different locations: for example we can say this bottled water is the same source water they sell in the States. In free process ontology a necessary condition for individuation is having descriptive properties *and* being *reidentifiable* on the basis of these descriptive properties. The referent of 'water' does not imply or contain any unique spatio-temporal location. Yet it is arguably (a) an individual and (b) a concrete individual, since (a) we can refer to it, reidentify it, and predicate of it, and (b) ascribe to it concrete properties: 'water is wet', 'water was added to water.' Note the difference between 'water' and an expression like 'the water in the glass on the table', 'the swirling water in the river', 'a mole of H_2O' – the referents of the latter expressions are *amounts* of water, which *can* be counted, as we will see presently. A stuff is not countable because is it not individuated via the occupation of a determinate spatial (or spatiotemporal) region. Stuffs are thus individuals that may be multiply-occurrent in space because they do not have as such, before amounts are measured out, a determinate spatio-temporal location. The generality and indeterminateness of pure free processes is intrinsic to the individuals and in some instances irreducible. Seibt has argued that activities, in particular subjectless activities (e.g., the referent of 'it is snowing'), share the spatial indeterminateness and functional individuatedness of stuffs. Based on the symmetric features of stuffs and activities, she introduces a unified category for concrete, general or indeterminate, individuals. Such ‘four-dimensional stuffs’ are called ‘free processes.’ Continuous amassable entities like stuffs and activities contrast with things and events which are always at least cardinally countable and have unique and determinate spatio-temporal locations (FPT(5)).[9]

The property FPT(1), so fundamental for free processes, is closely related to the Property of *homomerity* or *like-partedness*. Both can serve to (a) distinguish free processes from countables and (b) define countables (e.g., things and classical particles) as limiting cases of non-countables (Seibt 2002:32).

> FPT(1-a): x is normally homomerous iff x is of kind K and has $n \leq 4$ dimensions and there is at least one m-dimensional part of x, $m \leq n$, which is again of kind K.
> FPT(1-b): x is maximally homomerous iff x is of kind K and has $n \leq 4$ dimensions and for all m-dimensional parts of x, $m \leq n$, such that, it is again of kind K.
> FPT(1-c): x is minimally homomerous iff x is of kind K and has $n \leq 4$ dimensions and there is no m-dimensional part of x, such that $m \leq n$, and the part is again of kind K.

A part of water is again water, but a part of the billiard ball is not again a billiard ball. The ‘anhomomerity’ of the billiard ball can be taken as a case of ‘minimal homomerity.’ We can distinguish two kinds of countables: things or particles and events or structured developments. An event is for example the shower we were in just yet: it has a beginning and an end, a specific development and it happened, i.e., it is minimally homomerous in time. All countables are simply minimally homomerous free processes and so the ontological dichotomy between non-countables (e.g., stuffs and activities) and countables (e.g., things and events) is avoided. Normally homomerous entities can involve, or be constituted by, or even spatiotemporally overlap with minimally homomerous entities. Water is again exemplary: it is normally homomerous, but spatiotemporally overlaps with a set of H_2O-molecules each of which is minimally homomerous. Stuffs like water, wood, etc. not only are continuously amassable, they also can be measured: they have both the property FPT (1) and the property FPT(2). There are examples of stuffs or activities with merely property FPT(1), i.e., merely continuously amassable but not measurable stuffs and activities, such as anger, friendship, enjoyment, or the weather.

When we say ‘the billiard ball is black’, ‘the billiard has momentum **p**’ … then the individual ‘billiard ball’ carries the properties ‘black’, ‘momentum **p**’ … Not so in free process ontology: a free process is unsupported by a particular entity. The entity *is* the process. This is sometimes evident in the way we talk. We say: ‘It is raining’, not: ‘x is raining’. The basic entities of the world – so runs the basic tenet of free process ontology – are such ‘subjectless’ or ‘carrier-less’ four-dimensional stuff-activities, which are more or less homomerous, and more or less determinate with respect to their descriptive properties. Classical particles, assumed to be (a) fully determinate with respect to their descriptive properties including location, and (b) anhomomerous, are considered to be the limiting case of the homomerity and determinateness of a free process.

