"What is real?"

By Meinard Kuhlmann from *Scientific American* (August 2013)

Physicists speak of the world as being made of particles and force fields, but it is not at all clear what particles and force fields actually are in the quantum realm. The world may instead consist of bundles of properties, such as color and shape Physicists routinely describe the universe as being made of tiny subatomic particles that push and pull on one another by means of force fields. They call their subject “particle physics” and their instruments “particle accelerators.” They hew to a Lego-like model of the world. But this view sweeps a little-known fact under the rug: the particle interpretation of quantum physics, as well as the field interpretation, stretches our conventional notions of “particle” and “field” to such an extent that ever more people think the world might be made of something else entirely.

The problem is not that physicists lack a valid theory of the subatomic realm. They do have one: it is called quantum field theory. Theorists developed it between the late 1920s and early 1950s by merging the earlier theory of quantum mechanics with Einstein’s special theory of relativity. Quantum field theory provides the conceptual underpinnings of the Standard Model of particle physics, which describes the fundamental building blocks of matter and their interactions in one common framework. In terms of empirical precision, it is the most successful theory in the history of science. Physicists use it every day to calculate the aftermath of particle collisions, the synthesis of matter in the big bang, the extreme conditions inside atomic nuclei, and much besides.

So it may come as a surprise that physicists are not even sure what the theory says—what its “ontology,” or basic physical picture, is. This confusion is separate from the much discussed mysteries of quantum mechanics, such as whether a cat in a sealed box can be both alive and dead at the same time. The unsettled interpretation of quantum field theory is hobbling progress toward probing whatever physics lies beyond the Standard Model, such as string theory. It is perilous to formulate a new theory when we do not understand the theory we already have.

At first glance, the content of the Standard Model appears obvious. It consists, first, of groups of elementary particles, such as quarks and electrons, and, second, of four types of force fields, which mediate the interactions among those particles. This picture appears on classroom walls and in Scientific American articles. However compelling it might appear, it is not at all satisfactory.

For starters, the two categories blur together. Quantum field theory assigns a field to each type of elementary particle, so there is an electron field as surely as there is an electron. At the same time, the force fields are quantized rather than continuous, which gives rise to particles such as the photon. So the distinction between particles and fields appears to be artificial, and physicists often speak as if one or the other is more fundamental. Debate has swirled over this point—over whether quantum field theory is ultimately about particles or about fields. It started as a battle of titans, with eminent physicists and philosophers on both sides. Even today both concepts are still in use for illustrative purposes, although most physicists would admit that the classical conceptions do not match what the theory says. If the mental images conjured up by the words “particle” and “field” do not match what the theory says, physicists and philosophers must figure out what to put in their place.

With the two standard, classical options gridlocked, some philosophers of physics have been formulating more radical alternatives. They suggest that the most basic constituents of the material world are intangible entities such as relations or properties. One particularly radical idea is that everything can be reduced to intangibles alone, without any reference to individual things. It is a counterintuitive and revolutionary idea, but some argue that physics is forcing it on us.

THE TROUBLE WITH PARTICLES

When most people, including experts, think of subatomic reality, they imagine particles that behave like little billiard balls rebounding off one another. But this notion of particles is a holdover of a worldview that dates to the ancient Greek atomists and reached its pinnacle in the theories of Isaac Newton. Several overlapping lines of thought make it clear that the core units of quantum field theory do not behave like billiard balls at all.

First, the classical concept of a particle implies something that exists in a certain location. But the "particles" of quantum field theory do not have well-defined locations: a particle inside your body is not strictly inside your body. An observer attempting to measure its position has a small but nonzero probability of detecting it in the most remote places of the universe. This contradiction was evident in the earliest formulations of quantum mechanics but became worse when theorists merged quantum mechanics with relativity theory. Relativistic quantum particles are extremely slippery; they do not reside in any specific region of the universe at all.

Second, let us suppose you had a particle localized in your kitchen. Your friend, looking at your house from a passing car, might see the particle spread out over the entire universe. What is localized for you is delocalized for your friend. Not only does the location of the particle depend on your point of view, so does the fact that the particle has a location. In this case, it does not make sense to assume localized particles as the basic entities.

Third, even if you give up trying to pinpoint particles and simply count them, you are in trouble. Suppose you want to know the number of particles in your house. You go around the house and find three particles in the dining room, five under the bed, eight in a kitchen cabinet, and so on. Now add them up. To your dismay, the sum will not be the total number of particles. That number in quantum field theory is a property of the house as a whole; to determine it, you would have to do the impossible and measure the whole house in one go, rather than room by room.

