C.R.AIPS 3

Proceedings of *the Académie Internationale de Philosophie des Sciences*

Comptes Rendus de l'Académie Internationale de Philosophie des Sciences

Tome III

Models and Representations in Science

Éditeur

Hans-Peter Grosshans

Science and scientific realism: challenges from quantum physics

Dennis Dieks

History and Philosophy of Science, Utrecht University, Princetonplein 5, 3584 CC Utrecht, The Netherlands

1 Introduction

The current predominant philosophical view of scientific progress is a form of scientific realism that holds that science provides increasingly accurate representations of reality (see Alai 2017 and references therein). According to this "accumulative realist" view, scientific theories should be seen not only as tools for predicting observable phenomena, but also as accurate descriptions of real, albeit largely unobservable, processes and entities. Terms such as electron or quark, for example, should be understood as referring to submicroscopic objects that exist in the same way as the observable things around us. Many philosophers of science take this perspective almost for granted. They argue that the predictive success of theories, consistently verified by experiments, is convincing evidence for their truth. Indeed, they say, it would be miraculous if our theories could be so predictively successful without tapping into the unobservable processes responsible for what we see happening in the world; the best explanation for predictive success is undoubtedly truth.

It is widely recognized, nevertheless, that all scientific theories, even the most successful, are provisional. Every theory contains unresolved questions and areas where predictions fail. The history of science shows that even seemingly untouchable theories are eventually replaced by new ones. Yet proponents of accumulative scientific realism argue that the provisional nature of scientific theories and their replacement by newer theories does not indicate that current theories are fundamentally flawed. Rather, they argue that the consistent empirical success of a theory in a given domain demonstrates that the theory contains parts that are true or at least close to the truth. Scientific progress then consists in selecting, preserving and refining these accurate aspects, while abandoning or revising those parts of the theory that turn out to be incorrect and unnecessary for empirical success. Through this process, they argue, science gets closer and closer to the truth. Thus, the evolution of atomic theory from the idea of indivisible particles in 19th-century physics to the contemporary picture of atoms built up from subatomic particles such as quarks illustrates the gradual refinement of our understanding of atoms.

Models and Representations in Science, edited by Hans-Peter Grosshans.
Comptes Rendus de l'Académie Internationale de Philosophie des Sciences 3 (2025).
D. Dieks, Science and scientific realism: challenges from quantum physics, pp. 55–72.

In this article, we will challenge this notion of continuous and accumulative growth of our scientific knowledge of physical reality. Much of the philosophy of science literature on the subject focuses on 18^{th} and 19^{th} century physical theories and tends to overlook the important new problems posed by 20^{th} and 21^{st} century physics (see, however, Dieks 2017, Callender 2020, and Egg and Saatsi 2021, as examples of exceptions). To compensate for this bias, we will here concentrate on the relationship between quantum mechanics and classical physics. We will argue that accumulative realism in this case underestimates the drastic conceptual differences between the classical and quantum frameworks.

As we will explain, the fact that new theories are able to reproduce the empirical success of their predecessors does not entail that parts of the old ontology are (approximately) retained in the new theories. Instead, features of older theories often *emerge* from the predictions of newer theories, in limiting scenarios that represent only a small part of the broader scope of those newer theories. The ontologies that fit this broader range of the new theories may differ radically from what was assumed previously. Moreover, the huge gap between direct observation and the abstract formalisms of modern physics turns out to leave room for multiple conflicting ontological interpretations. Modern physics thus tangibly exacerbates concerns about both discontinuity and theoretical underdetermination.

2 Quantum mechanics

Understanding the argument of this article requires knowledge of only a small number of basic principles of quantum mechanics. Quantum mechanics has replaced classical mechanics because the latter fails to correctly predict the results of experiments involving submicroscopic matter. But quantum mechanics also introduces fundamental changes in the general conceptual framework of physics.

In classical mechanics, matter is depicted as composed of small particles possessing definite values of mass, position, and velocity, possibly also of additional properties like electric charge. The mathematical representation of classical particles therefore involves specifying the values of these quantities, typically focusing on position and velocity, or equivalently, position and momentum (denoted as (x, p), where $p = mv$, mass times velocity). Classical mechanics formulates laws of motion that dictate how these quantities change over time under the influence of forces.

Quantum mechanics replaces this intuitively clear and plausible picture with a considerably more abstract one. Instead of the classical particle representation (x, p), quantum mechanics introduces wave functions denoted as $\psi(x)$. Here, x still represents position, but not as a particle property as in classical mechanics. The precise physical interpretation of the mathematical symbols in quantum mechanics is a subject of debate, with various interpretations proposing different perspectives (this multiplicity of interpretations and its significance for our theme will be addressed later in this article). However, it is universally agreed-upon that in a *measurement* of position, the value x has a probability $|\psi(x)|^2$ of being observed as the outcome. This interpretative rule forms the core of what may be termed the standard or textbook interpretation of quantum mechanics.

