The ontology of quantum fields: entity and quality

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Speculations from God's position are illusory; we have no access to that position. Ontology concerns not with what exist as God ordains but with what exist as intelligible within the bounds of human understanding. It calls for analyzing not only nature but also the characteristics of our own thinking that make possible analysis and knowledge of nature, so that we do not inadvertently attribute our conceptual contributions to what exist naturally.

According to quantum field theory, the ontology of the universe is a set of interacting fields. How is it possible that the quantum fields, strange and remote as they are, become intelligible topics of scientific knowledge? What general concepts have we presupposed in talking about them?

The organizational outline of this conference suggests a theme of quantum field theory as a language or formal framework for fundamental theories in modern physics. This language, which enables us to talk about and study the subatomic world, is highly successful. Language philosophers have dug into many ontological presuppositions over the past decades. This interdisciplinary conference is a good place to build bridges between their results and the interpretations of quantum field theories. Among linguistic concepts, reference is closest to ontology; language meets reality when we refer to things. Let us examine two theories of reference and their relation to two basic ontologies in quantum field theory: individual entities and conjunctions of qualities. Specifically, we examine the concepts by which we individuate, identify, and describe entities within a field. The concepts of individual entity also imply an interpretation of spacetime in quantum field theory.

Entities and conjunctions of qualities

Entities constitute the prominent ontology of commonsense and most sciences. An entity is an individual with its distinct identity that assimilates its parts and persists through changes of its properties. Persons and planets are entities, so are cells and electrons and most things solid. Fluids and gases constitute the rival ontology of substance. However, we often make entities out of them, as in glasses of water or tanks of gas.

Fields are intangible and problematic for the ontology of entities. Modern physics discovers that the basic building blocks of the universe are a set of interacting quantum fields: matter fields such as the electron and quark fields, and interaction fields such as the electromagnetic and the gluon fields. Does a field, which is a continuum, consist of entities? Physicists talk about "particles" in quantum fields, but these turn out to be chunks of energy in field excitation, not entities but conjunctions of qualities without distinctive identities.

The ontology of conjunctions of qualities finds its foremost champions in empiricist philosophers. Sense impressions of colors and shapes, fundamental to empiricism, are conjunctions of qualities. Some empiricists argue that they should replace entities as the basic ontology. A few go further to deny the existence of entities. With the linguistic turn in philosophy, language and logic replace experiences as bases of argument. A battle joins between two theories of reference: direct and descriptive reference. The ontology of entities supports both, with gives primacy to direct reference. The ontology of conjunctions of qualities allows only descriptive reference.

The most common form of discourse is the subject-predicate proposition, and the most common subjects are entities. We pick out an entity as the subject and then describe it by some predicate, as in "Brutus was honorable." How do we pick out the subject of discourse? There are two general methods, *direct* reference as in "Brutus" and *descriptive* reference as in "Caesar's assassinator." Both methods are familiar. In most situations, however, descriptive reference depends on direct reference.

Two ontologies and theories of reference

	Individual entity	Conjunction of qualities
Examples	apple, atom, star, particles, wavepackets, local fields in quantum field theory.	quanta of field excitation: – bosons: no criterion of uniqueness, – fermions: Pauli exclusion principle.
Presuppositions	*kind* or *sortal concept*: differentiating criteria; *numerical identity*: uniqueness; *possibilities*: its properties can change.	*kind* or *sortal concept;* uniqueness is optional if possible.
Reference	direct and descriptive reference.	descriptive reference.
Representation	singular term and existential quantifier; index, independent variable. e.g., Goethe, x in $f(x)$	$\exists xFx$ without support of singular term, inverse function. author of *Faust*, $f^{-1}(y)$

Presuppositions in the ontology of entities

In direct reference, we use a singular term *a* to pick out the subject, often without mentioning its properties. Singular terms include proper names such as Brutus or electron 1, pronouns such she or it, and common nouns preceded by a definite article, such as *the* man or *this* molecule. In mathematical theories, singular terms are specific values of indices or independent variables of functions, e.g., values of i in p_i or values of x in $f(x)$.

Useful as it is, direct reference is philosophically controversial. It presupposes the ontology of entities. Talks about entities involve a rather complicated conceptual framework, which irritates philosophers because it is difficult to account for in predicate logic. In referring directly to an entity by a singular term, we have presupposed at least three general concepts: its numerical identity, its possible properties, and its kind.

