Locality in the Heisenberg Picture

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Abstract

Quantum entanglement is widely regarded as a nonlocal phenomenon, but Deutsch and Hayden (2000) have recently received growing support for their claim that in the Heisenberg picture, entanglement can be characterised locally using objects they call descriptors. I argue that the notion of locality underlying this claim is a flawed version of the principle of separability that I call *spatial* separability. An improved version, *spatiotemporal* separability, reveals that their claim is false. The proposed analysis of separability also reveals the crucial feature of quantum theory that makes it "spooky" in any picture: quantum entanglement entails that there are *non-qualitative* properties, which are profoundly different from the qualitative properties we have come to expect from classical physics.

1 Introduction

In 1935, Einstein, Podolsky and Rosen questioned the completeness of quantum mechanics, partly based on their conviction that no real change in a system could be a consequence of anything done to a spatially distant system. Einstein's later reflections would go on to give us further insights into his unshakable belief in locality. An analysis by Howard (1985, 1989) made it clear that Einstein's concerns can be separated into a principle of *local action* and a principle of *separability*, even if Einstein himself did not always clearly distinguish between the two. Loosely speaking, the former tells us that a physical theory must have only local *dynamics*, while the latter tells us that the properties postulated by the theory must always be reducible to local *properties*. Most interpretations of quantum mechanics violate at least one of these principles.

The principle of local action is the better known of the two principles and states that if A and B are spatially distant things, then an external influence on A will have no immediate effect on B (Healey and Gomes 2022, para 63; based on Einstein 1948). The overwhelming consensus is that Everett's (1957) theory, which removes any wave function collapse, does not violate the principle of local action. I will not retrace those well covered arguments, suffice it to say that the theory's dynamics are just those of unitary quantum mechanics, so effects propagate along conventional causal chains. When a quantum system is measured it can branch into different "worlds", but there will be no immediate effect on the local state of any distant system, even entangled partners. Only when the results of measurements are physically brought together will any correlation between the results be observed.

There is greater disagreement about whether Everett's theory preserves separability (which we will cover in more detail shortly), leading a number of authors to conclude that some form of locality is violated, as we see below.

> "[In Everettian quantum physics] the dynamics of the theory are local: there is no action at a distance... But quantum entanglement means that a great deal of the information contained within the quantum state is nonlocal..." (Wallace 2012, 304-5)

> "... a theory [such as the Everettian interpretation] can be dynamically local, whilst violating local causality... nonseparable theories allow additional ways in which correlations can be causally explained without action at a distance." (Brown and Timpson 2016, 117-8)

> "[On Everettian accounts] we have some sort of nonlocality, but not action at a distance." (Myrvold 2016, 254)

Sitting on the other side of the divide, Deutsch and Hayden (2000) have received growing support (Rubin 2001, Horsman and Vedral 2007, Kuypers and Deutsch 2021, Bédard 2021, Kong 2024) for the view that it is possible to characterise quantum properties in an entirely local manner by using the Heisenberg picture of quantum mechanics.

The aim of this paper is twofold. First, it is to show that Deutsch and Hayden's criterion for locality relies on a qualified version of the principle of separability and that removing the qualification renders their approach nonlocal. Second, it is to clarify the fundamental difference between quantum and classical properties that underlies our intuition that entanglement is a nonlocal phenomenon.

To achieve these ends, the paper proceeds as follows. I first review the essential features of the Heisenberg picture and what Deutsch and Hayden call *descriptors*, the objects they take to represent the intrinsic properties of a quantum system. Because Heisenberg states do not in general represent the physical state of system at a given time, it will be necessary to clarify our notion of separability. Taking our cue first from Howard 1989 and then from Healey and Gomes 2022, we will take it that to be separable, the intrinsic properties of a compound system must supervene on those of its subsystems.

Intrinsicality plays such an important role in separability that it will require some unpacking. Of particular importance will be the condition that a physical property of a thing is intrinsic only if it does not entail the existence of any other thing. We will see that descriptors represent physical properties that *do* entail the existence of other things, so cannot be intrinsic. However, the properties can claim a restricted form of intrinsicality that I will call *spatial* intrinsicality. Consequently, descriptors satisfy a similarly restricted version of separability, *spatial* separability, but not the more general form that I call *spatiotemporal* separability.

I will then examine the link between separability and locality, which will require that I first clarify the difference between properties that are nonlocal and those that are merely not local (extrinsic). I will propose that Deutsch and Hayden's notion of locality aligns with spatial separability but I will provide examples to demonstrate that spatial separability is not an adequate criterion for locality. Instead, I will argue that any property that is not spatiotemporally separable is nonlocal, implying that descriptors do in fact represent nonlocal properties.

Finally, the analysis of separability will have revealed a crucial but under-appreciated fact that lies at the heart of the locality debate: the properties of entangled systems are *non-qualitative*. That is, entangled systems have a unique and continuing relation with the *particular* systems they have become entangled with, which differs profoundly from the relations of classical physics.

2 Deutsch-Hayden Descriptors

Deutsch and Hayden propose that by using the Heisenberg picture, quantum systems can be completely described using only local information, even when they are entangled. In this section, we will review the Heisenberg picture generally and more specifically the formalism Deutsch and Hayden introduce to represent the properties of a system.

In the Schrödinger picture, we begin by specifying an initial state vector $|\psi(0)\rangle$ (or more generally, a density operator $\rho(0)$). The state vector is intended to represent the intrinsic properties of a system at a point in time. We represent any influence that might change that state by applying a unitary operator U, which evolves the state to $|\psi(t)\rangle = U\,|\psi(0)\rangle$. We link the state vector with experimental outcomes by using it to determine expectation values for some observable $\hat{q}$. An observable is also represented by an operator (in this case Hermitian) whose eigenvalues represent the possible values we might, in principle at least, observe through measurement. In the Schrödinger picture, the operator representing the observable never changes, so $\hat{q}$=$\hat{q}$(t)=$\hat{q}$(0) for all t. The expectation value of the observable at time t is given by 'sandwiching' the fixed observable between the state vector at that time and its conjugate transpose. Accordingly, the expectation value of the evolved state is given by:

$$\langle\psi(t)|\,\hat{q}\,|\psi(t)\rangle$$

which, through substitution, could also be expressed as:

$$\langle\psi(0)|\,U^{\dagger}\hat{q}(0)U\,|\psi(0)\rangle$$

In the Heisenberg picture, by contrast, the expectation value is calculated by taking the state vector to remain fixed ($\psi = \psi(t) = \psi(0)$) for all t, but evolving the *observable* by 'sandwiching' the initial observable between the unitary operators, such that $\hat{q}(t) = U^{\dagger}\hat{q}(0)U$. So the expectation value is:

$$\langle\psi|\,\hat{q}(t)\,|\psi\rangle$$

which through substitution returns the same result:

$$\langle\psi(0)|\,U^{\dagger}\hat{q}(0)U\,|\psi(0)\rangle$$

Deutsch and Hayden take one further step and propose that the Heisenberg state $|\psi(0)\rangle$ need not represent any actual property of the system but can be a standard constant, usually $|0,\ldots,0\rangle$. In this case, the Heisenberg state does not represent the initial state of the system but should rather be thought of as a reference vector.[1] As a consequence, the initial properties of the system must be introduced via an operator $U(0)$.

