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The nature of interpretation in quantum mechanics, hermeneutic circles and physical reality, with cameos of James Joyce and Jacques Derrida[1]

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Summary. The quest for finding the *right* interpretation of Quantum Mechanics (QM) is as old als 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 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 hermeneutics in Continental Philosophy.

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[1] The main title of this paper is borrowed from James Joyce's *Finnegans Wake* (1939, 244.15), as are the titles of the Sections, for reasons that will become evident to the imaginative mind as we proceed; the notation '244.15' is standard and means: page 244, line 15. Any edition can be consulted, because they all use the same pagination and lining.

1. Nuemaid Motts and a Nichtian Glossary

James Augustine Aloysius Joyce (1882–1941) constructed this tantaltuous and tumulising towertome *Finnegans Wake* (1939) in the 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 *axiomatised*, by Johnny 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 *analysed* and *criticised*, by Albert Einstein, Schrödinger, Wigner and others. All of this continues uptil the present day, including ever more physicists. Over the past decades, philosophers have joined the interpretation effort — with remarkable success, we dare add.

News broadcast in *Finnegans Wake*:[2]

> The abnihilization of the etym by the grisning of the grosning of the grinder of the grunder by the first lord of Hurteford expolodonates through Parsuralia with an ivanmorinthorrorumble fragoromboassity amidwhiches general uttermost confusion are perceivable moletons scaping with mulicules . . . Similar scenatas are projectilised from Hullulullu, Bawlawayo, empyreal Raum and mordern Atems.

Recall that in 1911 Lord Rutherford (lord of Hurteford) split the atom (etym), a detonation of sorts where electrons (moletons) and molecules (mulicules) escape, projectiles moving through empirical space (German *Raum*). The historical event was reported all around the globe, like in Paris (Hullulullu), Rome (Bawlawayo) and Athens (Atems).

Traces of both the Quantum and the Relativity Revolution in physics are scattered all over *Finnegans Wake*.

Philosophically, *Finnegans Wake* can be seen to raise the issue of what *meaning* is, even of what *language* is. We do not awaken this grand defining issue of the philosophy of language; we let it sleep.

To interpret a word, an expression, a sentence, a text, is *to assign meaning* to it. Clear and unambiguous kinds of texts, such as the telephone directory of Hullulullu, the weather forecast for tomorrow in Bawlawayo, the papers of Patrick Colonel Suppes, and the user manual of your brand new ten-dimensional retina-screen nanowave stringphone, do not stand in need of interpretation. Other kinds of text cry out earsplittingly for interpretation, of which *Finnegans Wake* arguably is the most clear and unambiguous instance ever created. An exposition of quantum mechanics is, in the company of novels and poems, somewhere between text that need no interpretation and texts that absolutely require interpretation, although admittedly it will be closer to the aforementioned than to the last mentioned. As Dummett (1925–2011) testified:[3]

[2] Joyce [1938], 353.22–23. [3] Dummett [1991], p. 13.

> 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*.

But standing in need of interpretation is something that *Finnegans Wake* and quantum mechanics (QM) share with lots of other texts, such as the earlier mentioned novels and poems. We must take a closer look to understand why they are special, to seek out what it is specifically that they have in common besides requiring (much or some) interpretation.

Joyce judged *natural-language-as-we-know-it* (whenceforth: Nalasweknowit) inadequate to describe what happens in the dream world. For this very purpose, Joyce created a 'new language', *if* that is the appropriate phrase, given how Joyce characterised his means of expression in *Finnegans Wake*: "nuemaid motts truly plural and plusible" (138.08–09) and a "nichtian glossery which purveys aprioric roots for aposteriorious tongues this is nat language in any sinse of the world" (83.10–11). Say no more. Heisenberg and Bohr judged Nalasweknowit, of which they considered 'the language of classical physics' a refinement, inadequate to describe what happens in the microphysical world, the world of *very* small physical entities and *very* brief physical processes.

