Interpretation and Reality in Quantum Mechanics

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Abstract

The quest for finding the right interpretation of Quantum Mechanics (QM) is as old as QM and still has not ended, and may never end. The question what an interpretation of QM is has hardly ever been raised explicitly, let alone answered. We raise it and try to answer it. Then the quest for the right interpretation can continue self-consciously, for we then know exactly what we are after. We present a list of minimal requirements that something has to meet in order to qualify as an interpretation of QM. We also raise, as a side issue, the question how the discourse on the interpretation of QM relates to Philosophy.

1. Introduction

There was a period during which quantum mechanics was created (1923-1939), by Werner Heisenberg, Max Born, Pascual Jordan, Wolfgang Pauli, P.A.M. Dirac and Erwin Schrödinger, was axiomatized, by John von Neumann, was applied, by numerous physicists, was interpreted, by Niels Bohr and Heisenberg, was demonstrated to exclude certain alternative theories, by Von Neumann, and was criticized, by Albert Einstein, Schrödinger and others. Over the past decades, philosophers have joined the interpretation effort - with remarkable success. It is often said:

> Physicists know how to use quantum mechanics and, impressed by its success, think it is *true*; but their endless debates about the interpretation of quantum mechanics show that they do not know what it *means*.

There exists a *natural-language-as-we-know-it*(NLAWKI). Heisenberg and Bohr judged NLAWKI, which they considered *the language of classical physics* inadequate to describe what happens in the microphysical world, the world of *very small* physical entities and *very brief* physical processes.

Small wonder. NLAWKI has developed while homo sapiens and its ancestry was wide awake, i.e., interacting with the macrophysical world filled with trees, rocks and animals, and with days, seasons and lifetimes. Man was occupied with fulfilling his biological needs of nutrition, protection and procreation, rather than with penetrating the ephemerally flashing realm of there microworld, explaining the phenomena by means of theories, or unravelling the mysteries of a realm of reality inaccessible by the unaided senses. No one had ever wanted or needed to go above and beyond the waking macrophysical world, or to transcend our biological needs, which we shared with the beasts. But, at some point, the time had come that we did want and did need to go precisely there, and we did want transcend our beastly needs. On Earth, *how*?

Back to the early 20th Century. Understanding the microphysical world was no longer deemed possible with NLAWKI. In order to grasp this realm of reality somehow, only a *symbolic description* by abstract mathematical means seemed possible. What the founding fathers of QM did was not very radical: a comparatively small yet significant enrichment of NLAWKI would initially turn out to be sufficient to unlock the secrets of the atom - but would eventually also lead to perplexities the world of science had never seen before.

2. What are the problems?

No matter how one characterizes QM precisely, e.g., as the deductive closure of a set of sentences (the postulates) in a formal language or through a class of models (structures in the domain of discourse of axiomatic set-theory), or some sophisticated combination of these, QM incontestably has propositional content, expressed in declarative sentences of NLAWKI, enriched with physical and mathematical vocabulary and with symbols.

QM makes a large variety of pronouncements about physical reality, measurements included, that can be and have been tested severely. Sometimes QM says things that raise our eyebrows sky high, like there be non-local correlations that do not fall off with distance and cannot be explained even by an appeal to the entire past of the carriers of the correlations (version of Bell's Theorem), and like a continuously observed kettle filled with water on the fire that never boils (quantum Zeno paradox). For the sake of clarity: we suppose that to observe is to measure, so by contraposition, not to measure is not to observe; to measure is not necessarily to observe. This is correct, because think of, say, measuring the presence of a neutrino or the energy of an electron, which are unobservable entities: we measure but cannot observe.Sometimes QM remains mute when we desperately crave for answers, like when we ask whether Schrödinger's unmeasured, and therefore unobserved cat is dead or alive, since QM does neither fulfill the truth-condition for the sentence *The unobserved cat is alive*, nor for *The unobserved cat is dead*, QM falls silent. Needless to add that the celebrated case of Schrödinger's cat extrapolates to the entire unmeasured part of the universe, which comprises nearly everything. We observe a few drops of the ocean of being. Nearly all of physical reality is *ontically indeterminate*, and therefore is not really reality at all ... QM forbids us to speak whereof we want to speak.

Notice that any use of a theory of meaning, which takes the use of words, expressions and sentences constitutive for their meaning, does not sit comfortably either with earlier saying displayed above: if, *first*, knowing the meaning of QM resides in knowing how to use it, and, *secondly*, granted that physicists know how to use QM in every which way, that is, knowing how to construct quantum-mechanical models of phenomena, knowing how to reason quantum-mechanically, knowing how to calculate measurement outcomes, knowing how analyze experiments using QM then they should *know* its meaning, whereas the endless debates about the interpretation of QM - which we shall provisionally call its *hermeneutic*(the theory of text interpretation) predicament - is taken to show the contrary, namely that they *do not know* what QM means.

If the project to *interpret* QM is, in good hermeneutic fashion, to assign meaning to it, we must ask which expressions of QM stand in need of interpretation, because, then, apparently their meaning is not obvious, or is ambiguous, or is obscure, or in any way stand in dire need of receiving clear and unambiguous meaning. If every expression in QM were perfectly clear, there would obviously be no need to interpret QM.

The vocabulary of QM is rather mathematical and its mathematical concepts are crystal clear. They do not stand in need of interpretation - Hilbert-space, self-adjoint operator, eigenvalue equation, unitary evolution, statistical operator, Clebsch-Gordan coefficients, Weyl-rays, unitary representations of a symmetry group, permutation operators, Wigner distributions, and what have you. The physical vocabulary, including physical magnitude, physical system, composite system and subsystem, physical property and physical relation also seem far from obscure. This is not to say that these concepts are beyond interpretation, let alone beyond metaphysical disputation. Concepts of QM that stand in need of interpretation are the physical state of a physical system and the probability for finding specific outcomes upon measurement, and certainly the concept of measurement itself. On the one hand, one can send everybody who raises questions about measurement to a laboratory: observe what is happening there and ask around; if that will not do, then nothing will. On the other hand, when we ask what a measurement is, we are after a general answer, a general concept of measurement, one that encompasses what happens inside all laboratories; everything we want to call a measurement should be an instance of our general concept, and everything we do not want to call a measurement should not be an instance of it. This general concept should cover our use of the word *measurement*, but need not cover it entirely, for we shall gladly pay the price of lack of full coverage for a clear general concept. In short, we are after a Carnapian(logical positivist - all knowledge is based on logical inferences from empirical observations) explanation of the concept of measurement. When a physical system qualifies as piece of measurement apparatus, when a physical interaction qualifies as a measurement interaction, when an event qualifies as a measurement event, and perhaps more, have been issues for analysis and controversy since the advent of QM. Certainly we want to count these issues part and parcel of discourse *the interpretation of QM?*.