While unconventional, Deutsch and Hayden claim that including a $U(0)$ operator can be theoretically beneficial because it explicitly accounts for the resources required to initially prepare the system (a claim we will not investigate here).

Deutsch and Hayden's real contribution to the locality debate comes from their discussion of the evolving Heisenberg observables, which they call the *descriptors* of a system. They claim that these descriptors provide us with all the necessary information to locally and completely describe a system, even after it becomes entangled with other systems.

Deutsch and Hayden develop their argument exclusively in terms of qubits (quantum bits), which they maintain can simulate any quantum system with arbitrary accuracy. Within that framework, the descriptor for qubit a of an n-qubit network is described by a triple of its observables, which we shall call its x-, y- and z-observables:

$$\hat{\boldsymbol{q}}_a(t) = (\hat{q}_{ax}(t), \hat{q}_{ay}(t), \hat{q}_{az}(t))$$

The three observables are represented as Hermitian matrices, which are analogous to the familiar 2×2 Pauli matrices with several important differences: the

1. As Bédard 2021 points out.

matrices are much larger, at $2^n \times 2^n$; each matrix is associated with a *specific* qubit; and, the matrices evolve over time (I will elaborate on these differences shortly).

The descriptor $\hat{\boldsymbol{q}}_a(0) = U^\dagger(0)(\hat{1}^{a-1} \otimes \hat{\boldsymbol{\sigma}} \otimes \hat{1}^{n-a})U(0)$ represents the initial properties of the system. If the system is prepared such that the initial Schrödinger state aligns with the reference vector ($|0,\ldots,0\rangle$), then $U(0)$ is simply the identity operator and the observables of the initial descriptor $\hat{\boldsymbol{q}}_a(0)$ will be:

$$\begin{aligned}\hat{q}_{ax}(0) &= \hat{1}^{a-1} \otimes \hat{\sigma}_x \otimes \hat{1}^{n-a}\\ \hat{q}_{ay}(0) &= \hat{1}^{a-1} \otimes \hat{\sigma}_y \otimes \hat{1}^{n-a}\\ \hat{q}_{az}(0) &= \hat{1}^{a-1} \otimes \hat{\sigma}_z \otimes \hat{1}^{n-a}\end{aligned}$$

These observables are matrices in which the a^{th} item in the tensor product is one of the three Pauli matrices ($\hat{\sigma}_x,\ \hat{\sigma}_y,\ \hat{\sigma}_z$), with the remainder identity matrices. From here, each descriptor evolves according to:

$$\hat{\boldsymbol{q}}_a(t) = U^\dagger \hat{\boldsymbol{q}}_a(0) U$$

where U represents the cumulation of all operations acting on the qubit up until time t.

This is not the place to delve into the full machinery of Deutsch and Hayden's approach, for which the reader should consult their original paper and the papers that build on their approach.[2] Instead, I will consider the key features with respect to a simple network. Take two qubits, denoted with the subscript a and b respectively, prepared in the Schrödinger state $|0_a 0_b\rangle$. The initial descriptors would then be:

$$\begin{aligned}\hat{\boldsymbol{q}}_a(0) &= (\hat{q}_{ax}(0), \hat{q}_{ay}(0), \hat{q}_{az}(0)) = (\hat{\sigma}_x \otimes \hat{1}, \hat{\sigma}_y \otimes \hat{1}, \hat{\sigma}_z \otimes \hat{1})\\ \hat{\boldsymbol{q}}_b(0) &= (\hat{q}_{bx}(0), \hat{q}_{by}(0), \hat{q}_{bz}(0)) = (\hat{1} \otimes \hat{\sigma}_x, \hat{1} \otimes \hat{\sigma}_y, \hat{1} \otimes \hat{\sigma}_z)\end{aligned}$$

These descriptors, derived as they are from the Pauli matrices, will satisfy the algebraic relations:

$$\begin{aligned}&[\hat{\boldsymbol{q}}_a(0), \hat{\boldsymbol{q}}_b(0)] = 0 && (a \neq b)\\ &\hat{q}_{ax}(0)\hat{q}_{ay}(0) = i\hat{q}_{az}(0) && \text{(and cyclic permutations)}\\ &\hat{q}_{aw}(0)^2 = \hat{1} && (w \in \{x, y, z\})\end{aligned}$$

From the second line above, we see a redundancy that means we only need two of the three descriptors to fully describe any qubit, so henceforth, we will just specify descriptors in terms of the observables $\hat{q}_{ax}(0)$ and $\hat{q}_{az}(0)$.

2. Such as Horsman and Vedral 2007, Kuypers and Deutsch 2021, and Bédard 2021.

An important feature of a descriptor is that it is a large matrix that contains enough information to 'record' the relations between the qubit it is assigned to and every other qubit. The descriptors $\hat{\boldsymbol{q}}_a(0)$ and $\hat{\boldsymbol{q}}_b(0)$ initially tell us that there are no relations between the observables of each qubit, which we read from the identity matrices in the tensor products for each. But as the qubits interact, the matrices will begin to fill with values that tell us how the relations between them have evolved.

Conveniently, every operation (gate) that acts on the system can be expressed as a function of the observables, since between them they represent all of the identity and Pauli matrices for each qubit. So, for example, the Pauli X (NOT) gate applied to the first qubit is the operator $U_{NOT} = \hat{\sigma}_x \otimes \hat{1}$, which we can equivalently represent as $U_{NOT} = \hat{q}_{ax}(0)$.