Small wonder. Nalasweknowit has developed while *homo sapiens* and its ancestry was wide awake, i.e. not dreaming, and was 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, which we share with beasts, rather than with penetrating the ephemerally flashing realm of dreams, 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. But, at some point in history, the time had come that we did want and did need to go precisely there, and we did want to transcend our biological needs. How and why did we do it?

Long story. Too long.

Back to the early 20th Century. Understanding the microphysical world was no longer deemed possible with Nalasweknowit. In order to grasp this realm of reality somehow, only a 'symbolic description', or a *Deutung*, by abstract mathematical means seemed possible. Of course nothing remotely like "multimathematical immaterialities" (394.31–32) were the means for Joyce to penetrate the realm of dreams. Joyce constructed numerous neologisms and *portmanteaux*: "the dialytically separated elements of precedent decomposition for the verypetpurpose of subsequent recombination" (614.34–35). In contradistinction to how Joyce accomplished his daunting task of evoking the phantasmagorical events of deep weep sleep, i.e. by creating *Finnegans Wake* and thereby replacing Nalasweknowit, what the founding fathers of QM did was something far less radical: a comparatively small yet significant enrichment of Nalasweknowit would initially turn out to be sufficient to unlock the secrets of the atom and to enter the suprasensical world — but would eventually and entirely unexpectedly also usher to perplexities the world of physics had never seen before . . .

2. Abnihilazation and Everintermutuoemergent

No matter how one characterises QM pecisely, 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, or as some category with objects and arrows (to show the world proudly you're in full command of the latest thing), QM incontestably has *propositional content*, expressed in declarative sentences of Nalasweknowit, enriched with physical and mathematical vocabulary, symbols included. 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 correlata (version of Bell's Theorem), and like a continuously *observed* kettle filled with water on the fire that never boils (quantum Zeno paradox).[4] Sometimes QM remains mute when we are convinced there must be an answer, like when we ask whether Schrödinger's unmeasured, and therefore unobserved cat *is* either dead or alive, since QM does neither fulfil the truth-condition for the sentence 'The *unobserved* cat is alive', nor for 'The *unobserved* cat is dead'. Here 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 nor more than a few droplets of the ocean of being. Nearly all of physical reality is *ontically indeterminate*. Therefore to speak of 'the measurement problem' is peculiar, and an historical accident in fact. The problem is better be called *the reality problem* of QM. QM forbids us to speak whereof we want to speak and need to speak: reality.

Notice parenthetically that a use theory of meaning, which takes the use of words, expressions and sentences constitutive for their meaning, does not sit comfortably with Dummett's locution 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 measure-

[4] 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.

ment outcomes, and knowing how analyse 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 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 stands 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 and there would not have been an interpretation debate. But there is.

QM is always presented in natural language enhanced by scientific vocabulary, mathematical as well as physical; many concepts are also expressed by symbols, as is common in mathematics. Logical concepts are also be prominently present: and, or, not, there is, for all, implies, follows from, is consistent with, if–then, etc. So the vocabulary of QM can be subdivided in:

(α) Logical Vocabulary,
(β) Mathematical Vocabulary,
(γ) Physical Vocabulary.

We shall take these in turn.

(α) The default option about the Logical Vocabulary that standard classical (sentential and predicate) logic can be used to make it precise. But this is already not entirely uncontroversial: some interpretations of QM require deviations from classical logic, e.g. quantum logic, others do not. We shall proceed with the default option, and addres below the issue whether 'a change of logic' counts as an interpretation of QM. Further, it is well-known that *scientific inference* is not exhausted by deductive reasoning: abductive, inductive, probabilistic and analogical reasoning are abound in science. To capture these rigorously is an ongoing effort in philosophy of science and philosophical logic. Since this topic has little if anything to do with the interpretation of QM, we gloss over it.

(β) The words in the Mathematical Vocabulary 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, irreducible unitary representations of a symmetry group, permutation operators, Wigner distributions, complex square-integrable function of n real variables, Von Neumann rings of operators, canonical commutator, and so forth.

