Part II
The Classical/Quantum Divide

Intermezzo

Part I was primarily concerned with the development of the language of physics and the ways in which it came to relate to the mathematical formulations used in physics. Part II has a different function. It develops a novel perspective for the interpretation of quantum physics. The present introduction is intended to serve a double function. First, since this is a very unfamiliar perspective for the interpretation of quantum physics, I will indicate why it is needed and how it will be developed. Second I presume that this book may be read by some philosophers and others who are not proficient in the mathematics of quantum physics. As an aid I will present a non-technical summary of the developments that follow.

The mid-1920s witnessed the birth of quantum mechanics, wave mechanics, and a linguistic crisis in attempts to give a coherent formulation of experimental results. Bohr effectively mitigated this crisis by introducing a semantic shift from ontological to linguistic considerations. Experimental physicists, like Clint Davisson were agonizing over the problem of how an electron could be both a particle and a wave. Bohr transformed this into an issue of determining the circumstances in which either particle or wave language supplies the appropriate vehicle for describing experimental situations and reporting results. After some version of the Bohrian semantic guidelines were assimilated and accepted, the linguistic crisis that precipitated the changes submerged beneath the conscious awareness of the physics community.

The interpretation of quantum mechanics as a system regularly reemerged as a problematic issue through the Bohr-Einstein debates, the introduction of hidden variable interpretations, through criticisms by philosophers like Karl Popper, and through paradigm shifts in the philosophy of science. These shifts led to attempts to give quantum mechanics and quantum field theory a rigorous mathematical formulation in accord with either an axiomatic or a semantic model of theories. Both methods shared a common feature. Language as such plays no role in the interpretation. Thus a realistic approach to interpreting a formulation of quantum mechanics that accords with the semantic method of interpretation asks: What must the world be like if this theory is true of it? If answers to this question are not convincing, then philosophers can switch from an ontological to an epistemological perspective, interpreting quantum mechanics or quantum field theory in terms of observables. There are variants. An anti-realist interpretation insists that a theory need not be true to be acceptable. A modal interpretation asks what might the world be like. In all these methods of interpretation language, considered as a separate unit, plays no role. Even a switch to an epistemological foundation relies on empiricists accounts of knowledge, rather than analysis or phenomenology. The most unfortunate consequence of this exclusion of linguistic analysis is an exclusion of experimental analysis. Experiments are cited only as supplying data that test theoretical predictions. This leads to a logical lacuna. In contemporary particle physics theoretical predictions are never tested by comparison with data as such. They are tested against inferences drawn from the data. These inferences are informal. As was indicated earlier we call inferences formal if they depend on syntactic rules whose validity does not depend an the matter to which the rules are applied. In an extension of this method, a formal interpretation of a theory imposes a semantics on an already formulated syntactic structure. Informal inferences rely on the meanings of the basic concepts employed and are generally context-dependent. Galison, Franklin, Pickering, and others have brought out the richness of the traditions in experimental research and their quasi-independence. Experimental inferences cannot be interpreted as phenomenological models of the theories being tested. To deal with these separated but coordinated inference systems we need a dual-inference model of the practice of physics. Earlier we discussed dual-inference systems and had some remarks on their role in classical physics. Formal and informal inference systems were coordinated by their relations to the same objects. However, we did not develop a general theory of dual-inference systems. I believe that an attempt to develop and impose a theory of dual-inference systems would be misleading, since informal inferences are context-dependent. Fortunately, there is a better approach. The development of atomic, and particularly of particle, physics has been characterized by a broad and detailed collaboration between theoreticians and experimenters. Accordingly, we will consider the discourse between theoreticians and experimenters. Our limited focus will be on the role of informal inferences and on how the framework of informal inferences relates to the mathematical formulations used in quantum physics. Two preliminary remarks give an initial orientation. First, in informal inferences there is no sharp distinction between syntax, semantics, and pragmatics. Material inferences often hinge on the meanings of the terms used. The practice depends on choices made by experimenters. Second, informal inferences rest on presuppositions, not axioms. In a formal system anything follows from axioms that allow contradictions. This also applies to informal inferences, as indicated by the dictum of medieval logicians: *Ex falso sequitur quodlibet*. Hence, the need to consider the presuppositions that are implicit in experimental inferences and methods of restricting their use to avoid contradictions. If the inferential system allows contradictions, then no inferences are reliable. Since theoretical predictions are tested against the conclusions of informal inferences, an unreliable inferential system does not supply an adequate basis for testing theoretical predictions.