The first general concept presupposed by the ontology of entities is *numerical identity*. Mary and Jane are identical twins who share all properties, but each has her numerical identity and is thereby distinct from her sister. Each name refers to a specific sister. Numerical identity is expressed by the singular term as a *rigid designator*, as Saul Kripke called it. It rigidly designates the same individual in different possible situations. "Mary" designates the same girl in a possible world where she is the only child.

The notion of *possibility* is important because things usually change over time, but we refer to the same thing even as it assumes different properties. However, the range of possible situations where a rigid designator works is limited. A car retains its identity through replacements of many parts, but ceases to exist when it is crunched into a cube of scrapped metal. The numerical identity of an entity is not absolute but *relative to a kind* of thing. This is apparent in talks about "this car" or "that man."

Many kinds exist. They can be divided into two general classes, kinds of thing and kinds of stuff. Stuff such as water or gold is undifferentiated. In contrast, things such apples and oranges are already individuated by their kind concepts. When we say apple, we have already presupposed some criteria of what counts as *one* apple. The criteria of differentiation constitute what Locke called *sortal concept* for apples. When we refer directly to an entity, we have tacitly assumed that the entity belongs to a kind of thing; hence, we have presupposed some sortal concepts.

Together the three general concepts, numerical identity, possibility, and kind constitute the concept of individual entities. They are what Aristotle called "basic substances" or "being-qua-being," this-something. In less imposing terminology, they are simply what we ordinarily call *things* and refer to directly in our everyday speech. Individual entities also occur in physical theories, for instance the particles and wavepackets in quantum mechanics and the local fields in quantum field theory. I will return shortly to show how the concepts of identity, possibility, and kind contribute to the representation of local fields.

Descriptive reference

Besides singular terms, we can also refer to things via descriptions. When the police puts out a bulletin for the bank robbers and the teacher asks about the highest peak on earth, they want whoever or whatever that fit the description. Most descriptive references subscribe to the ontology of entities, which people tacitly assume to be the objects of descriptions. To ensure specificity of reference, most descriptions utilize some direct reference, as to a particular bank or to the planet earth.

In mathematical theories, descriptive reference is facilitated by inverse functions. Mathematical functions play many roles in science, one of which is the subject-predicate proposition. When a function $f(x) = y$ serves this role, the independent or indexical variable x picks out various values within its range. To each value of x, which represents a subject, the function follows a rule in assigning a unique value of its dependent or dynamical variable y as the predicate. This is a case of direct reference. Descriptive reference inverts the process. The inverse function $f^1(y)$ takes a predicate and maps it into all subjects that satisfy the rule of assignment. Notice that the map from x to y is one to one, but the inverse map from y to x is one to many. This is intuitive; a thing has a definite property, but a quality can be possessed by many things. This apple is red, but redness is instantiated in many apples and other things. In short, descriptive reference is cruder than direct reference.

Direct reference is common in mechanics, descriptive reference in statistical mechanics and probability theories. Mechanics studies the velocities of individual particles. Statistical mechanics studies the number of particles with certain velocities. It is coarser grained.

Descriptive reference fits well in predicate logic. The basic form of proposition is $\exists xFx$, where x is the existential variable and F a predicate, e.g., "There is x and x is Caesar's assassinator." If Caesar was assassinated by several conspirators, x rounds them all up. Predicate logic also provides for direct reference in the form Fa, where a is a singular term, as in "Brutus is Caesar's assassinator." With the support of singular terms, the existential variable refers to entities with no difficulty.

Willard Quine advocated a regimented language that eliminates singular terms and direct reference, relying on pure descriptions. Peter Strawson rightly pointed out that shorn off the support of singular terms, pure descriptive propositions assert not "this entity has these qualities" but only "these qualities are instantiated." Quine happily banished entities and individuals from his ontology, which contains only conjunctions of qualities.

The ontology of conjunctions of qualities is attractive because of its conceptual simplicity. It dispenses with the concepts of possibility and numerical identity that are required for the ontology of entities. It is impossible for a conjunction of qualities to change qualities, for that would be a different conjunction. Pure qualitative descriptions cannot differentiate numerical identities. Redness is a universal, and "two rednesses" is meaningless.