(γ) The Physical Vocabulary includes: physical magnitude, physical system, composite system and subsystem, physical property and physical relation. These concepts also seem far from obscure. This is not to say that these concepts are beyond interpretation, let alone beyond *metaphysical* analysis. But debates in metaphysics on the nature of properties, relations (and existence for that matter) have had no bearing on debates on the interpretation of QM. Perhaps they should have? There seems little to say in utter generality. Any interpretation of QM that specifies conditions for the ascription of properties to physical systems can have a *realist* reading, which considers properties as abstract entities that are instantiated by physical systems, as well as a *nominalist* reading, which considers the mentioned conditions as application conditions for predicates. Such differences yield different interpetations of QM, but these differences are due to a prior metaphysical view that is independent of, and likely cannot be motivated by an appeal to, QM. Such differences in interpretation are uninteresting for those interested in QM. Interpretations of QM who differences are all due to such prior metaphysical views are hereby distinguised and deserve a special name: we shall call them *uninteresting* variants of each other.

Physical concepts of QM that stand in need of interpretation are: $(\gamma.\boldsymbol{i})$ certainly the concept of measurement itself, $(\gamma.\boldsymbol{ii})$ the probability for finding specific outcomes upon measurement, and $(\gamma.\boldsymbol{iii})$ physical state.

$(\gamma.\boldsymbol{i})$ 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 and distinct general concept. In short, we are after a Carnapian explication of the concept of measurement. By way of an interjection, we shall attempt this in the next Section. 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 the discourse 'the interpretation of QM'.

$(\gamma.\boldsymbol{ii})$ 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 $\mathcal{I}(\mathbb{R})$; probability is a branch of mathematical measure theory. Not for the scientist, who has to relate this 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 *generalised quantitative disposition*, and as does taking it as a *degree of belief of a human being* or a *degree of rational credence*. We have now entered the field of the interpretation of probability. Some hold that *quantum probability* is somehow special and different from probability as it occurs elsewhere in physics and in science generally. The challange then is to explain wherein this difference resides.

$(\gamma.iii)$ The physical state of a physical system can best be taken as a *primitive* concept, which can not be analysed further into other physical concepts. In QM, it can be and is represented mathematically in a variety of 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, or
- ⊛ a set of probability measures.

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 then associates a Hilbert-vector to the cat that is devoid of physical meaning, but enables the computation of probability measures over measurement-outcomes, which are filled with physical meaning. Thus we have physical meaningfulness out of physical meaninglessness. Sheer magic. Sadly magic does not help us to understand physical reality.

The wilful 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*, and we want QM to be logically compatible with this belief, at the very least, and preferrably to imply one or the other belief.[5] 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

[5] The border between dead and alive may be vague, in which case read for 'alive': not dead.

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.[6]

> □ **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: $B|\psi\rangle = b|\psi\rangle$.[7]

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' (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 — 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

[6] 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'.

case one should consider such property postulates as Carnapian *meaning postulates*, rather than synthetic postulates that are either made true or made 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 relativising 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 proces of decoherence.[8] They re-interpret and therefore change the meaning of words in Nalasweknowit. 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 mutandis* modal QM provides a different description of the microphysical world than standard QM does. This is the key insight of this paper 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 $(\gamma.i)$ measurement.

3. Multimathematical Murkblankered Immaterialities

3.1. Preambule

In English, as in most languages, *to measure* is a *verb*. The *noun* 'measurement' is derived from it: 'to perform a measurement' is synonyous with 'to measure'. To measure is a manifestation of intentional behaviour, 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 'measurement behaviour'. Therefore the concept of measurement is an *intentional* concept.

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

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

[8] See Wallace [2013] for a state of the art defence of the Everett Interpretation.

