

Persistence and Reidentification in Systems of Identical Quantum Particles: Towards a Post-Atomistic Conception of Matter

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The quantum symmetrization procedure that is used to handle systems of identical quantum particles brings into question whether the elementary constituents of matter, such as electrons, have the fundamental characteristics of persistence and reidentifiability that are attributed to classical particles. However, we presently lack a coherent conception of matter composed of entities that do not possess one or both of these fundamental characteristics. We also lack a clear *a priori* understanding of why systems of *identical* particles (as opposed to non-identical particles) require special mathematical treatment, and this only in the quantum mechanical (as opposed to classical mechanical) setting.

Here, on the basis of a conceptual analysis of a recent mathematical reconstruction of the quantum symmetrization procedure, we argue that the need for the symmetrization procedure originates in the confluence of identity and the active nature of the quantum measurement process. We propose a conception in which detection-events are ontologically primary, while the notion of individually persistent object is relegated to merely one way of bringing order to these events. On this basis, we outline a new interpretation of the symmetrization procedure which gives a new physical interpretation to the indices in symmetrized states and to non-symmetric measurement operators.

I. INTRODUCTION

The atomistic conception of matter posits that physical objects in our everyday environment consist of spatial arrangements of indivisible, elementary entities that persist indefinitely, and promises to account for our rich sensory experience of matter in terms of the motion and properties of these entities. This metaphysical conception runs like a golden thread through

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the history of physics, inspiring empirical discoveries such as the identification of the chemical elements (exemplified in Dalton's atomic theory of chemistry) and the discovery of subatomic particles. This conception is also woven into our fundamental theories of physics. In particular, the conceptual framework of classical particle mechanics treats matter as consisting of indefinitely persistent point particles which move continuously through space according to deterministic and reversible laws of motion, and can be reidentified if precisely tracked through time.

In the quantum era, the core claim of the atomistic conception appears to be alive and well: physicists commonly say that a helium atom is *composed of two electrons*; that a bubble chamber image shows *particle tracks*. However, construction of a quantum model of a system of identical particles (such as the two electrons in a helium atom) requires use of a specific mathematical symmetrization procedure (of which the so-called *symmetrization postulate* [25] is the centerpiece) in order to take into account of the particles' identity. And, in light of this procedure, it is far from clear whether one is justified in viewing these 'particles' as persistent and reidentifiable entities. Indeed, it has been widely claimed that identical particles lack one or both of these fundamental characteristics [15].

But, if that is so, how ought we to conceive of these 'particles'? Is it legitimate to consider them as objects at all? What exactly should replace the atomistic conception of microphysical reality? And, even more fundamentally, is there a compelling *a priori* reason why *quantum* systems of *identical* particles should necessitate such special treatment, given that special treatment is required neither for quantum systems of *nonidentical* particles nor for *classical* systems of identical particles? In this paper, we propose new answers to these longstanding questions.

The construction of a coherent post-atomistic conception of the denizens of the microphysical world which can be securely traced back to the quantum symmetrization procedure faces a key obstacle. The canonical view of the symmetrization procedure, first articulated by Dirac and now widespread, is that it is a formal expression of the fact that identical particles (namely those with the same time-independent properties such as mass and charge) are 'absolutely indistinguishable' from one another [12, §62]. Dirac's notion of indistinguishability was subsequently formalized as the *permutation invariance condition* [25], which is widely interpreted

as implying that identical particles cannot be meaningfully labelled and cannot be individually addressed via measurement, and thus lack an essential individuality-conferring characteristic¹.

Now, an immediate consequence of the permutation invariance condition is that identical particles are not reidentifiable. But assumptions of reidentifiability are integral to experimental practice. For example, in a bubble chamber, identical particles such as electrons are said to leave *tracks*. Yet each track is merely a sequence of separated bubbles: it is the *experimenter* who presumes that these bubbles are generated by—or are the *appearances* of—the *same* object. That is, the experimentalist posits that these bubbles are generated by persistent particles, and that these particles are reidentifiable, at least in this experimental context [19, §1]. Now, one might be tempted to brush aside such an assumption as merely conventional speech². However, that seems scarcely untenable: one measures particles' time-independent properties through the analysis of the shape of such tracks (for example, the curvature of a particle's track in a magnetic field yields the particle's mass-to-charge ratio). Hence, the canonical view appears to undermine the very empirical ground upon which quantum theory itself is built.

The tension between the canonical interpretation and assumptions fundamental to experimental practice has tended to be neglected or marginalized in most conceptual analyses until relatively recently, with most of the interpretational literature taking permutation invariance as the prime interpretational target. However, this tension has not gone without notice. For example, in his discussion of the meaning of particle statistics [34, §10–11], Schroedinger initially asserts that an atom 'lacks the most primitive property we associate with a piece of matter in ordinary life' and suggests that it 'consists of no stuff at all but is pure shape'. But he goes on to recognize the need to accommodate the phenomenon of particle tracks, and proposes that the notion of 'restricted identity' (or 'restricted individuality') becomes applicable under

¹ An alternative pathway to quantum statistics—beginning with Bose's procedure [3] for constructing quantum models of photon and particulate gases and culminating in Fock space (and associated commutation relations)—is generally taken to point to a similar (although not identical) conclusion [15, 34], namely that identical particles are in some sense not individuals, but are more akin to dollars in a bank account [34, §10] than to classical particles.

² For example, Chiara and di Francia dismiss the operational assumption of persistence in an experiment as 'mock persistence' on the grounds that it exists for a 'short time' [6]. For further details and a critique of this position, see [8, §5].

certain circumstances³.

In recent years, there has been renewed insistence that a viable interpretation of the symmetrization procedure allow for the emergence of reidentifiable identical particles under certain circumstances. For example, the requirement that particles with well-defined trajectories emerge in the classical limit of a system of identical quantum particles [4, 7, 9, 10]; or that identical particles can sometimes be reidentified through stable internal time-dependent properties (such as electrons whose z -components of spin are constant during an interaction) [1] or through spatial separation (for example being confined to separate electromagnetic traps), all echo Schroedinger’s ‘restricted identity’. However, reconciliation of this notion with the standard understanding of the symmetrization procedure remains highly problematic: on the standard reading of the symmetrization procedure, every electron is in the same reduced state. One recent proposal is to dispense with the interpretation that the indices in symmetrized states are *particle* labels (as they have been almost universally regarded heretofore) [5, 9], since this opens up the possibility of regarding a state like $\psi(x_1, x_2) = [\alpha(x_1)\beta(x_2) - \beta(x_1)\alpha(x_2)]/\sqrt{2}$ as a description of two fermions each in a specific one-particle state⁴. However, a consistent alternative interpretation of these indices has yet to be worked out⁵.

The primary objective of the present paper is to develop a novel post-atomic conception of identical quantum particles which reconciles the tension between the approximate reidentifiability of identical particles in certain physical contexts and the empirical adequacy of the symmetrization procedure. The approach differs from almost all previous work⁶ in a key methodological respect: rather than taking the symmetrization procedure (or the Fock space formalism) *as a given* and seeking to (re-)interpret it directly, it seeks to interpret a recent *reconstruc-*

³ Schroedinger suggests a quantitative condition that formalizes this notion [34, §13]. However, this condition (as well as the widely-used heuristic of non-overlapping particle wavefunctions (e.g. [35, p. 273–277]) is in interpretational tension with assumptions that are conventionally implicit in the interpretation of the symmetrization postulate (see Sec. V B).

⁴ A similar interpretation, based on other considerations, has been proposed by Saunders [32, §6.3] and by Ghirardi *et al* [16, 17].

⁵ Caulton considers the possibility that the indices refer to ‘nothing at all’ [5, §1.1], while Dieks and Lubberdink assert that they ‘have a merely formal significance’ [9]. See also [26] for a recent detailed discussion. In Sec. V C, we describe one unmet challenge faced by this view; and, in Sec. V D, present a new interpretation of the indices.

⁶ An recent exception is [24], which uses the reconstruction described in [18, 19] to ground the notion of particle number in identical particle systems.

*tion*⁷ of the Feynman form of the quantum symmetrization procedure [18, 19]. The secondary objective of the paper is to outline a new interpretation of the symmetrization procedure in light of this post-atomistic conception.

The centerpiece of the paper is an analysis of the relationship between reidentification and persistence in classical and quantum physics (Sec. II). This analysis demonstrates that, when dealing with a system of identical particles in the quantum setting, the *active* nature of quantum measurements imposes restrictions on experimental design, forcing the segregation of measurements (required for precise tracking) and interactions. This segregation in turn precludes precise particle tracking during the interaction phase, preventing reidentification of identical particles.