2.2. *Amounts of free processes and quantities of free processes*

With respect to a typical stuff like water we can look at the referents of ‘the water in the glass on the table’, ‘the swirling water in the river’ etc. instead of the referent of ‘water’; and with respect to a typical activity like raining, we can look at the referents of ‘the rain shower we were just in’, ‘the storm above Ghent’, etc., instead of the denotation of ‘raining’. ‘The water in the glass on the table’, ‘the swirling water in the river’, ‘the shower we were just in’, ‘the storm above Ghent’, etc. are all expressions which refer to amounts of free processes. An *amount* of x is situated in a determinate and unique location in space-time and is spatio-temporally bounded, i.e. it is ordinably countable in the sense of FPT(3) so that one can say *this* amount of water as distinct from *that* amount. In free process theory amounts are distinguished from *quantities*. Amounts have a determinate location, quantities do not – they are just specified with respect to measure (volume, temporal extent etc.) but still multiply occurrent. While *this cup of coffee* refers to an amount of coffee, the expression *a cup of coffee* refers to a quantity; *today’s hour of music* talks about an amount of music, *an hour of music* is about a quantity of music; etc. Unlike amounts, quantities are only cardinally countable in the sense of FPT(4) – since they do not have a determinate location we cannot say ‘which is which.’ An amount of a free process x can be written as a collection of measurable quantities plus a location. For example, consider a certain piece of wood, a stuff with normal homomerity. This piece of wood, which is an amount of the free process wood, denoted [wood], can be understood as a collection of measurable properties:[10]

> *Amount*: [wood] = (location l, volume a, weight b, …, inflammable (yes/no), buoyant (yes/no))

In the spatiotemporal region occupied by this piece of wood there is a certain quantity of wood:

> *Quantity*: {wood} = (volume a, weight b, …, inflammable (yes/no), buoyant (yes/no))

We can distinguish two kinds of properties: (a) occurrent properties, i.e., those that state a determinate value of a certain measure for measuring dimensions such as volume, weight, time etc.; (b) mutually dependent dispositional properties that are, first, *qua* dispositional properties, indeterminate with respect to their value and, second, depend on what other measurements have been performed on at least one other constituent quantity of the amount in question. For example the *inflammability* and *buoyancy* of a certain piece of wood are related in this way. If one sets the piece of wood on fire, one has destroyed that amount of wood, thereby making it impossible to render the property of buoyancy determinate. If one lets the piece of wood float on water then it becomes humid and does not burn any more. Both on a theoretical level and in the practice of the laboratory one supposes that for the classical world, all these kinds of incompatibility and all indeterminateness can be alleviated by giving a more fine-grained description or describing the phenomenon at a deeper level. Notoriously, this is quite different in the quantum domain.

One peculiarity of free process theory consists in the fact that *any* specification of a free process identifies another free process (mereologically related to the first). *Water* refers to one free process, *hot water* refers to another. Similarly for specifications of measurable units or locations the expressions *a cup of water* and *the water in my cup here* are about two different free processes which are each different from the free process referred to by *water*. In general, an amount of x or a quantity of x are themselves free processes different from (yet mereologically related to) x.

To conclude these cursory remarks about FPT and to move to our task, consider what I think would be the FPT-description of an electron. One electron is an amount of a minimally homomerous free process, ‘electroning’ as one might allow oneself to say for didactic purposes. Let us take the case of a spin 1/2-entity. We leave out QFT-considerations and stay within QM.

$$[\text{electron}] = (\text{location l, negative charge}, \pm\tfrac{1}{2}(\mathbf{S.n}), \pm\tfrac{1}{2}(\mathbf{S.n'}), \ldots)$$

The numbers **S.n**, **S.n’**, … are spin-components along directions **n**, **n’** …, each having two-fold degeneracy which gives rise to a two-dimensional orthonormal base in two-dimensional Hilbert space. With $\frac{1}{2}(\mathbf{S.n})$ we mean spin $\frac{1}{2}$ along **n**, $\frac{1}{2}(\mathbf{S.n'})$ means spin $\frac{1}{2}$ along **n’**, $-\frac{1}{2}(\mathbf{S.n})$ means spin $-\frac{1}{2}$ along **n**, etc. (It is well known that for quantum entities one cannot describe the spin state by giving the direction of angular momentum, but only by giving the component of angular momentum along some direction.) Some measurable quantities are already determinate by taking the amount of the free process, for example the charge. Others, like spin, are not, because not all spin observables can be determinate at the same time.