An extreme case of particles' being unpinpointable is the vacuum, which has paradoxical properties in quantum field theory. You can have an overall vacuum—by definition, a zero-particle state—while at the same time you observe something very different from a vacuum in any finite region. In other words, your house can be totally empty even though you find particles all over the place. If the fire department asks you whether anyone is still inside a burning house and you say no, the firefighters will question your sanity when they discover people huddled in every room.

Another striking feature of the vacuum in quantum field theory is known as the Unruh effect. An astronaut at rest may think he or she is in a vacuum, whereas an astronaut in an accelerating spaceship will feel immersed in a thermal bath of innumerable particles. This discrepancy between viewpoints also occurs at the perimeter of black holes and leads to paradoxical conclusions about the fate of infalling matter [see "Black Holes and the Information Paradox," by Leonard Susskind; Scientific American, April 1997]. If a vacuum filled with particles sounds absurd, that is because the classic notion of a particle is misleading us; what the theory is describing must be something else. If the number of particles is observer-dependent, then it seems incoherent to assume that particles are basic. We can accept many features to be observer-dependent but not the very fact of how many basic building blocks there are.

Finally, the theory dictates that particles can lose their individuality. In the puzzling phenomenon of quantum entanglement, particles can become assimilated into a larger system and give up the properties that distinguish them from one another. The presumptive particles share not only innate features such as mass and charge but also spatial and temporal properties such as the range of positions over which they might be found. When particles are entangled, an observer has no way of telling one from the other. At that point, do you really have two objects anymore?

A theorist might simply decree that our would-be two particles are two distinct individuals. Philosophers call this diktat “primitive thisness.” By definition, this thisness is unobservable. Most physicists and philosophers are very skeptical of such ad hoc moves. Rather, it seems, you no longer have two particles anymore. The entangled system behaves as an indivisible whole, and the notion of a part, let alone a particle, loses its meaning.

These theoretical problems with particles fly in the face of experience. What do “particle detectors” detect if not particles? The answer is that particles are always an inference. All a detector registers is a large number of separate excitations of the sensor material. We run into trouble when we connect the dots and infer the existence of particles having trajectories that can be traced in time. (Caveat: Some minority interpretations of quantum physics do think in terms of well-defined trajectories. But they suffer from their own difficulties, and I stick to the standard view [see “Bohm’s Alternative to Quantum Mechanics,” by David Z. Albert; *Scientific American*, May 1994].)

So let us take stock. We think of particles as tiny billiard balls, but the things that modern physicists call “particles” are nothing like that. According to quantum field theory, objects cannot be localized in any finite region of space, no matter how large or fuzzy it is. Moreover, the number of the putative particles depends on the state of motion of the observer. All these results taken together sound the death knell for the idea that nature is composed of anything akin to ball-like particles.

On the basis of these and other insights, one must conclude that “particle physics” is a misnomer: despite the fact that physicists keep talking about particles, there are no such things. One may adopt the phrase “quantum particle,” but what justifies the use of the word “particle” if almost nothing of the classical notion of particles has survived? It is better to bite the bullet and abandon the concept altogether. Some take these difficulties as indirect evidence for a pure field interpretation of quantum field theory. By this reasoning, particles are ripples in a field that fills space like an invisible fluid. Yet as we will see now, quantum field theory cannot be readily interpreted in terms of fields, either.

THE TROUBLE WITH FIELDS

The name “quantum field theory” naturally connotes a theory that deals with quantum versions of classical fields, such as the electric and magnetic fields. But what is a "quantum version"? The term “field” conjures up magnetic fields that cause iron filings to align themselves around a bar magnet and electric fields that cause hair to stand up on end, but a quantum field is so different from a classical one that even theoretical physicists admit they can barely visualize it.

Classically, a field assigns a physical quantity, such as temperature or electric field strength, to each point in spacetime. A quantum field instead assigns abstract mathematical entities, which represent the type of measurements you could conduct, rather than the result you would obtain. Some mathematical constructions in the theory do represent physical values, but these cannot be assigned to points in spacetime, only to smeared-out regions.

Historically, physicists developed quantum field theory by “quantizing” classical field theory. In this procedure, theorists go through an equation and replace physical values with “operators,” which are mathematical operations such as differentiation or taking the square root, and some operators can correspond to specific physical processes such as the emission and absorption of light. Operators place a layer of abstraction be- tween the theory and reality. A classical field is like a weather map that shows the temperature in various cities. The quantum version is like a weather map that does not show you “40 degrees,” but “√—.” To obtain an actual temperature value, you would need to go through an extra step of applying the operator to another mathematical entity, known as a state vector, which represents the configuration of the system in question.

