Adapted with permission from Anthony Sudbery, *Quantum Mechanics and the Particles of Nature*, Cambridge: Cambridge University Press, 1986. This book is highly recommended for further details.

Some meta-scientific vocabulary

This is vocabulary for use in statements *about* scientific statements.

Empiricism is the doctrine that the justification for any belief can only, ultimately, come from sense experience. There is room for a considerable range of views about what beliefs are justified, and to what extent, by what experiences; an extreme position is **solipsism.** A solipsist believes that nothing exists except himself or herself.

Positivism is a type of empiricism which says that the meaning of a scientific statement is related to the way in which that statement is tested (which must ultimately be by consulting sense experience).

Operationalism is the view that individual terms in a scientific theory should be defined by reference to experimental procedures. The model theory for this view is the special theory of relativity, with its operational definitions of distance and time. (Note that cosmology, even though it uses relativity theory, includes some non-operational terms, because when we're thinking on a cosmological scale we cannot define all our terms by reference to experiments.)

Pragmatism is the general philosophical view that the meaning of a statement resides in the way in which it governs our actions; it is true if it is useful. Most forms of pragmatism say that the notion of usefulness must be a large-scale or scientific notion, so that using a claim about quantum mechanics to make technology counts as useful but using it to impress someone at a party doesn't. **Instrumentalism** is a relatively narrow type of pragmatism which says that scientific theories are to be regarded as instruments for making predictions about the results of experiments.

The peculiarities of quantum mechanics

1. Indeterminism. With some exceptions (described below), theories of quantum mechanics differ radically from previous physical theories, not just because their assertions are probabilistic, but because of the fundamental status that is claimed for these assertions. Other uses of probability in physics arise in statements of partial knowledge about a situation; it is assumed that it would be possible to obtain further knowledge which would resolve a probability into certainties. Many versions of quantum mechanics, however, claim that there is no possibility of such further knowledge.

From the birth of experimental science until the advent of quantum mechanics, it had been a basic assumption that every event had a cause; but if the fundamental laws are probabilistic then some aspects of some events are uncaused. The feeling that to accept this is to do violence to the scientific spirit was expressed by Einstein in his famous saying 'I cannot believe that the good Lord plays dice'. To put this in a slightly different light, a general statement like 'every event has a cause' can be regarded not as a statement of *fact* (it can never be falsified), but as a statement of *intention*: we are going to look for a cause for every event. Then quantum mechanics constitutes an admission of failure.

However palatable or unpalatable it may be, indeterminism raises no conceptual problems which are peculiar to quantum mechanics. In examining any proposed interpretation of quantum mechanics, it is important to consider to what extent it serves to elucidate probability statements in general and to what extent it specifically attends to quantum mechanics.

2. Indeterminacy. The way in which properties are ascribed to particles and systems in quantum mechanics is a more puzzling departure from the procedures of classical mechanics. This has two aspects. First, most versions of quantum mechanics (but not all — see below) include a denial of definite values for properties which every particle must have in classical mechanics, such as position and momentum.

Secondly, and more seriously, most versions of quantum mechanics claim that some systems have indeterminate values of their properties at some times, e.g. just before a property is measured.

Indeterminacy is related to indeterminism, since it is the fact that the results of measurements are not rigidly determined by the state vector which makes it impossible to ascribe definite values of an observable to a system; but they should be distinguished, since there are theories in which all observables have definite values but the development of the system is not uniquely determined by those values.

3. **Inseparability.** Most versions of quantum mechanics (perhaps even all versions) deny the possibility of describing the world by dividing it into small parts and completely describing each part — a procedure which is often regarded as essential for the progress of science. Because of this feature, quantum mechanics is sometimes called a **holistic** theory.

4. **The projection postulate.** The projection postulate claims that a new wave function is born whenever we apply the Born rule. This has several problems:

I. The projection postulate is **ill-defined:** there is no precise definition of what constitutes a measurement (this is known as the **measurement problem**), and no specification of the time at which projection is supposed to occur.

II. It is **dualistic**, requiring a division of the world into (microscopic) object and (macroscopic) apparatus. It also splits the law of time development into the deterministic Schrödinger equation and the probabilistic projection postulate.