While the functional representation of gates in terms of initial observables is convenient, the real power of the Deutsch-Hayden notation lies in its representation of multi-qubit gates. A controlled Pauli X (CNOT) gate, which performs the NOT operation to qubit b just in case qubit a is in the Schrödinger state $|1\rangle$, can be expressed as:

$$U_{CNOT} = (\hat{1} + \hat{q}_{az}(0) + \hat{q}_{bx}(0) - \hat{q}_{az}(0)\hat{q}_{bx}(0))/2$$

Using this framework, some rather elegant results begin to emerge. The impact of three common gates – the NOT, the Hadamard (H), and the $\text{CNOT}_{a,b}$ gates (where a is the control and b the target qubit) – are shown below with the time arguments removed to reduce notational clutter:

$$(\hat{q}_{ax}, \hat{q}_{az}) \xrightarrow{NOT_a} (\hat{q}_{ax}, -\hat{q}_{az})$$

$$(\hat{q}_{ax}, \hat{q}_{az}) \xrightarrow{H_a} (\hat{q}_{az}, \hat{q}_{ax})$$

$$\left\{ \begin{array}{c} (\hat{q}_{ax}, \hat{q}_{az}) \\ (\hat{q}_{bx}, \hat{q}_{bz}) \end{array} \right\} \xrightarrow{CNOT_{a,b}} \left\{ \begin{array}{c} (\hat{q}_{ax}\hat{q}_{bx},\ \hat{q}_{az}) \\ (\hat{q}_{bx}, \hat{q}_{bz}\hat{q}_{az}) \end{array} \right\}$$

We can read from the first line that the NOT gate toggles the value of the z-observable, while the second line tells us that the H gate swaps the x- and z-observables, both of which seem familiar given their representation on the Bloch sphere. Of more interest is the last operation, in which two qubits interact. We see that the CNOT gate effectively results in both qubits 'exchanging' an observable value. The CNOT demonstrates a necessary (but not sufficient[3]) condition for entanglement that is writ large in the Deutsch-Hayden formalism – a full description of the properties of an entangled qubit must contain a reference to a property (or properties) of its entangled partner (more on this and its implications later).

3. Because there may be no observable consequence, such as applying a CNOT to the $|00\rangle$ state, which has no impact on the Schrödinger state and so leaves it unentangled.

It is also possible to use this approach to describe arbitrary rotations and phase shifts such that we could define a universal quantum gate set, but the few gates above will suffice for our purposes. More to the point, we now have the resources to represent a Bell state, in particular the Schrödinger state $(|00\rangle + |11\rangle)/\sqrt{2}$, which we achieve by applying a Hadamard followed by a CNOT gate. In terms of descriptors, the operation can be represented as:

$$\left\{ \begin{array}{c} (\hat{q}_{ax}, \hat{q}_{az}) \\ (\hat{q}_{bx}, \hat{q}_{bz}) \end{array} \right\} \xrightarrow{H_a, CNOT_{a,b}} \left\{ \begin{array}{c} (\hat{q}_{az}\hat{q}_{bx}, \hat{q}_{ax}) \\ (\hat{q}_{bx}, \hat{q}_{bz}\hat{q}_{az}) \end{array} \right\}$$

This combination of operations sees an exchange of observable values between a and b, but only after a's observables have been swapped, highlighting a second necessary condition for entanglement. Because the Heisenberg state is $|00\rangle$, the two qubits initially have a definite value in the computational basis. That is, if measured, each system would be found in the $|0\rangle$ state with certainty. For two systems to be considered entangled, neither qubit can have a definite value in any basis. As $|0\rangle$ is an eigenstate of $\hat{q}_{az}$ and $\hat{q}_{bz}$, if the system evolves such that either qubit has an observable in which only $\hat{q}_{az}$, $\hat{q}_{bz}$ or their product appear, then we know that the qubits cannot be entangled because at least one qubit has an observable with a definite value.[4]

For our purposes, the two key messages we should take from this analysis are: first, that descriptors provide a means to completely describe the properties of each individual qubit in a network; and second, that nothing other than these descriptors is required to completely describe the properties of the network as a whole.

3 Separability

As outlined earlier, two key principles have long been associated with locality: the principle of local action and the principle of separability. There seems little doubt that unitary quantum mechanics, and therefore Deutsch-Hayden descriptors, satisfy the former, but their status with respect to the latter is contentious. My goal is to demonstrate that Deutsch-Hayden descriptors only satisfy a qualified version of the principle, so the first step will be to establish clear criteria with which we can assess separability.

Howard was the first to clearly articulate the principle of separability, drawing on passages from Einstein such as the following:

> It is characteristic of these physical things that they are conceived of as being arranged in a space-time continuum. Further, it appears to

4. More generally, for pure bipartite entanglement, qubits a and b are said to be entangled if and only if there exists descriptors $\hat{q}_{ai}(t)$ and $\hat{q}_{bj}(t)$ such that $\langle \hat{q}_{ai}(t)\hat{q}_{bj}(t)\rangle \neq \langle \hat{q}_{ai}(t)\rangle\langle \hat{q}_{bj}(t)\rangle$.

be essential for this arrangement of the things introduced in physics that, at a specific time, these things claim an existence independent of one another, insofar as these things "lie in different parts of space." (Einstein 1948, translated by Howard 1985, 187)

To sharpen Einstein's idea, Howard introduced the notion of separability. He proposed that physical systems are separable if and only if they possess distinct physical states and the joint state of the systems is wholly determined by the separate states (Howard 1989, 225-226). On a conventional understanding of the determination relation, we can infer that the state of a compound system AB would be separable only if there is a function that maps the states of A and B to the states of AB. The simplest form of separability obtains when the state of a compound system AB is a simple conjunction or summation of the states of its subsystems. For instance, the mass of a compound system might simply be the summed mass of its subsystems. But more complex functions are also possible. For instance, the temperature of a system is wholly determined by the mass and velocity of its particles, but the function is not a simple summation of those masses or velocities.

On a technical note, determination is not precisely the right relation for our separability criterion because determination is typically taken to be an irreflexive relation. If A and B determine AB, then AB cannot also determine A and B. But there is no good reason to suppose that the relation relevant here should be irreflexive. It is of no concern if the state of a separable compound system AB also maps back to the state of the subsystems A and B – in fact, we expect it to be so in quantum mechanics. In the context of separability, the more precise relation is the philosopher's friend, *supervenience*, which entails a mapping from the subvenient set to the supervenient set but does not preclude a mapping in the opposite direction. Accordingly, instead of Howard's formulation, we will adopt Healey's (2022) version of state separability:

State separability: The state assigned to a compound physical system is separable if and only if it is supervenient on the states assigned to its component subsystems.

