1

Introduction

1.1 Motivation

The aim of this book is to introduce, develop, and apply *quantized detector networks* (QDN), an information-based, observer-centric approach to *quantum mechanics* (QM). Six reasons motivating our development of QDN are the following.

Avoidance of Metaphysical Speculation

There is such a variety of unproven (and unprovable) speculation concerning the interpretation of QM that the subject of this book, QDN, may appear at first sight to be yet another in this growing branch of metaphysics. In fact, our motivation is precisely the opposite. QDN was intended from the outset to reduce the level of metaphysics in the application of QM. To achieve this, our strategy is to move the traditional focus of attention away from *systems under observation* (SUOs) and toward the observers of those SUOs. In QDN, wave functions represent not states of SUOs but states of apparatus. We shall call such states *labstates*, to distinguish them from states of SUOs (which do have a place in QDN). It is only labstates that observers can ever deal with directly.

In this respect, QDN is an attempt at a more laboratory-based description of quantum physics than standard QM, focusing as much on *how* an experiment is done as on the results of that experiment. For example, instead of talking about the wave function of an electron, QDN talks about the labstate of the signal detectors that allow us to say anything about that electron in the first place. That is all, there is nothing deeper. Whether or not electrons actually "exist" is thereby relegated to an inessential metaphysical issue that we can choose to ignore.

It is important to understand what QDN does not say as much as what it does say. QDN does not say that electrons do not "exist". QDN merely asks for an empirical definition of "existence".

QM Is Much More Than a Calculational Device

Many physicists hold the utilitarian view that the success of quantum theory in predicting experimental data is sufficient for their purposes, and that further inquiry is really the business of metaphysics and therefore outside the scope of science proper. We cannot say that this is entirely unreasonable. However, we take the view that QM represents such a radical departure from the principles of classical mechanics (CM) that this pragmatical view cannot be all there is to the subject.

New Interpretations Lead to New Experiments

The history of QM is littered with the debris of various interpretations and paradigms. Planck's quantization of energy (Planck, 1900b), Bohr's radiation damping veto (Bohr, 1913), de Broglie's pilot waves (de Broglie, 1924), matrix mechanics (Heisenberg, 1925), wave mechanics (Schrödinger, 1926), the Copenhagen interpretation (Heisenberg, 1930), Hidden Variables (Bohm, 1952), the Relative State interpretation (Everett, 1957), decoherence (Zurek, 2002), and the Multiverse (Deutsch, 1997) are some of the most discussed views of what quantum theory means. We do not think any of these ideas are right or wrong in an absolute sense, because we do not know what that means. It is clear, however, as we shall argue later, that some interpretations are empirically vacuous, meaning that they can be neither proved nor disproved according to scientific empirical protocols. It is our inclination to avoid vacuous concepts and theories.

When examined in detail, each interpretation of QM has led to new insights and questions that have motivated new experiments, resulting in advances in physics.[1]

Strength in Diversity

There is no evidence for the view that there is, or even should be, a single, best way to do QM. For instance, while we believe that quantum electrodynamics (QED) can explain almost everything about the hydrogen atom, the Schrödinger wave equation does a good enough job most of the time and far more economically. QDN is but another way to describe and formulate quantum physics; it will have advantages in some contexts and disadvantages in others.

Logical Development

QDN is not intended to replace QM. On the contrary, QM works brilliantly and it would be foolish to think we could do better. QDN is intended to enhance QM in areas where little or no attention has been paid hitherto: the observer and their apparatus. QDN seems to us to be a logical application of successful principles that sooner or later would be developed further along the lines taken in this book.

---

[1] Not in every case, unfortunately.

Human Conditioning

There is now a great deal of empirical evidence for the proposition that humans see the world not as it is but how they have been conditioned to see it (Halligan and Oakley, 2000; Kahneman, 2011). This conditioning occurs because of various forces: evolutionary, genetic, cultural, linguistic, familial, political, and so on. CM is based on ordinary, everyday-life human experience. QM was developed recently, only just over a hundred years ago, and only once sufficient technology had been developed that could reveal the deficiencies in our classical conditioning. We have not caught up with QM in our modes of thinking, and it is not obvious that we ever will. It remains a natural tendency for even the most experienced quantum theorist to explain things in familiar terms, such as space, time, and particles. QDN can be seen as an attempt to steer the theorist away from those conditioned thoughts whenever it is wise to do so.