The wave function $\psi(x)$ evolves over time according to a deterministic equation known as the Schrödinger equation, which serves as the quantum analogue of the classical Newtonian equation of motion. Just as the classical equation of motion determines a particle's unique position and velocity at an instant t given its initial properties and all forces acting upon it, the Schrödinger equation determines a unique wave function $\psi(x,t)$ given the initial wave function $\psi(x,0)$ and all interactions and potentials.

This ultra-short summary of the difference between classical and quantum mechanics will form the basis for our argument that the very notion of a particle, and indeed the concept of a material object more broadly, becomes problematic within the framework of quantum mechanics. The core innovation on which we will focus is that quantum mechanics does not characterize its subject matter with the help of combinations of *properties*, like (x,p), but instead uses wave functions $\psi(x)$ whose meaning is given in terms of measurement outcomes and their probabilities, without reference to preexisting particle properties.

3 Modeling a macroscopic object in quantum mechanics

The mathematical formalism used by quantum mechanics diverges significantly from its classical counterpart. As we have seen, an important aspect is that the quantum formalism does not rely on the existence of objects with definite positions and velocities. This striking fact prompts questions about how quantum mechanics can accommodate the behavior of objects as we perceive them in our everyday experience. If quantum "entities" lack well-defined positions and velocities, the notion of following definite trajectories becomes dubious as well, which raises questions even about the identity of systems over time.

These concerns can be given a more rigorous, mathematical form. Consider the following scenario described classically: a box divided into two compartments by a threshold (represented mathematically by a potential barrier), with a small yet macroscopic ball placed in one compartment. For quantum mechanics to be empirically adequate in this situation, it must be capable of describing and predicting the behavior of the ball. Representing a localized ball with a wave function must involve assuming a very narrow $\psi(x)$;

indeed, a measurement of the ball's position should yield results confined to a narrowly defined region. On the basis of our classical experience we expect the ball, and therefore the narrow wave function assigned by quantum mechanics, to remain stationary in the absence of external forces; perhaps with some kind of quantum fluctuations.

As noted by Leggett and Garg (1985) in a paper discussing a very similar scenario, even physicists often tend to conceptualize such situations in broadly classical terms, despite years of exposure to quantum mechanics. However, applying the Schrödinger equation to the initial wave function, while considering the repulsive potential barrier representing the threshold, yields a result that defies classical expectations. Calculating $\psi(x,t)$ reveals a non-zero probability emerging over time for finding the ball in the other compartment, across the threshold. The wave function transforms into a "superposition" encompassing parts located in both compartments, implying that upon measurement, the ball may be found in either compartment.

Although the wave function extends across both compartments, quantum mechanics dictates that a measurement will always yield the ball in either the left or right compartment—never both simultaneously. This prediction of quantum mechanics aligns with our classical expectations and invites an interpretation in terms of a classical object. We could accordingly suppose that an at all times localized ball exhibits quantum fluctuations, occasionally traversing the threshold to end up in the alternate compartment.

However, Leggett and Garg demonstrated that if we assume that in such scenarios objects are always localized either in the left or the right compartment, and that this could be verified, in principle, by means of measurements that disturb the object only insignificantly, an inequality analogous to Bell's inequality must be satisfied. This inequality involves correlations between the results of position measurements conducted at various times.

The two assumptions needed for the argument—always definite localization of objects and the possibility in principle of non-invasive measurements revealing these locations--are typical of classical physics. Leggett and Garg take these assumptions to define what they call "macroscopic realism". Indeed, it is essential for the classical worldview that there are objects with always definite positions, and the predictions made for these positions by classical physics are always assumed to correspond to what is found in observation. However, in well-chosen quantum versions of the scenario (with the right forms for the potential barrier and the ball's interaction with it) the quantum mechanical predictions violate the Leggett-Garg inequalities. This violation establishes that it is possible to experimentally disprove the classical picture of an always localized object moving between compartments.

Several such experiments have been conducted since 1985. The results accord with the quantum mechanical predictions, and conflict with “macro realism”.

This result may be interpreted as simply another piece of evidence for the universal validity of the non-classical ontology provided by quantum mechanics, even at the macroscopic level, and as such it may be deemed unsurprising (Bacciagaluppi 2016). Indeed, there are good reasons anyway to believe that quantum mechanics does not stop to be valid at some border line between what is microscopic and what is macroscopic. If this universal validity is accepted, then the non-existence of classical objects with always definite and non-invasively measurable dynamical quantities is only to be expected, since this is the rule in the microscopic quantum realm (more on this in the next section).