Probability is mathematically represented by a normed additive mapping from some Boolean subset family of $\mathbb{R}$, say the intervals $\mathcal{I}(\mathbb{R})$, to the interval $[0,1] \subset \mathbb{R}$:

$$\mathrm{Pr} : \mathcal{I}(\mathbb{R}) \to \mathbb{R} \tag{1}$$

So for the mathematician, this is all there is to probability: a normed measure on $\mathcal{I}(\mathbb{R})$. Not so for the scientist, who has to relate the normed measure to the world. The quantum-mechanic has to relate probability at the very least to measurement outcomes. The only way to do this is via relative frequencies. But whether probability is a limiting relative frequency amounts to taking a further philosophical step, as does identifying probability with *objective change*, as does identifying it with *propensity*, i.e., some generalized quantitative disposition, and as does taking it as a *degree of subjective belief* or a *degree of rational credence*. We entered the field of interpreting probability. Some hold that *quantum probability* is somehow special and different from probability as it occurs elsewhere in physics and in science generally. The discussion of whether this is true, and how quantum probability then differs from probability applied elsewhere is however not a central theme in the interpretation of QM - at best it is a peripheral theme.

Like the concept of probability, the concept of *physical state* is primitive, yet unlike probability, it can be and is represented mathematically in many distinct ways: as a

- a normed Hilbert-vector, or
- a Weyl-ray, or
- a statistical operator acting on a Hilbert-space, or
- a positive map on a C^*-algebra.

Maybe calling a Hilbert-vector (or Weyl-ray, or ...) *the mathematical representative of the physical state* of a physical system is a *mistake*: a Hilbert-vector should remain a physically uninterpreted and purely mathematical concept in QM, an auxiliary device to calculate probability distributions of measurement outcomes. There is no *physical state* of the unmeasured cat in purgatory: we are led to believe that the cat has, or is in, a *physical state* by mistakenly trying to attribute physical meaning to a Hilbert- vector that is a superposition of two vectors, which according to the standard property postulate we associate with a cat having the property of being dead and one having the property of being alive, respectively. We believe the unmeasured cat is some particular physical state but perhaps it isn't. QM associates a Hilbert-vector to the cat, which is devoid of physical meaning, but enables the computation of probability measures over measurement-outcomes, which are full of physical meaning. Thus we have physical meaningfulness out of physical meaninglessness. Sheer magic. Magic does however not help us to understand physical reality.

The willful jump to meaninglessness seems however a cheap way out. I don?t like it. We believe that the unmeasured cat is either stone dead or breathing, because *tertium non possibilium*(In logic, the law of excluded middle (or the principle of excluded middle) is the third of the three classic laws of thought. It states that for any proposition, either that proposition is true, or its negation is true.), and we want QM to be logically compatible with this belief, at the very least, and preferably to imply one or the other belief. After all, QM also predicts that as soon as we peek at (i.e., measure) the cat, through a pinhole, unbeknownst to the cat, it *is* either dead or alive. Rather than to withhold physical significance from the Hilbert-vector, we should try to assign physical significance to it (or to a Weyl-ray, or ...). For how else could it determine physically meaningful probability measures over measurement-outcomes? No physical significance in, but physical significance out? That ought to be unacceptable. One way is to connect Hilbert-vectors to equivalence classes of preparation procedures in the laboratory. This won't help us however with Schrödinger's unmeasured cat. This won't help us with anything, because superpositions are the rule, not the exception. The founding fathers of QM started with electrons in superpositions, soon other elementary particles followed, then atoms, and nowadays we have bucky-ball molecules and circulating currents in superconducting metals in superpositions in the laboratory. The march of superpositions from the realm of the tiny to the realm of medium-sized dry objects is not halting.

So-called *modal interpretations* of QM have taught us that the cat ceases to be a problem as soon as we reject *half* of what we shall call the *Standard Property Postulate* of QM, which one can find the classic texts of Von Neumann [1932] and Dirac [1928] - and which remains nearly always tacit in textbooks on QM. Any author on QM who presents Schrödinger's cat as a problem in that it is neither dead nor alive, tacitly assumes that it is necessary for the cat to be in a relevant eigenstate in order to be either dead or alive. The Standard Property Postulate is also known as *the eigenstate-eigenvalue link*.

- **Standard Property Postulate (Dirac, Von Neumann).** *A physical system S having physical state $|psi\rangle \in \mathcal{H}$ has quantitative physical property mathematically represented by the ordered pair $\langle B, b\rangle$, where B is an operator representing some physical magnitude and where $b \in \mathbb{R}$,* iff $|\psi\rangle$ *is an eigenstate of B having eigenvalue b: $B|\psi\rangle = b|\psi\rangle$.*

When it is no longer necessary for the state to be an eigenstate of B in order for physical system S to have a property of the sort $\langle B, b\rangle$, then the unmeasured cat *can* be either dead or alive even when its state is not a corresponding eigenstate - but is a superposition of such eigenstates. The compatibility between QM and our belief that the unmeasured cat is either dead or alive is saved. What can be adhered to, then, is not the Standard Property Postulate but the • **Sufficiency Property Postulate**, according to which it is sufficient (but not necessary) for the system to be in some eigenstate of B in order to possess property $\langle B, b \rangle$ (one drops one conjunct of the Standard Property Postulate).

Logically weakening a postulate seems however to have little to do with *interpretation* in the hermeneutic sense of assigning meaning to expressions whose meaning is unclear, ambiguous or obscure. Indeed, for modal interpreters of QM, the problem of interpretation is to find *the right conditions for property ascriptions* - in addition to the stingy Sufficiency Property Postulate -, rather than to dwell on the meaning of *physical state* (or Weyl-ray, or ...). (We say *stingy*, because a physical system is almost never in an eigenstate, so one can almost never invoke the Sufficiency Property Postulate.) This points away from hermeneutical activity when considering interpreting QM to changing the postulates - unless one subscribes to a theory of meaning such that changing the conditions for the ascription of properties changes the meaning of the word *property*, in which case one should consider such property postulates as Carnapian *meaning postulates*, rather than synthetic postulates that are made true (or false) by the way the world is.

It is in order to mention the exception of Oxonian Everettians, who under the lead of S.W. Saunders tinker with the meaning of *existence* and tensed expressions by relativizing them to a *perspective*, a *branch*, and who, like all Everettians, assign special significance to the terms of the state vector when expanded in a special basis, which is selected by the physical process of decoherence. They reinterpret and therefore change the meaning of words in NLAWKI. Hermeneutics in action. One could also maintain that the problem of interpreting QM just is the problem of finding an intelligible physical meaning to attribute to the mathematical concept of a Hilbert-vector (or ...) in such a way that our belief that the unmeasured cat is either dead or alive survives whilst leaving the Von Neumann postulates of QM untouched in all their glory, save perhaps minor modifications. But then modal interpreters of QM are *not interpreting* QM. There is no hermeneutic activity going on. What, then, are they doing?