In Sec. III, I argue that this *in-principle loss of reidentifiability*—arising through the confluence of particle identity and the active nature of quantum measurement—deprives the metaphysical notion of persistent particles of empirical cover. However, I also argue that the notion of persistent particle cannot be entirely jettisoned, for it is this basic conception which organizes our primary experimental data, in particular underpinning measurement of intrinsic particle properties. In light of these considerations, I interpret the reconstruction described in [18, 19] as a formal means of reconciling these dueling ideas by *relaxing* the notion of persistent particle without eliminating it entirely. This is achieved by taking *detection-events* (rather than particles) as the primary reality, and then formulating two distinct object-models—the so-called *persistence* and *nonpersistence* models—of the same experimental data, only one of which (the persistence model) posits that the detection-events are underpinned by persistent particles.

The post-atomistic metaphysical conception that thereby emerges is further developed in Sec. IV, and can be summarized as follows. Identical particles do not simply *exist* in a context-independent sense. Rather, what exists are detection events. These events cannot, in general, be regarded as the *appearances* of microscopic objects. Rather, the notion of ‘particle’ as a persistent entity is tied to a specific model—the persistence model—of those events. This

⁷ As described in [20], reconstruction of a mathematical formalism is valuable stepping-stone in the elucidation of physically-obscure features of that formalism.

model is only strictly valid in limiting cases, and its approximate validity in certain experimental contexts justifies the operational assumption of particle reidentifiability in those contexts. In a helium atom, the synthesis of the two object-models is needed to describe the underlying microphysical reality, so that the particle notion is not unreservedly applicable. Thus, what unambiguously exists is the physical system as a whole, not the electrons themselves.

In Sec. V, I outline a new interpretation of the symmetrization procedure. In brief, the symmetrization procedure is *not* a mathematical expression of the idea that identical particles are indistinguishable. Rather, it is a formal means of synthesizing two different objects models (the persistence and nonpersistence models) of the same detection-event data. Indices in a symmetrized state do not refer unequivocally to particles. A number of other consequences are also described.

Finally, in Sec. VI, I briefly discuss the relation of the interpretative proposal described herein with the some related ideas, summarize some of the proposal's implications for the nature of physical objects (see Table III), and pose some open questions.

II. REIDENTIFICATION IN CLASSICAL AND QUANTUM PHYSICS

In everyday life, one is scarcely aware of the distinction between persistence and reidentifiability. The visual and tactile appearances of naturally-occurring physical bodies are so rich and diverse that they yield an essentially unique perceptual signature which usually suffices for their reidentification. In those rare circumstances when one is confronted with many objects of similar appearance, one can fashion perceptual handles by various means—using a microscope to see the distinctive pattern of nicks in several similar coins, or affixing a tiny barcode tag onto each of the ants in a colony. Alternatively, one can reidentify an object—such as a particular bird in a flock as it passes overhead—by tracking it intently over time.

However, in their quest for precise prediction through mathematization, physical theories simplify, regularize, and quantify the description of material bodies. As described below, this process of abstraction has led to the erosion—gradually, then suddenly—of the resources available for reidentifying bodies (see summary in Tables I and II).

| Physical situation | Momentary Appearance | Primary Means of Reidentification | Secondary Means of Reidentification |
|--|----------------------|--|--|
| Everyday objects | Rich, detailed | Similarity of momentary appearances (<i>e.g. people in a small group</i>) | Tracking through time (<i>e.g. flock of birds overhead</i>) |
| Single classical particle | Point-like events | Track continuously (<i>enables measurement of time-independent properties</i>) | None |
| Several nonidentical classical particles | Point-like events | Track each continuously through arena of interaction | Measure time-independent properties of each before and after interaction phase |
| Several identical classical particles | Point-like events | Track each continuously through arena of interaction | None |

TABLE I: *Reidentification in everyday experience and in classical mechanics.*

A. Classical Mechanics

Classical physics exalts our most readily quantifiable sense—the visual—over the others, resulting in the Cartesian conception of physical bodies as geometric entities of pure extension. Once extension is dropped as a primitive property, one arrives at the Newtonian conception of a physical body as a collection of interacting *particles*—extension-free persistent entities embedded in a geometric space which serve as centers of force.

Position is the only directly measurable property of a Newtonian particle, assumed to be rendered perceptible to any degree of precision via our visual sense (if appropriately instrumentally augmented). Therefore, unlike the objects of everyday experience, all Newtonian particles instantaneously appear alike—as a point-like spatial event or *flash* (see Table I). Accordingly, *tracking* is the primary means of reidentifying such particles, the possibility of which is granted by theoretical assumptions: each particle is assumed to move continuously in space,

and an ideal experimenter is assumed to be capable of making precise measurements of a particle's position without disturbing any of its properties (see Fig. 1).

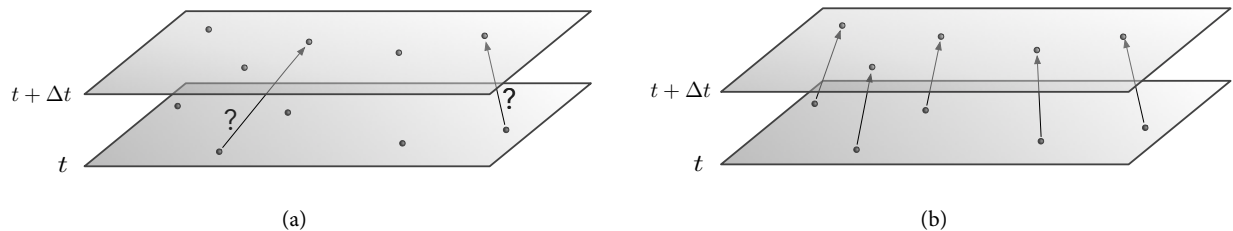


FIG. 1: *Reidentification of classical particles.* An ideal experimenter records a pattern of flashes at closely-separated times, t and $t + \Delta t$, which are assumed to be generated by persistent particles. (a) If the experimenter cannot assume that the particles move continuously (or via small ‘jumps’), he cannot reidentify them. That is, he is unable to say ‘*this* flash at t is generated by the same particle as *that* flash at $t + \Delta t$ ’, even though he knows (from the assumption of persistent particles) that the same particle is responsible for one of the flashes at t and one of the flashes at $t + \Delta t$. (b) If the experimenter *can* assume that the particles move continuously (or via small ‘jumps’), then approximate reidentification becomes possible. If the particles move continuously (as posited by classical physics), the precision of such reidentification can theoretically be increased indefinitely by reducing the size of Δt , and tends to exactness in the limit at $\Delta t \rightarrow 0$.

Since particles instantaneously appear alike, the time-independent properties—mass and charge—attributed to a particle by the theories of classical physics are concealed behind a featureless exterior, only becoming manifest (and thus measurable) when the particle moves in an experimental context under an experimenter’s control. Thus, the measurement of the time-independent properties of a particle, which are theoretically attributed to the particle in the moment, require that it be reidentifiable over an interval of time (see Fig. 2).

Once the time-independent properties of a set of particles are so measured, they can sometimes serve as a *secondary* means of reidentification. In particular, given a set of non-identical particles (*i.e.* particles that differ from one another in their time-independent properties), a specific particle can be reidentified after its interaction with the others provided that the particles’ time-independent properties are measured before and after such an interaction (see Fig. 3a).