If quantum theory is universally valid, the question arises of why the concept of a classical object with well-defined properties works so well in our ordinary dealings with the physical world. The answer, from the point of view of quantum mechanics, is that in everyday circumstances factors are present, in particular “decoherence” mechanisms, that mask typical quantum effects like dissipation of the wave function and the occurrence of superpositions. As a result, classical patterns *emerge* in observational results: although everything happens in accordance with the quantum rules, and although precise measurements can reveal the inapplicability of a classical particle picture, a coarse-grained description exhibits patterns that look like classical particle behavior. In other words, the (approximate) applicability of a classical particle picture is an *emergent phenomenon*—a point whose relevance for the scientific realism debate will be discussed later in this article.

4 Quantum objects

Experimental evidence supporting the validity of quantum mechanics even at near-macroscopic scales has accumulated in many forms over recent decades. This evidence suggests that macroscopic entities exhibit the same fundamental characteristics as submicroscopic entities. Thus, the existence of classical objects is challenged in a general and coherent way, which reinforces the conclusions drawn from specific tests like the Leggett-Garg experiments.

That our classical intuitions about objects fail in the submicroscopic world has for long been common knowledge. A standard illustration is the double slit experiment. Suppose an electron is made to traverse a screen with two slits, and we attempt to discover through which slit the electron passes. Quantum mechanics predicts, and we actually find in experiments, that on traversal the electron is always found in exactly one single slit. This is analogous to what we explained for the ball in the box scenario: the ball will always be found in exactly one single compartment. But, returning to the case of the electron, we know that the assumption that the electron goes through exactly one slit leads to trouble if we consider other possible experiments. In particular, when we measure where the electron lands on a second screen (after having traversed the double-slit screen without experiments taking place there) we will be confronted with the effects of interference, whose explanation needs the assumption of contributions from *both* slits. According to standard quantum mechanics this implies that the electron was *not* localized in one of the slits when it traversed the screen (the Bohm interpretation, about which more later, offers the non-standard alternative explanation that it is a *field*, existing in addition to the electron and guiding the electron's motion, that goes through both slits). This standard conclusion is similar to what was inferred from violations of Leggett-Garg inequalities in our box scenario, namely non-localizability of the ball in general, despite the fact that position *measurements* always find the ball at definite positions.

The problems with classical objecthood go even further. In one-ball or one-electron scenario's, as discussed above, there seems no reason to doubt that at all points in time we are dealing with the same entity. So, there is no immediate conflict with the classical notion that objects possess synchronic and diachronic *identities*. Classical objects differ from each other at any given instant in at least one physical characteristic (they have synchronic identities), and they can be individually followed over time on the basis of their different trajectories (diachronic identities). But in quantum mechanics (again, in its standard form and interpretation) this is generally not the case. A collection of what we intuitively would like to call "n particles of the same kind" (for example, a collection of n electrons) is not represented quantum mechanically by a set of n individual one-particle wave functions. This is known as the "problem of identical quantum particles" (Dieks 2023b).

Suppose, to illustrate the point, that we have two electrons, described quantum mechanically. Suppose further that we perform initial position measurements, with results x_A and x_B, and that we repeat these experiments at a later moment, with results x_C and x_D. Now, in the general situation there is no answer to the question whether the electron initially found at x_A is the same as the electron found later at x_C, or whether it happens to be the electron found at x_D. The theory does not give us genidentity criteria for what happens between successive measurements.

Nevertheless, under certain circumstances patterns in measurement results may emerge that do suggest the presence of particles following definite trajectories and possessing individual identities. This may happen, for example, in the case of diluted gases (as argued by Schrödinger 1950) or in the presence of decoherence. In such cases a classical particle model may work well for certain practical purposes . However, precision measurements exploring fine-grained features of the situation will still be able to reveal that such a particle model cannot be taken literally. These models therefore function as pragmatic tools yielding useful results within a restricted context, but cannot be said to represent the physical world in a truthful fashion.

5 Emergence as a challenge for scientific realism

As emphasized in the preceding section, the applicability of the classical picture according to which the physical world is populated by objects with individual identities is something that *emerges* in circumstances not too far from those of our everyday experience. Here, emergence may be defined as the appearance of novel and unexpected patterns in the predictions of a theory as long as we stay within a restricted part of its domain of application. The classical domain, i.e., the set of conditions under which classical models can be used successfully, is determined by requirements like high temperatures, many degrees of freedom, and velocities low relative to the speed of light; it is a minute part of the total domain of quantum theory.

The principles of the underlying more fundamental theory remain valid within the domain where emergence occurs, and this is reflected by the fact that the emergent descriptions are only approximately valid. It always remains possible in principle to verify that emergent pictures are only adequate in a coarse-grained treatment; with the help of precision experiments the emergent "laws" may be falsified.