They are changing the theory of QM by *changing* (one of) its postulates, which results in a *different* theory of QM, just like changing the parallel axiom of Euclidean Geometry results in a *different* geometrical theory. When that different geometrical theory, if true, tells us that the structure of space is different from what Euclidean Geometry tells us, then *mutatis mutan-*

dis(changing [only] those things which need to be changed) modal QM provides a different description of the microphysical world than standard QM does. This is the key insight of these notes and the essence of our alternative view of what it means to *interpret* QM. But before we turn to that, first the promised interjection on measurement.

3. Mathematical Necessities of Measurement

3.1. Preamble

In English, as in most languages, *to measure* is a *verb*. The noun *measurement* is derived from it: to measure is to perform a measurement, and to perform a measurement is to measure. To measure is a manifestation of intentional behavior, i.e., it is a type of *action*, performed by a human being, with a purpose - or by any being having the cognitive capacities to exhibit it. Therefore the concept of measurement is an *intentional* concept.

The concept of measurement is expressed most explicitly by the statement: *someone* (p) measures *something* ($\mathcal{A}$) that pertains to *something* (S) using *something* else(M) and obtains *result* a:

$$\text{Measure}(p, \mathcal{A}, \mathsf{S}, \mathsf{M}, a) : p \text{ measures } \mathcal{A} \text{ of } \mathsf{S} \text{ by means of } \mathsf{M} \text{ and obtains } a. \tag{2}$$

There are *kinds* of measurements, whose extensions are subclasses of the extension of (2): demolition measurements, ideal measurements, extensive measurements, perfect measurements, sharp measurements, weak measurements, ... The word *measurement* occurs in combinations with other words, especially in science; these combinations ex- press different but allied concepts, which we call *measurement concepts*: measurement event, measurement process, measurement procedure, measurement result, outcome, measurement interaction, measurement apparatus, measurement theory, measurability. In every case, the suffix *measurement* points to a *kind*: measurement events are a *kind* of events, they form a subclass of the class of all events; measurement processes are a *kind* of processes, they form a subclass of the class of all processes; etc. The purpose of this Section is to analyze the concept of measurement (2) and other measurement concepts, but only those in so far needed in the core concept Meas (2). The other measurement concepts will have to wait.

In our statement on the concept of Measurement (2), five things are connected: human being p, value a, entity S, entity M, and magnitude $\mathcal{A}$. The challenge is to characterize these concepts in a way that does not rely on the concept of measurement or any of the allied concepts, otherwise we awaken the spectre of circularity. We gloss over the concept of a human being and move now to the other concepts from the five things, one per Subsection.

3.2. Values

Value a is a number. Number a is a rational number ($a \in \mathbb{Q}$), because every measurement has a finite accuracy. Since two measurement results, a and b, can be taken as the real and the imaginary part of a complex number, there is room for extending $\mathbb{Q}$ to $\mathbb{C}_{rat} \subset \mathbb{C}$, the set of complex numbers having rational real and imaginary parts. Nonetheless we continue with $\mathbb{Q}$ and bracket $\mathbb{C}_{rat}$.

To count is also a form of measurement, with a natural number as the result. One can count the number of children in the class room with infinite accuracy: there are 23 children in the class room, or 23,000..., and not 23±1, let alone 23.0±0,2. (In these cases, the outcome still is a rational number, because $\mathbb{N} \subset \mathbb{Q}$; so we can stick with $a \in \mathbb{Q}$).

3.3. Entities

We measure the emission spectrum *of* Hydrogen; we measure the mass *of* the Earth or *of* a positron; we measure the intensity *of* the radio-active radiation *of* the nuclear power plant in Harrisburg; we measure the acidity *of* the liquid in this flask; etc. Clearly *what* we measure, $\mathcal{A}$, always pertains to something (S), and that something, that entity, we take to be a *physical system*, as broadly construed as possible: it consists of matter and fields, and is located in space-time. This makes physical systems, in metaphysical parlance, *concrete* rather than abstract entities.

3.4. Measurement Apparatus

A measurement apparatus also is a physical system, that much seems clear. We thus need a criterion to tell us *which* physical systems qualify as a measurement apparatus and which do not. We proceed stepwise, (A)-(C): in each step we consider a concept that we shall use in characterizing what a measurement apparatus is.

(A) *Observability.* Surely a measurement apparatus M is a physical system that we, human beings that measure, should be able to see (or hear ...). Otherwise M is of no use to us! So M has to be *observable* by us. This raises immediately the further question which physical systems are *observable*. Philosophers of science have pondered this question. We shall not repeat the ensuing literature but mention the rather obvious philosophical criterion for the extrinsic property of observability. Let p be a normal person, of sound mind and having normal eye-sight.

Criterion for Observability. Physical system S is observable iff for every p: if p were in front of S in broad daylight with open eyes, then p would see S.

Van Fraassen famously insisted that the observability of objects, events, facts, processes, is a subject for scientific research, not for philosophical analysis.

If S is observable, then S seems to have properties that are observable, notably its shape and colors. What is it that we actually *see*? In full generality, this is a metaphysical question, which we wish to bracket. We therefore limit ourselves to a characterization of an observation predicate, remaining neutral about whether predicates express universals or tropes(figurative and metaphorical language and various other technical senses).

Criterion for an Observation Predicate. A predicate F applied to physical system S is an *observation predicate* iff for every p: if p were in front of S in broad daylight with open eyes, then p would judge that $F(\mathsf{S})$ or judge that $\neg F(\mathsf{S})$ relying only on linguistic knowledge and on looking at S.

The addition of *relying only on linguistic knowledge* is to prevent that *theory*, broadly construed, is relied on in order to judge whether $F(\mathsf{S})$ or that $\neg F(\mathsf{S})$. Suppose around 2,000 BC an Egyptian girl is taught that what we call *the sun* is the god Ra. The other morning the girl wakes up, looks at the sky and says: “A god has appeared in the sky”. She formed this judgment by looking at the sky. But *being a god* should not qualify as an observation predicate. It doesn't according to our Criterion, because *a god* relies on some religious theory, that informs us about gods in general and Ra in particular. That goes above and beyond *linguistic knowledge*, i.e., knowledge of meaning, knowledge of how to use words, the capacity to display appropriate linguistic behavior by uttering words, expressions and sentences in given circumstances, and by understand- ing words, expressions and sentences when others utter them. Person p must have some linguistic knowledge, by the way, otherwise p could not form the judgement that $F(\mathsf{S})$ or that $\neg F(\mathsf{S})$. As soon as theoretical knowledge is needed to understand what predicate F means, F cannot be an observation predicate. Caveat: the distinction between linguistic knowledge and theoretical knowledge is not exactly unproblematic, and even controversial. Similarly for the one between observation and theoretical predicates. What to do when rejects these distinctions? Nothing. Read on. Simply cut away this distinction from our statements about measurement.