However, given a set of *identical* particles (a theoretical possibility that is granted by classical mechanics), reidentification by pre- and post-interaction measurement of time-independent

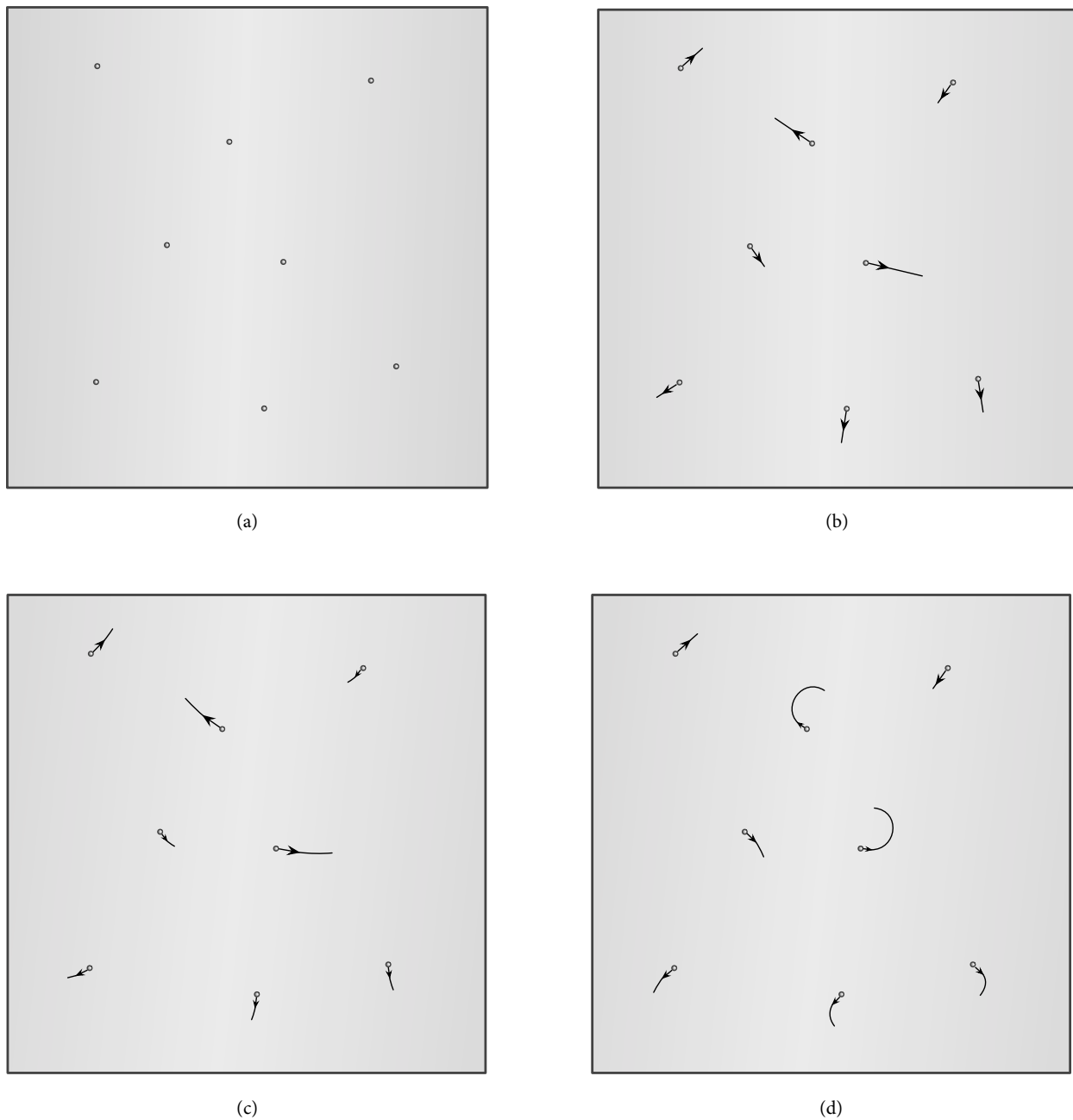


FIG. 2: *Measuring intrinsic and extrinsic properties of classical particles.* An ideal experimenter makes a series of snapshots of a set of classical particles. (a) In any snapshot, the particles all look alike, namely as point-like flashes. (b) If a series of snapshots over an interval $[t, t + \Delta t]$ are collated, reidentification enables attribution of a *trajectory*—here a straight line segment—to each particle. A particle’s velocity at time t can then be estimated from the direction and length of its trajectory in a sufficiently small interval $[t, t + \delta t]$. (c) If a mass-independent force (such as that supplied by a spring) is applied, the particles’ trajectories depart from linearity, from which their masses can be computed. (d) If a **B**-field is applied perpendicularly to the plane of the paper, the trajectory of a charged particles is circular (or helical), the curvature of which enables computation of the particle’s charge (given its mass).

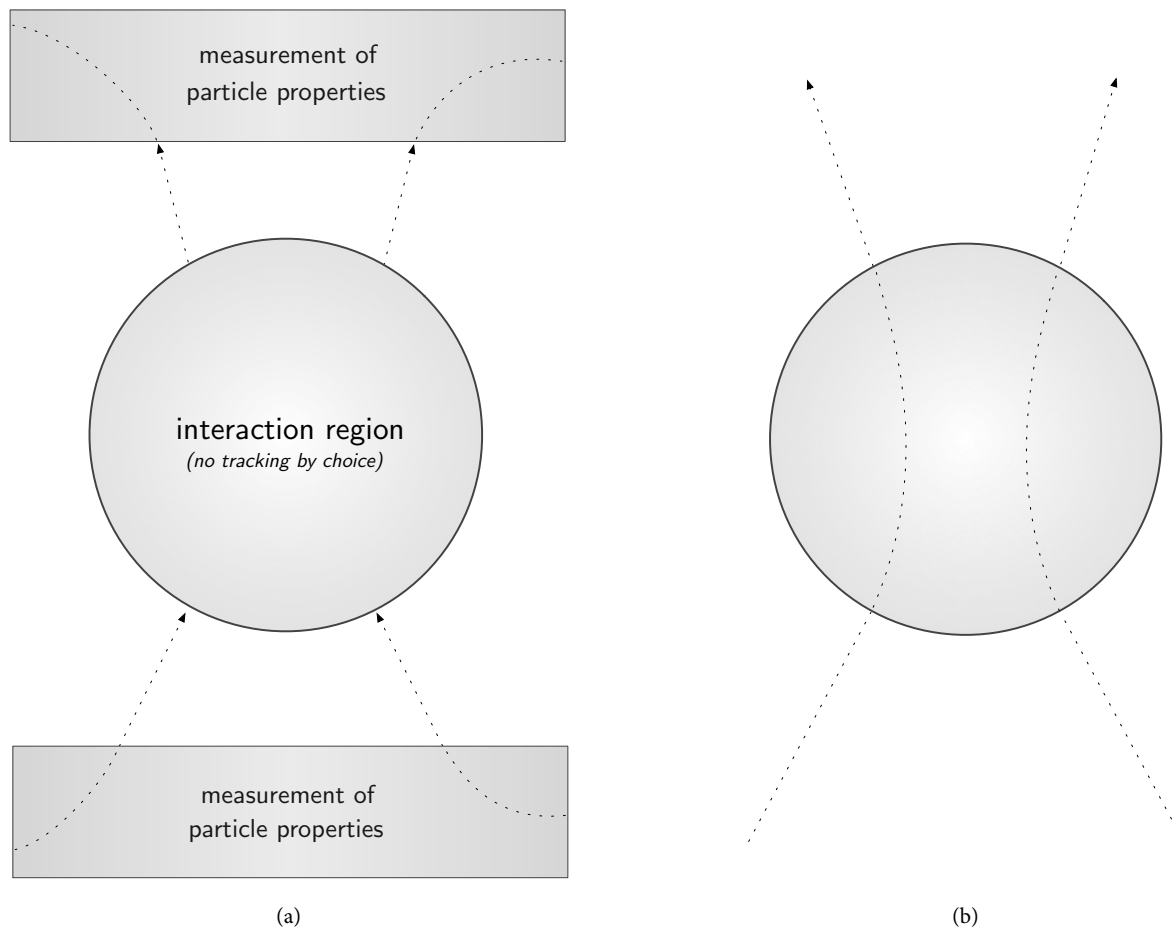


FIG. 3: *Reidentifying interacting classical particles.* (a) If the particles are nonidentical, they can be reidentified provided that one measure their time-independent properties (mass, charge) before and after the interaction, rendering unnecessary any tracking within the interaction region. (b) If the particles are identical, their reidentification requires that they be tracked sufficiently precisely as they pass through the arena of interaction.

properties is evidently impossible. Accordingly, reidentification of a specific particle can *only* be achieved by precisely tracking the particle as it makes its way through the arena of interaction (see Fig. 3b).

B. Quantum mechanics

Quantum theory dispenses with many of the key conceptions that are central to classical physics. In particular, the quantum formalism dispenses with the notion that measurement is a passive process that can register the position of a physical object without affecting its physical state. Instead, measurement is regarded an active process whose outcome can only be

predicted probabilistically, and which leads to a corresponding change in the object’s state. Consequently, in the design of any experiment, the free evolution of a physical object, or its interaction with others, both of which are treated by the formalism as a deterministic process, must be segregated from any measurement processes if they are to be studied *as is*.