With this background we can outline the inner logic implicit in the material that follows. We begin with the linguistic crisis of the mid 1920s and the semantic guidelines stemming from Bohr that avoided the contradictions physicists were encountering. These developments led to the famous, or notorious, Copenhagen interpretation of quantum mechanics. This is now widely rejected by philosophers as a seriously misleading guide to the interpretation of quantum mechanics as a theory and rejected by some of the physicists who pay attention to such issues as inadequate to advances in quantum field theory and particle physics. When quantum mechanics is interpreted *as a theory* and the Copenhagen interpretation is taken as an interpretation of that theory, then it is almost impossible to understand the original position of the Copenhagen patriarchs. Bohr, Pauli, and Heisenberg all defended the idea that quantum physics is best understood as a rational generalization of classical physics. Before rejecting this idea as preposterous we should indicate how this approach can be developed and whether it can make a contribution to interpreting quantum physics.

Bohr's basic program was very simple. The resolution of the linguistic crisis led to guidelines for extending basic classical concepts and for restricting their usage in quantum contexts. He regarded the mathematical formalism as an inferential tool, not as a theory to be interpreted. The development of the mathematical formalism hinged on representing basic classical terms, such as 'position', 'momentum', and 'energy' by mathematical operators and translating restrictions on the use of these terms into restrictions on the use of the corresponding operators. Then one has the basis for a mathematical formalism that relates in a coherent way to the proper usage of terms in experimental contexts and the inferences experimental analysis supports.

This is a polar opposite to formal interpretations. It also seems like a preposterous example of a tail wagging a dog. Quantum mechanics has clearly replaced classical mechanics as the basic science of reality. Nevertheless, this approach is worth exploring for at least two reasons. The first is an Occamist approach to interpreting physics. If the theory can function on this minimalist basis then it is not necessary to interpret the mathematical formalism as a theory. A functional interpretation suffices. Second, we are concerned with the interrelation of formal and informal inference systems. They cannot be related by any method that trivializes the role of experimentation. Hence we will attempt to relate them by beginning on the other end, with informal inferences. Does an analysis of the distinctive features of quantum experiments supply a basis for developing the mathematical formalism of quantum mechanics? My answer to this question relies on an exploitation of the work of two outstanding quantum theoreticians, Paul Dirac and Julian Schwinger. Dirac introduced and Schwinger developed the idea that the distinctive features of quantum measurements expressed in classical terms supply a basis for developing the mathematical formalism of quantum mechanics. I will call this the 'measurement interpretation'. It is essentially an austere version of the Copenhagen interpretation. The new label is needed to avoid identifying the measurement interpretation with the various versions and misinterpretations of Copenhagen found in the literature.

This background clarifies the argument threading through the tapestry of issues that unfolds. We begin with the formation of the orthodox, or Copenhagen, interpretation of quantum mechanics and focus on Bohr's clarification of the use and limits of classical concepts in quantum contexts. Then we consider his relatively unknown analysis of the roles of 'particle' and 'field' in nuclear physics and quantum field theory. Next we show how these semantic rules can guide the formation of the mathematical formalism. We use Schwinger's extension of the measurement interpretation to quantum electrodynamics and quantum field theory to assess the limits of validity of the measurement interpretation. There are two types of limitations. First, the measurement interpretation, or any version of the Copenhagen interpretation, does not supply a proper basis for evaluating quantum mechanics as a theory. This is because the measurement interpretation treats the mathematical formalism as a calculational tool, not as a theory. Second, and more pertinent to the present development, the measurement interpretation is inadequate to advances in quantum field theory and quantum cosmology. However, it is functionally adequate to non-relativistic quantum mechanics, quantum electrodynamics, and basic quantum field theory.