So much for the observability of measurement apparatus M.

(B) *One-one Correspondence.* When we read that the pointer of an voltmeter points to 22 V, we ascribe the property of an electric potential difference to a circuit; when I read 86 kg on the display of a scale while standing on it, I conclude that my body has a mass of 86 kg; etc. So what we need is a one-one correspondence between observable properties of M and values of the magnitude $\mathcal{A}$ that M is measuring. Or better, *intervals of values* rather than values because of the finite measurement accuracy: result $I = 1.04 \pm 0.07$ mA describes an observable property of an ammeter that corresponds to an infinite set of electric current values, namely interval [0.97,1.11].

(C) *Relevant Interaction.* So a measurement apparatus M of magnitude $\mathcal{A}$ is an observable physical system that leads to a one-one correspondence between certain sets of values of $\mathcal{A}$ and observable properties of M?

Almost right. Dupe can assign a rational number to few solid objects lying on the table in front of him using pencil and paper: Dupe looks at an object and writes down some arbitrary rational number. Dupe claims to have measured the masses of these objects, because we have a one-one correspondence between observable properties of the paper (the ink spots on it that express rational numbers) and values of the physical magnitude mass of the objects. Yet surely the pencil and paper do not qualify as a *measurement apparatus that measures mass.* Pencil and paper can be used *to report* measurement outcomes, but they are not themselves pieces of mass-measurement apparatus. Furthermore, just *writing down an arbitrary rational number* with a pencil on a piece of paper *is not measuring* anything. If a one-one correspondence were enough, then measurement results would be what we want them to be, would become wholly under our control, whereas a measurement outcome seems to be something that is entirely beyond our control, something that has nothing to do with what we want. Particular measurement outcomes may be the ones we want, hope, wish, expect or fear. But *which* outcomes we shall actually obtain when we measure is beyond our control and indifferent to our needs, hopes, wishes, expectations and fears.

Perhaps we should require that the one-one correspondence *must be the result of a particular physical interaction* between measured object S and measuring object M. Dupe's one-one correspondence was not due to an interaction between the objects on his table and the paper. Which particular physical interaction? The physical interaction that occurs in explaining how M works, specifically how the one-one correspondence between (sets of) values of $\mathcal{A}$ and (observation) predicates that apply to M comes about. Let us call that physical interaction $\mathcal{A}$-relevant - which thus partly is an epistemic concept.

We arrive at the following criteria.

Criterion for an $\mathcal{A}$-Measurement Apparatus. Physical system M is a measurement apparatus of physical magnitude $\mathcal{A}$, or briefly, an $\mathcal{A}$-measurement apparatus, iff

(M1) M is observable;

(M2) there is a one-one correspondence between (observation) predicates F which apply to M, and sets of values of $\mathcal{A}$; and

(M3) the correspondence of (M2) is the result of the $\mathcal{A}$-relevant physical interaction between physical system S, to which $\mathcal{A}$ pertains, and M.

> **Criterion for a Measurement Apparatus.** Physical system M is a measurement apparatus iff there is some physical magnitude $\mathcal{A}$ such that M is an $\mathcal{A}$-measurement apparatus.

The young tree in the park garden is a measurement apparatus of the dichotomic(choosing between two antithetical choices, between two distinct alternatives) physical magnitude *presence of wind*($\mathcal{W}$): if it oscillates visibly, then $\mathcal{W}$ has value 1 (presence of wind), and if it remains unmoved, then $\mathcal{W}$ has value 0 (absence of wind). Conclusion: a piece of measurement apparatus need not be a *technological artifact*, designed and constructed by human beings. Mother Nature produces pieces of measurement apparatus too, unintendedly, which is why being a technological artifact for M is not part of the criterion for a measurement apparatus.

4. Magnitudes

Etymologically the word *magnitude* comes from the Latin *magnus* (big, large) and *magnitudo* (measure of bigness). Here *measure* means *unit*, which suggests that magnitude is a quantified conception of some property: we speak of magnitude when we can quantify some property and we can measure it, no matter how indirectly. Think here of mass as quantity of matter (Newton), momentum as quantity of motion (Huy- gens), volume as quantity of 3-dimensional space, acidity as quantity of acid in a solution (Arrhenius), biomass as quantity of matter produced in carbon, hydrogen and oxygen, electric current as quantity of electricity (Gilbert), and so forth.

A general definition of magnitude is not around. An appealing idea seems to define a magnitude as a *quantified* or *quantitative property*. Measuring magnitude $\mathcal{A}$ of physical system S and obtaining value a would then show that S possesses a quantified property that we could represent by: $\langle \mathcal{A}, a \rangle$. But this runs afoul against standard QM, which has taught us that measuring $\mathcal{A}$ definitely is *not* revealing a property possessed by S before the measurement. On the contrary, property $\langle \mathcal{A}, a \rangle$ gets ascribed to S *just after* a measurement has ended and the state of S collapses to an eigenstate that belongs to a, which then is an eigenvalue of the representing operator $\widehat{A}$ acting on the Hilbert-space $\mathcal{H}$ associated with S.

Thus we take magnitude $\mathcal{A}$ as primitive and define a *quantitative property* as

$\langle \mathcal{A}, a \rangle$, where $a \in \mathbb{V}(\mathcal{A}) \subseteq \mathbb{R}$, the set of values of $\mathcal{A}$, or as $\langle \mathcal{A}, a, u(\mathcal{A}) \rangle$ when magnitude $\mathcal{A}$ has a *unit.* If needed, $\mathbb{V}(\mathcal{A})$ can include complex numbers, in which case $\mathbb{V}(\mathcal{A}) \subseteq \mathbb{C}$.

A few examples ($\mathbb{R}^+$ contains 0):

$$\langle \text{mass}, \mathbb{R}^+, \text{ kilogram} \rangle \quad , \quad \langle \text{length}, \mathbb{R}^+, \text{ meter} \rangle \quad , \quad \langle \text{energy}, \mathbb{R}^+, \text{ joule} \rangle \quad (3)$$

We have now taken care of everything that is involved in the concept of measurement (2). Next we present our explication of measurement.