1.2 Physics, Not Metaphysics

To motivate the QDN approach, we review in this chapter some of the conceptual foundations of QM that are relevant to us here. Before we do that, however, a few words of caution about the relationship between physics and metaphysics seem advisable.

In this book, whenever we refer to *metaphysics*, we shall mean the study of propositions and assertions that cannot be empirically tested, that is, cannot be assigned a truth value relative to any physical context. In our view, it would be a serious error to leave the interpretation of QM to metaphysicists and philosophers. If they had something to contribute that was empirically testable, then they would be physicists, not metaphysicists and philosophers.

However, while it is true that physics is properly concerned only with empirically testable propositions, this does not mean that physicists should never deal with abstract concepts. Physicists after all only do physics because of the way they think and are motivated. Those processes are not currently regarded as legitimate concerns in physics, but that is probably due to the status of technology at this time.[2]

Moreover, physicists use mathematics all the time, because it is the best language in which to formulate theories and propositions about the subject. But all of that takes place in the theorist's mind; theories do not exist by themselves. Mathematics is based on axioms and postulates that are tested not empirically but only for internal logical consistency.

Furthermore, the process of objectivization (the attribution of material existence and properties to recurring and persistent physical patterns and processes)

---

[2] This may well change with advances in the neurosciences. Observers are fundamental to physics, so how observers operate and fit into the grand scheme of things seems a reasonable subject for investigation.

is the only way that physics is done. Significant examples are the concepts of SUO, observer, particle, atom, molecule, wave function, space, time, apparatus, and so on. These are all mental constructs and essentially metaphysical in nature.

There is a paradox of sorts here involving the use of mathematics in physics. A conventional, indeed perhaps ubiquitous, view about empirical physics is that the empirically discovered laws of physics are independent of observers. Yet observers are indispensable. Observers are needed first to formulate theories (which do not exist except in the minds of theorists) and then to test those theories empirically. It is a metaphysical proposition to assert or to believe the proposition that the properties of objects "exist" independently of observers or observation. How could we prove that proposition? We shall call this idea the *realist* interpretation of physics, otherwise known as realism.

The paradox is that the realist interpretation has been remarkably successful in classical physics, that is, the interpretation of phenomena according to the laws of CM based on the Newtonian space-time paradigm or the Minkowski/general relativistic spacetime paradigm. That success has led many physicists to believe that this interpretation should apply to the whole of physics.

The paradox we refer to above has an additional twist: the classical realist position simply does not work when applied to real physics experiments that go beyond a certain basic level of sophistication. It just does not. The empirical evidence against the classical realist position as the be-all and end-all is now virtually unbreakable, although there will always be theorists who do not accept that statement. We have in mind the Bell inequality-type experiments that are discussed in Chapter 17. These have now established beyond much reasonable doubt that classical intuition is deficient when it comes to quantum physics (by which term we mean those experiments where quantum phases are significant). Therefore, something has to give.

This book is an explanation of our interpretation of what quantum mechanics really means, which is that it is a theory of observation. This involves the observer as well as the observed.

The resolution of the above-mentioned paradox that led us to QDN was the painful acceptance of the fact that physics is done by humans. This fact is painful in that the current tendency in physics is to avoid reference to humans specifically, and to marginalize observers as much as possible. There is a standard reason given for this, often referred to as *the principle of general covariance*. This is the assertion that the laws of physics are intrinsic and independent of observers.

The principle of general covariance is, when examined properly, a vacuous proposition, but the paradox is that it works in CM, particularly in general relativity (GR). Some theorists even employ it in their formulations of quantum theory. Such efforts invariably end up as branches of mathematical metaphysics, because QM is all about real world physics and experimentation. We think that perhaps science has reached the point where observers should be factored much more into the equations somehow. That agenda is not easy, and is what this book is all about. What helps greatly here is the hard fact that, logically, there can be no empirical evidence for the realist position or for the universality of the principle of general covariance, because the very notion of empirical evidence necessarily involves human observers. You cannot have your cake and eat it. You cannot use observation to prove that the laws of physics are independent of observation.