Each quality can has many instances. If we want to specify a single referent by descriptive reference, we must add an explicit qualification to assert that its referent is unique: $\exists xFx(\forall y(Fy \leftrightarrow y \equiv x))$, "$x$ is F, and for all y, y is F if and only if y is identical to x." Of course, whether the uniqueness stipulation is valid depends on the predicate F and the structure of the real world. Quine suggested that we find a unique predicate for every thing. That prodigious extravagance in substance concepts is a heavy price to pay for economizing on two general concepts. More important, even if he was willing to pay, the structure of the real world may not allow it.

Quanta of field excitation

There are conjunctions of qualities without numerical identities. Examples are the quanta of field excitation in the number representation of quantum field theory. Although often called a "particle," a field quantum – a quantum of excitation in a field – is not a particle in the ordinary sense of being similar to a tiny pebble, which is an individual with its numerical identity. It is just a chunk of energy satisfying the field's dispersion relation, $h\omega_k$, where *k* stands for the wavevector, spin, and other relevant quantum numbers. These quantum numbers are the definite predicates for the states of the field quanta, by which we refer to various field quanta.

A value of the dispersion relation is a predicate that can apply to many field quanta. If we need to distinguish one field quantum from another, we need to add explicit uniqueness criteria. Such criteria are sometimes available. Notable examples are the quanta for fermion fields such as the electron field. Here the Pauli Exclusion Principle asserts that no two quanta can be in the same state. With this additional principle, description succeeds to refer to a single quantum. The success, however, is qualified. Quanta of excitation are clearly defined only in free fields. When fields interact, as they must, field quanta become dubious.

Even for free fields, uniqueness criteria are not always available. This is the case for boson fields such as the electromagnetic field. Here the field quantum is the photon and a value of the dispersion relation specifies a photon's state. Many photons can share the same state. We call a laser beam coherent, because it consists of zillions of photons all in the same state. Thus, we can tell *how many* photons there are in a coherent state, but we cannot distinguish one photon from another. The case of photons shows limit to the discriminative power of descriptive reference.

By putting the whole burden of ontology on the sortal concept, descriptive reference accentuates the importance of the criterion of differentiation. Unfortunately, even in field theories, where we are dealing with only a few kinds of thing, sortal concepts alone are insufficient to guarantee the uniqueness of reference. The situation becomes far more desperate when we consider the infinite diversity of things that the elementary fields can combine into.

In complicated circumstances, advocates of descriptive reference sneak in another notion to secure the uniqueness of entities, space or spacetime region. Instead of a particular rabbit, Quine talked about the particular space region where the predicate rabbithood is instantiated. With that, he quietly changed the ontology by adding a spatial substance underneath the conjunction of qualities. Instead of being merely the value of a variable, he switched to the traditional pincushion model where qualities are like pins that stick on to a bare substance or an empty space region.

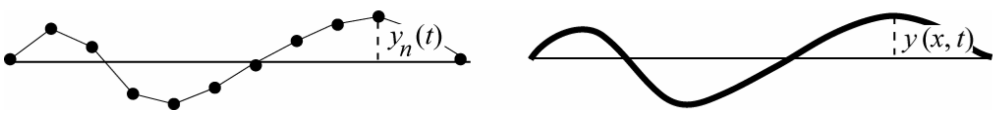
Now we come to the interesting question. What is the ontological status of space or spacetime regions? What quality does an empty space region have that differentiates it from other regions? When the question is taken seriously, we see that the conceptual simplicity of descriptive reference is deceptive. For with space regions, it smuggles back the concept of numerical identity that it claims to discard. This is best seen in the concrete case of field theories, where spacetime is treated explicitly.

Fields and quantum field theory

Most physical theories distinguish between dependent and independent variables, or dynamical and indexical variables. The roles and interpretations of the two variables are always different.

In classical and quantum mechanics that address the motions of individual planets and particles, position is a dynamical variable whereas time is the only indexical variable. Few people regard time as a substance, a kind of river in which matters flow. Time is absolute and objective because mechanics describe dynamical processes and processes are inherently temporal. A process is temporally extended and composed of many stages, which are indexed by the temporal parameter. In other words, the process has an intrinsic temporal structure.

A big change in field theories is that position changes from a dynamical variable to the same status as time. The change closely relates to the characteristics of fields. To see the significance of position as indexical, let us start from a composite system that is not a field.



The position y is a dynamical variable, but the spatial variable x serves the same role as the index n.