4.1. Main Dish

Much of the labour we had to perform to arrive at a criterion for the core concept of measurement, has already been performed in our analysis of a measurement apparatus.

Criterion for Measurement. *p measures $\mathcal{A}$ of* S *by means of* M *and obtains a* iff

(1) p is a person,

(3) $\mathcal{A}$ is a magnitude,

(3) S is a physical system,

(4) M is an $\mathcal{A}$-measurement apparatus,

(5) $a?\mathbb{V}(\mathcal{A})$ (a is a value of $\mathcal{A}$),

(6) p makes S and M physically interact $\mathcal{A}$-relevantly and this $\mathcal{A}$-relevant interaction results in $\mathcal{A}$ having value a, which M registers or displays.

Does this criterion cover all measurements that have been, are and will be performed by anyone anywhere? I would be surprised if it did. For example, how about measuring the length of the table by a tapeline? Is the result of 250 cm, the value of the length of the table, a result of a *length-relevant physical interaction between table and tapeline*? Their interaction consists of no more than they absorb some of each other's emitted electro-magnetic radiation... For another example, how about measuring time by a clock? When the clock is the measurement apparatus M, what is the physical system

S? Perhaps also M: it measures the length of its worldline of spacetime, although that presupposes the Theory of Relativity. But let's stop, and ask what a measurement interaction is.

> **Criterion for Measurement Interaction.** A physical interaction I between two physical systems is a measurement interaction iff there is a physical magnitude $\mathcal{A}$ such that at least one of the physical systems is an $\mathcal{A}$-measurement apparatus and I is an $\mathcal{A}$-relevant physical interaction.

This characterization of measurement interaction is not entirely physico-ontological but partly empistemological, just as measurement is, due to our characterization of what an $\mathcal{A}$-relevant interaction is (see above). This is how it ought to be, for to mea- sure is to acquire knowledge. Measurement is also a species of knowledge acquisition. Quantum-mechanical measurement theory provides more detailed mathematical representations of measurement interactions. Back to the interpretation of QM.

5. What is quantum mechanics?

The Prime Directive of Physics is that numbers calculated by using a physical theory (or model or hypothesis or principle) should coincide with numbers measured that pertain to physical systems the theory is supposed to be about. Suppose there is a minimal set of postulates of QM in the sense that the Prime Directive is obeyed: the postulates are just enough to calculate measurement outcomes and their probability measures, and these outcomes match what is being measured. Call this: *minimal QM* (soon to be characterized rigorously).

When the aim of physics is

- to explain the (observed and unobserved) phenomena, *or*
- to understand why things happen when they happen, *or*
- to find out what physical reality is like, what it is made of, what there is, what exists, what the properties and relations are of the actual beings, and how the actual beings behave and influence each other, *or*
- to reveal the structure of the universe as it is in and of itself, *or*

- any other aim that goes above and beyond merely calculating putative measurement outcomes,

then, already then, minimal QM falls short of reaching the aim of science, for instance by telling us nothing about the fate of the cat and any other physical system that is not measured. Minimal QM leaves too many meaningful questions about physical reality wide open. When minimal QM is a failure, must it not be refused entrance to the body of scientific knowledge? Is the current presence of QM in that body not a cyst which should be surgically removed?

Nay nay, do not be afraid. I am not going to propose *that*. The presence of minimal QM is wonderful, provided we *extend* it so as to approach the aim of physics more closely. To provide an interpretation of QM is, we submit, *to add postulates to those of minimal QM so as to provide answers to questions about physical reality that we deem meaningful and that pertain to physical systems falling within the purview of minimal QM*; extending minimal QM may very well involve *changing and usually extending its sparse vocabulary.* Van Fraassen:

> Ideally, belief presupposes understanding. This is true even of the mere belief that a theory is true in certain respects only. Hence we come to the question of interpretation: under what conditions is this theory true? What does it say the world is like? These two questions are the same.
>
> (...)
>
> Suppose we agree that there can, in logical principle, be more than one adequate interpretation of a theory. Then it follows at once that interpretations go beyond the theory; the theory plus interpretation is *logically stronger* than the theory itself. For how could there be differences between views, all of which accept the theory, unless they vary in what they add to it?

There may be hermeneutical activity in the wake of extending minimal QM in the literal sense of the word, in that the meaning of certain expressions have to be adjusted to fit the intended extension of minimal QM, but the core interpretational activity is to extend minimal QM by adding postulates, which implies (*salute* Van Fraassen) to provide QM with logically stronger truth-conditions (than the ones of minimal QM). What is minimal QM precisely? Here follows an attempt to characterize it, call it QM_0. Let $\mathcal{I}(\mathbb{R})$ be a Boolean subset algebra of closed intervals of the real line.

> **P0. Hilbert-Space Postulate (Von Neumann).** *Associate some Hilbert-space $\mathcal{H}$ to physical system S, and a direct-product Hilbert-space to a composite physical system with the factor Hilbert-spaces being associated to the disjoint subsystems.*

> **P1. Evolution Postulate (Schrödinger).** *Time is represented by the real continuum ($\mathbb{R}$). IF no measurements are performed in time-interval $\Delta \in \mathcal{I}(\mathbb{R})$ on physical system S, THEN at every moment in time $t \in \Delta$, associate a Hilbert-vector $|\psi(t)\rangle \in \mathcal{H}(\mathbf{P0})$ to S such that there is a connected Lie-group of unitary operators acting in $\mathcal{H}$ such that $|\psi(t)\rangle = \mathcal{U}(t)\,|\psi(0)\rangle$, where $|\psi(0)\rangle$ is associated to S at time $t = 0$, and where $\mathcal{U}(t)$ is a group member, such that $\mathcal{U}(t + t') = \mathcal{U}(t)\mathcal{U}(t')$, for every $t, t' \in \Delta$.*

> **P2. Magnitude Postulate (Von Neumann).** *Represent physical magnitudes of interest by operators acting in $\mathcal{H}(\mathbf{P0})$ that have a spectral resolution. Restrict the domain of this resolution to $\mathcal{I}(\mathbb{R})$, so that we consider only: $\mathcal{I}(\mathbb{R}) \to \mathcal{P}(\mathcal{H}), \Delta \mapsto P^B(\Delta)$, where $P^B(\Delta)$ is a projector from the Hilbert-lattice$\mathcal{P}(\mathcal{H})$ that belongs to the spectral resolution of B.*

> **P3. Probability Postulate (Born).** *The probability for finding a value in interval $\Delta \in \mathcal{I}(\mathbb{R})$, at time t, upon measuring physical magnitude represented by operator B ($\mathbf{P2}$) when Hilbert-vector $|\psi(t)\rangle \in \mathcal{H}$ is associated to S at time t $\mathbf{P0,P1}$, equals the expectation-value of $P^B(\Delta) \in \mathcal{P}(\mathcal{H})$; in Redhead notation:*
>
> $$\Pr([B]^{|\psi(t)\rangle} \in \Delta) = \langle\psi(t)|\, P^B(\Delta)\, |\psi(t)\rangle \tag{4}$$

For the sake of brevity, we have left out the Symmetrization Postulate, which is about composite systems of similar particles (Bose-Einstein, Fermi-Dirac statistics).