If there is one thing that QM teaches us, then, it is the uncomfortable lesson that not all intuition stands up. Sometimes, particularly when it comes to quantum processes, the natural human interpretation of what is believed to be going on is inconsistent, or just meaningless.

Our considered view, then, is that QM is not a theory describing objects per se but a *theory of entitlement*. QM provides us with a set of rules that tells us what we as observers are entitled to say in any particular context, *and no more*. The good news is that this theory of entitlement is self-consistent and has definite mathematical rules that have never yet been found to fail.

We illustrate the sort of scientific philosophy that guides us in this book with the following, scenario A. Suppose a hundred, a thousand, a million observers had independently measured some quantifiable property about some SUO S and had come up with the same numerical value to within experimental error. Then it would be natural to assert that S "has" that property. That is something we do all the time. We say that our house "has" four bedrooms, that our car "is" white, that John "is" tall, and so on. The logic seems inescapable. The world around us "has" properties that we discover.

But when it comes to quantum physics, there is now enough evidence that tells us that we cannot always rely on the above assertion. We cannot exclude the possibility that the very processes used to "see" those presumed properties of SUOs create, in some way, those very properties. If we take this as a warning, then the only thing that we would be entitled to say about scenario A with real confidence is only what we could be sure of: that a hundred, a thousand, a million observers had independently performed some procedure and obtained the same number to within experimental error.

This may sound limited, cautious, lacking in vision, and so on. But the history of empirical quantum science over the last several decades has shown unambiguously that if we made the realist assertion that SUOs "have" measurable properties, then sooner or later we would come to an empirically observed breakdown of some prediction based on that assertion. The theorist Wheeler went so far as to formulate this principle of entitlement in the form of what he called the *participatory principle*:

> Stronger than the anthropic principle is what I might call the participatory principle. According to it we could not even imagine a universe that did not somewhere and for some stretch of time contain observers because the very building materials of the universe are these acts of observer-participancy.

> You wouldn't have the stuff out of which to build the universe otherwise. This participatory principle takes for its foundation the absolutely central point of the quantum: No elementary phenomenon is a phenomenon until it is an observed (or registered) phenomenon.
>
> (Wheeler, 1979)

So how should we interpret the empirical agreement of the observers' measurement on system S? The answer is to look only at what the facts tells us, and in this case, they tell us no more than that a bunch of observers agree on a measured value. The important point is that there is consistency (or reproducibility) in their observations. It is *consistency* that is the key here and in all empirical science (and indeed mathematics). Consistency requires observers, for if we did not have observers, who is the judge of consistency? Therefore, we should interpret the laws of physics not in terms of absolute properties of systems under observation, but as consistency relationships between what observers do.

This means that we are proposing a psychological shift in emphasis, a change in our perspective of what physics is about. In QDN, physics is not the study of SUOs and the determination of their assumed properties, but the study of the relationship between observers and their apparatus. That is the basic logic on which QDN has been developed. QDN is essentially a theory of *entitlement*, a set of rules for what observers can say with relative confidence about their apparatus under contextually relevant circumstances.

We need to add one critical comment here. The QDN approach emphatically does *not* assert or require us to believe that nothing exists outside of observation. Indeed, were we to take such an attitude, we would have no way of calculating the transition amplitudes needed to make predictions. As theorists, we are entitled to model the *information void*, the unobserved regime between state preparation and outcome detection, in any way that leads to successful predictions. To that extent, QM really is like a black box of tricks, whose workings we can only guess at.

1.3 A Brief History of Quantum Interpretation

Before 1900

To understand the impact QM had on physics, we should first understand the principles of CM that most physicists accepted prior to 1900, the year in which Planck stated his quantum hypothesis.