There are *kinds* of measurements, whose extensions are subclasses of the extension of (2): demolishion 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 express different but allied concepts, which we call *measurement concepts*: measurement event, measurement process, measurement procedure, measurement result, measurement outcome, measurement interaction, measurement apparatus, measurement theory, measurability. In every case, the suffix 'measurement' points to a *kind*, or *subspecies*: 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 process; *etc*. The purpose of this Section is to analyse the core concept Meas (2). The other measurement concepts will have to wait (they can however easily be defined in terms of Meas).

In our *analysandum*, 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 characterise these concepts in a way that does not rely on any measurement concept, otherwise we awaken the spectre of circularity. We outsource the concept of a human being to philosophical anthropology and move now to the other concepts from the putative *analysans*, 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, i.e. a finite number of significant digits. Since two measurement results, a and b, can be taken as the real and the imaginary part of a complex number $a + \mathrm{i}b$, there is room for extending $\mathbb{Q}$ to complex numbers with rational real and imaginary parts ($\mathbb{C}_{\mathrm{rat}} \subset \mathbb{C}$). Nonetheless we continue with $a \in \mathbb{Q}$ and bracket $\mathbb{C}_{\mathrm{rat}}$.

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 $23,000\ldots$, and not 23 ± 1, let alone $23,0 \pm 0,2$. (In these cases, the outcome still is a rational number, because $\mathbb{N} \subset \mathbb{Q}$; so we can stick to $a \in \mathbb{Q}$.)

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 entities rather than abstract ones.

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. We proceed stepwise, **(i)–(iii)**: in each step we consider a concept that we shall use in characterising what a measurement apparatus is.

(i) *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 mention here 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 and were looking at S, 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. For a scientific characterisation of observability, see Muller [2005].

If S is observable, then S seems to have *properties* that are observable, notably its shape and colours. What *is* it that we actually *see*: the object or its properties, or both? In full generality, this is a metaphysical issue we wish to bracket. We shall limit ourselves to a characterisation of an observation predicate, remaining neutral about whether predicates express universals or tropes, or no entity at all additional to the subject of predication.

> **Criterion for an Observation Predicate.** A predicate F applied to observable physical system S is an *observation predicate* iff for every person p: if p were looking at S in broad daylight and looking at S, then p would immediately judge that $F(\mathsf{S})$ or immediately judge that $\neg F(\mathsf{S})$ relying only on looking at S and not making any inferences or appealing to some theory; such judgements we call *observation judgements*.

The addition of 'and not making anyl inferences or appealing to some theory' is to prevent that *theory*, broadly construed, is relied on in order to judge whether $F(\mathsf{S})$ or that $\neg F(\mathsf{S})$. Consider a Stern-Gerlach experiment. To judge that the electrons have spin up is not an observation judgement, because 'spin' is a predicate that cannot be understood without understanding some QM, and because electrons are unobservable, whereas judging that 'there is a black dot in the upper half of the white screen' is an observation judgement, with 'having a block dot in the upper half' being the observation predicate applied to white screens, which is an observable physical system. We point out that person p must possses a language, otherwise p could not form the judgement that $F(\mathsf{S})$ or that $\neg F(\mathsf{S})$. As soon as knowledge of a theory is needed to understand what predicate F means, F cannot be an observation predicate. Every observation judgement trivially is always 'concept-laden', because a predicate expresses a concept and an observation predicate is no exception. Judgements like 'the electrons have spin up', made while looking at the screen, is a 'theory-laden' judgement.[9]

So much for the observability of measurement apparatus M.

(ii) *One-one Correspondence*. When we read that the pointer of a Volt-meter 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 single values because of the finite measurement accuracy: result $I = 1.04 \pm 0.07$ mA describes an observable property of an Am-meter that corresponds to an infinite set of electric current values, namely interval $[0.97,\ 1.11] \subset \mathbb{Q}$.