3. AERTS' THOUGHT-EXPERIMENT AND THE ONTOLOGY OF QUANTUM MECHANICS

Let us begin with a reminder about some essential components of the EPR-experiment. First, two spin 1/2-entities are produced by the decay of a single spin 0-entity S at a central point (called the source); second, spatially well-separated coincidence measurements of spin are performed, when performed along the same direction in space on S1 and S2 giving the results $s_m = -1/2, 1/2, \ldots$ for S1, in perfect anti-correlation with the results $t_n = \frac{1}{2}, -1/2, \ldots$ for S2; third, before the measurements the entity S can only be described by an "entangled" state *k* (a non-factorizable state in the tensor product of the state spaces of S1 and S2).

The EPR-experiment is mysterious since the correlations of simultaneous and spatially well-separated measurements calls for an explanation. Is there a direct (stochastic) causal link between the two wings of the experiment, is it the state coming from the source that causes the measurement results, or is there some other ingenious explanation? We already touched on this in the introduction. However, quite independently of the question of how to explain the correlations violating outcome independence, one might pursue the modest task of trying to understand the type of entity the experiment talks about. Even though in descriptions of the EPR-setting we speak of two spin 1/2-entities, the compound entity is in a non-factorizable state. The experiment highlights a general feature of quantum entities that one can formulate as follows: if two distinguishable entities S1 and S2 are joined into a whole S, then S can very easily exhibit states that do not allow to distinguish S1 and S2 within S.[11]In these cases one could say: when S exists, S1 and S2 do not exist anymore. Classical particles do not exhibit this feature: when two parts are joined into a whole, they can be distinguished within the whole also afterwards, or vice versa, the parts of a whole can be distinguished even before the whole is *de facto* divided into its parts.

On the other hand, classical stuffs behave in this respect rather similar to quantum entities. Suppose volume is the only measurable property. When we join two amounts of water each containing a quantity of 10 liters of water, the combined amount – call it W – contains a quantity of 20 liters. Even though the measurable property determining the quantity of water contained in W is determinate in this case, the amount has indeterminate parts. Let us assume that the quantity of water contained in W is obtained by adding two (uniquely located) amounts of water, W1 and W2, containing each a quantity of 10 liters. If at a later time one extracts 10 liters from W the question: “Are these the first or the second 10 liters that were combined to make up W?” makes no sense. There are two (uniquely located) amounts W3 and W4 containing each a quantity of 10 liters. As long as W1 and W2 existed, W did not exist, and as long as W exists, W3 and W4 do not exist. Within W there exist two quantities of 10 liters which cannot be distinguished. They become distinguishable only by ‘dishing out’ twice from W a quantity of 10 liters, i.e., by creating two amounts combining a quantity of 10 liters with two different locations.

The idea of the Aerts-experiment should by now appear quite straightforward: exploit the analogy between on the one hand the confluence and separation of amounts of water and on the other hand the entanglement and separation of quantum entities, in order to construct a macroscopic experiment with water exhibiting outcome dependence comparable to the outcome dependence in EPR-experiments. There are two vessels, V1 on the left and V2 on the right, connected to each other by a tube Tu. We will refer to V1, V2, Tu together as V. The tube is attached to the bottom of V1 and V2. If it stays hidden, then we will not be aware that what appears to be two amounts of water can be considered as one connected amount of water.[12] We fill V1 with 10 liters of water and we fill V2 with 10 liters of water. The state k of the compound entity is 20 liters. For the experimentalist who fills V1 with 10 liters of water and V2 with 10 liters of water, it seems as if V1 contains 10 liters of water and V2 contains 10 liters of water. At V1 there is a vessel R1 and a siphon to extract water from V1 and at V2 there is a vessel R2 and a siphon to extract water from V2. Suppose we perform the following coincidence-measurement: we extract once more than 10 liters from V1 and once more than 10 liters from V2. If we extract more than 10 liters from V1 we state the outcome as $s_m = 1/2$ otherwise we state the outcome as $s_m = -1/2$; if we extract more than 10 liters from V2 we state as outcome $t_n = 1/2$, otherwise we state as outcome $t_n = -1/2$. If carried out the experiment will give the following measurement results stated in liters of water measured at R1 and R2: (12,8), (7,13), ... In terms of the special convention for stating these measurement results the combined outcome will be: (1/2, −1/2), (−1/2, 1/2), ... We will never see the values (1/2, 1/2). The single outcomes for R1 and R2 depend on each other.[13]