When in the history of physics new physical theories replace older ones, the phenomena predicted by the old theory typically resurface in a restricted part of the domain of application of the new theory. For example, thermodynamic regularities emerge from the theory of atoms and molecules for temperatures well above zero degrees Kelvin and in the presence of many degrees of freedom; Newtonian-like behavior emerges from special relativity when velocities are low relative to the speed of light; etc. In all such cases highly accurate experiments can expose the falsity of the principles of the emergent theories, and this is in fact usually (an important part of) the reason that the old theory was superseded at all.

The importance of emergence in the transition from one theory to the next suggests that the relationships between successive theories are usually not about incremental growth of our knowledge of objects we were already familiar with, but involve the discovery of completely novel entities and processes. Emergence thus poses a challenge to the brand of realism in which it is assumed that scientific progress consists in the addition of new details to our description of fundamental constituents of matter already figuring in older theories.

The problem is aggravated by the fact that the scope of newer theories is usually vastly greater than that of older and superseded theories. This entails that emergent patterns, although considered fundamental in older theories, occupy only a very tiny portion of the domain of applicability of successor theories. Thus, what were considered stable and fundamental building blocks of matter in previous theories later stop to be building blocks at all but rather become ephemeral patterns arising under special conditions.

In an earlier publication devoted to this topic (Dieks 2023a) we discussed how these considerations apply to the relation between Aristotelean and Newtonian mechanics. It is true that the Aristotelean laws of motion (using forces that impart velocities to objects) emerge from the very different Newtonian ones (with forces that cause accelerations) in circumstances where appreciable friction counteracts the accelerating forces. But despite this point of contact between the two theories, it appears inappropriate to maintain that the Newtonian world picture is a refinement of the Aristotelean one. Rather, the Newtonian framework completely replaced the Aristotelean doctrine, and the point of contact between the two is nothing but a logical consequence of the requirement that new theories should be able to reproduce the (limited) empirical success of their predecessors. Similarly, as argued in Section 4, the very concept of an object possessing an individual identity only becomes applicable in a coarse-grained description of a very small part of the quantum domain. Again, it is improper to comment that quantum theory merely adds details to our descriptions of submicroscopic particles (like electrons) that we already recognized as fundamental building blocks of matter in our pre-quantum theories. Rather, quantum theory introduces a completely new view on the nature of physical reality, according to which classical particles simply do not exist.

In the following section we will consider how realists might respond to this challenge.

6 Realist replies

The relation between the quantum realm in which there are no objects and the macroscopic world where objects abound, brings to mind Eddington's famous reflection about his two tables, the scientific and the ordinary one (Eddington 1948). The scientific table is mostly empty space, with here and there some protons and electrons, which themselves are "immaterial", Eddington says. By contrast, the ordinary table is solid and full of substance. As Eddington argues, from a modern scientific point of view, ordinary tables do not exist.

This paradoxical situation may be addressed by pointing out that there are stable object-like patterns in what can be observed on the macroscopic level, and that the object-language that we use is tailored to deal with such patterns. Within the context of that linguistic practice, we are entitled to say that the statement "tables exist" is *true*; indeed, the everyday term "table" in this case refers to phenomenal patterns whose existence can be verified. As Steven French (2014) argues, this is one of several available strategies for making true the statement “There are tables”, without commitment to tables as parts of our physical ontology.

The question that should be answered in order to judge the viability of accumulative realism is whether strategies of this kind succeed in salvaging the intuition that science progresses by gradually adding details to our knowledge, thus refining our picture of the world. *Prima facie* this seems a tall order given our specific problem situation, namely that quantum mechanics questions the very notion of an object instead of discovering additional properties of objects. But let us take a closer look.

A standard realist move for reducing the conceptual distance between successive theories is the introduction of the notions of *approximate* and *partial* truth. The idea is that although descriptions of entities given by serious and mature but now superseded scientific theories did not get it completely right, they were not completely wrong either: they were close to the truth. The idea behind “partial truth” is that only some parts of old theories, namely the parts essential for the empirical success of those theories, can have this claim to approximate truth. With these conceptual refinements the central tenet of accumulative realism becomes that the evolution of science is a process in which parts of theories that were essential for their empirical success are preserved and updated, while inessential parts are discarded.

This strategy appears to be of little help if the discontinuity between classical theories, which are all object-based, and quantum mechanics is at stake. Indeed, the concept of an object is absolutely essential for classical physics. For example, Newton’s laws of motion only make sense for material bodies following well-defined paths and undergoing accelerations. The empirical success of classical mechanics depends completely and essentially on these laws and the predictions made with them. So, it must be expected that objecthood will be retained in the transition from classical mechanics to quantum mechanics, if something like accumulative realism is to be right. However, we have already concluded that objects do not occur in the conceptual framework of standard quantum theory.