Notice that QM_0 only speaks of *physical systems, physical magnitudes and* *probability distributions over measurement outcomes.* The theory QM_0 is sufficiently strong to enjoy an extremely wide variety of confirmation. We point out that physical magnitudes can be identified with equivalence classes of measurement procedures, so *physical magnitude* can be eliminated from the primitive physical vocabulary (at the price of adding *measurement procedure*). Not a word in QM_0 about physical states, physical properties and physical relations. No not one. *Stricto sensu*(Strictly speaking) QM_0 is a mathematical recipe to calculate probability distributions over measurement outcomes. QM_0 says little if anything about physical reality outside the laboratory, let alone about the microphysical world. This is unacceptable.

QM_0 does not include the notorious projection postulate (for a moderately precise statement, see below). Can QM_0, then, deal with repeated measurements? If not, QM_0 may be an empirical failure.

The game of physics. One group of people, the Experimenters, produce numbers by manipulating various technical artifacts, and another group of people, the Theoreticians, think of mathematical recipes that also produce numbers. The aim of the game is that those numbers should match. The Experimenters usually begin and the Theoreticians then must match whatever the Experimenters come up with. If the Theoreticians fail, they lose and the Experimenters win; if the Theoreticians succeed, they win and the Experimenters lose. Sometimes the Theoreticians begin and then the Experimenters have to match. This is the game of physics, even the game of science, in a nutshell I take it. But *why* do we play this game? Out of boredom? For the hell of it? I say: *No no no.* We play it because we want the Theoreticians to win, because when they win repeatedly with the same theory, that theory may be knowledge of physical reality, may provide explanations of the phenomena that make us understand physical reality, and gathering such knowledge is the epistemic aim of physics. Otherwise the repeated success of the theory would be a miracle and we don't believe in miracles.

Standard, or *orthodox quantum mechanics* (OxQM) qualifies as an interpretation in the sense above of being an extension of QM_0, for it enriches the vocabulary of QM_0, strengthens some of its postulates and adds new postulates to it. The language of OxQM includes: physical properties and physical states. The Hilbert-Space Postulate (**P0**) becomes the

- **Pure State Postulate (Von Neumann).** *Every possible pure physi-*

cal state of a physical system is mathematically represented by a normed vector in some Hilbert-space, which we associate with the physical system.

(The *pure* alludes to a more general State Postulate encompassing also mixed states, which are not mathematically represented by Hilbert-vectors. We gloss over this.) Also the Standard Property Postulate is added, as well as the controversial

- **Projection Postulate (Dirac, Von Neumann).** *IF one performs a measurement of physical magnitude B on a physical system, when it has state $|\psi(t)\rangle \in \mathcal{H}$ at the moment $t \in \mathbb{R}$ of measurement, AND one finds outcome in $b \in \Delta \in \mathcal{I}(\mathbb{R})$, with Δ the measurement accuracy of measuring value $b \in \Delta$, THEN immediately after the measurement outcome $b \in \Delta$ has been obtained, the post-measurement state of the physical system is represented by $P^B(\Delta)\,|\psi(t)\rangle$.*

The Probability Postulate (**P3**) entails that the probability of finding a measurement-outcome, when measuring physical magnitude B, that does not lie in the spectrum of B vanishes. Since it depends on one?s interpretation of probability of whether it follows that finding a measurement-outcome that is not in the spectrum of B is impossible, an explicit postulate is needed to exclude this. Here it comes.

- **Spectrum Postulate (Schrödinger, Von Neumann).** *All and only values from the spectrum of an operator that represents a physical magnitude are its possible measurement-outcomes.*

So much for minimal QM_0 and its standard interpretation (aka orthodox quantum mechanics: OxQM). Let us turn for a moment to a few other interpretations.

6. The Inescapable Morality of the Intelligible

Bohr's Copenhagen Interpretation has long been, and perhaps still is, the interpretation most physicists adhere to. It adds the following postulates to QM_0, resulting in, say, CopQM.

- **Quantum Postulate (Bohr).** *Every quantum phenomenon is indivisible; disconnected considerations of its parts are inappropriate, because the interaction between object-system and preparation and registration apparatus is not eliminable due to Planck's constant ($h > 0$).*

By the *quantum phenomenon*, Bohr means the whole of the preparation apparatus, which one uses to prepare the object-system in a particular physical state, the registration apparatus one uses to measure some physical magnitude, and of course the physical system that is being subjected to preparation and measurement, the *object-system.* In classical physics one can appropriately consider parts, without mentioning other parts or the whole. In CopQM the Quantum Postulate rules, which is however limited by the

- **Buffer Postulate (Bohr).** *The literal description of preparation and registration apparatus, and of the measurement outcomes, is given in the language of classical physics; the Deutung(Interpretation) of the object-systems proceeds by means of mathematical concepts.*

Finally there is the

- **Complementarity Postulate (Bohr).** *The quantum phenomenon, specifically the experimental arrangement of the pieces of measurement apparatus (preparation and registration apparatus), determines which classical concepts are applicable. There are pairs of classical concepts, like wave/particle, kinematics/dynamics, space-time/causality, that are never jointly applicable in a single experimental arrangement but only in mutually exclusive experimental arrangements and in this way provide an exhaustive description of the object-system. Such pairs are called* complementary. *They are however jointly applicable in so far as the relevant Indeterminacy Inequality permits.*

According to Bohr, the language of classical physics is indispensable for QM. Bohr viewed this language as a *refinement* of NLAWKI: material objects in space, that persist over time and whose properties change over time as a result of causal processes. The *classical language* is unambiguous and accurate, so that the objectivity of QM is guaranteed.

By *classical science* in general, Bohr meant scientific inquiry where the role of the scientist, the subject and his thought and talk, can be ignored, thus resulting in a subject- independent hence objective description or explanation of a part of reality that falls within the relevant scope of scientific inquiry. Classical physics, usually by definition the whole of physics accepted in the year 1900, qualifies as *classical* in Bohr's sense. Classical physics is needed to guarantee the objectivity of QM.