As we shall detail below, these changes erode the resources available for particle reidentification, even by an ideal observer (see Table II). Moreover, in certain situations involving identical particles, the experimenter is deprived of *any* means to reliably reidentify particles, putting considerable pressure on the very idea that elementary particles are—*without qualification*—individually persistent entities.

| Physical situation | Momentary Appearance | Primary Means of Reidentification | Secondary Means of Reidentification |
|--|----------------------|---|--|
| Single quantum particle | Point-like events | Inferences based on pre- and post-interaction measurements (<i>unable to track during interaction phase</i>) | None |
| Several nonidentical quantum particles | Point-like events | Measure particles’ independent properties before and after interaction phase | None (<i>unable to track during interaction phase</i>) |
| Several identical quantum particles | Point-like events | Approximate tracking possible in some contexts (<i>bubble chamber, with separated tracks</i>), not others (<i>electrons in a helium atom</i>) | None (<i>unable to track during interaction phase</i>) |

TABLE II: *Reidentification in quantum physics.*

1. *Reidentification in a one-particle quantum system*

In its minimal instrumental interpretation, the quantum formalism takes as primitive the notions of *physical system*, *measurement*, and *interaction*, and applies to an idealized experi-

ment in which the system is subjected to a sequence of measurements and interactions implemented by macroscopic devices. Thus, the physical system is treated as a persistent entity, retaining its identity for the duration of the experiment. Measurements differ from interactions in that measurements yield macroscopically-observable events (such as scintillations on a phosphorescent screen or audible clicks). It is through these events that the physical system comes to be indirectly known.

For example, consider an experiment that an experimenter would typically describe as one in which electrons are liberated at a heated filament, accelerate through a wire-loop detector, diffract through a crystal lattice, and then impact a phosphorescent screen. The experimenter presumes that a click of the wire-loop detector followed moments later by a point-like flash on the screen both constitute imprecise position measurements of the same electron. The interaction of the electron with the crystal lattice is then modelled via a potential function typically drawn from a classical physical description of the crystal.

In such an arrangement, the experimenter's confidence that he has *reidentified* an electron—that the entity which presently generates a scintillation is the same as the entity that elicited a click moments earlier—does not rest upon having tracked that electron from filament to screen. Indeed, due to the invasive nature of quantum measurements, any attempt to carry out fine-grained tracking of the electron would uncontrollably interfere with the process during which the electron interacts with the crystal. Thus, reidentification necessarily depends upon various *indirect*, empirically-grounded inferences: the scintillations practically cease once the filament is cooled to room temperature; the rate of scintillations increases with filament temperature; the scintillation pattern is shifted if an external magnetic field is applied (as would be expected for charged particles emitted from the filament); and so forth.

The measurement of a particle's time-independent properties depends upon the possibility of fashioning an experimental context in which the experimenter can reliably infer that successive measurement outcomes are generated by the same particle, despite being unable to continuously track the particle. Such a situation obtains in a bubble chamber: an experimentalist parses a bubble-chamber image into *tracks*, each presumed to have been generated by a single particle during a portion of its life-history (see Fig. 4). Each track consists of a sequence

of separated yet closely-spaced bubbles, and these bubbles are modelled as the outcomes of successive inexact position measurement of the same object, between which the particle is assumed to evolve through interaction with its environment. In certain portions of a track, the particle can be safely assumed to be under the influence of an environment (such as an arrangement of electric and magnetic fields) that is under the experimenter's control, enabling its time-independent properties to be measured.

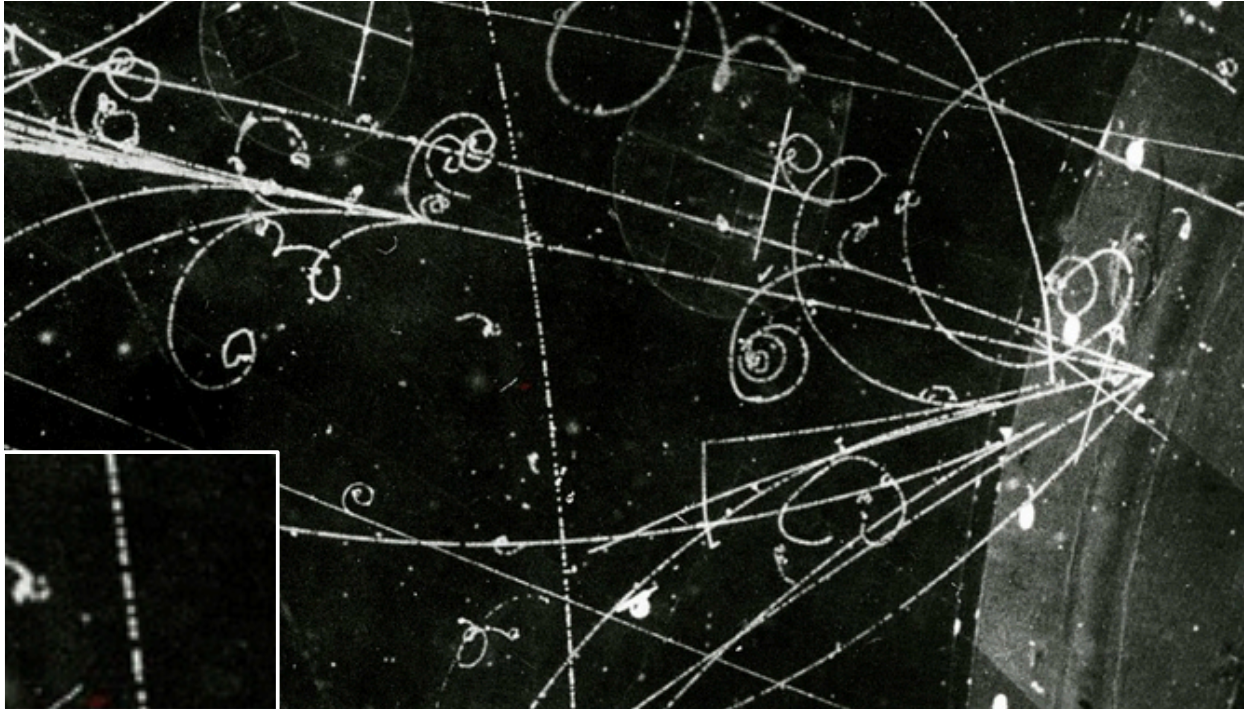


FIG. 4: *Reidentification and measurement of a particle's time-independent properties in a bubble chamber.* A bubble chamber image is parsed into distinct 'tracks', each of which is assumed to be due to a specific particle. The inset (bottom left) indicates that a track in fact consists of a sequence of discrete bubbles. The particles move in helical trajectories due to an applied magnetic field, which enables calculation of the particles' charge to mass ratio. (Image courtesy of Brookhaven National Laboratory).

2. *Reidentification in a system of two particles*

Consider an experiment to study the interactions of two *non-identical* particles. Let us suppose that, in the first phase of such an experiment, one has measured the time-independent properties of each particle by passing each through a bubble chamber. Now let the particles be

allowed to interact with one another, without the intrusion of measurement. Once the interaction phase is completed, the particles' time-independent properties can again be measured. As the particles are non-identical, they can, in principle, be perfectly reidentified.

However, consider an analogous experiment to study the interaction of two *identical* particles, such as two electrons. Reidentification of each particle by measurement of its time-independent properties before and after the interaction phase is no longer possible. But, unlike the corresponding classical experiment, particle tracking during the interaction phase is *also* impermissible if one wishes to study the undisturbed interaction of the particles. Therefore, the experimenter no longer possesses any reliable means to reidentify the particles. As in the above-considered case of a non-ideal observer of two identical *classical* particles, the experimenter can sometimes make educated guesses based on prior knowledge. For example, in the extreme case where the electrons happen to be separated by a continent or a light-year, it is usually safe to assume that their putative 'interaction' is negligible, so that one can safely assume that the pre- and post-detections in the bubble chamber in a given lab are generated by the same electron. However, if one wishes to study a collision between two electrons, one cannot track the electrons during the collision phase itself, and abrupt changes in the electrons' tracks due to their interaction are to be expected, depriving the experimenter of any basis for such guesses.

III. PERSISTENCE AND NONPERSISTENCE OF IDENTICAL QUANTUM PARTICLES

As we have seen above, in an experiment to study the interaction of two identical quantum particles, reidentification is not, in general, possible. *Is one still justified in assuming that, during the interaction phase, there exist two individually persistent entities?* On the face of it, we do not seem to have latitude to do otherwise: having apparently posited particles at the ground-floor of our physical theories (classical and quantum mechanics), we seem to have committed ourselves to the idea that these particles are *unconditionally* persistent—persistent in *all* contexts.

Nevertheless, since we have lost any reliable means of reidentification while two electrons are interacting, and since this loss of capability is due to the confluence of two fundamental assumptions—the existence of identical particles in nature, and the active nature of quantum

measurements—the assumption of *individual persistence* during this interaction phase is metaphysically exposed. Ontological modesty beckons us to contemplate some way of conceiving what happens during the interaction phase which do not commit us to this assumption. Encouragement to do so comes in the form of numerous pivotal episodes in the history of physics where such contemplation, spurred by the awareness that certain fundamental assumptions appeared to lack empirical cover, bore fruit⁸.