In quantum mechanics, state separability has a clear mathematical formulation that satisfies this condition, which for pure states, only obtains when the subsystems are not entangled.[5] A pure state of a bipartite quantum system

5. For mixed states, the state can be represented as a density operator ρ^{AB}, which is is considered separable in quantum mechanics if and only if it can be written as $\rho^{AB} = \sum_i p_i \rho_i^A \otimes \rho_i^B$ where $p_i \geq 0$, $\sum_i p_i = 1$. As an anonymous referee points out, this type of separability does not always align with the general notion of state separability. For instance, when the states of the subsystems are classically correlated they are considered separable (not entangled) but would not satisfy Healey's condition. We can take it that both Howard and Healey have implictly assumed we have full knowledge of the state of the systems, and therefore the separability condition applies only when the joint system is

$|\psi^{AB}\rangle$, defined on a Hilbert space $H_A \otimes H_B$, is separable if and only if it can be written as the tensor product of the state of its subsystems, that is: $|\psi^{AB}\rangle = |\psi^{A}\rangle \otimes |\psi^{B}\rangle$. To satisfy this condition, the state of AB must supervene on the states of A and B, so we can understand the condition as the quantum mechanical implementation of the more general separability criterion.[6]

A hallmark of state separability is that when the states of the individual subsystems are completely specified, those states will also be sufficient to completely specify the state of the whole. And conversely, with nonseparable states, specifying the state of the subsystems is *not* enough to specify the state of the compound system. This is exactly what we find with entangled systems in the Schrödinger picture – the joint state of the compound system is not completely specified by the state of its individual subsystems; we also need information about the relations between the states of each subsystem.

We will shortly examine whether Deutsch and Hayden's approach conforms with the principle of separability but before we do, we will need to address an issue that threatens to derail our efforts. While state separability is regarded an appropriate test of separability in the Schrödinger picture, what is referred to as a *state* in the Heisenberg picture is quite different from a Schrödinger state or a classical state. For a start, Heisenberg states do not change over time. For Deutsch and Hayden, the properties of a system are encoded in its descriptor *and* the Heisenberg state rather than in the state alone, so it will be important to ensure our criterion for separability holds across the different pictures of quantum mechanics, and ideally across different physical theories.

4 Theory independent separability

The type of separability we have considered thus far is *state* separability, which is the standard approach to understanding separability in quantum mechanics. In the Schrödinger picture, a state is conventionally taken to represent the properties of a system at a point in time (as it is for most classical theories). So when the state of a system is separable, it follows that the properties of that system are separable. That is, the properties of the compound system supervene on the properties of its subsystems.

But a Heisenberg state rarely represents the properties of a system. The Heisenberg state is a constant that does not change over time and, under the

in a pure state. To examine Deutsch and Hayden's proposal, we need only consider pure states, so will not consider mixed states further.

6. Strictly speaking, the product function presented here is a sufficient but not necessary condition for the more general form of separability which, as Winsberg and Fine (2003) point out, could also be satisfied with other functions. However, if A and B are the only objects in the subvenient set (and not, for example, both measurement settings), the product function seems the most plausible choice. Fogel (2007) surveys the options and provides a more comprehensive analysis of each.

Deutsch-Hayden approach, is an arbitrary reference vector that need not represent the system's properties at *any* time. Instead, the information that represents the system's properties at each point in time is encoded in its descriptor, which must be combined with the Heisenberg state to arrive at a complete representation of its physical state.

Because the Heisenberg state does not (on its own) represent the physical state of the system at any time, separability of the Heisenberg state is certainly not a sufficient condition for separability. Instead, separability should obtain whenever the properties of a system (its physical state) supervenes on the properties (physical states) of its subsystems. As we will see shortly, Howard's separability more specifically requires that the *intrinsic* properties of a system should supervene on the intrinsic properties of its subsystems. In fact, intrinsicality will turn out to be such a critical feature of our theory independent version of separability that it is worth taking a few moments to review the concept.

We will understand intrinsicality in the sense proposed by Lewis (1983): that statements that ascribe intrinsic properties to something must be *entirely about* that thing. (Lewis's original characterisation also included several other, overlapping notions,[7] but the differences will be largely irrelevant for our purposes.) Intrinsic properties can be contrasted with *extrinsic* properties.[8] Statements ascribing extrinsic properties tell us about a thing's relations with *other* things. We might say of system A, for instance, that it is heavier than system B, a statement that expresses a property of system A but is not entirely about system A.

Lewis's original characterisation of intrinsicality is not precise enough for our purposes but later work by himself and others provides greater clarity. After refining Kim's (1982) definition of an "internal property", Langton and Lewis (1998) and later Lewis (2001) proposed that an intrinsic property must be compatible with what they call *loneliness*. To be compatible with loneliness, it

7. "A sentence or statement or proposition that ascribes intrinsic properties to something is entirely about that thing; whereas an ascription of extrinsic properties to something is not entirely about that thing, though it may well be about some larger whole which includes that thing as part. A thing has its intrinsic properties in virtue of the way that thing itself, and nothing else, is. Not so for extrinsic properties, though a thing may well have these in virtue of the way some larger whole is. The intrinsic properties of something depend only on that thing; whereas the extrinsic properties of something may depend, wholly or partly, on something else. If something has an intrinsic property, then so does any perfect duplicate of that thing; whereas duplicates situated in different surroundings will differ in their extrinsic properties." (Lewis 1983, 197) See Marshall (2016), for a more fulsome discussion of the differences between each criterion. The duplication criterion is somewhat distinct from the others but yields similar overall conclusions, albeit via a more circuitous path.

8. Extrinsic properties are sometimes called *relational* properties, but we will avoid that term because relations can also exist between the internal parts of a system so a property could be both intrinsic and relational.

must be possible for something to have that property, even if no other physical thing existed.

The intuition behind this condition is clear: the intrinsic properties of a thing should be the properties of that thing and that thing alone, so should not depend on its relations with other things. That is, an intrinsic property should not depend on the properties of any other thing, including whether any other thing exists. The ultimate test of intrinsicality is therefore whether a property could be instantiated even if the thing it was ascribed to were the only thing in existence.

By way of example, *being a person* can be an intrinsic property because something could be a person even if it was alone in the universe, but *being a sister* cannot, because it requires a certain relation with another person – a sibling. *Being a sister* is not compatible with loneliness because a person could only have that property if at least one other person existed.

Let us formalise this notion of intrinsicality as follows:[9]

> **Intrinsicality:** A property is intrinsic to a system if and only if it does not entail the existence of any other system.

With that established, we can return to see why properties must be intrinsic to be separable. If separable properties did not need to be intrinsic, we would find that entanglement would be ruled separable on a technicality. The extrinsic properties of a subsystem include the relations that subsystem has with other subsystems. If A and B are entangled, then *being entangled with* B would be an extrinsic property we could ascribe to system A. In that case, the entanglement property would supervene on the properties of system A alone because being entangled with B is an extrinsic property of A. In fact, any relation between the systems could be expressed as an extrinsic property of either of the component systems, so separable properties must be intrinsic to avoid the situation where every relation automatically qualifies as separable.