III. It makes **causality** subjective: as Schrödinger's cat paradox illustrates, it makes physical events consequences of their observation, instead of saying that events are observed because they happen.

IV. It gives no account of continuous observation.

In discussing the various interpretations of quantum mechanics we will pay particular attention to the way they explain the projection postulate.

Seven interpretations of quantum mechanics

No one interpretation of quantum mechanics is generally accepted (although the phrase 'the Copenhagen interpretation' is often used as a synonym for 'orthodoxy', whatever the user thinks that is; it has been applied to at least four different interpretations). After each interpretation we will give the main objections to it. This list of interpretations is not exhaustive (there are others), and the objections given here are not meant to be definitive, or even necessarily meaningful; you may well decide that some of them are wrong or don't make sense.

1. The minimal interpretation

On this view, which was strongly expressed by Bohr (in Copenhagen, hence the vague but common label 'Copenhagen Interpretation'), one should not attempt to interpret the state vector in order to extract information about quantum objects; one should not even speak of quantum objects. The state vector is just a mathematical device used in calculating the results of experiments; to perform such calculations successfully is the sole purpose of any scientific theory.

Such experiments must (logically must) be described in the terms of classical physics, since the apparatus consists of macroscopic objects; we do not know how to describe our experiences with such objects to each other except in the terms of classical physics. If we mention microscopic objects it is only as a shorthand device to refer to some features of a calculation which relates different classically described states to each other.

Similarly, the minimal interpretation does not apply to any cosmological questions which are too large-scale to be posed as experiments.

In following this interpretation it is important to distinguish between **preparation** and **measurement** of a system. A preparation occurs at the beginning of an experiment and is associated with an initial state vector; a measurement occurs at the end of an experiment and its various possible outcomes are associated with vectors which are given probabilities by Schrödinger's equation and Born's rule.

This view dissolves all the puzzles concerning quantum objects, since it says there are no such objects to be puzzled about.

It also dissolves all puzzles concerning the projection postulate. Recall that the projection postulate claims that a new wave function is born whenever we apply the Born rule. In the minimal interpretation there is no projection postulate, for any calculation concerns only a preparation and a measurement, and cannot be extended to describe anything that happens after the measurement; so there is a result from applying the Born rule, but that result is not a new wave function. If an experiment carries on after a measurement M which gave the result α, then one is embarking on a new experiment whose preparation procedure consists of performing the measurement M and selecting the cases in which the result was α.

Objections. This interpretation has been called 'extended solipsism'. A solipsist refuses to accept that the experience of seeing a tree is evidence that the tree exists; there are only his or her own sense experiences. Likewise, a follower of the minimal interpretation refuses to accept that the formation of a charged particle track in a bubble chamber is evidence for the existence of the charged particle; there are only macroscopic events. This is a solipsism on behalf of macroscopic apparatus towards the microscopic objects it perceives. This idea may have been much more plausible in the 1920s when the minimal interpretation was first proposed, when good evidence for the existence of microscopic particles was still fairly new; it seems very strange in the 21st century when we work with microscopic particles all the time, and not just in experiments but also in (for example) engineering and cosmology.

Moreover, it cannot be true that the sole purpose of a scientific theory is to predict the results of experiments. Why on earth would anyone want to predict the results of experiments? Most of them have no practical use; and even if they had, practical usefulness has nothing to do with scientific inquiry. Predicting the results of experiments is not the *purpose* of a theory, it is a *test* to see if the theory is true. The purpose of a theory is to understand the physical world.

Note that there are *two* issues here: one is that the minimal theory is instrumentalist, and the other is that it only allows us to consider experiments which we can perform ourselves. We are not allowed to apply the minimal interpretation to the larger-scale phenomena which we need to consider if we're going to do cosmology.

Although the strict instrumentalist philosophy which underlies the minimal interpretation is often expressed in the form given here, and is open to the above objection, Bohr's formulation was less crude: 'The task of science is both to extend the range of our experience and reduce it to order'. Heisenberg combined this with an *operationalist* view: he taught that a theory should only contain experimentally observable quantities, and proposed that this principle should be applied to elementary particle physics by renouncing all mention of the time evolution of the state vector between preparation and measurement. So not only do microscopic particles strictly speaking not exist except when we make a measurement at the end of an experiment (as Bohr thought), according to Heisenberg we should not even *mention* anything except for the preparation of experiments and measurements of their results. This makes it impossible to even discuss cosmology.