Imagine the vertical oscillation of N identical beads attached at various positions to an inelastic weightless thread whose ends are fixed. We index the beads by integers $n = 1, 2 \ldots N$. The temporal variation of the nth bead's vertical displacement from its equilibrium position is represented by the dynamical variable $y_n(t)$. The entire string of beads is described by N coupled equations of motion for the $y_n(t)$'s, taking into account the tension of the thread and the masses of the beads.

Now imagine that the number of beads N increases but their individual mass m decreases so that the product mN remains constant. As N increases without bound, the beads are squashed together, and in the limit we obtain an inelastic string with a continuous and uniform mass distribution. Instead of using integers n which parametrize the beads, we use as index real numbers x, $0 \leq x \leq L$ for a string of length L. Instead of $y_n(t)$, the dynamics of the string is characterized by $y(x, t)$, called the *displacement field* of the string.

In $y(x, t)$ we have two positional variables that are categorically different. The vertical position y is a dynamical variable. The horizontal x is an indexical variable with the same status as n. A particular value of x designates a specific point *on the string*, just as a value of n designates a specific bead. Note that x a spatial index but not an index of space points in which the string sit; it remains fixed when the string moves spatially. We can theoretically abstract the characteristics of variable x and say it is a one-dimensional continuum satisfying Dedekin's notion of completeness, but this theoretical continuum represents only a structural aspect of the string and not an independent entity that can be torn out of the string.

Generally, a field $\psi(x)$ is a dynamical variable for a continuous system parameterized by one or more continuous variables, usually spatial and temporal, which I summarily call x. The field dynamical variable ψ, on the other hand, is usually *not* spatial; the displacement field is an exception. What changes may be electric field strength or quantum phase.

Consider Dirac's equation for the free electron field:

$$\{i\text{h}\gamma^{\mu}\,\partial/\partial x^{\mu} - mc\}\ \psi(x) = 0.$$

It contains four kinds of term:

Indexical variable	x	spatiotemporal parameter with components (x^0, x^1, x^2, x^3)
Dynamical variable	$\psi(x)$	local field operator representing the electron field
Differential operator	$\partial/\partial x^{\mu}$	change of ψ with respect to μth component of x
Constants	h, m, c, γ^{μ}	Planck's constant, mass of electron, speed of light, Dirac matrices

The differential operator, which relates the dynamical variable for various x, is paramount in cementing various local fields into an integral electron field, but its complex function is beyond the scope of this talk.

The two variables x and ψ are the chief ontological concepts for the electron field. How do we interpret them separately? In other words, how do we analyze the electron field into smaller entities? I will consider two general approaches, which I call the horizontal and vertical analysis.

The pincushion model of fields

"Horizontal" analysis decompose a physical field into two layers, which we separately refer to by the variables x and ψ. x is the bare substantival spacetime and ψ an energetic coating, probably in the form of quanta of excitation. The two layers are related explicitly by "supporting" or "containing." This horizontal analysis is crude. To know more about the structure of the field, we need to analyze each layer further into smaller entities and to find criteria for matching them up. The second analytic step breaks the spacetime substance into many points or tiny regions, each of which is a bare particular. Thus we get the pincushion model of entity, where an entity consists of two parts, a cushion that is a bare particular, on which stick various pins that are its qualities.

Bare particulars are entities stripped of all features and qualities. They are some kind of basic substance in traditional philosophy. In field theories, they become empty spacetime points or regions. The notion of bare particulars has been under criticism for centuries, for its proponents can give no account of how to individuate them or refer to them. Many arguments in the philosophy of spacetime show that bare spacetime allows no criterion of differentiation because there is no way to mark the boundaries. Ordinarily, we differentiate spacetime regions by the material features in them. Devoid of matter, this differentiation fails.

Suppose we ignore the problem of differentiation and assert by brute force that there are bare particulars or empty spacetime regions. How do we refer to them? We cannot refer to them descriptively, because they are all identically featureless. If we refer to them at all, we must do so directly, which means that we have presupposed the notion of numerical identity. Actually, the whole purpose of the bare spacetime regions is to perform the job of the concept of numerical identity, for it works on the intuition that no two things can be in the same space at the same time. Instead of simply acknowledge the concept that we use in thinking, it does the job of identification by the heavy ontological machinery of positing a distinctive substance. Ontology does not come free; it demands concepts for representation.