If separability entails that the properties of component systems are intrinsic, it is easy to see that the properties of the compound system must also be intrinsic. If not, any extrinsic property of a compound system would qualify as nonseparable because it would not supervene on the intrinsic properties of the subsystems. For instance, *being smaller than the Sun* is an extrinsic property of the Earth and the Moon as a compound system, but the property does not supervene on the intrinsic properties of the Earth and the Moon because it also depends on the size of the Sun.

9. While this version of intrinsicality is appropriate for straightforward physical properties such as those represented by descriptors, it does not generalise to all properties. Langton and Lewis show that compatibility with loneliness is not always a necessary or sufficient condition for intrinsicality. In particular, they argue that properties that entail loneliness and disjunctive properties must also have (or lack) certain other features. Fortunately, a descriptor could never *entail* loneliness and it does not represent disjunctive properties, so we can safely ignore these complications.

There is one last aspect of intrinsicality that will be important for analysing Deutsch-Hayden descriptors. Intrinsicality can be spatial, temporal or spatiotemporal. We are most familiar with spatiotemporally intrinsic properties, which are properties that are compatible with loneliness in both space and time; that is, properties that do not depend on the existence of any other thing now or ever. A property such as *being over six feet tall* is spatiotemporally intrinsic. A person could be over six feet tall even if no other physical thing existed at any other place or any other time.

Other properties might be compatible with spatial or temporal loneliness, but not both. If we say that a person is *taller now than when they were a child*, the property does not depend on the existence of any physically separate thing now but does depend on the existence of another temporal part of the same person in the past. We might call such a property spatially but not temporally intrinsic. By contrast, the property *being presently taller than their sister* depends on the existence of a sister now but does not depend on the existence of any physical thing in the past or future, so would be temporally but not spatially intrinsic. (See the footnote for more rigorous conditions.[10])

We now have all the pieces we need to formulate our criteria for separability. Rather than referring to the "subsystems" of a compound system, we will formulate these criteria in terms of parts so that we can more naturally accommodate compounds composed of either (or both) spacelike or timelike separated parts. We will also assume that the systems and their parts are always physical. With these refinements in place, our most general notion of separability is:

> **Separability:** An intrinsic property of a compound system is separable iff it supervenes on the intrinsic properties of the compound system's parts.

As with intrinsicality, we can then identify three subcategories of separability: spatial separability, where the spatially intrinsic properties of a compound system supervene on those of its spatially separated parts; temporal separability, where the temporally intrinsic properties of a compound system supervene on those of its temporally separated parts; and spatiotemporal separability, where a property is both spatially and temporally separable. The last of these seems equivalent to the version of spatiotemporal separability proposed by Healey (1991) and Healey and Gomes (2022). However, where Healey describes spatial separability in terms of *properties* and spatiotemporal separability in terms of

10. Take a property P ascribed to a time extended physical object A, with $A_{\Delta t}$ representing a temporal part of that object. P is *spatially intrinsic* to $A_{\Delta t}$ iff P's instantiation is compatible with there being no physical thing existing at spacelike separation from any temporal part of $A_{\Delta t}$. P is *temporally intrinsic* to $A_{\Delta t}$ iff P's instantiation is compatible with there being no physical thing (including A) existing at timelike separation from every temporal part of $A_{\Delta t}$. P is *spatiotemporally intrinsic* iff it is both spatially and temporally intrinsic.

processes (a term he does not fully explain), I have opted for a more consistent presentation of these intimately connected concepts.

5 Separability of Descriptors

With the assessment criteria clarified, we can now return to evaluate the separability of the properties represented by Deutsch-Hayden descriptors. We have established that separable properties must be intrinsic properties, and that intrinsic properties must be compatible with loneliness. Our first question then: are the properties represented by descriptors compatible with loneliness?

First, let us consider the way descriptors are represented mathematically. A descriptor is composed of three matrices, one for each observable. The entries of each matrix are complex numbers that can change over time. For an isolated qubit, each observable is represented by a 2×2 matrix that does not depend on any other qubit and so represents a property that is compatible with loneliness. But if the qubit is part of a larger network, the size of the matrix for each observable must be increased according to the number of qubits in the network ($2^n \times 2^n$). The larger matrix is required to record the potential interactions between the qubit to which they are assigned and every other qubit in the network. The entries in the matrix will also differ depending on which qubit is being represented.

To illustrate: say the descriptor for the x-observable of qubit a has the initial matrix value $\hat{\sigma}_x \otimes \hat{1} \otimes \hat{1}$. The two identity matrices in the tensor product imply that there are exactly two other qubits in the network. Furthermore, the location of $\hat{\sigma}_x$ (the first term in the product) is a unique identifier, which in this case we have assigned to qubit a. The descriptors for the two other qubits, call them b and c, would also be composed of three terms, two of which are identity matrices, but the sigma value would become the second and third terms respectively. Despite containing no explicit reference to qubits b and c, the matrix for qubit a implicitly entails their existence. In fact, the matrix entails their existence even before the qubits have interacted. Accordingly, the descriptor does not represent a property that is compatible with loneliness, so does not represent an intrinsic property of qubit a.

As the number of qubits in the network increase, the matrix representation of the descriptors become exponentially large. For a realistic system, the total number of other systems it could potentially interact with is enourmous, and therefore the descriptor would be astronomically large. But it is not the size of the descriptor that should concern us (although it may concern some). Instead, it is the fact that each system in the universe has a specific, uniquely identifying position in each other system's descriptor.

One response Deutsch and Hayden could make is that, initially at least, the matrices representing a qubit only contain local information, with the elements representing other qubits filled entirely with identity matrices, so providing no information about them. In fact, these other qubits may not even exist. The matrix might be made large enough to accomodate some arbitrarily large, even infinite, number of other *potential* qubits. If so, the size of the matrix might tell us nothing about how many other qubits there actually were, or indeed if there were any other qubits at all, and so would be compatible with loneliness.