2. The literal interpretation

This is the interpretation which is implicit in most modern textbooks. They speak as if the state vector is an objective property of a system in the same sense as the values of coordinates and momentum are objective properties of a system in classical mechanics. The projection postulate is then a statement about an actual change in the state vector following a measurement.

In this interpretation indeterminism and indeterminacy are simply accepted as facts about the world. Inseparability means that it is not possible to apply this interpretation to subsystems; one cannot say that individual objects have state vectors, but is forced to consider the state vector of the universe.

Objections. The state vector cannot be an objective property of an individual system, for, because of the statistical nature of this interpretation of quantum mechanics, it is not possible to establish by experiment that the state vector is one vector rather than another.

In addition, all the unsatisfactory features of the projection postulate stand as objections to the literal interpretation of quantum mechanics.

3. The objective interpretation

The literal interpretation can be modified by supposing that the state vector is restricted to lie in certain subspaces of state space (see elsewhere in this book for full details), and that it makes spontaneous and instantaneous transitions from one of these subspaces to another with probabilities determined by the Schrödinger equation.

This interpretation eliminates all mention of measurement and projection, and thus avoids all the problems associated with the projection postulate.

Objections. In this interpretation, the development of a system is not solely determined by the state that it happens to be in. Thus the interpretation involves a proliferation of properties of the system. Moreover, some of these properties cannot be determined by experiment.

It is not clear to what extent this interpretation is compatible with special relativity. The state vector must be taken as describing the entire universe, and instantaneous transitions in this state vector seem to conflict with the fact that simulteneity is relative.

4. The epistemic ('subjective') interpretation

Instead of being taken as an intrinsic property of the system, the state vector can be regarded as a representation of the observer's knowledge of the system. Then indeterminacy in the values of observables becomes simply lack of knowledge of these values; and both inseparability and the projection postulate lose their mystery. There is nothing mysterious in the fact that the state vector of a system changes after a measurement if that just means that the observer's knowledge changes; the very purpose of a measurement is to increase one's knowledge.

Objections. Because it refers to a particular observer, this interpretation is sometimes criticised for being subjective. However, the concept of knowledge contains both subjective and objective elements: a statement that a person N knows a proposition P is a statement both about the person (that they believe P) and about the proposition (that it is true). The subjective element can be removed from the epistemic interpretation by considering all possible observers and defining a unique state vector for the system as that which represents the maximum possible knowledge which any observer can have. But this is then an intrinsic property of the system, so that we are back to the literal interpretation.

The attempt to explain away the projection of the state vector as simply an increase in knowledge is shown to be unsuccessful by considering the maximum obtainable knowledge. If this changes, it must be because of a change in the system itself; and the problems of when this happens, and why it should happen when it cannot be derived from the Schrödinger equation, remain unresolved.

This can be clearly seen by considering the case of a decaying unstable particle; when the observer acquires knowledge that the particle has decayed, this is clearly because it *has* decayed, which is hardly a subjective claim.

On the other hand, if one is prepared to accept the charge of subjectivity and insists that the state vector refers to the knowledge of a particular observer, then one faces the question 'What is it that the observer knows?' If it is something about the system, we are back to the literal or objective interpretation; if it is something about the results to be expected from future experiments, we are back to the minimal interpretation.

5. The ensemble interpretation

Some authors deny that the state vector describes the state of an individual system: it can be properly applied only to a large number of systems, all prepared in the same way. In other words, in order to do quantum mechanics, according to this interpretation, we have to start with an "ensemble", which is a set of experiments, all set up in exactly the same way.

Then quantum mechanical probabilities refer to the fraction of the ensemble in which an experiment has a particular result. Those subsystems for which a result α was obtained in an experiment constitute a subset of the original collection, and therefore form a different ensemble; naturally, this is described by a different state vector. Thus the process of projection is not an interruption to the Schrödinger evolution of the ensemble, but a shift of attention to a different ensemble.

Objections. This interpretation is a way of understanding any probabilistic theory.