The pincushion model breaks up an ordinary entity with identity and qualities into two entities, the cushion and the pins. Then it assigns the numerical identity to the cushion and the qualities to the pins. The results are two distinct kinds of entity. Entities of one kind have numerical identities but no quality; entities of the other kind have qualities but no identity. We refer to them by two distinct methods, one directly and the other descriptively, and hope that somehow they match to each other. I can find no explanation of how the marriage works. We do not have enough concepts to handle the extravagant ontology.

Local symmetry and local fields

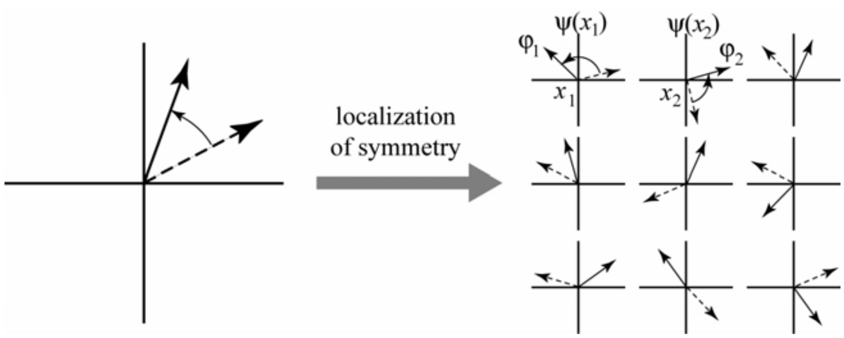
We can get a more parsimonious ontology by analyzing the field "vertically." Realizing that we need several general concepts to refer to entities directly, we interpret the operator $\psi(x)$ as the two-pronged variable for a single kind of entity, local field. Local fields are particular individuals represented by two general concepts, numerical identity represented by x and possible properties represented by ψ. We refer to the local fields directly via the variable x and describe each individual referred to by the predicate ψ. This interpretation agrees with the usual saying that x is the independent variable in the equation and ψ the dependent variable. Together $\psi(x)$ represents a single set of entities, the local fields. The electron field is a dynamical system consisting of infinitely many dynamical local fields, each identified by a value of the spatio-temporal parameter x and is a particular individual. That is it. We need not go further and decompose a local field into a cushion and its pins. We cannot; the decomposition requires more concepts that we have.

Earlier I said that direct reference presupposes three general concepts, numerical identity, possibility, and the sortal concept of a kind of thing. In field theory, the numerical identities of the local fields are represented by the spatio-temporal variable x. The other two concepts, possibility and kind, are combined in the notion of the state space.

A common way in physics to delineate a *kind* of system is to find its *state space* that encompasses all *possible* states or all *possible* properties that systems of that kind can assume. State spaces are not physical spaces but mathematical structures or sets of mathematical entities endowed with certain structures. A state space not only contains a set of possible states but also includes the relations among the states.

A fundamental characteristic of a field is its symmetry. A symmetry characterizes features that are invariant under a group of transformations. For example, a square is unchanged by rotation through 90, 180, 270, and 360 degrees, and by reflection about its bisectors and diagonals. These transformations define the symmetry of a square. Symmetry is a way to describe properties objectively. By excluding anything that changes in the transformations, it erases extraneous elements in ordinary descriptions, e.g., labels on the four corners of the square. Various quantum fields have various symmetries, mathematically characterized by various symmetry groups: e.g. the unitary group $U(1)$ of the electromagnetic interaction or the group $SU(3)$ for the strong interaction. A symmetry group consists of a set of transformations with certain mathematical structures. To say that a field has a certain symmetry means that its state space has features that remain invariant under all transformations in the symmetry group.

In global symmetry, a symmetry transformation applies across the whole field, which implies that the field is characterized by a single state space. Gauge field theory localizes the symmetry group to each point in the field by allowing transformations at a point to proceed independently of transformations in other points. Consequently, each point in the electron field is represented by its state space disjoint from the state spaces at other points. Endowed with its own numerical identity represented by x and its private state space to represent its dynamical properties ψ, it becomes a genuine entity, a local field $\psi(x)$.



To see the ontological significance of the localization of symmetry, remember that the electron field as a whole spans the universe, and we want to analyze it into a set of local fields to which we can individually refer. All these local fields should belong to the same kind; they are all electron local fields, as distinct from quark local fields, with which they will interact. The symmetry group is the characteristic of the electron field as a whole. It also serves as the sortal concept or kind concept that individuates the electron local fields. The state spaces of the local fields are all mirror images of the same symmetry group $U(1)$, therefore the local fields all belong to the same kind. Because the localized state spaces are all disjoint from each other, the extend of one local state space becomes the sortal criterion of what counts as one local field. Thus the localization of symmetry explicitly demonstrates the operation of the sortal concept in individuation.