On some level, this peculiarity of quantum fields does not seem surprising. Quantum mechanics—the theory on which quantum field theory is based— does not traffic in determinate values either but only in probabilities. Ontologically, though, the situation seems weirder in quantum field theory because the supposedly fundamental entities, the quantum fields, do not even specify any probabilities; for that, they must be combined with the state vector.

The need to apply the quantum field to the state vector makes the theory very difficult to interpret, to translate into something physical you can imagine and manipulate in your mind. The state vector is holistic; it describes the system as a whole and does not refer to any particular location. Its role undermines the defining feature of fields, which is that they are spread out over spacetime. A classical field lets you envision phenomena such as light as propagation of waves across space. The quantum field takes away this picture and leaves us at a loss to say how the world works.

Clearly, then, the standard picture of elementary particles and mediating force fields is not a satisfactory ontology of the physical world. It is not at all clear what a particle or field even is. A common response is that particles and fields should be seen as complementary aspects of reality. But that characterization does not help, because neither of these conceptions works even in those cases where we are supposed to see one or the other aspect in purity. Fortunately, the particle and field views do not exhaust the possible ontologies for quantum field theory.

STRUCTURES TO THE RESCUE?

A growing number of people think that what really matters are not things but the relations in which those things stand. Such a view breaks with traditional atomistic or pointillist conceptions of the material world in a more radical way than even the severest modifications of particle and field ontologies could do.

Initially this position, known as structural realism, came in a fairly moderate version known as epistemic structural realism. It runs as follows: We may never know the real natures of things but only how they are related to one another. Take the example of mass. Do you ever see mass itself? No. You see only what it means for other entities or, concretely, how one massive body is related to another massive body through the local gravitational field. The structure of the world, reflecting how things are interrelated, is the most enduring part of physics theories. New theories may overturn our conception of the basic building blocks of the world, but they tend to preserve the structures. That is how scientists can make progress.

Now the following question arises: What is the reason that we can know only the relations among things and not the things themselves? The straightforward answer is that relations are all there is. This leap makes structural realism a more radical proposition, called ontic structural realism.

The myriad symmetries of modern physics lend support to ontic structural realism. In quantum mechanics as well as in Einstein's theory of gravitation, certain changes in the configuration of the world—known as symmetry transformations—have no empirical consequences. These transformations exchange the individual things that make up the world but leave their relations the same. By analogy, consider a mirror-symmetric face. A mirror swaps the left eye for the right eye, the left nostril for the right, and so on. Yet all the relative positions of facial features remain. Those relations are what truly define a face, whereas labels such as "left" and "right" depend on your vantage point. The things we have been calling "particles" and "fields" possess more abstract symmetries, but the idea is the same.

By the principle of Occam's razor, physicists and philosophers prefer ideas that can explain the same phenomena with the fewest assumptions. In this case, you can construct a perfectly valid theory by positing the existence of specific relations without additionally assuming individual things. So proponents of ontic structural realism say we might as well dispense with things and assume that the world is made of structures, or nets of relations.

In everyday life we encounter many situations where only relations count and where it would be distracting to describe the things that are related. In a subway network, for example, it is crucial to know how the different stations are connected. In London, St. Paul's is directly connected to Holborn, whereas from Blackfriars you need to change lines at least once, even though Blackfriars is closer to Holborn than St. Paul's. It is the structure of the connections that matters primarily. The fact that Blackfriars Tube station has recently been renovated into a nice new station does not matter to someone trying to navigate the system.

Other examples of structures that take priority over their material realization are the World Wide Web, the brain's neural network and the genome. All of them still function even when individual computers, cells, atoms and people die. These examples are loose analogies, although they are close in spirit to the technical arguments that apply to quantum field theory.

A closely related line of reasoning exploits quantum entanglement to make the case that structures are the basis of reality. The entanglement of two quantum particles is a holistic effect. All the intrinsic properties of the two particles, such as electrical charge, together with all their extrinsic properties, such as position, still do not determine the state of the two-particle system. The whole is more than the sum of its parts. The atomistic picture of the world, in which everything is determined by the properties of the most elementary building blocks and how they are related in spacetime, breaks down. Instead of considering particles primary and entanglement secondary, perhaps we should think about it the other way round.

You may find it is strange that there could be relations without relata—without any objects that stand in that relation. It sounds like having a marriage without spouses. You are not alone. Many physicists and philosophers find it bizarre, too, thinking it impossible to get solid objects merely on the basis of relations. Some proponents of ontic structural realism try to compromise. They do not deny objects exist; they merely claim that relations, or structures, are ontologically primary. In other words, objects do not have intrinsic properties, only properties that come from their relations with other objects. But this position seems wishywashy. Anyone would agree that objects have relations. The only interesting and new position would be that everything emerges purely on the basis of relations. All in all, structural realism is a provocative idea but needs to be developed further before we will know whether it can rescue us from our interpretive trouble.