CM is a view of physical reality that is predicated on the way that humans normally perceive and interact with their environment. Without any additional equipment, a typical human interacts with their surroundings by vision, by touch, by sound, by taste, and by smell. Several critical facts about each of these senses conspire to lead the human brain to subconsciously create mental models of their environment, and it is these models that were used by theorists such as Newton, Lagrange, and Hamilton as the basis on which to construct CM. Four of these critical facts are the following.

Length and Time Scales

Humans are relatively enormous compared with atomic scales, so much so that the existence of atoms was not established conclusively until just over a hundred years ago. Matter therefore gives the impression of being continuous. Moreover, the dynamical processes responsible for the stability of atoms and molecules have time scales that are long enough to create the illusion that we shall refer to as *persistence*, the idea that SUOs and observers exist as meaningful entities over significant intervals of time and therefore can be objectified (that is, can be given individual identities).

Daylight Is Bright

To the human eye, daylight is relatively bright. The human brain interprets objects that it sees visually not in photonic, that is, discrete, terms but rather as a continuous process. The net effect is to create the illusion that well-defined objects or SUOs exist over extended time scales in continuous space and time.

Apparent Observer Independence

Different human observers looking visually at an object will generally agree that they see the same thing, albeit with different relative positions and velocity components. This belief leads to the principle of general covariance mentioned above, the idea that intrinsic properties of SUOs are independent of observers and frames of reference.

Zero Observational Cost

When humans see and hear objects, there is generally no noticeable effect back on those objects due to that observation. In quantum physics this is referred to as *noninvasive measurability*.

These facts and others, such as the way that the human brain processes information, all conspire to give the impression that objects under observation “have” physical properties independent of any observer. Moreover, these properties can be measured nondestructively and understood by the rules of classical mechanics. For example, in Newton’s laws of motion, there is no mention of any apparatus or observer, apart from the implication that these laws are stated relative to inertial frames of reference.

After 1900

Up to 1900, virtually all physicists thought about space, time, matter, and the way physics was to be done in the above classical terms. The advent of special relativity (SR) in 1905 in no way changed this perspective: special relativity is all about the differences between observers and how they see things classically, and not about those things themselves. Indeed, theorists such as FitzGerald (FitzGerald, 1889), Larmor (Larmor, 1897), and Lorentz (Lorentz, 1899) had been working out many of the details of SR well before 1900, basing their work on the Newtonian space-time paradigm. Their work and that of Einstein in his landmark 1905 paper on SR (Einstein, 1905b) had nothing to do with what Planck started in 1900. So little, in fact, that bridging the gap between SR and QM remains perhaps the greatest challenge in mathematical physics.

Up to 1900, Planck had been trying to understand the empirical data from experiments on black body cavities, using Newtonian physical principles and Maxwell's theory of electromagnetism. That approach led to the prediction that the intensity of light emitted from a black body would grow with frequency, but the data indicated otherwise. In 1900, in order to understand the data, he approached the problem in a new way, departing from conventional principles.

To understand properly what Planck did *not* say in 1900, we need to understand what Einstein *did* say in 1905. In that year, Einstein explained the photoelectric effect in terms of particles of light (Einstein, 1905a). These particles subsequently became known as photons (Lewis, 1926). What seemed paradoxical, and still does to this day, is that photons are regarded as particles associated with Maxwell's theory of electromagnetism, a classical theory that predicts that light is a wave process and not a particulate process.

Planck did *not* assert that light itself was quantized. What he said was that the black body data could be explained if the assumed atomic oscillators lining the walls of a black body cavity could *absorb and/or emit* electromagnetic radiation only in well-defined amounts, known as quanta:

> Let us consider a large number of monochromatically vibrating resonators – N of frequency ν (per second), N' of frequency ν', N'' of frequency $\nu'', \ldots$, with all N large number – which are at large distances apart and are enclosed in a diathermic medium with light velocity c and bounded by reflecting walls. Let the system contain a certain amount of energy, the total energy E_t (erg) which is present partly in the medium as travelling radiation and partly in the resonators as vibrational energy. The question is how in a stationary state this energy is distributed over the vibrations of the resonators and over the various of the radiation present in the medium, and what will be the temperature of the total system.
>
> To answer this question we first of all consider the vibrations of the resonators and assign to them arbitrary definite energies, for instance, an energy E to the N resonators ν, E' to the N' resonators $\nu', \ldots$. The sum
>
> $$E + E' + E'' + \cdots = E_0$$
>
> must, of course, be less than E_t. The remainder $E_t - E_0$ pertains then to the radiation present in the medium. We must now give the distribution