Without the specifications of free process ontology all of this stays more or less on the level of an intuitive analogy illustrating the possibility of a common cause that has effects which it does not make statistically independent (i.e. which it does not screen of). With free process ontology, however, the analogy becomes more precise and more profound. Let us redescribe the experiment in terms of the FPT-notions introduced above and try to make good on the two goals mentioned in section 1, namely, (A) to show where and how the Aerts-experiment clarifies the EPR-experiments (i.e. specify the relevant analogies and disanalogies) using free process ontology; (B) to show how free process ontology supports CD.

(A) The water in the Aerts-experiment is a particular amount of water and can consequently be written as a collection of measurable quantities (weight, volume, . . .) with a location. We are only interested in the quantity of volume contained in the amount W:

$$\{W\} = (20 \text{ liters})$$

Compare this with the FPT-representation of the singlet state in the EPR-experiment. We will write spin along a particular direction as before. For the singlet state we have zero-amount of spin for all directions, so the quantity of spin contained in the amount E of 'electroning' that is the compound of two electrons is this:

$$\{E\} = (0\ (\mathbf{S.n}), 0\ (\mathbf{S.n'}), \ldots)$$

The individual E has zero spin for all directions *and* these measurable quantities are indeterminate, since they are mutually incompatible.

There are three disanalogies between the entities involved in the two experiments, which we need to identify:

(a) Aerts' convention hides the fact that there is an infinite number of ways we can divide the water W in two quantities of water:

$$\{W\} = (5 \text{ liters}, 15 \text{ liters}) = (4 \text{ liters}, 16 \text{ liters}) = (12 \text{ liters}, 8 \text{ liters}) = .$$

In contrast there are only two possible ways of dividing 0(**S.n**): in 1/2(**S.n**) − 1/2(**S.n**) and −1/2(**S.n**) + 1/2(**S.n**). That is:

$$\{E\} = (0(\mathbf{S.n}), 0(\mathbf{S.n'}), \ldots) = (1/2(\mathbf{S.n}) - 1/2(\mathbf{S.n}), 0(\mathbf{S.n'}), \ldots)$$
$$= (-1/2(\mathbf{S.n}) + 1/2(\mathbf{S.n}), 0(\mathbf{S.n'}), \ldots) = \ldots$$

To restate, while in the Aerts experiment we have an infinite number of ways of dividing 20 liters, there are only two ways of dividing the zero amount of spin.

(b) There is only a finite number of measurable quantities in our idealized example of water W: volume, weight, . . . which are all compatible and thus determinate. In contrast, there are an infinite number of measurable spin-quantities: **S.n**, **S.n'**, ...

(c) The disanalogies mentioned under (a) and (b) do not strike me as significant. A more problematic difference might be, however, that in the Aerts-experiment there is nothing that corresponds to the incompatibility of spin-properties in the EPR-experiment. But it is certainly admissible to add something to the Aerts-experiment that establishes an incompatibility of properties in the macroscopic setting. What about if we were to exchange the occurrent property 'has volume of value v' for the dispositional (operational) property 'yields value v when measured for volume', which we denote as A(yes/no), and then added another dispositional property, for example 'vaporizes when heated up'. We would then have:

$$\{W\} = (\text{A(yes/no), vaporizes(yes/no), \ldots})$$

The amount of water can be indeterminate, because of the incompatibility with the other dispositional property.