BUNDLES OF PROPERTIES

A second alternative for the meaning of quantum field theory starts from a simple insight. Although the particle and field interpretations are traditionally considered to be radically different from each other, they have something crucial in common. Both assume that the fundamental items of the material world are persistent individual entities to which properties can be ascribed. These entities are either particles or, in the case of field theory, spacetime points. Many philosophers, including me, think this division into objects and properties may be the deep reason why the particle and field approaches both run into difficulties. We think it would be better to view properties as the one and only fundamental category.

Traditionally, people assume that properties are “universals”— in other words, they belong to an abstract, general category. They are always possessed by particular things; they cannot exist independently. (To be sure, Plato did think of them as existing independently but only in some higher realm, not the world that exists in space and time.) For instance, when you think of red, you usually think of particular red things and not of some freely floating item called “redness.” But you could invert this way of thinking. You can regard properties as having an existence, independently of objects that possess them. Properties may be what philosophers call “particulars”—concrete, individual entities. What we commonly call a thing may be just a bundle of properties: color, shape, consistency, and so on.

Because this conception of properties as particulars rather than universals differs from the traditional view, philosophers have introduced a new term to describe them: “tropes.” It sounds a bit funny, and unfortunately the term brings inappropriate connotations with it, but it is established by now.

Construing things as bundles of properties is not how we usually conceptualize the world, but it becomes less mysterious if we try to unlearn how we usually think about the world and set ourselves back to the very first years of life. As infants, when we see and experience a ball for the first time, we do not actually perceive a ball, strictly speaking. What we perceive is a round shape, some shade of red, with a certain elastic touch. Only later we do associate this bundle of perceptions with a coherent object of a certain kind—namely, a ball. Next time we see a ball, we essentially say, “Look, a ball,” and forget how much conceptual apparatus is involved in this seemingly immediate perception.

In trope ontology, we return to the direct perceptions of infancy. Out there in the world, things are nothing but bundles of properties. It is not that we first have a ball and then attach properties to it. Rather we have properties and call it a ball. There is nothing to a ball but its properties.

Applying this idea to quantum field theory, what we call an electron is in fact a bundle of various properties or tropes: three fixed, essential properties (mass, charge and spin), as well as numerous changing, nonessential properties (position and velocity). This trope conception helps to make sense of the theory. For instance, the theory predicts that elementary particles can pop in and out of existence quickly. The behavior of the vacuum in quantum field theory is particularly mind-boggling: the average value of the number of particles is zero, yet the vacuum seethes with activity. Countless processes take place all the time, involving the creation and subsequent destruction of all kinds of particles.

In a particle ontology, this activity is paradoxical. If particles are fundamental, then how can they materialize? What do they materialize out of ? In the trope ontology, the situation is natural. The vacuum, though empty of particles, contains properties. A particle is what you get when those properties bundle themselves together in a certain way.

PHYSICS AND METAPHYSICS

How can there be so much fundamental controversy about a theory that is as empirically successful as quantum field theory? The answer is straightforward. Although the theory tells us what we can measure, it speaks in riddles when it comes to the nature of whatever entities give rise to our observations. The theory accounts for our observations in terms of quarks, muons, photons and sundry quantum fields, but it does not tell us what a photon or a quantum field really is. And it does not need to, because theories of physics can be empirically valid largely without settling such metaphysical questions.

For many physicists, that is enough. They adopt a so-called instrumentalist attitude: they deny that scientific theories are meant to represent the world in the first place. For them, theories are only instruments for making experimental predictions. Still, most scientists have the strong intuition that their theories do depict at least some aspects of nature as it is before we make a measurement. After all, why else do science, if not to understand the world?

Acquiring a comprehensive picture of the physical world requires the combination of physics with philosophy. The two disciplines are complementary. Metaphysics supplies various competing frameworks for the ontology of the material world, although beyond questions of internal consistency, it cannot decide among them. Physics, for its part, lacks a coherent account of fundamental issues, such as the definition of objects, the role of individuality, the status of properties, the relation of things and properties, and the significance of space and time.

The union of the two disciplines is especially important at times when physicists find themselves revisiting the very foundations of their subject. Metaphysical thinking guided Isaac Newton and Albert Einstein, and it is influencing many of those who are trying to unify quantum field theory with Einstein's theory of gravitation. Philosophers have written libraries full of books and papers about quantum mechanics and gravity theory, whereas we are only beginning to explore the reality embodied in quantum field theory. The alternatives to the standard particle and field views that we are developing may inspire physicists in their struggle to achieve the grand unification.