> of the energy over the separate resonators of each group, first of all the distribution of the energy E over the N resonators of frequency ν. If E considered to be continuously divisible quantity, this distribution is possible in infinitely many ways. We consider, however – this is the most essential point of the whole calculation – E to be composed of a definite number of equal parts and use thereto the constant of nature $h = 6.55 \times 10^{-27}$ erg·sec. This constant multiplied by the common frequency ν of the resonators gives us the energy element ε in erg, and dividing E by ε we get the number P of energy elements which must be divided over the N resonators. If the ratio is not an integer, we take for P an integer in the neighbourhood.
>
> (Planck, 1900a)

Planck's idea was altogether conceptually different from that of Einstein. We can see the difference directly in the above quote from Planck's paper: Planck is concerned there with E_0, the energy associated with the oscillators, whereas Einstein discussed $E_t - E_0$, the energy of the radiation in the cavity. These are very different things.

Einstein was a confirmed realist who never accepted Bohr's interpretation of QM, that is, the set of ideas generally referred to as the Copenhagen interpretation. We have to side with Bohr here: the assertion that photons "exist" is a vacuous one. How could we confirm that there are "particles of light" *without* using detectors that are themselves subject to Planck's quantum principle, absorbing and/or emitting energy in discrete amounts only?

QDN can be understood as a return to Planck's original position, away from the objectification of quanta as "things" and toward the view that quanta characterize processes of observation as they are in the real world of physics. QDN is fully in accord with the principles laid down by Heisenberg, Born, and Bohr, but not with the diametrically opposing views held by followers of HV or the Many Worlds paradigm. We regard those as vacuous, reflecting the classical conditioning that humans are generally subjected to: no more than contextually incomplete attempts to explain the nonclassical rules of quantum mechanics in realist terms.

1.4 Plan of This Book

The nature of the subject we are discussing makes a division into four themes helpful. Each theme has its own particular characteristics and flavor.

The first theme, *Basics*, runs from Chapters 1 to 9. This theme builds up the formalism of QDN from basics, starting with a review of what QDN is about, then turning to the mathematics of classical bits, then quantum registers, and finally the positive operator-valued measure (POVM) approach to quantum physics.

The second theme, *Applications*, runs from Chapters 10 to 20. In it, QDN is applied to a number of experiments that show how QDN differs from standard quantum formalism. We include recent, exciting experiments, typically in quantum optics, such as quantum eraser, delayed choice, and Bell and Leggett–Garg inequality experiments.

The third theme, *Prospects*, runs from Chapters 21 to 26, and is more speculative than the previous themes. In it, we discuss the prospects for future application of the QDN formalism, such as the possibility of constructing a generalized theory of observation.

The final theme, *Appendices*, consists of material that stands alone but is referred to at various places in the other themes.

1.5 Guidelines for Reading This Book

The subject of quantum mechanics and its interpretation has had a long and tortuous history. There is now good empirical evidence for the statement that quantum processes cannot be explained using classical modes of thinking.

It is inevitable that we should comment in this book on topics that may appear metaphysical; that is unavoidable because there is no point in presenting a detailed mathematical formalism (which we do in due course in this book) if we do not say what we think it means in real-life terms. This book is aimed squarely at representing what is actually done in a laboratory, not what is imagined is done.

Although the substantive mathematical formalism starts in Chapter 3, we would advise the reader to go over the first two chapters, in order to gain a feeling for what we are about in this book. The mathematics relating to those concepts is developed in the main body of the text. Most of that mathematics will be familiar and not reviewed in much detail, but where novelty is encountered, mathematical structures are explained more fully.