(iii) *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. McGuffey can assign a rational number to the three billiard balls lying on the table in front of him using pencil and paper: McGuffey looks at a ball and writes down some arbitrary rational number. McGuffey claims to have measured the masses of these balls, for 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. Yet surely the pencil and paper do not qualify as a piece of *mass-measuring equipment*. Pencil and paper can be used *to report* measurement outcomes, but they are not themselves pieces of mass-measurement equipment. Furthermore, just writing down an arbitrary rational number with a pencil on a piece of paper is not measuring anything. McGuffey has *not* measured the mass of the billiard balls. If a one-one correspondence were enough, then measurement results would be what we want and choose them to be, and 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 and choose. 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. Reality has a decisive

[9] Granted that it is controversial whether obseration predicates can be cleanly characterised and discerned from 'theoretical' predicates, we take sides in this controversy, in favour of there being clear and distinct observation predicates. For a recent defence, see Votsis [2015].

say in it. Reality bites back.

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. McGuffey'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 an *$\mathcal{A}$-measurement apparatus* iff
(M1) M is observable; and
(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 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.

3.5. 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 (Huygens), 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 quantitative 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 collapes to an eigenstate that belongs to value a, which then is an eigenvalue of the $\mathcal{A}$-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 possible values of $\mathcal{A}$, or as $\langle \mathcal{A}, a, \mathrm{u} \rangle$ when magnitude $\mathcal{A}$ has a *unit* u. 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):

$$\langle \text{mass},\ \mathbb{R}^+,\ \text{kilogram} \rangle\ , \qquad \langle \text{length},\ \mathbb{R}^+,\ \text{meter} \rangle\ , \qquad \langle \text{energy},\ \mathbb{R},\ \text{joule} \rangle\ . \tag{3}$$

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

3.6. Main Dish

Much of the labour we had to perform to arrive at an *analysans* of our *analysandum*, that is, at a criterion for the core concept of measurement, has already been performed above, 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,
(2) $\mathcal{A}$ is a physical magnitude,
(3) S is a physical system,
(4) M is an $\mathcal{A}$-measurement apparatus,
(5) $a \in \mathbb{V}(\mathcal{A})$, the set of possible values of $\mathcal{A}$, and
(6) S and M physically interact $\mathcal{A}$-relevantly, or p makes them 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 ever 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 'lenght-relevant physical interaction between table and tapeline'? Their interaction consists of no more than they absorb some of each other's emitted electromagnetic 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. What we can do in the face of rods and clocks is to call the explicated concept above *Interaction Measurement*; measuring lengts and times by means of rods and clocks, respectively, the fall under the concept of Non-Interaction Measurement, a concept to be explicated in the future. 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 the $\mathcal{A}$-relevant physical interaction.

This characterisation of measurement interaction is not entirely physico-ontological but partly empistemological, just as measurement is, due to our characterisation of what an $\mathcal{A}$-relevant interaction is (see above). This is how it ought to be, for to measure is to acquire knowledge. Measurement also counts as a species of knowledge acquisition. Quantum-mechanical measurement theory provides more detailed mathematical representations of measurement interactions, but it leaves the conceptof measurement, remarkably, un-analysed.[10] Back to the interpretation of QM.

4. Building supra Building pon the Banks for the Livers by the Soangso

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* (QM_0, soon to be characterised rigorously).

The epistemic aim of physics can be several things:

- to save the observed phenomena;
- to save the observed and unobserved phenomena;
- to explain the observed and unobserved phenomena;
- to understand why things happen when and where they happen;

[10] See Suppes [2001], pp. 63–73, for some general Measurement Theory; see Bush, Lahti and Mittelstaedt [1996] for physical measurement theory. The concept of a measurement apparatus is not analysed but taken for granted in both books, remarkably.

- 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;
- to reveal the structure of the universe as it is in and of itself;
- any other aim that goes above and beyond merely calculating putative measurement outcomes.

Save the first two aims, QM_0 falls short of reaching any of these aims of physics, for instance by telling us nothing about the fate of the cat and any other physical system that is not measured or observed. QM_0 leaves too many meaningful questions about physical reality wide open. When QM_0 is a failure, must it not be refused entrance to the body of scientific knowledge? Is the current presence of QM_0 in that body not a cyst which should be surgically removed?