But, if we wish to entertain a kind of context-dependent persistence, we seem to have no choice but to give up the idea of ‘particles’ as basic. Seemingly the only recourse is to *take the flashes themselves as basic*, and thus to regard the notion of particle as a *secondary* notion—as a conceptual device for threading a sequence of flashes, a device that is only applicable in certain experimental contexts.

This shift of ontological ground—away from *object*, towards *event*—affords the flexibility to construct two *different* object-models of the same flash-data (see Fig. 5). Consider an experiment in which two flashes are registered at t_1 and then later at t_2 , and let us refrain from specifying the experimental context (one may have two ‘particles’⁹ in a bubble chamber, two interacting ‘particles’, or some other context). The first model—the *persistence* model—is the familiar one: each flash is presumed to be the momentary appearance of a persistent object (‘particle’), which enables one to say that one of two possible *transitions*¹⁰ occurred unseen between times t_1 and t_2 (see Fig. 5a). That is, the persistence model gives us warrant to say that one of the flashes at t_2 was generated by *the same* entity as one of the flashes at t_1 .

However, a second model—the *nonpersistence* model—of the same flash-data is also possi-

⁸ Notable examples include the empirical inaccessibility of (i) the state of absolute rest (posited by Galileo, leading to his principle of relativity), (ii) the simultaneity of distant events (noted as conventional by Poincaré, leading to Einstein’s relativity of simultaneity), and (iii) the state of absolute non-rotation (noted by Mach, who proposed that rotation be viewed relative to the ‘fixed stars’, an idea exploited by Einstein in formulating his general theory of relativity).

⁹ Here and subsequently, scare quotes on the words *particle* or *particles* is a shorthand way of indicating that the word is being used in the customary manner that physicists talk, but that this is strictly speaking not correct in the given context since the validity of the assumption of individual persistence implicit in such language is—from this point onwards—regarded as contingent upon the object-model which is used to account for the observed detection-events.

¹⁰ Note that quantum theory does *not* give us warrant to say that the particles traversed specific paths between flashes.

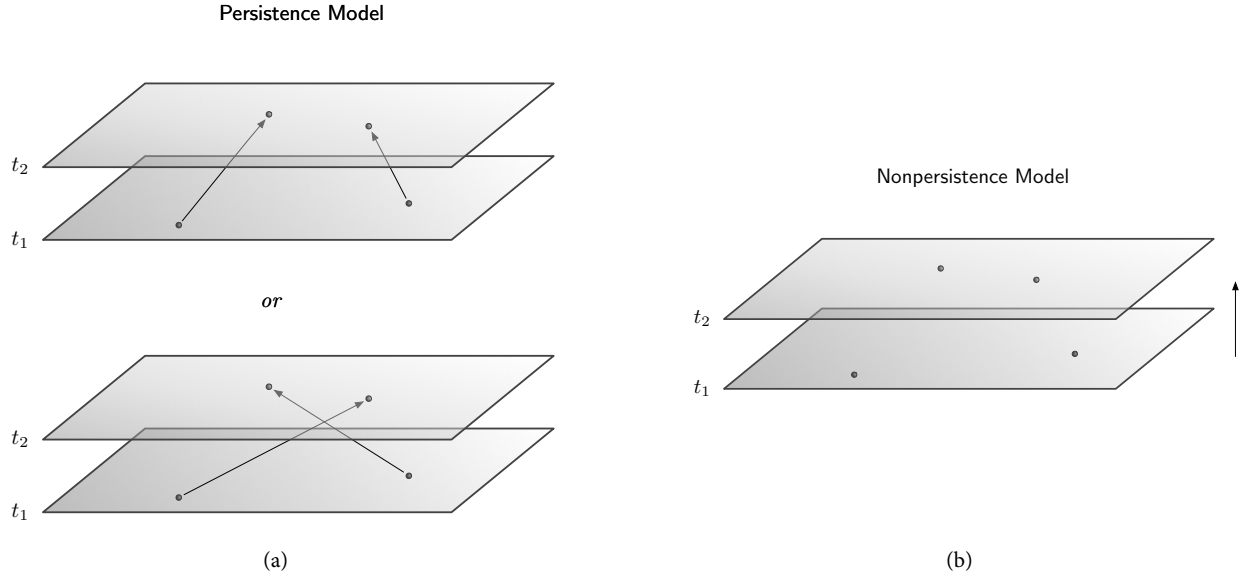


FIG. 5: *Persistence and nonpersistence models of flash-data.* Two flashes are registered at time t_1 and at time t_2 . Two different object-models of this data are possible. (a) The persistence model posits that each flash is the momentary appearance of a persistent object ('particle'). Hence, according to the persistence model, two possible transitions are compatible with the flash data, only one of which occurred. Note that an arrow connecting two flashes signifies only that the same particle is responsible for both of the flashes, not that the particle traversed a particular trajectory. (b) The nonpersistence model posits that both flashes at each time are the momentary appearance of a single holistic object. Hence, according to this model, there is but a single transition compatible with the flash data.

ble. In that model, one regards the two flashes at each time as the momentary appearance of a *single* persistent object (see Fig. 5b). What speaks against such a posit is our experience with everyday physical objects, which habituates us to believe that the location of physical objects coincides with the locations of their appearances. But, if we are prepared to set aside this aspect of mental conditioning and entertain a more abstract conception of physical object, we see that such a model indeed avoids positing the existence of individually persistent objects in contexts where this posit lacks empirical warrant. We remark that, from the perspective of the nonpersistence model, it would—strictly speaking—be incorrect to say 'the physical system *consists* of two particles', or to say 'two particles are interacting with each other', for such language implicitly presumes individual persistence.

Now, if it is the case—as suggested above—that the notion of particle is a presumption of

quantum theory, how could the nonpersistence model possibly be compatible with it? The answer is subtle: although the genesis of quantum theory *began* with such concrete models as Bohr’s model of an electron in a classical orbit around a proton, and Schroedinger’s equation for one and then many particles, the quantum formalism articulated by Dirac and von Neumann abstracts from this starting point to such an extent that the notion of particle *per se* is left behind. Thus, even though the particle notion is commonly used to *talk* about quantum models of microscopic systems, it is not integral to the abstract quantum formalism itself. In its stead is the notion of an abstract *physical system* which (as mentioned previously) persists for the duration of an experiment and retains its identity in spite of interactions with its environment. The quantum formalism also abstracts from the familiar idea of measurement. Whereas ‘measurement’ is typically visualized as an act performed by a spatially localized physical device which yields a correspondingly localized outcome, the quantum formalism treats measurement in an abstract manner which makes no reference to space. This allows for the possibility of a measurement outcome consisting of two (or more) flashes registered at separate (possibly widely-separated) locations at the same time. That is, these flashes can *collectively* be regarded as a *single* outcome of a measurement on a physical system¹¹.

A. Derivation of the quantum symmetrization algorithm for a system of identical particles

Above, we have proposed two quite different object-models of the same event-data. But how can one use *two* models of the same data to construct a predictive theory? In particular, while the persistence model effectively parses the data into ‘tracks’ underpinned by two persistent objects, the nonpersistence model offers no such analysis, and might well for this reason alone be dismissed as scientifically sterile in the sense of not providing the traction necessary to build up a predictive theory.

However, rather than attempting to build a theory on the basis of either model alone, perhaps it is possible to somehow *synthesize* them. But how it could it be possible to do so when these models are *inconsistent* in their posits as to the nature of the entity (or entities) that

¹¹ In applications of the standard quantum formalism—for example to a system consisting of a pair of nonidentical entangled particles—the notion of measurement is commonly handled in this more abstract manner.

underpin the data? The key point is that although the two models differ in the claims that they make about the nature of the entity (or entities) that exist in between the detections, these claims can, by their very nature, only be *indirectly* probed via experiment, for the experimenter actually *observes* detector clicks or flashes, not the posited entities in themselves. Thus, the data provides sufficient latitude to combine key features of *both* models into a predictive model.