According to accumulative realism, this is an occasion where the notion of *approximate* truth should be invoked. The idea is that although objects as characterized within classical theory do not figure in quantum mechanics, they have quantum counterparts that are quite close to them. This might appear a plausible thought. Indeed, the jargon of quantum physics is full of terms like electron, proton, and so on, that evoke images of little balls—and in the physics literature pictorial representations of quantum experiments with such imagery (black dots indicating electrons, for instance) are often used.

However, equally often the picture of propagating waves is employed. In fact, as has been a subject of discussion since the early days of quantum mechanics, both particle and wave images are merely flawed pictorial tools born out of necessity, since there exist no satisfactory classical "anschaulich" representations of quantum "systems". As we have seen, such "systems" in standard quantum mechanics do not even possess individual identities, so that the very talk about "them", "entities", and similar, is already an abuse of language. The conceptual gap with the classical modes of description is deep. There is no way in which small refinements of the classical notion of a particle can bring us close to the concept of a "quantum particle" (a term used for lack of a better one).

This is not to say, of course, that there is no connection between classical particle theory and quantum mechanics. As discussed before, in certain limiting situations quantum predictions exhibit patterns that closely approximate patterns predicted by classical particle theory. This is a typical case of emergence. But what emerges are patterns in predictions; possibly also patterns in *events* that occur independently of measurements, although the latter is not part of standard quantum mechanics. This emergence in the classical limit does not change the quantum concepts in any way: quantum systems never turn into classical particles, even though in certain restricted limiting situation classical particle models start working well on the phenomenal level.

So, the appeal to approximate and partial truth seems ineffective if accumulative realism is to be saved. An alternative and possibly more promising strategy is that of giving a "functionalist" twist to the realist position (e.g., Cordero 2024). The core idea of functionalist realism is that objects should not be characterized via the basic ontology of theories, but rather by their observable (in the sense of measurable) manifestations. As Cordero (2024) puts it, we should think in terms of "functional" entities, individuated by their *causal effects*. In other words, functional entities are characterized by what they *do* rather than what they *are*. Following this idea, we can have functional classical particles within the classical regime of quantum theory, leaving it open what their "deep quantum ontology" is. Of course, quantum predictions never fully coincide with the predictions of classical theory, not even in the classical limit. Therefore, the emerging functional entities are only "effectively" classical: they closely approximate the behavior of the particles from classical mechanics.

So, in functionalist realism quantum particles are defined as the things responsible for quantum behavior, whereas classical particles are defined by patterns resembling trajectories and other familiar particle-like structures.

Since quantum mechanics makes predictions that in the classical limit are close to those of classical mechanics, the functionalist realist account allows us to argue that within the classical regime of quantum mechanics classical particles are actually present (even though this existence claim must be understood as relative to a coarse-grained, effective description). From the functionalist realist point of view it is not just patterns in predicted phenomena that emerge; the classical particles *themselves* emerge from the quantum realm, as functional and effective entities.

This way of speaking about entities at different levels of description and precision resembles the strategy for handling Eddington's tables mentioned at the beginning of this section. As such, it has the merit of being close to practice. Indeed, who would deny the existence of tables, even in the face of what fundamental physics tells us? But as already noted by Eddington, the relativization with respect to context and degree of precision make effective functional entities less attractive for realist purposes. Clearly, tables cannot figure in any fundamental ontology; even on the macroscopic level improving the precision of measurements makes it possible to put the substantiality of tables in doubt. "Tables", characterized by solidity and substantiality, thus becomes a "for all practical purposes" concept. Functionalist realism therefore runs the risk of boiling down to a pragmatist position, according to which we may call real scientific models that work to a certain degree of precision within a limited domain of application.

The latter position would lead to difficulties for standard scientific realism. Scientific practice abounds with models that work well in restricted contexts; sometimes there are even several different models that may be used in the same situation. If all such models are to have an equal claim to being representative of physical reality, a fragmented and even incoherent picture results. Such a patchwork of descriptions is not what standard realism is striving for. The basic motivation for standard realism is the desire to find the unique description actually fitting the physical world as it really is. This "multiplicity objection" against functionalist realism relates to the more general problem of theoretical underdetermination, about which more in the next section.

With regard to *accumulative* realism, the prospects offered by the functionalist turn seem bleak. If the picture of the world provided by a theory is nothing more than a model functioning well within certain limits, there is no clear reason why newer and better theories, with more extensive domains of application and more precise predictions, will only incrementally extend and refine earlier models. The only certainty is that successes of the old theory will be reproduced by the new theory, with improved precision. But for this to happen emergence is sufficient; there is no need for retention of descriptive elements of the old theory. Therefore, to give accumulative realism a chance, not every possible empirically successful model should *ipso facto* be accepted as descriptive; some selection criterion enabling a distinction between models with fundamental content and merely pragmatic models is needed. But the turn to effective functionalism, with its emphasis on "things that work", does nothing to solve this hard and general problem for scientific realism.