Nay nay, do not be afraid, I am not going to propose surgery. On the contrary, QM_0 will be the basis of it all.

> **Definitions.** An *interpretation of* QM is another theory that is physically equivalent to QM_0, changes the vocabulary of QM_0, and extends the postulates of QM_0.
>
> A theory is *physically equivalent to* QM_0 iff that theory is empirically equivalent to QM_0 and does not extend the physical vocabulary but may change the mathematical and logical vocabulary of QM_0.
>
> A theory is *empirically equivalent to* QM_0 iff that theory is confirmed by exactly the same actual and possible measurement outcomes as QM_0.

An interpretation of QM must provide answers to questions about physical reality that we deem meaningful and that pertain to physical systems falling within the purview QM_0. We point out that our definition of an interpretation of QM is in harmony with what Van Fraassen says about it:

> Suppose we agree that there can, in 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?[11]

There may be hermeneutical activity in the wake of extending QM_0 in the literal sense of the word, in that the meaning of certain expressions has to be adjusted to fit the intended extension of QM_0, but the core interpretational activity is to extend QM_0 by adding postulates and vocabulary.

What is QM_0 precisely? Here follows an attempt to characterise it.

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, where $\mathcal{I}(R)$ is a Boolean subset algebra of intervals of $\mathbb{R}$,
THEN at every moment in time $t \in \Delta$, associate a Hilbert-vector $|\psi(t)\rangle \in \mathcal{H}$ (**P0**) *to S such that there is a connected Lie-group of unitary operators acting in $\mathcal{H}$ such that $|\psi(t)\rangle = U(t)|\psi(0)\rangle$, where $|\psi(0)\rangle$ is associated to S at time $t = 0$, and where $U(t)$ is a group member, obeying the equation: $U(t+t') = U(t)U(t')$, for every $t, t' \in \Delta$.*

P2. Magnitude Postulate (Von Neumann). *Represent physical magnitudes of interest by operators acting in $\mathcal{H}$* (**P0**) *that have some 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 positive operator 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* (**P2**) *when Hilbert-vector $|\psi(t)\rangle \in \mathcal{H}$ is associated to S at time $t \in \Delta$* (**P0, P1**)*, equals the expectation-value of $P^B(\Delta) \in \mathcal{P}(\mathcal{H})$; in Redhead-notation ($[B]^{|\psi(t)\rangle}$ is the value of B when S is in state $|\psi(t)\rangle$):*

$$\Pr\big([B]^{|\psi(t)\rangle} \in \Delta\big) \;=\; \langle\psi(t)|P^B(\Delta)|\psi(t)\rangle \;. \tag{4}$$

For the sake of brevity, we have left out the Symmetrisation Postulate, which is about composite systems of similar particles, although one should think of QM_0 as including it.

Notice that QM_0 only speaks of *physical systems, physical magnitudes and probability distributions over measurement outcomes*, which exhausts its physical vocabulary. 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 — *alas* 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* 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 and then obtaining the same outcome (for discrete spectra)? If not, QM_0 may be an empirical failure. An adherent of QM_0 may uphold that the relative frequencies of repeated measurements can be described by conditional probability measures. A critic may respond that conditionalising in QM is the same as applying the Projection Postulate. Etc.[12]

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 helluvit? 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 phonemena that make us understand physical reality, and gathering such knowledge is the epistemic aim of physics. Otherwise the repeated empirical success of the theory would be a miracle and we don't believe in miracles.