All modal interpretations obviously qualify as interpretations of QM and are much more modest in their extensions of the vocabulary of QM_0 than Bohr *classical science*. One modal interpretation rejects the projection postulate of QM, rejects measurement as a primitive concept in the vocabulary, makes the Evolution Postulate (**P1**) hold unconditionally, and replaces the standard property postulate with the Sufficiency Property Postulate and the

- **BiModal Property Postulate (Dieks-Vermaas).** *The subsystems of a composite system have one of the quantitative properties $\langle B, b\rangle$, such that the basis of the Schmidt biorthogonal decomposition of the state of the composite system is the eigenbasis of B, with probability as in the Probability Postulate* (**P3**).

The Everett interpretation also qualifies as an interpretation of QM because it changes the vocabulary of QM_0 (adding the concept of a *branch*, or a *perspective*, or a *world*, and deleting the concept of measurement as primitive), adds a branching postulate:

- **Branching Postulate (Everett).** *Consider a particular basis of the Hilbert-space $\mathcal{H}$ associated with any physical system S, and expand its physical state $|\psi\rangle \in \mathcal{H}$ (State Postulate) in this basis, say $|\phi_j\rangle \in \mathcal{H}$, for $j = 1, 2, ...dim(\mathcal{H}$. Then relative to branch j, S has the physical property $\langle B, b_j\rangle$, where $B\,|\phi_j\rangle = b_j\,|\phi_j\rangle$.*

A solution of the problem *which* basis to consider is nowadays sought by an appeal to *decoherence*, which is the generic phenomenon that when a physical system S is in a physical environment (radiation, heat bath, air), the state becomes diagonal in some particular basis, the *decoherence basis*. Often this basis corresponds to the physical magnitude energy or position, and it is this basis, *preferred* so to speak by Mother Nature, that is then considered in the Everett Postulate above, notably by Oxonian Everettians. They thus have physical reasons to attach ontological significance to the terms of ψ when expanded in one basis rather than an infinitude of other bases - perhaps even excellent physical reasons -, but that does not mean that they do adhere ontological significance to *these* terms, and that means that EvQM goes above and beyond QM_0, - and, of course, differs from OxQM.

Even Bohmian Quantum Mechanics (BQM) qualifies. BQM adopts the Hilbert-space of complex wave-functions on configuration space. For the sake of simplicity, we con- sider 2 spinless particles in 3-dimensional space, having masses m_1 and m_2. The wave- function of the composite system is: $L^2(\mathbb{R}^3) \otimes L^2(\mathbb{R}^3) \simeq L^2(\mathbb{R}^6)$.

- **Bohmian State Postulate.** *The state of this 2-particle system is represented by: $\langle \psi, \mathcal{Q} \rangle$, where $\psi : t \mapsto \psi(t) \in L^2(\mathbb{R}^6)$ (**P0. Hilbert-Space Postulate** and $\mathcal{Q} : t \mapsto \mathcal{Q}(t) \in \mathbb{R}^6$ (**Position Postulate:** see below).*

Just as in QM_0, ψ is postulated to obey the Schrödinger equation. Vector $\mathcal{Q}(t)$ consists of 6 components, and can be written as $\langle \mathcal{Q}_1(t), \mathcal{Q}_2(t) \rangle$, where $\mathcal{Q}_1(t), \mathcal{Q}_2(t) \in \mathbb{R}^3$. Vector $\mathcal{Q}_1(t)$ represents the position of $\mathbf{p}_1$ at time t and similarly $\mathcal{Q}_2(t)$. Like in classical mechanics but unlike in OxQM, in BQM every particle always has a position. Bohmians *complete* QM by adding $\mathcal{Q}$ to ψ.

- **Position Postulate.** *The positions of the particles are determined by ψ via the Guiding Equation, which is for particle 1:*

$$m_1 \frac{d\mathcal{Q}_1(t)}{dt} = \hbar Im \left(\frac{\nabla_1 \psi(\mathbf{q}_1, \mathbf{q}_2, t)}{\psi(\mathbf{q}_1, \mathbf{q}_2, t)} \right)_{\mathbf{q}_1 = \mathcal{Q}_1(t)} \tag{5}$$

  where ∇_1 is the gradient, with respect to $\mathbf{q}_1$, and $Im(z) \in \mathbb{R}$ is the imaginary part of $z \in \mathbb{C}$. Similarly for particle 2. One should not confuse $t \mapsto \mathcal{Q}_1(t)$ with $\mathbf{q}_1$: the afore-mentioned describes the path of particle 1 in 3-dimensional space, whilst the last-mentioned is a physically uninterpreted variable of ψ.

  The left-hand-side of the Guiding Equation (5) is a time-derivative of the position of particle 1, which is the definition of its velocity:

$$\mathbf{v}_1^{\psi}(t) = \frac{d\mathcal{Q}_1(t)}{dt} \tag{6}$$

  where the superscript 'ψ' is there to emphasize that the velocity is determined by ψ, via eq. (5), which pertains to the composite system.

There is further an • **Equilibrium Postulate**, which posits the Born-measure for position probabilities. From this and an elaborate story that reduces all measurements to position measurements, the Probability Postulate follows.

Legend for table below. All theories entail the postulates of QM_0, which are therefore omitted; only the additional postulates are mentioned. By '1/2' is meant the Sufficiency Property Postulate. • **Categorical Evolution Postulate**: always unitary evolution over time, whether measurements are performed or not.

	OxQM	BiModQM	CopQM	EvQM	BQM
St. Prop. Post.	+	1/2	1/2	1/2	-
Pure State. Post.	+	+	+	+	+
Projection Post.	+	-	+/-	-	-
Spectrum Post.	+	+	+	+	+
Categ. Evol. Post.	+	+	+/-	+	+
Quantum Post.	-	-	+	-	-
Buffer Post.	-	-	+	-	-
Compl. Post.	-	-	+	-	-
BiMod. Prop. Post.	-	+	-	-	-
Branching Post.	-	-	-	+	-
Bohm. State Post.	-	-	-	-	+
Position Post.	-	-	-	-	+
Equilibr. Post.	-	-	-	-	+

7. True Inwardness of Reality

What we have not done is to expound yet another interpretation of QM, to defend one or to criticize one. What we have done is something more modest. We have expounded what it means to *interpret* QM and it means, in a nutshell, this: to extend QM_0 by adding postulates and enriching the vocabulary. This is achieved by proceeding as follows.

1. List the concepts that the interpretation employs *in addition* to those of minimal QM (QM_0), which are: physical system, physical subsystem, physical magnitude, probability, measurement; explain these additional concepts.

2. Mention whether the physical concepts of QM_0 change in the new interpretation, i.e., whether the meaning of the words expressing them differs in the new interpretation when these words are already employed in QM_0; explain these differences.