A specific problem arises for the case of quantum versus classical because functionalist realism defines entities "by what they *do*". Quantum particles are characterized by their causal effects, and the hope is that the thus defined entities are sufficiently close to their classical counterparts to make accumulative realism a viable option. But any characterization of quantum particles by their causal effects presupposes that there *are* causally effective individual entities in the quantum domain. As we have noted before, however, according to standard quantum mechanics this assumption is unjustified. The worry that functionalist constructions possess a pragmatic character with a limited scope rather than that they are able to reflect reality "as it is" is thus reinforced.

Summing up, "functionalist realism" is steeped in considerations about coarse graining and restricted domains that relate to human interests and limitations. This raises doubts about its value as a proper realist position. Rather than operating with a correspondence notion of truth, it seems bound up with a pragmatic truth concept. Moreover, even if this pragmatic aspect is recognized and accepted, it remains unclear whether and how functionalist realism could offer a better chance of representing scientific progress as a process of accumulation than standard selective realism paired with approximate truth (the first position discussed in this section).

A final strategy to be mentioned is that of "structural realism". According to structural realism scientific knowledge is knowledge of structures rather than of *things* characterized by monadic properties. From the structural perspective, particles (and objects in general) are nodes in the network of relations that constitutes the structure representing the scientific picture of the world. The idea of accumulative realism is now transformed into the view that the structures posited by old theories survive as parts of new structures.

For our theme the important question is whether structural realism proffers new resources that make it possible to avoid the problems for accumulative realism encountered in the preceding discussion. In particular, does the structural conception make the transition from classical particles to the non-particle-like quantum world more continuous than other forms of realism?

It is difficult to see how this could be the case. The mathematical structure of quantum mechanics is very different from that of classical mechanics. On the quantum side we have the mathematics of Hilbert vector spaces, in which the vectors (and density operators) represent states and linear operators stand for physical quantities. The standard way of representing subsystems of the universe is by reference to the factor spaces in tensor product Hilbert spaces representing composite systems; the states defined in these factor space are usually called one-particle states. It is not evident how this standard account should be reworked into a completely structural one. But anyway, what will result will have the character of relations between one-particle states, i.e., vectors (or density operators) in Hilbert space. In this way one may also obtain relations between physical quantities, via the standard rule that an eigenvector of an operator represents a well-defined value of the physical quantity associated with the operator. By contrast, on the classical side particles are represented by points in phase space, so that a structural account will refer to the relations between such points.

But the relations between quantum states in Hilbert space generally have a very different character from the relations between points in phase space. The best that can be achieved, it seems, are structural similarities that are valid in a restricted domain and in a coarse-grained description. But this brings us back to the problems faced by functionalist realism, discussed previously.

Of course, a certain amount of partial and approximate agreement between successor theories will certainly exist, since new theories have to reproduce (and improve!) the empirical success achieved by their predecessors. This will also be true for structuralist accounts. But such limited continuity has to be expected even within an empiricist analysis of science and does not need accumulative realism for its explanation (Dieks 2023a).

Finally, structural realism faces the problem that the structure of quantum mechanics (or any other physical theory) is not something that is unambiguously given. Not all interpretations of quantum mechanics use the same mathematical formalism. This implies that different interpretations will often propose different structures as descriptions of the physical world. So, structural realism, like other forms of realism, faces the problems posed by theoretical underdetermination.

7 Theoretical underdetermination

The underdetermination of physical theories by empirical evidence is sometimes portrayed as an artificial problem, conceived by philosophers but not present in a serious way in scientific practice. For example, Musgrave (1985) states that typical examples of underdetermination from the philosophy of science literature are contrived constructions while he is aware of only one real (though harmless) case, namely that Newtonian cosmological models only differing in their absolute velocities (i.e., velocities with respect to absolute space) are all in accordance with the same empirical data (because of the Galilean principle of relativity). This verdict of lack of real significance is incorrect: even in classical physics, several classical theories have more than one version, which is reflected in different mathematical formalisms. In quantum mechanics, however, different interpretations, associated with different portrayals of the fundamental physical world, play a particularly important role and have become the subject of debate in a dedicated "foundations of physics" literature. For our theme, namely the viability of accumulative realism, the contrast between interpretations that rely on the standard quantum formalism and the so-called Bohm interpretation is especially interesting.