In [18, 19], it is shown how these models can be mathematically synthesized. Here we re-strict summarize the main features of the derivation and their significance. The synthesis takes place in the context of the Feynman formulation of quantum theory¹², within which the persistence and nonpersistence models can readily be described (see Fig. 6). Specifically, in the persistence model, one treats the two flashes registered at t_1 as two distinct outcomes, each the manifestation of a measurement on a separate persistent subsystem. Accordingly, given the outcomes a and b registered at t_1 and the outcomes c and d registered at t_2 , two possible transitions could have occurred—the transition (which we shall arbitrarily call the *direct* transition) in which the same subsystem is responsible for outcomes a and c , and the *indirect* transition in which the same subsystem is responsible for outcomes a and d . And, following the Feynman formalism, one assigns an amplitude to each transition, namely α_{12} to the direct, α_{21} to the indirect. In contrast, in the nonpersistence model, one treats the two flashes registered at each time as a *single* outcome of a measurement performed on a physical system. Accordingly, there is but a single transition between the outcome at t_1 and the outcome at t_2 , which is assigned amplitude α .

The synthesis of these models is achieved through the *operational indistinguishability postulate* (OIP) which posits that $\alpha = H(\alpha_{12}, \alpha_{21})$, where H is some function to be determined. An analogous statement is posited for a three-stage experiment in which flashes are registered at *three* successive times.

One can motivate the OIP by the idea that the actual transition amplitude should incorporate *both* of the possible transitions posited in the persistence model, even though, according to the persistence model, only one such transition can occur. That is, the persistence model

¹² The Feynman formalism is described in [14], and is systematically derived and restated in an operational framework in [21].

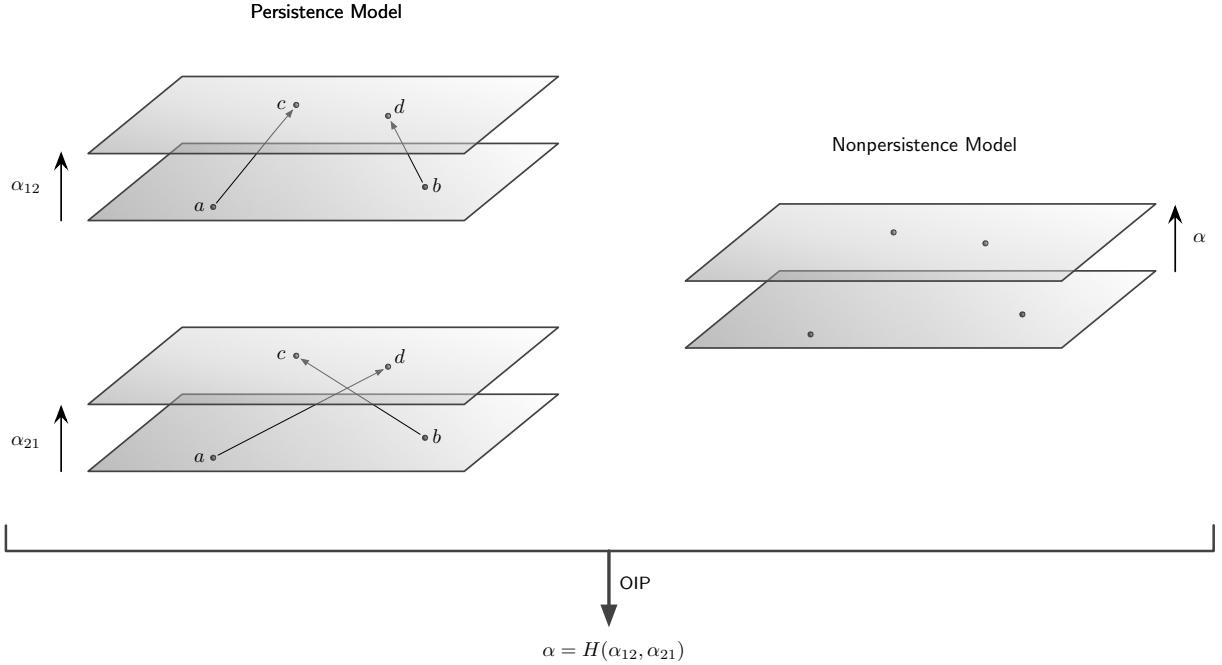


FIG. 6: *Synthesis of persistence and nonpersistence models.* An ideal experimenter registers two flashes at t_1 and two flashes at t_2 . Two models—a persistence model and a nonpersistence model—of this data are constructed, and are described in the Feynman formalism. (i) *Left:* according to the persistence model, two particle transitions compatible with the flash data. These transitions have amplitudes α_{12} and α_{21} . (ii) *Right:* in the nonpersistence model, the two flashes at each time constitute a single measurement outcome generated by a holistic object. Thus, according to this model, there is a single transition, whose amplitude is α . (iii) *Bottom:* The operational indistinguishability postulate (OIP) posits that the relation $\alpha = H(\alpha_{12}, \alpha_{21})$ holds between the amplitudes in this model, where H is a complex-valued function to be determined. In [18], it is shown that an isolation condition and the requirement of consistency imply that $H(\alpha_{12}, \alpha_{21}) = \alpha_{12} \pm \alpha_{21}$, with the sign corresponding to bosonic or fermionic behavior.

should not be taken as ‘carving nature at the joints’, but rather as an expedient way to analyse, and thus render tractable, the experimental data. In a more general context where we suspect that this model is not strictly valid, the idea is that rather than dispensing with the model entirely, one can move beyond it in a manner that is strictly speaking at odds with the assumption of individual persistence that underwrites it by mathematically *combining* the amplitudes of the two transitions that the model itself would deem mutually exclusive.

The form of the to-be-determined function H is importantly constrained in the following manner. We have already noted that, when isolated from one another in a bubble chamber, two

electrons *can* be reidentified, and one therefore has reasonable grounds to regard the bubbles in each ‘track’ as the manifestations of an individual persistent entity. This idea motivates the *isolation condition* which applies in the special case where one or more of the transition probabilities in the persistence model is zero. In the case of two separated electrons in a bubble chamber, this would mean that one does not need to consider the possibility that the two electrons surreptitiously ‘swap’ tracks. In this case, the isolation condition posits that the persistence model alone should be adequate—that is, it is correct to say that each flash on a given track is due to a persistent individual. This translates into a condition on H , namely $|H(z, 0)| = |z|$ and $|H(0, z)| = |z|$.

From the assumptions described above, the requirement of consistency fixes the form of H for two ‘particles’: $H(\alpha_{12}, \alpha_{21}) = \alpha_{12} \pm \alpha_{21}$, where the \pm sign corresponds to bosonic (+) and fermionic (−) behavior, which is Feynman’s symmetrization postulate. The derivation can also be extended to the more general case of N ‘particles’ [18]. As discussed in Sec. V, these results can be re-expressed in terms of quantum states to enable comparison to the quantum symmetrization procedure [18, 19].

IV. RELATION BETWEEN EVENTS AND OBJECTS IN THE MICROPHYSICAL REALM

In everyday perception, one usually moves seamlessly from the experience of sensations to thoughts about objects and their properties. Thus, one looks into the distance and says “I see a flock of seagulls just over the horizon”, not “I experience such-and-such pattern of colored patches in my visual field which I interpret as the momentary appearances of such-and-such persistent objects that bear such-and-such properties”. The same is true when one uses observations of *one* object to make inferences about *another* object, a device often employed in instances where the latter leaves a fleeting or negligible sensory impression. For example, if standing at the water’s edge one suddenly observes a vortex-like swirl forming on the surface of a lake, one might say that the wind is spinning it up even though the wind in ones vicinity is insensible.

We are wont to extend such inferences to the microscopic world. Thus, upon seeing a flash on a phosphorescent screen, one typically imagines that there is an object—an electron, say—

which, shortly after that flash, has the property of being located in the vicinity of where the flash was observed. Now, as we have discussed (§II B 1), physical experimentation must assume that inferences such as these are at least *sometimes* valid in order to get a handle on the microscopic world. However, as described above, when dealing with a system of identical ‘particles’, the object(s) that underpin the event-data are, in general, *relativized to a model*. Such relativization severs any straightforward link between an event (such as a click of a wire-loop detector) and statements about an underlying microscopic object.

For example, suppose one is dealing with a system conventionally described as one of ‘two interacting electrons’. Upon seeing two flashes due to the activation of two wire-loop detectors, one cannot *in general* say ‘two electrons were just detected, one here and one there’. This sentence holds true in the persistence model, but not in the nonpersistence model. According to the nonpersistence model, one should say ‘the system manifested an outcome consisting of two flashes, one here and one there’. And this mode of expression is the more general one, with the former only approximately valid in certain contexts¹³. One might be tempted to assert that the flashes are momentary objects, but the nonpersistence model would not license the attribution of anything other than position to such objects, so these objects would certainly not be the same as the *electrons* posited by the persistence model (which model licenses the attribution of time-independent properties such as mass and charge).