Standard, or *orthodox quantum mechanics* ($\mathrm{QM}_{\mathrm{ox}}$) 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 $\mathrm{QM}_{\mathrm{ox}}$ adds: physical properties and physical state. The Hilbert-Space Postulate (**P0**) becomes the

□ **Pure State Postulate (Von Neumann).** *Every possible pure physical 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 $|\psi(t)\rangle = U(t)|\psi(0)\rangle \in \mathcal{H}$ until the moment $t_m \in \mathbb{R}$ of measurement, AND one finds outcome in $b \in \Delta \in \mathcal{I}(\mathbb{R})$ at time t_m, 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: $P^B(\Delta)|\psi(t)\rangle$. Using the Heaviside step-function $\theta : \mathbb{R} \to \{0, 1\}$ (0 for negative arguments, 1 for positive arguments and 0):

[12] See e.g. Fraassen [1991], pp 227–231.

$$|\psi(t)\rangle \;=\; \theta(t-t_{\rm m})U(t)|\psi(0)\rangle + \theta(t_{\rm m}-t)U(t-t_{\rm m})P^B(\Delta)|\psi(t_{\rm m})\rangle\,. \tag{5}$$

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 $\mathcal{A}$ are the possible measurement-outcomes of $\mathcal{A}$.*

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

5. The Ineluctible Morality of the Intelligible

Bohr's Copenhagen Interpretation has long been, and perhaps still is, the interpretation most physicists adhere to; it pervades textbooks on QM. It adds the following postulates to QM_0, resulting in, say, QM_{B}.

□ **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 QM_{B} 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 *of the object-systems proceeds by means of mathematical concepts.*

Finally there is the

□ **Complementarity Postulate (Bohr-Heisenberg).** *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 Nalasweknowit: 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 *cs*. 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 bi-orthogonal 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 adds a branching postulate:[13]

□ **Branching Postulate (Everett).** *Consider a particular basis of the Hilbert-space $\mathcal{H}$, associated with 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 $j = 1, 2, \ldots dim(\mathcal{H})$. Then relative to branch j,* S *has physical property $\langle B, b_j \rangle$, where $B|\phi_j\rangle = b|\phi_j\rangle$.*

[13] Our approach belies the often heard phrase that Everettian QM *is* QM, or *is* 'the quantum-mechanical formalism without any interpretation'. Dream on.

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, so to speak 'preferred by Mother Nature', which then is considered in the Everett Postulate above, notably by Oxonian Everettians. They thus have physical reasons to attach ontological significance to the terms of $|\psi\rangle$ 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 adere ontological significance to *these* terms, and that means that $\mathrm{QM}_{\mathrm{Ev}}$ goes above and beyond QM_0, — and, of course, differs from $\mathrm{QM}_{\mathrm{ox}}$.

Even Bohmian Quantum Mechanics (BQM) qualifies as an interpretation of QM. BQM adopts the Hilbert-space of complex wave-functions on configuration space. For the sake of simplicity, we consider 2 spinless particles in 3-dimensional space, having mass 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:* $\langle\psi, \boldsymbol{Q}\rangle$, *where* $\psi : t \mapsto \psi(t) \in L^2(\mathbb{R}^6)$ (**P0. Hilbert-Space Postulate**) *and* $\mathbf{Q} : t \mapsto \mathbf{Q}(t) \in \mathbb{R}^6$ (**Position Postulate**: see below.)

Just as in QM_0, ψ is postulated to obey the Schrödinger equation. Vector $\mathbf{Q}(t)$ consists of 6 components, and can be written as $\langle \mathbf{Q}_1(t), \mathbf{Q}_2(t)\rangle$, where $\mathbf{Q}_1(t)$, $\mathbf{Q}_2(t) \in \mathbb{R}^3$. Vector $\mathbf{Q}_1(t)$ represents the position of $\mathbf{p}_1$ at time t, and similarly $\mathbf{Q}_2(t)$. Like in classical mechanics but unlike in $\mathrm{QM}_{\mathrm{ox}}$, in BQM every particle always has a position. Bohmians 'complete' QM by adding $\mathbf{Q}$ to ψ.