When we talk about a particular electron local field, $\psi(x_1)$, we acknowledge its kind by the structure of its state space. To distinguish it from other local fields with identical state spaces, we have its numerical identity x_1. Under a particular set of boundary conditions, the electron field is in a particular state, which means that each of its local fields realizes a particular state out of all possibilities in its state space. For instance, the local field $\psi(x_1)$ realizes the state φ_1. Its neighbor $\psi(x_2)$ realizes another possible state φ_2. The relations among the realized states of various local fields are governed by the field equation. The realized states of all local fields constitute the actual state of the electron field as a whole. Because $x = (x^0, x^1, x^2, x^3)$ is a four-dimensional variable, each local field $\psi(x)$ is an instantaneous "event." If we fix the spatial components and vary time x^0, then $\psi(x^0, x^1{}_1, x^2{}_1, x^3{}_1)$ represents the temporal change at a specific spatial location of the electron field according to the field equation.

The local field $\psi(x_1)$ realizes another of its possible states under another set of boundary conditions. Nevertheless, although the realized state φ_1 is different, the spatio-temporal parameter x remains the same. The value x_1 continues to be the identity of the same local field $\psi(x_1)$, no matter what state it realizes. This is because the differential operator operates on the field state ψ but not on the variable x. This is the difference between indexical and dynamical variables.

Of course, the four components of x are not arbitrary but exhibit certain structure. In quantum fields, this structure is the Minkowski spacetime of special relativity. As the spatio-temporal relation among the numerical identities of local fields, it is a substructure of the electron field but is not dynamical, not unlike the architecture of a building. We can mathematically abstract it from the field structure, just as we can examine the architecture abstractly in blueprints. However, we cannot physically yank it out of the field as an empty substance that exists independently of matter, just as we cannot physically yank the architecture out of a building as an independent substance. The field ontology consists of only local fields with their spatio-temporal identities.

Linguistically, the spatio-temporal variable x has the same function as the pronoun *it*. *It* refers to different things in different contexts, but in a fixed context, it works like a name that designates a particular thing. In ordinary language, the context is fixed by the circumstance of discourse. In field theories, we can fix the context by choosing a particular coordinate system, which assigns a set of four numbers to each value of x as its coordinates. The coordinates of x_1 function as the name for the local field $\psi(x_1)$. Names are tags, and we can tag the local fields because their concepts include the numerical identity as the "bulletin board" without which the tags would not stick. Furthermore, the names are rigid designators, as Kripke argued. They rigidly designate the same local fields through all possible worlds relevant to the electron field. Thus, quantum field theory lays out clearly the concepts by which we directly refer to individual entities.

Summary

To sum up, ontological discussions depend heavily on the concepts that we have presupposed when talking about what there are. Research on reference has shown that there is no conceptual free lunch. Descriptive reference is conceptually simpler. It requires only one general concept, that of a kind or sortal concept, for instance the dispersion relation of the excitation of field quanta. The simplicity restricts the ontology of descriptive reference to conjunctions of qualities. The bundle ontology is too simplistic for field theory, for which the number representation alone is not sufficient. Furthermore, for many bundles, for instance the quanta of boson fields, it fails to individuate the bundles uniquely. To account for the uniqueness of reference, many philosophers sneak in the notion of bare particular or empty spacetime regions. The move spoils conceptual simplicity without saving descriptive reference, because the featureless spacetime regions cannot be picked out by descriptions. Conclusion: we need more general concepts for an ontology with particular entities to which can individually refer.

The theory of direct reference shows that to refer to individual entities, we need the combination of three general concepts: numerical identity, possibility, and kind. All three concepts appear in quantum field theory to represent the local fields: numerical identity in the spatio-temporal parameter, kind and possibility in the symmetry group space localized to each point in the field. They show that to talk about concrete particular to which we can individually refer, we need the triplex of concepts. We should not carelessly multiply ontology to create mysterious substances simply to mirror the concepts that we use. More specifically, just because in talking about concrete particulars we have used the concept of numerical identity, we need not posit bare particulars or empty spacetime regions to answer for the concept. If we do, we will find ourselves at a loss to show how we individuate and refer to those empty spacetime regions. In short, what there are do not mirror what concepts we use to think about them.

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