The Power of Inconsistency in Anti-Realist Realisms about Quantum Mechanics (Or: Lessons on How to Capture and Defeat Smoky Dragons)

Christian de Ronde*

Philosophy Institute Dr. A. Korn, Buenos Aires University - CONICET
Engineering Institute - National University Arturo Jauretche, Argentina.
Federal University of Santa Catarina, Brazil.
Center Leo Apostel for Interdisciplinary Studies, Brussels Free University, Belgium.

Abstract

In this work we argue that the power and effectiveness of the Bohrian approach to quantum mechanics is grounded on an inconsistent form of anti-realist realism which is responsible not only for the uncritical tolerance —in physics— towards the "standard" account of the theory of quanta, but also —in philosophy— of the alarming reproduction of quantum narratives. Niels Bohr's creative methodology can be exposed through the analysis of what John Archibald Wheeler called "the great smoky dragon". We will discuss the existence of such dragons within the "minimal interpretation" applied by physicists in the orthodox textbook formulation of quantum mechanics as well as within the many "supplementary interpretations" introduced by philosophers —or philosophically inclined physicists— in order to solve the infamous measurement problem. After analyzing the role of smoky dragons within both contemporary physics and philosophy of physics we will propose a general procedure grounded on a series of *necessary theoretical conditions* for producing adequate physical concepts that —hopefully— could be used as tools and weapons to capture and defeat these beautiful and powerful creatures.

Key-words: Realism, empiricism, representation, observability.

Ts'ui Pe must have said once: I am withdrawing to write a book.
And another time: I am withdrawing to construct a labyrinth.
Every one imagined two works; to no one did it occur
that the book and the maze were one and the same thing.

Jorge Luis Borges.

1 Realism and Anti-Realism in Physics

Physics was born during the 6th Century B.C. in the Greek city of Miletos, on the coast of Asia Minor, where the Ionians had established rich and prosperous colonies. Three men —Thales, Anaximander, and Anaximenes— appeared in quick succession claiming the existence of what they named *physis* —translated later on as 'reality'. For the first time in the history of western thought physicists replaced mythical stories and narratives by rational explanation. As remarked by Jean-Pierre Vernant:

*This paper is dedicated to the memory of Diego Armando Maradona who taught me, when I was a very young child, that the impossible can be achieved.

> "Myths were accounts, not solutions to problems. They told of the sequence of actions by which the king or the god imposed order, as these actions were mimed out in ritual. The problem found its solution without ever having been posed. However, in Greece, where the new political forms had triumphed with the development of the city, only a few traces of the ancient rituals remained, and even their meaning had been lost. The memory of the king as creator of order and maker of time had disappeared. The connection is no longer apparent between the mythical exploit of the sovereign, symbolized by his victory over the monster, and the organization of cosmic phenomena. When the natural order and atmospheric phenomena (rains, winds, storms and thunderbolts) become independent from the functions of the king, they cease to be intelligible in the language of myth in which they had been described hitherto. They are henceforth seen as questions open for discussion. These questions (the genesis of the cosimic order and the explanation for *meteora*), in their new form as problems, constitute the subject matter for the earliest philosophical thought. Thus the philosopher takes over from the old king-magician, the master of time. He constructs a theory to explain the very phenomena that in times past the king had brought about." [50, p. 402]

The impact of this shift from myth to *theory* would reinforce the transformation of the structure of the Greek society and as a consequence, preachers, mediums and kings would be forced to share their power with the first physicists and philosophers. In this new democratic system known as science, all citizens would be entitled to gain knowledge about reality:

> "[Before the Milesians,] [e]ducation was based not on reading written texts but on listening to poetic songs transmitted from generation to generation. [...] These songs contained everything a Greek had to know about man and his past —the exploits of heroes long past; about the gods, their families, and their genealogies, about the world, its form, and its origin. In this respect, the work of the Milesians is indeed a radical innovation. Neither singers nor poets nor storytellers, they express themselves in prose, in written texts whose aim is not to unravel a narrative thread in the long line of a tradition but to present an explanatory theory concerning certain natural phenomena and the organization of the cosmos. In this shift from the oral to the written, from the poetic song to prose, from narration to explanation, the change of register corresponds to an entirely new type of investigation —new both in terms of its object (nature, *physis*) and in terms of the entirely positive form of thought manifested in it." [50, p. 402]