But this response would fail to recognise that when the Heisenberg state is set to $|0,...,0\rangle$, as Deutsch and Hayden suggest, the initial descriptor $\hat{\boldsymbol{q}}_a(0)$ is determined by the operator $U(0)$.[11] The operator $U(0)$ acts on the full Heisenberg state and is identical for every qubit, so must encode the initial properties of every qubit in the network. Consequently, the matrix elements representing other qubits are not, in general, filled with identity matrices. $U(0)$ is not compatible with loneliness because it contains information about the initial properties of every system in the network.[12]

One might object that the matrices underlying the Deutsch Hayden approach are just artefacts we find useful for calculations. While the matrices for each qubit need to be large enough to allow for potential interactions with other qubits in the future, it is possible that no interactions will ever take place. In that case, the properties represented by the descriptor for a qubit might never depend on the properties of any other qubit. If a qubit never interacts with any other, the full mathematical representation becomes redundant and a single 2×2 matrix would suffice for each observable. In that case, the formalism adopted by Deutsch and Hayden, where observables at any time are shown as a function of the t_0 observables of specific qubits, provides a more economical representation of each qubit's properties. If qubit a and qubit b interact, the descriptor for qubit a could evolve to $(\hat{q}_{ax}\hat{q}_{bx}, \hat{q}_{az})$, which more accurately expresses the fact that the current properties of qubit a depend only on the past properties of qubit a and b. Nevertheless, it is clear that the descriptor for qubit a entails the existence of qubit b at some time in the past, because the observable $\hat{q}_{bx}$ (more fully, $\hat{q}_{bx}(0)$) could only have been instantiated by qubit b at t_0. Regardless of the formalism, the unique identification of each observable with a specific qubit is necessary to capture the fact that quantum interference only manifests between entangled qubits (more on this point later).

It is logically possible that qubit b once existed, interacted with qubit a, and then ceased to exist. In that sense, descriptors represent properties that are compatible with *spatial* loneliness. The qubit could have the properties represented by the descriptor at any moment in time, even if no other physical thing existed at that time. However, descriptors do not, in general, represent

11. More completely: $U^{\dagger}(0)(\hat{1}^{a-1} \otimes \hat{\boldsymbol{\sigma}} \otimes \hat{1}^{n-a})U(0)$.

12. More conventionally, the Heisenberg state would simply be identical to the initial Schrödinger state, which similarly contains information about the initial properties of every system in the network.

properties that are spatiotemporally intrinsic because the observables of entangled qubits do depend on the existence of their entangled partners at some time.

Having resolved the issue of intrinsicality, we can readily address the question of separability. Recall that a property of a compound system is *spatially* separable iff it is a spatially intrinsic property that supervenes on those of its spacelike separated parts. The descriptors for any network of qubits are nothing more than the set of descriptors for the individual qubits, so if descriptors represent spatially intrinsic properties, they must also represent spatially separable properties. Conversely, descriptors do not, in general, represent spatiotemporally separable properties because they do not represent spatiotemporally intrinsic properties.

Before we move on to discuss the connection between separability and locality, it is worth pausing to understand how we should categorise the properties represented by Schrödinger states. While the Heisenberg picture and the Schrödinger picture are mathematically equivalent, they ascribe different properties to a qubit. In Deutsch and Hayden's formulation of the Heisenberg picture, the properties of the world are represented by descriptors, which in effect describe how the system was prepared and how it has evolved over time. In the Schrödinger picture, state vectors describe the properties of a system at a single point in time. By construction, the latter do not refer to any past or future property, so they are temporally intrinsic.[13] But the state vector for entangled qubits necessarily entails the existence of both qubits, so the joint Schrödinger state represents a property that is spatially intrinsic to the pair of qubits but does not supervene on the spatially intrinsic properties of each qubit individually. So, in contrast to Deutsch-Hayden descriptors, Schrödinger states represent properties that are temporally separable but not spatially separable. The common ground between both pictures is that the joint states represent properties that are not spatiotemporally separable.

13. A number of papers purport to demonstrate steering or entanglement through time (for instance, Ma et al. 2012; Megidish et al. 2013). These papers use the Schrödinger picture and represent relations between timelike separated systems as nonseparable. While the experiments can equally well be explained using conventional entanglement between spacelike separated systems, the ease with which they can be reinterpreted as relations between timelike separated systems does highlight the fragility of the distinction. Indeed, Glick (2019) argues that there is nothing incoherent or paradoxical about taking entanglement between timelike separated systems seriously.

6 Do Descriptors Represent Local Properties?

We have seen that descriptors represent spatially separable properties, which suggests they satisfy a qualified version of the principle of separability, but does that warrant describing them as *local*? In this section, we will look at how property locality is generally understood and then consider how Deutsch and Hayden have framed it. I will propose that their notion of locality aligns with spatial separability but will show why this account is flawed. (In the discussion to follow, recall that we are focussing on property locality and have taken for granted that the dynamics of Everettian quantum mechanics are local.)

To begin, let us step back and consider why any property might be regarded as nonlocal. Marshall and Weatherson (2018) propose that any property that is not intrinsic is nonlocal, which has some intuitive merit. Extrinsic relations are not instantiated in just one location. For instance, *being shorter than the Eiffel Tower* is not a local property of mine because its instantiation depends on the properties of the Eiffel Tower, which is physically distant from me.

But bearing in mind the history of the nonlocality debate, a more nuanced approach is called for. Nonlocality has long been associated with something "spooky" and mundane extrinsic properties such as *being shorter than the Eiffel Tower* hardly seem to fit that description. Such properties are clearly not local properties of the object to which they are ascribed, but nor do they seem exceptional enough to qualify as nonlocal. I propose to differentiate between properties that are extrinsic (not local) and the subset of those properties we would describe as *nonlocal*. That is, to agree with Marshall and Weatherson that extrinsic properties are not local but to reserve the term *nonlocal* for the type of non-classical relation that bothered Einstein so much.

We might say that the relations between the intrinsic properties of things, such as *x is shorter than y*, are mere extrinsic properties. But it would seem appropriate to call a property *nonlocal* if it was held in virtue of a relation that did not supervene on the intrinsic properties of its relata; that is, if the relation was nonseparable (we will return to which type of nonseparability is relevant in a moment).

I should also clarify that with the conditions I have proposed, nonseparability is not itself a nonlocal property because it is ascribed to compound systems rather than subsystems. The classification seems natural when we consider that when a nonseparable relation such as entanglement is ascribed to a group of systems, there is a clear sense in which the relation is local to the group because it is an intrinsic relation among members of the group. That is, the nonseparable relation is a property of the group that does not depend on the properties of any system that is spatially or temporally distant from the group. It is only when the relation is translated into an extrinsic property and ascribed to some subset of the group that the property could even be described as *not local*. For instance, if systems x and y are entangled with each other and no other systems, then the entanglement relation is local to the compound system xy in the sense that it does not depend on the properties of any systems that are physically distant from xy. But while the relation might be local to the compound system, we can confidently say that *being entangled with* y could not be a local property of system x. If we regard entanglement as a nonseparable relation, then we would also be justified in taking *being entangled with* y to be a nonlocal property of x.