What we have pointed out before about the difficulties in quantum mechanics with the notion of objecthood presupposed the standard Hilbert space formalism of quantum mechanics. In fact, there are two versions of this standard formalism, depending on whether a special evolution mechanism is assumed for what happens during measurements, namely a "collapse" of the quantum state, or whether ordinary Schrödinger evolution is assumed to be universally valid—in the latter case one speaks of unitary quantum mechanics. The diversity does not stop here. For one thing, there are several conflicting proposals for how to construe the descriptive content of unitary quantum mechanics (one notorious proposal being the many worlds interpretation). But this variety need not concern us here since all these variants adopt the Hilbert space formalism as basic and represent physical systems by Hilbert space vectors (or, equivalently, by wave functions). This representation is the essential reason why objects with individual identities and with definite properties are problematic in standard quantum mechanics.

But there exists an alternative version of quantum mechanics, in which the notion of an object is not problematic at all, but rather fundamental. This is the Bohm interpretation of quantum mechanics (Bohm 1952). According to Bohm, quantum mechanics is a theory about the behavior of *particles*, i.e., objects in the classical sense, possessing definite positions and velocities at all times. So, the world picture provided by quantum mechanics according to Bohm is radically different from the world picture(s) yielded by standard quantum mechanics.

In the Bohm interpretation, the wave function is not viewed as the complete characterization of a quantum system, but is interpreted as an additional player—either a physical field or a new term appearing in the laws of motion. In both cases, the wave function influences the motion of the particles. As it turns out, this influence is such that the wave function corresponds to the probability that a particle will find itself at position x, via the equation $P(x) = |\psi(x)|^2$. Note the difference with standard ideas: the usual view is that quantum systems do not possess definite positions independently of measurements, but that nevertheless a well-defined result x will be created in a position measurement. Quantum mechanics, in this standard view, is indeterministic in the sense that it is generally not determined, before a measurement, what the exact outcome x of a measurement will be. The theory only specifies the probabilities of all possible outcomes, via the formula $P(x) = |\psi(x)|^2$. By contrast, in the Bohm interpretation a position measurement simply reveals the preexisting position of a particle. However, because of a lack of control of the precise initial conditions, repetitions of the experiment will generally not give the same results. There will be a statistical distribution of particle positions, represented by the same formula $P(x) = |\psi(x)|^2$. The meaning of the symbol x occurring in this formula is therefore different in the two cases: according to standard ideas it is a value created in a measurement, but in the Bohm theory it represents a particle property that existed already before the measurement.

The above is only a brief summary of a central idea of the Bohm interpretation. A more extensive discussion should deal with the precise form of the laws governing the motion of the Bohmian particles and with the way the wave function figures in these laws. But the preceding paragraph already suffices to make it understandable that standard quantum mechanics and the Bohm view strongly diverge with respect to their portrayals of physical reality. Nevertheless, the two interpretations make exactly the same empirical predictions. That is, the possible values x of outcomes of experiments, plus the statistical distribution of these values in repeated experiments, are identical in the two cases. What is different is the *meaning* of these outcomes, their place in the two respective worldviews; whether the outcomes are created during measurements or reveal preexisting particle properties.

This metaphysical difference is parallelled by a difference in mathematical structure of the two theories. The collection of all physical states in standard quantum mechanics, as represented in the mathematical formalism, forms a vector (Hilbert) space, as was mentioned before. One of the consequences is that two states (vectors) can be added, which will form a new state. This is the so-called superposition principle. In contrast, the particle state space of the Bohm theory has the structure of classical state spaces: it is a manifold of points with coordinates x, v (position and velocity) in which it makes no sense to add states.

We have argued in Sections 4 and 5 that accumulative realism faces a problem when dealing with the transition from classical physics to quantum mechanics, because the notion of an object, which is central in the classical theory, disappears in quantum mechanics. We now see that this conclusion should be qualified: its validity depends on the version of quantum mechanics that we are contemplating. In the Bohm version of quantum mechanics objecthood remains a central notion, and accumulative realists could here argue that in the classical-to-quantum transition more is learned about the true nature and behavior of fundamental particles like electrons and protons. (This is certainly not uncontroversial, though, since the Bohmian quantum particles possess characteristics that deviate strongly from those of their classical counterparts, so that the accumulative realist idea of incremental refinement is questionable; but this is a subject outside the scope of the present paper).

If the transition from classical mechanics to Bohmian quantum mechanics is a case of continuous growth of our knowledge about particles, this may seem a vindication of accumulative realism. If accumulative realism is the natural, intuitive and close-to-common-sense philosophical position that it proclaims itself to be, one would accordingly expect that the Bohm interpretation is the preferred version of quantum mechanics in actual physical practice. This, however, is not the case. The Bohm theory is only accepted by a minority of physicists, and the standard formalism (including such at first sight outlandish interpretative ideas as the many-worlds interpretation) is much more popular. So, the idea of continuity that is behind accumulative realism does not appear to be a driving force behind actual physical research. Even in the presence of what arguably might be considered a version of quantum mechanics that is continuous with classical physics, the majority of physicists opts for radically different ideas.