An important aspect of our approach in this book is the concept of *architecture*, by which we mean a verbal or diagrammatical description of the processes involved in an experiment. Different experiments may have different architectures. For example, an elementary particle scattering experiment will usually involve an initial *in* state, an intermediate scattering regime, and a final *out* state. That architecture is sufficient to describe electron–proton scattering at relatively low energies, but if unstable particles are emitted in what appears to be the final state, then their decay processes require the architecture to be extended in time to include the detection of their decay products. Another important example of architectural differences concerns the distinction between *pure* states and *mixed* states in QM. Architecture is involved intimately in delicate subjects such as Bell inequality experiments, where failure to appreciate details of architecture, particularly those involving counterfactual arguments, can lead to confusion and misleading conclusions to be arrived at.

Acronyms are used extensively throughout this book. We follow the general convention that the first instance of an acronym in any chapter is defined at that point and the acronym used thereafter in that chapter. For convenience, there is a list of acronyms after the Preface.

Where important concepts, paradigms (modes of thinking), and theories are encountered, we will capitalize their first letters. For instance, we shall write Absolute Time and not absolute time, Universe and not universe, and so on.

1.6 Terminology and Conventions

Basic mathematical concepts such as vector spaces and Hilbert spaces are reviewed in the Appendix.

Maps, Operators, Transformations

If U and V are two vector spaces over the same field, then any process, linear or otherwise, that takes any vector in U into V or back into U will be referred to as a *map*, *operator*, or *transformation*, depending on context.

Retractions

If f is a function that maps a set A into a set B, we denote the set of image points in B by $f(A)$. In this book we encounter situations where $f(A)$ is a proper subset of B, which means that there are elements in B that are not images of any element in A. If f is an injection, which means that there is a one-to-one correspondence between elements in A and elements in $f(A)$, then the retraction $\overline{f}$ of f is the well-defined function with domain $f(A)$ that takes elements from $f(A)$ back into A, given by $\overline{f}(f(a)) = a$ for any element a of A. We shall use retractions a lot in this book.

The Two Worlds

As QDN was being developed, it became clear that the theory was dealing with two separate worlds: the inner world of the system under observation and the outer world of the observer and their apparatus. Linking these two worlds are the quantum processes of interest. Therefore, it became necessary to devise a notation that could readily distinguish between these two worlds, yet retain all the characteristics of quantum mechanics.

Our notational solution to this problem is the following. We shall deal frequently with a *total Hilbert space*, the tensor product $\mathcal{H} \otimes \mathcal{Q}$ of two Hilbert

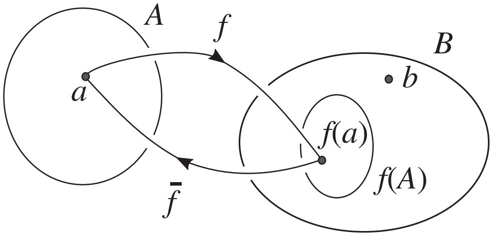

Figure 1.1. If $f : A \to B$ is an injection and $f(A)$ is a proper subset of B, then there are elements such as b in B for which the retraction $\overline{f}$ of f is not defined.

spaces. The first Hilbert space $\mathcal{H}$ will contain the *system states*, the imagined states of the SUO, and for those we shall use the conventional and familiar Dirac bra-ket notation $|\Psi\rangle$, with inner product $\langle\Phi|\Psi\rangle$, and so on. The second Hilbert space, $\mathcal{Q}$, will be a quantum register containing the *labstates*, the quantum states of the apparatus. For these labstates we shall use bold notation $\boldsymbol{j}$ and their duals will be denoted $\overline{\boldsymbol{j}}$. Labstate inner products are denoted $\overline{\boldsymbol{i}}\boldsymbol{j}$, and so on. *Total states* are elements of the total Hilbert space and denoted by $|\Psi, i) \equiv |\Psi\rangle \otimes \boldsymbol{i}$, noting the round bracket on the left-hand side of this definition. Inner products of total states are given by

$$(\Phi, i|\Psi, j) = \langle\Phi|\Psi\rangle\overline{\boldsymbol{i}}\boldsymbol{j}. \tag{1.1}$$

The use of bold font for labstates and overlined bold font for their duals is consistent with the question and answer formalism described in the next chapter.