We emphasize that although the quantum model *synthesizes* the persistence and nonpersistence models, these models are not thereby rendered dispensable. Indeed, this is precisely the intended distinction between synthesis and unification¹⁴. In particular, the persistence model plays a vital role, not only (as we have seen) enabling measurement of the time-independent properties of ‘particles’, but as the point of connection to classical physics, which is needed in order to mathematically flesh out the quantum model of the system¹⁵. As a result, we seem

¹³ Quantitatively, the former is approximately valid in cases where either $|\alpha_{12}| \ll |\alpha_{21}|$ or $|\alpha_{12}| \gg |\alpha_{21}|$, so that $H(\alpha_{12}, \alpha_{21})$ is well-approximated by α_{12} or by α_{21} . In such cases, the quantum state of the system is well-approximated by a product state (see [19, §3.3])

¹⁴ The distinction between synthesis and unification is discussed in the context of Bohr’s notion of complementarity in [13].

¹⁵ For example, in the Dirac–von Neumann formalism, the quantum Hamiltonian of a system of two nonrelativistic structureless interacting quantum particles is obtained by mathematical transformation of the classical

fated to juggle between object-models, depending upon the experimental context. The only common ground between these models is the event-data.

To be clear: the events themselves are registered by objects (such a wire-loop detectors) which are unproblematically treated as individually persistent. Indeed, an entire set of persistent macroscopic objects (the laboratory walls; rulers and clocks) comprise a physical reference frame which enables one to say *where* and *when* such events occur. These persistent objects thus provide a *portal* through which we probe the microscopic realm.

However, since inferences from such events to statements about *microscopic objects and their properties* depend upon the object-model under consideration, and since *two* incompatible object-models are in general needed to understand the behavior of the physical system, it seems appropriate to regard the events as ontologically primary, and the microscopic objects referenced in such statements as secondary¹⁶.

V. REINTERPRETATION OF THE SYMMETRIZATION PROCEDURE

The point of departure for most interpretations of identical quantum particles is the mathematical procedure articulated by Dirac [11, 12] and Heisenberg [22]. In this section, we (i) describe the canonical understanding of the meaning of this procedure (Sec. V A), and summarize its difficulties (Sec. V B); (ii) discuss one difficulty encountered by the recent suggestion that the particle-label interpretation of indices in symmetrized states be dropped (Sec. V C); and (iii) outline a new interpretation of the symmetrization procedure based on the conception of identical quantum particles described herein (Sec. V D).

Since authors vary in what they take to be the exact content of the symmetrization procedure, we begin with a brief statement of the procedure, emphasizing details that are essential to its practical application.

mechanical Hamiltonian of two interacting point particles.

¹⁶ Quine has suggested taking events as primary based on consideration of identical particles [28, p. 498]. However, he implicitly retains the notion of individual persistence, which undermines the argument.

A. The quantum symmetrization algorithm

Consider a system of n identical particles. Construction of a physical model of this system takes place via a two-step procedure, to which we refer as the quantum symmetrization algorithm (QSA):

1. Set up the problem as if the particles were *nonidentical*, and solve for the possible states of the system, $\psi(x_1, x_2, \dots, x_n)$.
2. Now restrict consideration to:
 - (a) *Symmetrization Postulate (SP)*. States that are *symmetric* or *antisymmetric*, with the choice of symmetry to be determined by the type of particle under consideration; and
 - (b) *Symmetric Operator Constraint (SOC)*. Measurement operators (observables) that are *symmetric*.

In the first step, one obtains the set of possible states by setting up and solving the Schroedinger equation, where the Hamiltonian is typically based on the classical Hamiltonian of the system. The particles, being identical, have the same time-independent properties, so that the classical Hamiltonian, $H(x_1, p_1; x_2, p_2; \dots, x_n, p_n)$, is a symmetric function of the particles' time-dependent properties, $H(x_{\pi(1)}, p_{\pi(1)}; \dots, x_{\pi(n)}, p_{\pi(n)}) = H(x_1, p_1; \dots, x_n, p_n)$ for any permutation π . The quantum Hamiltonian obtained through application of the standard classical-quantum correspondence rules is accordingly symmetric in the measurement operators corresponding to these time-dependent properties. Hence, at this stage, particle identity is only reflected in the symmetry of the quantum Hamiltonian.

In the second step, the restriction to symmetric or antisymmetric states is known (after [25]) as the *symmetrization postulate (SP)*. The choice of symmetry type is determined by particle spin via the spin-statistics theorem (SS), which we do not regard as a component of the QSA itself. Many authors insist upon the restriction to symmetric measurement operators—to which we refer as the *symmetric operator constraint (SOC)*—but some allow non-symmetric measurement operators (for further discussion, see e.g. [2, Ch.5]).

The application of the QSA is guided by a meta-rule—to which we refer as the *no-overlap rule* (NR)—which posits that the second (symmetrization) step of the algorithm is unnecessary if the wavefunctions of the particles (as computed in step one) do not significantly overlap. In Dirac’s formulation, this rule was implicit in the user’s choice of system, but was subsequently made explicit (for example, by Schroedinger [34]).

B. Dirac’s interpretation: identical particles are ‘indistinguishable’ under interchange

Alongside his formal statement of his symmetrization procedure, Dirac offered an *interpretation*, namely that identical particles are ‘indistinguishable’, a notion he subsequently fleshed out in the assertion that there is ‘no observable change’ when any two identical particles are ‘interchanged’ (or swapped) [12, §62]. A recurring tendency in the interpretational literature is to conflate Dirac’s interpretation with his mathematical symmetrization procedure¹⁷. However, we must emphasize these are distinct: only the latter—understood as a *mathematical recipe* that can be reproducibly applied to physical situations of interest—has empirical warrant. Dirac’s interpretation itself faces a number of difficulties.

a. Symmetric operators are incompatible with reidentification. In articulating the notion of ‘indistinguishability’, Dirac makes use of the particular instance where two particles are ‘interchanged’. In terms of the discussion in Sec. II, this corresponds to the case where an experimenter only has access to the system of two electrons before and after the process of interchange, in which case we have seen that reidentification is indeed thwarted. However, the symmetric operator constraint (SOC) that follows as a consequence implies that reidentification is thwarted even if the experimenter has access to the system *during* the interchange process. Formally, given two states $\psi(x_1, x_2; t_1)$ and $\psi(x_1, x_2; t_2)$ of the system, the SOC implies that the experimenter cannot measure the position of ‘particle 1’ at times t_1 and t_2 since the operator x_1 is not symmetric.

¹⁷ A few illustrative quotes (which could be multiplied considerably): (i) “It is a fundamental principle of quantum mechanics that two particles of the same kind are absolutely indistinguishable.” [6]; (ii) “If there is any consensus as to what particle indistinguishability means, it is its formal expression in quantum mechanics: particles must have exactly the same mass, spin, and charge, and their states must be symmetrised, yielding either symmetric or antisymmetric wave-functions. This much was set in stone by Dirac almost a century ago.” [32, p.1].

b. State assignment is dependent upon the user's choice of 'system'. The no-overlap rule (NR) is essential to the application of the QSA, for it covers the situation of two electrons in separate laboratories (in separate electromagnetic traps) subject to their own experimental tests, in which case the NR gives each experimenter license to regard their electron independently from the other. The meta-rule is at odds with the symmetrization postulate (SP), but this tension is normally concealed in *applications* of the QSA as the *user* chooses the system—such as a helium atom or a box of ideal gas—to which to apply the algorithm, and in most practical circumstances the physically-meaningful choice is unambiguous. However, the tension becomes manifest if one considers two electrons confined to a chamber: if the chamber is originally chosen as the system of interest, the NR dictates that the QSA be applied, in which case the electrons are assigned an antisymmetric state. If the chamber is then suddenly opened, the electrons remain in an antisymmetric state since the state's symmetry is invariant under temporal evolution. However, after sufficient time, the two electrons would almost certainly be found widely separated. But, if that is the case, another prospective user of the QSA has reason to invoke the NR and ascribe a *product* state to the two electrons. These state assignments are formally inconsistent, as can be seen by comparing the reduced density matrices assigned to the electrons in the two instances.

C. Dropping the particle-label interpretation of indices

Throughout the QSA, the indices—in both states and operators—are interpreted as particle labels. However, as mentioned in the Introduction, it has recently been suggested that this interpretation be dropped [5, 9]. Amongst other things, this would open up the possibility of regarding symmetrized product-states such as $[\alpha(x_1)\beta(x_2) - \beta(x_1)\alpha(x_2)]/\sqrt{2}$ as describing two distinct electrons, one in state α and one in state β , rather than each in the same reduced state [9, 10].