(B) We promised to show that CD(2) follows from free process ontology. First, note that in a way the stuff water is a stranger entity than a compound quantum entity described with $\otimes_i H_i$. The reason is that the Hilbert-spaces are labeled $i = 1, 2 \ldots$, which suggest that, despite the non-factorizable states, it is in principle still possible to actually count the entities in the entangled state, while water has no parts that can be counted in the way we presented it above (water has the property FPT(2)).[14] In QM we are considering cardinally countable minimally homomerous entities, i.e. entities with property FPT(4). Such entities are in the same class as *quantities* of water (not amounts of water, which have the property of ordinal countability FPT(5)). The existence of non-occurrent states in Bose–Einstein statistics is a strong argument in favour of the Fock-space formalism of QFT (Teller (1995)). QFT, which is probably the more fundamental theory, makes ordinal countability of quanta impossible. So both QM and QFT suggest that quantum entities are *quantities* of free processes in the sense of FPT. To be sure, for any *amount* of a classical stuff like water, there is always the physical *possibility* (but see endnote 13) of complete particularization at the level of molecules, i.e., to consider the stuff or quantity as an assembly of ordinally countable, uniquely located (particular) entities. But recall that this does not hold for *quantities* of classical stuffs. A quantity of stuff (10 liters of water) does not, as such, have a determinate unique spatiotemporal location. It can be *assigned* a location, thereby turning the quantity into an amount containing a quantity. Such an assignment does not, however, consist in 'determining which quantity goes where' or 'which amount has which quantity.' Both of these sentences make no sense since quantities, being only cardinally countable and not uniquely located in spacetime, are not traceable in spacetime. When dividing the 20 liters of water into two vessels (i.e., two amounts: uniquely located or particular, ordinally countable entities) we cannot meaningfully ask where the first quantity of 10 liters went. So even while it is possible to determine *how many* quantities a certain amount of water (e.g., the left vessel) contains (e.g., two quantities of 5 liters), it is not possible to determine *which* quantities of 5 liters it contains, because quantities are not individuated in this sense of 'which'. This is strongly parallel to the situation in QFT. In QFT it is a measurement interaction that 'induces' the superposition state to be projected on one of the eigenvectors, and even then we cannot say which quantum has which eigenvalue, but only how many.

We already drew attention to the difference between concrete entities that are uniquely located in spacetime, i.e., have determinate spacetime locations (= particular, = ordinally countable entities, = amounts) and those concrete that are in an indeterminate sense located in spacetime, that are simply somewhere in spacetime (= cardinally countable, = non-particular, = quantities). Due to the conceptual separation between particular individuals, which are uniquely and determinately located, and non-particular individuals, which are indeterminately located (just *somewhere*), free process theory is capable of accommodating quantum entities into an integrated ontology.

Remember that CD is the claim that the entity described by the singlet state has no definite position in space, which is also formulated as the claim that it 'does not exist in space'. If we interpret this along the lines of the previous paragraph, we have carried out what we promised in the introduction. But CD can also be taken as a stronger claim: the EPR-entity is not located *anywhere in space*, not just located indeterminately. Could the process-ontological interpretation of EPR-phenomena also be put to use in order to articulate such a strong reading of CD? This is certainly possible. In this case we need to construe the zero quantity of spin in the usual QM-description as *no* quantity of spin, i.e. the compound entity in the singlet state has no amount (because of the possible indeterminateness of the position variable) and no quantity of angular properties. Given that in FPT it holds that any free process that is spatially located is either an amount (if determinately located) or a quantity (if indeterminately located), free processes that are neither amounts nor quantities are not spatially located. If we take the compound quantum entity E in a non-separable state of the EPR-experiment to be a free process (rather than a quantity of amount of a free process) we characterize it in effect – just as the strong reading of CD says – as a real individual (we can refer to E and reidentify it for further reference) which does not exist in space. Measurements produce amounts of such EPR-processes: individuals that are uniquely and determinately located in space.

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NOTES

[1] My translation of a remark by Einstein in a personal conversation with Louis De Broglie reported in De Broglie (1956, p. 236): «Il me dit encore qu'il avait peu de confiance dans l'interpretation indéterministe et qu'il blâmait l'orientation trop formelle que commençait a prendre la Physique quantique; forgant peut-être quelque peu sa pensée, il me disait que toute théorie physique devrait pouvoir, en dehors de tout calcul, être illustrée par des images si simples «qu'un enfant même devrait pouvoir les comprendre.»»

[2] Compare for example the ingenious Mermin-contraption (for example) in Mermin (1985).

[3] See chapter four of Redhead (1987).

[4] The name outcome independence was coined by Abner Shimony. The inventor named the condition *completeness*. See Redhead (1987) for references and the precise mathematical formulation.