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

$$m_1 \frac{d\mathbf{Q}_1(t)}{dt} = \hbar \,\mathrm{Im} \left(\frac{\nabla_1 \psi(\mathbf{q}_1, \mathbf{q}_2, t)}{\psi(\mathbf{q}_1, \mathbf{q}_2, t)} \right)_{\mathbf{q}_1 = \mathbf{Q}_1(t)} , \tag{6}$$

where ∇_1 *is the gradient, with respect to* $\boldsymbol{q}_1$, *and* $\mathrm{Im}(z) \in \mathbb{R}$ *is the imaginary part of* $z \in \mathbb{C}$. *Similarly for particle 2.*

One should not confuse $t \mapsto \mathbf{Q}_1(t)$ 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 (6) is a time-derivative of the position of particle 1, which is the definition of its velocity:

$$\mathbf{v}_1^{\psi}(t) \;=\; \frac{d\mathbf{Q}_1(t)}{dt}\;, \tag{7}$$

where the superscript 'ψ' is there to emphasise that the velocity is determined by ψ, via eq. (6), 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.

Legenda 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.

	QM_{ox}	BiModQM	QM_{B}	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.	−	−	−	−	+

6. True Inwardness of Reality

What we have not done is to expound yet another interpretation of QM, to defend one or to criticise 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.

❶ 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.

❷ 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.

❸ Mention whether the logical concepts of QM_0 change in the new interpretation, i.e. whether they deviate from those expressed in classical logic, and explain these differences.

❹ 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.

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

❻ List the questions that 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 interpreation 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, to get more grip on its content. 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*.[14] Heidegger gave birth to *existential hermeneutics*, an endeavour 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 ('to experience truth').

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."[15] "There is nothing outside context", expresses the same, Derrida later explained.[16] 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 artefacts. 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.

Parenthetically, in *Finnegans Wake* Hermeneutic Circles are Everywhere (HCE).

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[14] Wright [1971], p. 5. [15] Derrida [1967], pp. 158–159. Derrida was parenthetically heavy influenced by *Finnegans Wake*, see Derrida [1984]. [16] Derrida [1988], p. 148.

We tentatively conclude that there is no such thing as 'quantum hermeneutics'.[17] This conclusion savours 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 Nalasweknowit, not in use and nowhere expressed in other texts, may very well have to be constructed for this purpose. Steps ❷–❺ 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 1920ies; 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 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 excellance*, a philosopical activity is required to aid physics to achieve its aims.

We want to unveilop the theory of the building blocks of matter and their interactions. We need to destructify the obscuritads it bangcreated, in order to sunshine physical reality by a syntasm of ison and remagination. For we want to understand. We need to understand. We shall understand. In our stream of consciousness, from swerve of shore to bend of bay, we want to float and fly, transpicuously and persparantly, and not to drown and die.

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

[17] In the sense of hermeneutics as understood in the philosophical tradition sketched above. In another, literal sense, 'quantum hermeneutics' just means 'quantum interpretation'.

> 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.[18]

7. Patrick Colonel Suppes

Permit me to admit that it feels awkward to contribute to an edited volume for Patrick Colonel Suppes (1922–2014). For Suppes has been suspiciously silent in all of his writings about the interpretation of QM. Did he fancy the Copenhagen Interpretation? Did he prefer some modal interpretation? Was he an Everettian in cloack and dagger? No favourites at all? Lame agnosticism? Brute rejection of the very issue of the interpretation of QM as a pseudo-issue? Was he aware of the obscuritads that circumveilop us?

Suppes has not been entirely silent about QM. Everything he has written about QM is about or connected to *probability* (available at his website of Stanford University, spanning *seven* decades).[19] Concerning the issue of the *the interpretation of probability*, however, in and outside QM, Suppes has also been suspiciously silent about where his sympathy lies, his insistence that the differences in interpretation of probability ought to be characterised mathematically notwithstanding.[20] Was he a devout Bayesian? Or some frequentist? Did he believe in propensities?

If there were answers, they have been blown away by the winds of immortality.

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[19] Suppes [1963], [1965]. [20] Suppes [2001], Chapter 5.

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