I have discussed the relationship between nonseparability and nonlocality but have not yet been clear about which type of separability I have been invoking: spatial, temporal or spatiotemporal. Deutsch and Hayden do not explicitly mention separability in their paper, but their account of locality appears to align with spatial separability. They claim that the local characterisation of quantum information (which I take to represent the properties of a qubit) must satisfy the criterion, attributed to Einstein, that "the real factual situation of the system S_2 is independent of what is done with the system S_1, which is spatially separated from the former" (Deutsch and Hayden 2000, 1760). A plausible reading of the criterion is that the "real factual situation of the system S_2" is referring to the physical properties of S_2 and "what is done with the system S_1" is referring to variations to the physical properties of S_1. Furthermore, because the criterion does not contemplate that there could be "real facts" about S_1 and S_2 as a compound system that are independent of the "real facts" about S_1 and S_2 individually, it almost certainly presupposes that the former would somehow supervene on the latter.

Since "what is done" to a distant system could include eradicating it from existence, the "Einstein criterion" entails that to be local, a property ascribed to a thing must be independent of the existence of any other spatially separated system in the universe. In other words, local properties must be spatially intrinsic. Further, if the properties of every compound system supervene on the spatially intrinsic properties of their subsystems (as they do in Deutsch and Hayden's approach), then those higher-level properties will all be spatially separable.

But the Einstein criterion does not require local properties to be *spatiotemporally* intrinsic. In fact, it is entirely silent on properties of systems that are timelike separated, and for good reason – based on his work on relativity, Einstein would almost certainly have allowed that the properties of S_2 could depend on what was done to the properties of S_1 when S_1 was in the past light cone of S_2.

So on Deutsch and Hayden's view, it appears that local properties must be spatially intrinsic but need not be spatiotemporally intrinsic. The primary challenge for this view is that there are many properties that meet the Einstein criterion, and so are spatially intrinsic, that are clearly not local properties. For instance, I could be ascribed the property *being 6 inches shorter than Abraham Lincoln*. This property meets the Einstein criterion because *being 6 inches shorter than Abraham Lincoln* is not affected by what is done to any system that is spatially separated from me.

In the language of intrinsicality, *being 6 inches shorter than Abraham Lincoln* is a spatially intrinsic property of mine. This odd classification comes about because Lincoln and I exist at two different times. I could have that property even if there were presently no other physical things in the universe, so the property is compatible with spatial loneliness. The property may not be nonlocal, but as an extrinsic property, it is certainly not a local property of mine either.

More to the point, this view of property locality would lead us to conclude that every relation between time-extended things was local, regardless of the nature of the relation. To see why, consider two systems, a and b, and some arbitrary relation between them at t_n, which we can denote $R(a_n, b_n)$. The relation $R(a_n, b_n)$ is not spatially intrinsic to a, but the relations between a now and b at some previous time are spatially intrinsic, because they do not depend on b existing now. Consequently, the relations $R(a_n, a_0)$ and $R(a_n, b_0)$ qualify as spatially intrinsic properties of system a at t_n. Similarly, the relations $R(b_n, b_0)$ and $R(b_n, a_0)$ qualify as spatially intrinsic to system b at t_n. Because $R(a_n, b_n)$ supervenes on these spatially intrinsic properties, we must conclude the relation – which could be any arbitrary relation – will be spatially separable.

More concretely, consider a relation that seems paradigmatically nonlocal. Imagine that two particles (a and b) were in an entangled state despite never having interacted. Locally, each particle is in a maximally uncertain state that never changes over time (assuming no external influences), but globally their values display perfect correlation. Such a property would seem as nonlocal as we could hope for. But the relation will be spatially separable because it supervenes on their spatially intrinsic properties – namely, the relations between the particles at different times. That is, the relation between a_n and b_n (perfect correlation) supervenes on the relations between: a_n and a_0 (identity); a_n and b_0 (perfect correlation); and b_n and b_0 (identity). The first two relations qualify as spatially intrinsic properties of a_n, while the last qualifies as a spatially intrinsic property of b_n.

Clearly, the "Einstein criterion" (spatial intrinsicality) does not provide us with an adequate account of locality. A better criterion would codify our intuition that a local property of a thing must be a property of that thing and that thing alone.[14] That is, the local properties of a thing should not depend on

14. There might, arguably, be one exception. If we regard a temporal part as a "thing", then a relation between (say) part A and part B could conceivably be regarded as a local property of part A alone, despite depending on the existence of part B. For instance, we might take *being heavier than*

the properties of other things, regardless of where or when those other things existed. More precisely:

> **Local property:** A property is local to a system at time t iff it is a spatiotemporally intrinsic property of that system at time t.

This criterion has the welcome consequence of clarifying that *being six inches shorter than Abraham Lincoln* is not a local property of mine. It also clarifies that the local properties of a system at a specific time do not include its properties at other times. For instance, we would not say that an object's properties on Tuesday are (necessarily) local to it on Wednesday. The criterion also allows a nonseparable property (such as entanglement) to be considered a local property of a compound system, regardless of whether we consider it a nonlocal property when ascribed to the individual subsystems.

We finally find ourselves in a position to provide a definitive criterion for assessing whether a property is nonlocal. Nonlocal properties are not merely extrinsic properties, they are the subset of extrinsic properties that are held in virtue of a nonseparable relation between the system they are ascribed to and another system. More precisely:

> **Nonlocal property:** A property of a thing is nonlocal iff it is not spatiotemporally intrinsic to that thing in virtue of a spatiotemporally nonseparable property ascribed to a compound system of which the thing is a part.

On this definition, a Deutsch-Hayden descriptor for an entangled qubit represents a nonlocal property because it is not spatiotemporally intrinsic, and it is not so in virtue of the spatiotemporally nonseparable relation that holds between it and the qubits it is entangled with.

We have established that descriptors represent properties that are nonlocal in at least some sense. But the place we have arrived at seems far removed from our original conception of nonlocality. It may have initially seemed that nonlocal properties should be properties of spacelike separated systems, but we are now ascribing nonlocal properties to timelike separated systems. Are these properties really that different from classical properties? Has nonlocality lost the "spookiness" that Einstein once saw in it?

In the next section, I examine the underlying feature of nonlocal properties that makes them radically different from the relations of classical physics.

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it was yesterday to be a local property of a system even though it implies the same system existed yesterday. We might allow some leeway here if we (rightly or wrongly) take different temporal parts of the same time extended system to be numerically identical with each other. For our purposes, we can ignore this complication because our focus is only on relations between *different* systems.