[5] Both philosophers and physicists have done the same thing. See Teller's analogy between quantum entities and amounts of money in the bank in Teller (1995, pp. 29–30) and the references in the footnote on p. 29 of Teller (1995). Note that the money analogy is actually due to Schrödinger (as Teller acknowledges).

[6] This specific way of presenting the creation-discovery view was given in more detail in Christiaens (2002). I do not elaborate here on other elements of the creation-discovery view, such as the idea of hidden measurements and hidden correlations. The Aerts-experiment was proposed before the hidden-measurements view on quantum measurement and can therefore be discussed independently of the hidden measurement/hidden-variables component of the creation-discovery view.

[7] See for instance Cao 1999 and Kuhlmann et al. 2002.

[8] FPT is the formal scheme in which Seibt's Free Process Theory is couched. Core ideas of Free Process Theory and sketches of FPT are to be found in Seibt (1990), Seibt (1995), Seibt (1996a), Seibt (1996b), Seibt (2000), Seibt (2001a), Seibt (2002). I am drawing here in particular on Seibt (2001a) and Seibt 2002.

[9] The reach of the concept of free process goes beyond the particularities of common parlance. QFT may provide one of the scientific theories to which free process ontology can be applied to. The state of a simple physical system typical for QFT – a free quantum field – is described by a state vector in a Fock space. A typical state is superposition of ket vectors

$|n_1, n_2, \ldots, n_i, \ldots>$ spanning the Fock space. The number n_i is the occupation number, telling you how many quanta posses the eigenvalue q_i. There are two remarkable facts here. The first is that the ket vector allows only to say that n_i quanta have eigenvalue q_i, but not which ones. Secondly, a linear combination of these ket vectors makes it impossible to tell how many quanta have a particular eigenvalue; we only know that if we would measure and we would obtain a particular ket-vector, then we would have the occupation numbers specified by that ket-vector. But superposition is ubiquitous and frequent in the quantum world, which means that a lot of the time FPT(4) in not an option in the quantum world. QFT is a fundamental theory of matter, arguably the fundamental theory of matter. In other words, there is no 'classical' reality underlying these facts. For an accessible exposition of quantum field theory, see Teller (1995).

[10] I simplify here Seibt's presentation of amounts, applying FPT to Aerts' analysis of 'a piece of wood' in Aerts (1981), Aerts (1983a) and Aerts (1983b).

[11] The state space of a compound quantum entity is the tensor product of the state spaces of the compounds. For a specific observable of the compound entity there is an orthonormal collection of eigenvectors in the state space of the compound entity. These states are factorizable. Note that in his 1981 and 1982 Aerts proved with quantum logical tools that QM cannot describe separated entities.

[12] But note that even if we see the tube we could still say that there are two amounts, the one on the right hand side up to the middle of the tube, and the one on the left hand side, up to the middle of the tube. Suppose one would calibrate the sides of the vessels V1 and V2, then it is easy to locate the amounts in which the 20 l are separated. If you get (5 l, 15 l), then these two amounts were already there before the measurements.

[13] The Aerts-experiment is 1) a nice illustration of a common cause that does not screen off its effects – i.e. the measurements results obtained in both "wings" of the Aerts-experiment – because they are carried out on an entity that is one whole, but appears to be two separate entities; 2) an illustration of a common cause, which is not easily recognized as such, since the effects appear to be unconnectable as long as the two measurements are taken to happen on two spatially separate entities. When we identify the common cause, we see that it does not make its separate effects statistically independent, which usually leads to k being discarded as possible common cause. In both experiments we have a violation of factorization: $\Pr(s_m \ \& \ t_n) \neq \Pr(s_m).\Pr(t_n)$. In both experiments it holds that the probabilities for the measurement results are also not rendered probabilistically independent if the common cause k is taken into account: $\Pr(s_m \ \& \ t_n) \neq \Pr(s_m/k).\Pr(t_n/k)$.

[14] Unless one would immediately turn to the molecular level in the case of water. This is not obvious, since it involves physicalist reductionism (the idea that water can be completely described in the vocabulary of physics, i.e., that all properties of water can be reduced to the most fundamental physical description). See the section on reductionism in Boyd et al. 1991.

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