Of course, the presence of different but empirically equivalent theoretical schemes in the actual practice of physics poses a challenge for scientific realism in general. If there are several mutually conflicting pictures of reality that can equally be associated with our best physical theories, then how can the thesis be supported that physics provides us with a representation of the physical world as it really is? The further specification of the realist position to the effect that scientific progress is accumulative, consisting in the addition to and refinement of earlier obtained descriptive truth, does not make the position more plausible. It denies the possibility of radical conceptual change concerning essential elements of earlier theories, and thus makes itself vulnerable to empirical disconfirmation.

8 A skeptical conclusion

Accumulative scientific realism is an epistemically optimistic position. While it admits that we are unable to directly perceive what is hidden behind the surface of observation, it argues that scientific theorizing can nevertheless uncover hidden truths at least approximately. Moreover, when new and better theories supplant previous ones, accumulative realism posits that this refines and expands the kernel of truth already present in the older theories. The so-called no-miracles argument is usually cited as justification for these beliefs: the empirical success of our scientific theories would be incomprehensible, and nothing short of a miracle, if our theories did not come close to the truth in essential respects. Since we do not want to be forced to believe in miracles, we apparently have no alternative but to believe that the scientific method is truth-conducive. Apparent counterexamples from scientific practice (the notorious "pessimistic meta-induction") must therefore be able to be refuted by showing that radical conceptual changes involve only non-essential parts of older theories.

However, the comparison of classical mechanics and quantum mechanics does not confirm the leitmotif of continuous growth of truth during scientific progress. As we have argued, the transition from classical physics to quantum theory has completely overturned previous conceptual frameworks, including their essential properties. It follows that preserving essential elements of laws and ontology cannot be necessary to understand the empirical success of earlier, now obsolete, theories. Indeed, a different explanation is available: from the standpoint of standard quantum theory the empirical success of classical mechanics is a consequence of the *emergence* of classical-like patterns, in certain limiting cases. Such emergence does not require the preservation of laws or ontology. More generally, our analysis appears to lend support to the skeptical conclusion that successful scientific theorizing leads to the detection of general patterns and successful descriptive possibilities, but need not postulate a unique truth in order to do so.

References

Agazzi, E., (ed.) (2017). Varieties of Scientific Realism. Objectivity and Truth in Science. New York: Springer.

Alai, M., (2017). The debates on scientific realism today: knowledge and objectivity in science. In Agazzi (2017), 19–47.

Bacciagaluppi, G. (2016). Einstein, Bohm and Leggett-Garg. Chapter 4 in E. Dzhafarov, S. Jordan, R. Zhang, and V. Cervantes (eds.), Contextuality from Quantum Physics to Psychology. Singapore: World Scientific.

Bohm, D. (1952). A suggested Interpretation of the quantum theory in terms of "hidden" variables, I and II. Physical Review 85, 166–179; 180–193.

Callender, C. (2020). Can we quarantine the quantum blight? In S. French and J. Saatsi (eds.), Scientific Realism and the Quantum. Oxford: Oxford University Press, 57–77.

Cordero, A. (2017). Retention, truth-content and selective realism. In Agazzi (2017), 245–256.

Cordero, A. (2024). On the structure and accumulation of realist content. Epistemology & Philosophy of Science 61, 134–150.

Dieks, D. (2017). Underdetermination, realism and objectivity in quantum mechanics. In Agazzi (2017), 295–314.

Dieks, D. (2023a). Emergence, continuity, and scientific realism. Global Philosophy 33:44. DOI: 10.1007/s10516-023-09696-w.

Dieks, D. (2023b). Emergence and identity of quantum particles. Philosophical Transactions of the Royal Society A 381: 2022.0107. DOI: 10.1098/rsta.2022.0107.

Eddington, A. S. (1948). The Nature of the Physical World. Cambridge: Cambridge University Press.

Egg, M., Saatsi, J. (2021). Scientific realism and underdetermination in quantum theory. Philosophy Compass 2021, e12773. DOI: 10.1111/phc3.12773.

French, S. (2014). The Structure of the World: Metaphysics and Representation. Oxford: Oxford University Press.

Leggett, A. J., Garg, A. (1985). Quantum mechanics versus macroscopic realism: Is the flux there when nobody looks?, Physical Review Letters 54, 857–860.

Musgrave, A. (1985). Realism versus Constructive Empiricism. In P. M. Churchland and C. A. Hooker (eds.), Images of Science. Chicago: Chicago University Press, 197–221.

Schrödinger, E. (1950). What is an elementary particle? Endeavour 9, 109–116.