3. List the postulates that the new interpretation adds to those of QM_0; if postulates of QM_0 are not among those of the new interpretation, show that these postulates of QM_0 become theorems in the new interpretation.

4. Mention whether some (or all) of the postulates of QM_0 change in the new interpretation; explain these changes.

5. List the questions that minimal QM_0 does not answer, or the problems that QM_0 does not solve, and show how the new interpretation of QM answers (some of) them and solves (some of) them, respectively.

The above list ought to be the to-do list for every interpreter of QM.

Thus the interpretation of QM turns out to be *not the same as* how *to interpret* is generally interpreted in philosophy, which is: *to assign meaning to*. Depending on the interpretation under consideration, there is more or less of interpretation in the last-mentioned sense going on; but the thesis that this is *all* that is going on in the discourse on the interpretation of QM is like saying that arranging the table is all that is going on in the preparation of a dinner.

Is the interpret.ation of QM, then, perhaps a special case of hermeneutics as we have come to know it in continental philosophy, where we think of the likes of Schleiermacher, Dilthey, Heidegger, Gadamer and Derrida? Is the discourse on the interpretation of QM an hermeneutical discourse in his sense, i.e. is there such a thing as *quantum hermeneutics*? Let us briefly take a closer look at hermeneutics in philosophy.

The word *hermeneutics* comes from the Greek word for interpretation or translation ($\varepsilon\rho\mu\eta\nu\varepsilon\upsilon\omega$), which derives from the name of the Greek mythological figure Hermes, who deciphered messages of the gods and communicated them to human mortals. Aristotle introduced hermeneutics in philosophy in his *De Interpretatione*, by distinghuishing the symbols or signs (*symbola*) from the affect they have on our minds (*pathemata*) as well as from the entities they represent (*pragmata*), of which the mental affections are representations (*homoiomata*). Hermeneutics in philosophy is the study of written texts in context, in order to understand the text better, notably to come to know what the text expresses, to which the text provides access. The study of sacred texts in Talmudic, Vedic, Biblical and Apostolic traditions belong to *theological* or *religious* hermeneutics; they have one leg in mythology (Hermes) and the other one in philosophy (Aristotle). The context of the text is usually taken to be the historical context in which the text is produced (Dilthey), in order to understand the views and intentions of the author (Schleiermacher) or to understand what the text itself expresses (Dilthey), where ?understanding? has to be understood in the sense of Droysen's *verstehen* rather than *erklären*. Heidegger gave birth to *existential hermeneutics*, an endeavor to understand human existence, *Dasein*, directly, without mediation by text and language generally. Inquiry into written text in context, call it *textual hermeneutics*, is something else: indirect and further removed from life as we live and experience it. Existential hermeneutics was further developed by Heidegger's pupil Gadamer [1960], who further delved into individual human experience, mediated by language however, in particular by spoken language in conversation.

The *hermeneutic circle*, an idea introduced by Heidegger, has various manifestations.

One is that in order to understand parts of a text, one needs to understand the text as a whole, and in order to understand the whole text, one needs to understand its parts. The process of interpretation, leading to an ever increasing understanding, thus proceeds in a circle of reading and re-reading. One understands the postulates of QM better after one has understood the whole of QM, and one understands the whole of QM better after one has understood the postulates. This is however not what is going on in the discourse of the interpretation of QM. Another manifestation of the hermeneutic circle is the reciprocity between text and context. But inquiry into the historical context of the advent of QM, and into what the effect of the historical context on the content of quantum-mechanical texts has been belong to the discourse of the history of QM, not to the interpretation of QM. So this second manifestation of the hermeneutical circle also is definitely not what is going on in the discourse of the interpretation of QM.

Derrida took a turn in textual hermeneutics by considering only *other texts* as the context of a text, leading to his notorious assertion "There is nothing outside the text". "There is nothing outside context", expresses the same, Derrida later explained. Notice that we only have access to the past, to the factual historical context in which a text is written, by means of other texts - and occasionally images and artifacts. Use of words in other texts resonate in the text under consideration, and their use in the text under consideration resonate back in all other texts. This seems yet another manifestation of the hermeneutic circle. But, again, this hardly helps to capture what is going on in the interpretation of QM.

We tentatively conclude that there is no such thing as *quantum hermeneutics.*

This conclusion savors an *a priori* possible and perhaps promising connexion between the discourse of (i) philosophy of physics and of (ii) hermeneutics in philosophy - and philosophy of language we submit. Interpreting QM is not merely *a matter of semantics* or penetrating deeper into quantum-mechanical texts and their context. What is at stake in the discourse of the interpretation of QM is *how* and *what* microphysical reality is, *how to understand* microphysical reality - if it is understandable by us at all -, granted that QM provides us with the best basis to answer these questions. What is at stake here are answers to all sorts of questions concerning microphysical reality, the world of the tiny and the brief, and to physical reality generally. Hopefully the answers to these questions jointly provide some coherent understanding of physical reality. Finding answers becomes a matter of finding the right additional postulates to extend QM_0, rather than just keeping the postulates fixed and re-interpreting expressions occurring in them. Novel concepts, alien to NLAWKI, not in use and nowhere expressed in other texts, may very well have to be constructed for this pur- pose. Steps 1, 2 and 3 are supposed to involve precisely radical conceptual change.

Hence in one of the most successful areas of natural science, quantum physics, an interpretational inquiry was launched by theoretical physicists in the 1920s; later philosophers joined in, with a vengeance. A mainstream interpretation was settled, of Copenhagen design. But it did not last. Copenhagen QM has left too many questions unanswered. Schrödinger complained that the interpretational problems of QM were shelved, not solved. In his Nobel Lecture of 1969, Murray Gell-Mann notoriously declared that an entire generation of physicists was brainwashed into believing that the interpretation problems of QM were solved, by the Great Dane. To interpret QM is to extend minimal QM_0 and its vocabulary, which permits the expression of more concepts than the language of QM_0 permits. Since forging novel concepts is a philosophical activity par excellence, a philosophical activity is required to aid physics to achieve its aims.

The final word is to B.C. van Fraassen, with an empiricist twist at the end:

> Why then be interested in interpretation at all? If we are not interested in the metaphysical question of what the world is really like, what need is there to look into these issues?
>
> Well, we should still be interested in the question of how the world could be the way quantum mechanics - in its metaphysical vagueness but empirical audacity - says it is. That is the real question of *understanding*. To *understand* a scientific theory, we need to see how the world could be the way that the theory says it is. An *interpretation* tells us that. The answer is not unique, because the question *How could the world be the way the theory says it is?* is not the sort of question to call for a unique answer. Faith in the actual truth of a good answer, so interpreted, is neither required by *understanding*, nor does it help.