The concept of an ensemble is vague, because it is not clear what is meant by 'a large number' of systems. If the statements about fractions of an ensemble are to be experimentally meaningful, the ensemble must consist of a finite number of systems. But then there is the possibility that an experiment on the ensemble will yield results in proportions different from those given by the theory. How serious this problem is depends on the size of the ensemble, which is not given by the general theory. Even if the ensemble is large and hence the results are close to those predicted by the theory, the theory itself predicts that the results will not be exactly the same as those predicted by the theory! Hence the theory cannot claim to make any definite predictions.

This problem of a finite ensemble is essentially the same as the problem of lack of definiteness faced by decoherence theories.

On the other hand, if the ensemble is infinite and any finite collection of systems is just a sample from it, then the ensemble is merely a theoretical entity (as opposed to an observable entity). In this case, the ensemble is associated with a particular system in exactly the same way as the state vector is associated with the system in the literal interpretation.

6. The relative-state and many-worlds interpretations

Everett's **relative-state** interpretation is a version of the literal interpretation which makes it possible to speak of the state of a subsystem. It insists, however, that the state of any system has no absolute meaning but is only defined relative to a given state of the rest of the universe. The only state which has an absolute meaning is that of the whole universe, including all observers and their consciousness. This incorporates the projection postulate by emphasising that it is a conditional statement — *if* the result of an experiment was α_1, then the state of the system is ψ_1 — and including this conditionality in the formalism. In this case, ψ_1 is what an observer who has seen α_1 will use to make predictions, and yet the relative state interpretation says that it only describes part of the state vector ψ of the whole universe, and a different observer may be using a differen partial state vector ψ_2 to make different predictions. In 1957, Everett proved the consistency of this procedure of retaining the full state vector, and showed that it could account for the agreement between different observers about what they thought had happened in a particular experiment (even though another part of the universal state vector described a different result).

The **many-worlds** interpretation is a picturesque account of the relative-state interpretation which describes the total state of the universe ψ as a universe which has split into two branches, in one of which the state of the system is ψ_1, the experiment has given the corresponding result α_1, and all observers (in that branch) are aware of that result; while in the other branch the course of events has gone according to another state, ψ_2. In general, wherever the conventional theory requires an application of the projection postulate the many-worlds interpretation says that the Universe splits into 'parallel' worlds of the kind familiar from science fiction stories.

Objections. The relative-state interpretation differs very little from the objective interpretation. By making the universal state vector develop purely according to the Schrödinger equation, it does not formally include the indeterminism which is nevertheless present in the reality experienced by the observers it describes. It might seem more honest to make the formalism describe that reality and no other, i.e. to drop the parts of the universal state vector which describe a situation which we actual observers know to be false. However, by not doing this the relative-state interpretation avoids the ambiguities of the projection postulate.

The many-worlds interpretation sells the pass. To say that an experiment had a result β in some parallel universe (when we observed it to have the result α) is surely just another form of words for saying that it might have had the result β, but didn't. We are perfectly entitled to define the 'real world' to be the one in which what we observed to happen did happen; then the splitting of the universe into several branches, only one of which is real, is exactly the same process as that described by the projection postulate, and is beset by exactly the same problems of defining when and under what circumstances it should happen.

In defence of the many-worlds interpretation, it can be claimed that it is justifiable to call an event 'real' if it can have an observable effect, and that this is true of the experimental results which we did not observe, because of possible interference between different parts of the Universal state vector. These effects are present in the objective interpretation, in which the situation is described by saying that the future development of the system is affected by the unrealised possibilities for the results of past experiments.

7. Hidden-variable interpretations

Hidden-variable theories claim that all observables have precise values at all times. These theories differ in how they predict the results of experiments, although they all use the Schrödinger equation or something very similar (such as a relativistic variant of the Schrödinger equation). Some hidden-variable theories, such as the Transactional interpretation, are time symmetric and therefore may have implications for cosmology.

Objections. If the hidden variables are so carefully hidden as to make them undetectable apart from the state vector, one has very little reason to believe in them. Bohm's hidden-variable theory, for example, contains implausible assumptions about the 'quantum potential' which determines particle positions.

There is a continuum between hidden-variable interpretations and objective interpretations. Some choices of special subspaces in the objective interpretation make it a type of hidden-variable interpretation.

Bell's theorem shows that hidden-variable interpretations, whether deterministic or not, must postulate either instantaneous action at a distance (conflicting with special relativity) or backwards causation.