The measurement interpretation is a semi-classical, or phenomenological, interpretation of quantum mechanics. It uses properly restricted classical concepts as a semantic basis for interpretation. Since quantum mechanics is the fundamental science of physical reality, an interpretation of quantum mechanics should rest on a quantum, rather than a classical, foundation. Many interpretations attempt to accomplish this in an ontological way by relating a suitably reconstructed mathematical formulation to the reality it is a theory of. I follow the practice of physics in relating the mathematical formalism to its experimental basis, a framework of consistently reportable claims. Physicists go beyond this basis through experimental discoveries and theoretical hypotheses. I attempt a very limited philosophical advance. First I clarify the relative ontology of the measurement interpretation and then consider characteristic quantum properties and processes that this framework cannot accommodate and that a quantum interpretation must accommodate. A *relative* ontology is an explicitation of an account of reality implicit in or presupposed by a systematization of some branch of knowledge. As discussed earlier, one systematization of our ordinary language relies on a basic subject/object distinction and represents physical realty as an interrelated collection of spatio-temporal objects with characteristic properties and causal properties. We defer a consideration of the subject aspect to the final chapter. This is a minimal *lived-world* ontology, not an account of physical reality as it exists objectively. Particular sciences may have a relative ontology that plays a presuppositional role. Thus, much of chemistry relies on an account of atoms and molecules with definite sizes and shapes.

An ontology of objects with properties is inadequate to the quantum realm. Quantum mechanics treats *systems* with properties. Three distinctively non-classical properties characterize quantum systems: superposition of states, interference, and non-locality. Also, in a sharp break with classical methods, quantum physics treats *virtual* processes in the same way as observable processes. This claim is elaborated by examining the treatment of virtual processes in quantum electrodynamics, where they emerged into prominence. Before attempting an interpretation of this physics we consider a preliminary question. What function does any interpretation of a scientific theory, or a scientific practice, fulfill?

We distinguish an implicit functional interpretation from an explicit imposed interpretation. An explicit interpretation is useful either when the functional interpretation is perceived as inadequate to advances in physics, or when one is asking external questions about a theory or practice, or tradition. My method of interpretation focuses on the practice of physics, rather than on reconstructed theories, and looks for a revised interpretation that meets three requirements. It must incorporate the features of the measurement (or Copenhagen) interpretation that account for its unprecedented empirical success. To put quantum physics on a quantum, rather than a semi-classical, foundation, it it should assign a foundational role to the characteristic features that distinguish quantum from classical physics. Finally, it should be capable of accommodating advances in quantum field theory and quantum cosmology. The two leading replacement candidates are a *many-worlds* interpretation and a *consistent-histories* interpretation. I indicate why I consider the Gell-Mann–Hartle version of the consistent histories interpretation a reasonable choice.

The concluding chapter has a novel purpose. Contemporary philosophy manifest a sharp gap between analytic or phenomenological treatments of the lived world and analyses of scientific theories as relatively isolated units. The present work brings out the underlying conceptual continuity between an ordinary-language framework and the developing language of physics. This modifies both ends of the philosophical gap. It undercuts the presuppositions analysis and phenomenology often rely on to downgrade the role of science. It undercuts the methodology of interpreting scientific theories as isolated units insulated from lived-world ontology. I examine the bearing this change has on some basic philosophical problems. I am more concerned with analyzing how the *problematic*, or the implicit presuppositions, must be modified than in proposing solutions. The issues considered are: the continuity underlying scientific development; realism, reductionism versus emergence, and the interrelation of the human and scientific realms.