7 Why Are Nonlocal Properties Spooky?

The concept of property locality presented in this paper hinges on the concept of spatiotemporal separability. Our intuitions might have supported a close connection between locality and spatial separability, but the link with spatiotemporal separability may be less obvious. Spatiotemporal separability requires that the properties of a system must not depend on properties of any other system in the past, present or future. But even classical intrinsic properties seem to violate this condition because they depend on the properties of other things in the past. For instance, the velocity of a coloured ball struck by a white ball will depend (among other things) on the previous velocity of the white ball. However, the dependence in this case is causal, rather than the sort of ontological dependence we see with nonseparability. The white ball has played a causal role in the current velocity of the coloured ball, but that velocity does not entail any particular property of the white ball in the past, nor that the white ball even existed in the past. The influence of the white ball is a contingent fact; it is possible that the coloured ball could have had the very same velocity, but from entirely different causes.

By contrast, a descriptor assigned to an entangled qubit necessarily entails the previous existence of its entangled partner(s). The notation makes the dependence clear. If the x-observable for qubit a at time t is $\hat{q}_{ax}(t) = \hat{q}_{ax}(0)\hat{q}_{bx}(0)$, qubit b must have existed at t_0. If there were no qubit b, there could be no property with the unique value represented by $\hat{q}_{ax}(0)\hat{q}_{bx}(0)$.

The properties descriptors represent will causally depend on the properties of their entangled partners, but they will also exhibit a form of ontological dependence. Specifically, the properties a descriptor ascribes to an entangled qubit could not exist unless a particular individual (the entangled partner) existed at some time in the past.[15]

The way we represent classical properties might ostensibly imply a similar form of dependence, but the similarity is deceptive. To explain: say the current velocity of the coloured ball equals half the previous velocity of the white ball, which we denote $v_c(t) = v_w(t-1)/2$. The identity relation in this case expresses a relation between the current state of ball c and the past state of ball w, so appears to entail the existence of w in the past. However, we could equally replace $v_w(t-1)/2$ with a value, such as 5m/s, or with a function of the velocity of some causally unrelated system x, so $v_c(t) = v_x(t)$. The value representing the velocity of these disparate systems can be identical because the classical property is qualitative – that is, the instantiation of the property does not depend on the existence of any particular individual.

By contrast, a descriptor for an entangled qubit does not represent a qual-

15. Implying that the dependence could be more narrowly classified as past rigid existential dependence.

itative property. The property can only be instantiated if the particular qubit referenced in the descriptor existed at some previous time. The fact that the descriptor is associated with specific individuals is no mere artifice either, it plays a critical role in the theory by telling us when we will see interference. Because the observables from different qubits at t_0 commute, we will only see interference when the descriptors for interacting qubits include observables from *the same qubit*. Loosely speaking, when a qubit becomes entangled with another, it passes on a unique property that could not, even in principle, have originated from any other qubit.[16]

Here we see the underlying connection between nonlocality and spatiotemporal nonseparability. Unlike classical relations, relations that are spatiotemporally nonseparable are relations between the *particular individuals* that form a compound system. The properties of each subsystem are nonlocal because they are not entirely independent of each other. The properties may have been the result of causal interactions in the past, but they remain a unique and continuing relation between the entangled subsystems. The Deutsch-Hayden approach is nonlocal in just this sense – the descriptors for a network might supervene on the descriptors for the individual qubits, but the descriptors for individual qubits are not *entirely about* that qubit so do not represent independent properties.

In the Schrödinger picture, nonlocality is clearer but the non-qualitative nature of entanglement is obscured because it is represented as a single state of a compound system rather than a relation between independent states. Even so, the joint state must (explicitly or implicitly) identify the individual subsystems precisely because the state is assigned to a compound system.[17] Regardless of the formalism we use, entanglement must be represented as a unique relation between individuals, a fact the Deutsch-Hayden approach brings sharply into focus.

As a non-qualitative property, entanglement is profoundly different to the

16. Descriptors, or at least t_0 observables, could potentially be thought of as representing tropes – particular properties of individual qubits. But the matter is complicated by the fact that, after an interaction, an observable for one qubit can appear as a term in the other qubit's descriptor. Further investigation would be required before we could conclude that accepting descriptors as a representation of quantum properties entailed accepting trope theory as a general ontology.

17. For instance, when we assign the state $(|00\rangle + |01\rangle + |11\rangle)/\sqrt{3}$ to a compound system, we must also specify which terms in the tensor products are assigned to which qubits, although in practice we often omit labels and simply assign each qubit a position in the tensor products. (In symmetrical states, such as Bell states, the qubits' positions would be interchangeable and would not strictly need assignment, but those are special cases.) We can see the non-qualitative nature of such states when we consider that when assigned to different compound systems the states are equivalent but not identical, because they specify relations between different individuals. Accordingly, it would be inappropriate to propose, for example, that $(|0_a 0_b\rangle + |0_a 1_b\rangle + |1_a 1_b\rangle)/\sqrt{3}$ was identical to $(|0_c 0_d\rangle + |0_c 1_d\rangle + |1_c 1_d\rangle)/\sqrt{3}$.

properties we find in classical physics.[18] Properties such as an object's mass, size, charge or velocity may have been affected by interactions with other systems in the past, but their current properties could also have been the result of different interactions with a different set of systems. In quantum mechanics, by contrast, it is of fundamental importance that it is *this* system that is entangled with *that* system.

8 Concluding remarks

Deutsch and Hayden have argued that the Heisenberg picture allows us to characterise quantum properties locally using objects they call *descriptors*. I have assessed their claim against the principle of separability and found that descriptors only conform with the principle in a restricted sense. Descriptors represent properties that are *spatially separable* – that is, they supervene on the spatially intrinsic properties of individual qubits. But spatially intrinsic properties are not intrinsic *simpliciter* because they include extrinsic relations between temporally separated things. Moreover, spatial intrinsicality is an inadequate criterion for locality because we can use temporally extrinsic properties to recast any physical relation as spatially separable.

I have proposed a more stringent criterion for property locality, *spatiotemporal separability*, which requires that a local property of a thing must not entail the existence of any other thing. Spatiotemporal separability may at first seem too strong a criterion, but our analysis has revealed why this form of separability is relevant to locality. A nonseparable relation such as entanglement is a relation between the properties of a particular set of systems. The nonqualitative nature of this property sets it apart from the qualitative properties we have come to expect from classical physics. While there might not be action at a distance in the Heisenberg picture, there is still something spooky about it.

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18. Except perhaps in relation to the properties of spacetime itself, but that is an issue for another paper.

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