However, it is unclear whether a consistent re-interpretation of these indices is possible. One unresolved difficulty is as follows. In step 1 of the QSA, one typically obtains the quantum Hamiltonian, \hat{H} , for a system from the corresponding classical Hamiltonian, H , via standard correspondence rules. At this step, the indices in \hat{H} are taken to be particle labels, inheriting

the interpretation of the labels in H . Now, dropping the particle-label interpretation entirely would undermine the physical justification of step 1. The other option would be to retain the particle-label interpretation in step 1, but to drop it at step 2. But what could be the *a priori* justification for *changing* the interpretation mid-stream? The re-interpretation of the QSA described below (Sec. V D) provides such a justification.

D. New interpretation of the QSA

Here we outline a new interpretation of the QSA based on the post-atomistic conception described herein. Further technical details (including generalization to more than two particles) and broader conceptual implications (for example, concerning identical particle entanglement) will be presented elsewhere.

As described in [18], the Feynman symmetrization postulate can be re-expressed in terms of quantum states. For two particles moving in one dimension,

$$\psi_{\text{ID}}(x_1, x_2) = \psi(x_1, x_2) \pm \psi(x_2, x_1) \quad x_1 \leq x_2. \quad (1)$$

Here, ψ_{ID} is the state of the system as described within the nonpersistence model, and is defined (and normalized) over reduced configuration space, $x_1 \leq x_2$. The function $\psi(x_1, x_2)$ describes the system in the persistence model and is defined over full configuration space, $(x_1, x_2) \in \mathbb{R}^2$.

Formal extension of ψ_{ID} into the full configuration space yields

$$\tilde{\psi}_{\text{ID}}(x_1, x_2) = \frac{1}{\sqrt{2}} [\psi(x_1, x_2) \pm \psi(x_2, x_1)], \quad (2)$$

where now (x_1, x_2) ranges over \mathbb{R}^2 . Formally, this equation is the same as the symmetrization postulate, but the object-duality interpretation gives it a new meaning: the symmetrization postulate is not *selection rule* that picks out allowed states (symmetric or antisymmetric states) within a single object-model, but rather as a *bridging relation* between two object-models. Although this state is permutation invariant, it is a *mathematical artefact* of the formal extension of ψ_{ID} to full configuration space, *not* (as widely asserted) a fundamental physical symmetry.

The meaning of the indices in the SP is obscured and muddled in Eq. (2), but can be seen clearly in Eq. (1): on the right-hand side of Eq. (1), they refer to individual particles; but, on the

left-hand side, they refer to *locations* of detection-events. Hence, in step 1 of the QSA, where one models a system in the persistence model (ignoring particle identity), the indices refer to individual particles; but in step 2, their meaning becomes model-dependent.

As mentioned in Sec. III, the reconstruction incorporates an isolation condition. In Eq. (1), when the isolation condition is satisfied, $\psi(x_2, x_1)$ can be neglected in comparison to $\psi(x_1, x_2)$, so that $\psi_{\text{ID}}(x_1, x_2)$ reduces to $\psi(x_1, x_2)$. Hence, there is no need to impose a non-overlap metarule (NR) from the outside. When the isolation condition is satisfied, the persistence model itself suffices—thus, the particle notion becomes applicable, and the indices refer to particles.

Finally, in view of this re-interpretation, the QSA's restriction to symmetric measurement operators (SOC) is unnecessary. For example, the operator x_1 applied to $\psi_{\text{ID}}(x_1, x_2)$ measures the location of the left-most detection:

$$\langle x_1 \rangle_{\text{RCS}} = \iint_{x_1 \leq x_2} x_1 |\psi_{\text{ID}}(x_1, x_2)|^2 dx_1 dx_2. \quad (3)$$

Similarly, the operator $(x_2 - x_1)$ yields the distance between the detections. When the isolation condition is satisfied, one can interpret the x_i as *particle* labels, in which case x_1 measures the location of the leftmost particle, and $(x_2 - x_1)$ the distance between them.

VI. CONCLUDING REMARKS

We have presented a post-atomistic conception of systems of identical quantum particles in which detection events are ontologically primary, and particles (as persistent entities) are a secondary or emergent notion. The need for such a radical departure from the atomistic conception originates in the confluence of two basic facts—(i) the existence of particles that are *entirely alike* in their intrinsic properties (in contrast to the objects of everyday experience); and (ii) the *active* nature of the quantum measurement process (in contrast to the nondisturbing—or sight-like—nature of classical measurement). This confluence thwarts particle reidentification during interactions, which in turn deprives of empirical cover the assumption that particles persist during interaction. This motivates the shift of ontological focus from particles to detection events.

This shift opens up the space to contemplate two distinct object-models of the same event-data, which provide sufficient flexibility to accommodate both approximate reidentification and the richer holistic behavior described by the symmetrization postulate. This object-model duality may be regarded as providing Schroedinger’s notion of ‘restricted individuality’ [34, §11]—or related notions such as Bigaj’s weak transtemporal identity [1, §5]—with a clear conceptual foundation. Table III contrasts the proposed conception with our understanding of physical objects derived from everyday experience and/or classical physics.

We have also outlined a new interpretation of the QSA, now understood as a consequence of model synthesis *not* particle indistinguishability. This gives precise physical meaning to the indices in symmetrized states, which thereby substantiates concerns previously raised about the metaphysics implicit in such labels [29, 30], as well as supporting more recent proposals that the particle-label interpretation of indices in symmetrized states be revised [5, 9, 10]. The interpretation also gives an explicit physical meaning to non-symmetric measurement operators, thereby addressing an issue that is pivotal to property-assignment in identical particle systems (e.g. [2, §5.1]).

We conclude with a few open questions.

First, the conception advanced herein privileges microphysical events over microscopic objects. But, unlike the event ontologies of, say, Russell [31] and Whitehead [37], it does not extend that privilege into the macroscopic realm, since persistent and reidentifiable macroscopic objects (rods and clocks) are operationally necessary for the space-time coordination of microphysical events (Sec. IV)¹⁸. But should one regard this macro/micro distinction as fundamental or merely a consequence of the contingent fact that we need a framework of persistent objects in order to learn about microphysical reality?

Second, the holistic object posited by the nonpersistence model confers a new kind of holism to a system of identical particles. How does that holism relate to, or differ from, that which is often attributed to systems of entangled nonidentical particles (e.g. [23, 27, 33])? Perhaps identical particle holism is an instance of object holism, while entanglement of nonidentical

¹⁸ These operational considerations echo Strawson’s arguments that reidentifiable objects are a precondition for linguistic reference [36, I.1.2].

particles is (as suggested in [27]) an instance of property holism. If so, how do these two flavors of holism combine in the context of a system of entangled identical particles?

| Characteristic of everyday and/or classical physical objects | Revision in light of proposed dual object-model interpretation of identical quantum particles |
|--|---|
| Objects exist independently of observation and physical context. | Due to object-model duality, identical ‘particles’ do not, in general, exist at the same level as persistent macroscopic objects. |
| Objects exist continuously (‘persist’) between observations. | Both the persistence and nonpersistence models posit that their respective object(s) persist. But they differ in the object(s) that they posit as underpinning the detection-events. |
| A unique object underpins a sensory appearance. In classical mechanics, each point-like event (flash) corresponds to a particle. | In the microscopic realm, the events generated by a system of identical ‘particles’ in general require a duality of object-models for their description. So a flash does not in general correspond to a unique object, and is therefore not the ‘appearance’ of a microphysical object. |
| Objects are ontologically primary, events are secondary. | Due to object-model duality, microscopic events (flashes) cannot generally be attributed to a unique object. Consequently, microscopic events are ontologically primary and microphysical objects secondary. Persistent macroscopic objects are presumed as they are needed for the spacetime coordination of events. |
| There are many objects (as many as there are localized appearances). | The persistence model posits many individually persistent identical objects. But the nonpersistence model posits a single holistic object per type of elementary ‘particle’. |
| An object momentarily exists in space just where it momentarily appears. | The holistic object posited by the nonpersistence model manifests as many distinct flashes, which may be widely separated. Such objects are appropriate when the individually persistent objects posited as underlying the separate flashes are not reidentifiable in principle. |
| An object is composed of elementary particles, which underpin its existence. | Microscopic composites (such as multi-electronic atoms) require that a holistic object (posited by the nonpersistence model) be taken into account. Thus, they contain elementary ‘particles’ <i>potentially</i> , not <i>actually</i> . The formation of a composite from identical particles involves emergence of a holistic object. |

TABLE III: Nature of physical objects in light of interpretation of identical quantum particles.

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