Three fundamental presuppositions would guide this new form of thought and praxis. First, that *physis* is not chaotic, that it possesses an internal order, what the Greeks called —after Heraclitus— a *logos*. Second, that *physis* is one, indivisible and inseparable. Like Heraclitus would express: "Listening not to me but to the *logos* it is wise to agree that all things are one" [f. 50 DK]. Third, that even though "*physis* loves to hide" [f. 123 DK] the logos of physis could be actually known through the development of *theories*, namely, through the creation of unified, consistent and coherent schemes of thought that could explain phenomena. Already the first philosophers showed a clear recognition of the difficult problems involved within this scheme. To relate the *logos* of men to the *logos* of *physis* was obviously a difficult task, but through hard work and sensibility the latter could be revealed in the former.[1] *Theories* relate on the one hand to *physis* (the One), and on the other to the multiplicity of phenomena (the Many). And it is this kernel aspect which marks the characteristic feature of scientific understanding itself. While 'The One' implies a unified theoretical standpoint of analysis grounded in *physis*, 'The Many' relates to the multiplicity of different phenomena and observations. In this way, theories became the bridge between a unified understanding of reality and the multiplicity of experience. As a young Wolfgang Pauli would explain to his friend Werner Heisenberg during a conversation in 1921:

> "knowledge cannot be gained by understanding an isolated phenomenon or a single group of phenomena, even if one discovers some order in them. It comes from the recognition that a wealth of experiential facts are interconnected and can therefore be reduced to a common principle. [...] 'Understanding' probably means nothing more than having whatever ideas and concepts are needed to recognize that a great many different phenomena are part of coherent whole. Our mind becomes less puzzled once we have recognized that a special, apparently confused situation is merely a special case of something wider, that as a result it can be formulated much more simply. The reduction of a colorful variety of phenomena to a general and simple principle, or, as the Greeks would have put it, the reduction of the many to the one, is precisely what we mean by 'understanding'. The ability to predict is often the consequence of understanding, of having the right concepts, but is not identical with 'understanding'." [34, p. 63]

[1] In this respect, it is important to recognize that physicists never claimed that *theories* "mirrored" reality. In fact, the idea that reqlism implies a one-to-one correspondence relation between theory and reality-in-itself is an idea constructed by anti-realists in order to diminish the possibilities of considering realism.

Of course, as we all know, very soon a strong opposition to these realist ideas also appeared in Athens, which had already become during the 5th. Century B.C., the rich and prosperous capital of Greek Empire. Sophists, as they would be called, would produce the first assault against the realist program arguing that there is no such thing as 'a reality of things', and even if such thing would exist, we would not be able to grasp it. Sophists argued assuming a more skeptic down to earth position that we humans can only refer to our own perception. It makes no sense to talk about a reality independent of subjects because we individuals have only a *relative* access to things, an access limited by our own personal experience. As Protagoras would argued: "Man is the measure of all things, of the things that are, that they are, of the things that are not, that they are not" [DK 80B1]. From this sceptic standpoint, sophists criticized the physical idea of theoretical knowledge: realists —namely, physicists and philosophers— are too naïve, they do not recognize their own finitude and thus have ended up believing they can access the infinite, the real. The first battle of the war between realists and anti-realists had begun.

As we know, it took the power of both Plato and Aristotle to overcome the sophist anti-realist riot. Through the creation of conceptual (or metaphysical) systems; they were both able to provide answers to the sophists and take the realist program a step further. Metaphysics —regardless of the many different ways in which this term has been used— implied an essential shift in the representation of *physis*, going from 'first elements', on which pre-socratics had based their theories (e.g., fire, water, air, etc.), to an interrelated system of abstract concepts and principles. Plato's and Aristotle's metaphysical systems were analyzed, discussed criticized and developed for two millennia keeping realist ideas in the center of the stage of Western thought. But with the rise of modernity in the 16th and 17th centuries things would begun to drastically change. The scientific revolution that took place in modernity might be regarded not only as a culmination of the Greek scientific path, but also as the beginning of its dissolution. On the one hand, the idea of the 'One and the Many' was consistently articulated not only conceptually but also formally through the development of infinitesimal calculus. Physicists had finally constructed the first closed, unified, consistent and coherent formal-conceptual representation of physical reality, namely, classical mechanics. Through its development, physicists were capable of producing not only a conceptual qualitative understanding of phenomena but also the quantitative capacity to compute their accurate prediction. The understanding of the world and reality had been finally united within a space-time atomist representation of the physical world. The mathematical notion of *invariance* captured the essential idea of the Greeks, namely, the consistent unified understanding of a state of affairs given through multiple *reference frame* dependent representations. Essential to this development was the recognition by David Hume that empirical observations were incapable to ground a secure path for scientific knowledge. The notion of *causality* was not something to be found within experience but instead a (metaphysical) concept that we humans imposed to phenomena as the result of mental habit and custom. In turn, it is this same finding which allowed the development of the notion of *objectivity* by Immanuel Kant. Objectivity captured the essential mathematical content of invariance but now in purely conceptual terms. And it is through the combination of both invariance and objectivity that modern physics was able to succeed in producing what the Ancient Greeks had searched for, namely, a rigorous set of formal-conceptual conditions for producing a subject detached representation of a real *state of affairs* —conditions to which we will return in section 5. However, on the other hand, even though modernity marks a period of essential accomplishments and advancements for the realist project, the 16th and 17th centuries might be also considered as marking the beginning of the anti-realist era. The human perspective was —once again— beginning to be considered as the true fundament of knowledge. Both rationalism, with the cartesian *cogito*, and empiricism, with their direct reference to experience, would begin to philosophize placing the subject at the center of their considerations. In doing so they were also introducing an essential separation within reality itself. As Heisenberg explains in *Physics and Philosophy*:

> "The great development of natural science since the sixteenth and seventeenth centuries was preceded and accompanied by a development of philosophical ideas which were closely connected with the fundamental concepts of science. It may therefore be instructive to comment on these ideas from the position that has finally been reached by modern science in our time. The first great philosopher of this new period of science was René Descartes who lived in the first half of the seventeenth century. Those of his ideas that are most important for the development of scientific thinking are contained in his *Discourse on Method*. On the basis of doubt and logical reasoning he tries to find a completely new and as he thinks solid ground for a philosophical system. He does not accept revelation as such a basis nor does he want to accept uncritically what is perceived by the senses. So he starts with his method of doubt. He casts his doubt upon that which our senses tell us about the results of our reasoning and finally he arrives at his famous sentence: *'cogito ergo sum.'* I cannot doubt my existence since it follows from the fact that I am thinking. After establishing the existence of

the I in this way he proceeds to prove the existence of God essentially on the lines of scholastic philosophy. Finally the existence of the world follows from the fact that God had given me a strong inclination to believe in the existence of the world, and it is simply impossible that God should have deceived me. This basis of the philosophy of Descartes is radically different from that of the ancient Greek philosophers. Here the starting point is not a fundamental principle or substance, but the attempt of a fundamental knowledge. And Descartes realizes that what we know about our mind is more certain than what we know about the outer world. But already his starting point with the 'triangle' God-World-I simplifies in a dangerous way the basis for further reasoning. The division between matter and mind or between soul and body, which had started in Plato's philosophy, is now complete. God is separated both from the I and from the world. God in fact is raised so high above the world and men that He finally appears in the philosophy of Descartes only as a common point of reference that establishes the relation between the I and the world. While ancient Greek philosophy had tried to find order in the infinite variety of things and events by looking for some fundamental unifying principle, Descartes tries to establish the order through some fundamental division. But the three parts which result from the division lose some of their essence when any one part is considered as separated from the other two parts. If one uses the fundamental concepts of Descartes at all, it is essential that God is in the world and in the I and it is also essential that the I cannot be really separated from the world. Of course Descartes knew the undisputable necessity of the connection, but philosophy and natural science in the following period developed on the basis of the polarity between the *'res cogitans'* and the *'res extensa,'* and natural science concentrated its interest on the *'res extensa.'* The influence of the Cartesian division on human thought in the following centuries can hardly be overestimated, but it is just this division which we have to criticize later from the development of physics in our time." [33, pp. 41-42]

The main accomplishment of the so called Enlightenment period —which marks the starting point of the anti-realist approach to science [20]— is the separation of *physis* in three different regions that would become complex in themselves and difficult to interrelate. It is this dissection that would allow in later times to destroy completely the meaning and content of the notion of reality itself. *Divide et impera.* This is the motto that might best characterize the anti-realist strategy against realism that begun in Modernity. Physics and philosophy were also beginning to be torn apart. While the first was reassigned the specific role of discussing about the material world, the latter had only to worry about matters of human nature. René Descartes would cut the Greek notion of reality —the One— into three separated "realities": that of the I (*res cogitans*), that of the world (*res extensa*) and that of God. Very soon the new architectonic designed by the physicist and philosopher Immanuel Kant would take the reality of the Cartesian God —which secured the certain relation between *res cogitans* and *res extensa*— further away from the reach of science, into an un-knowable *noumenic* dimension. In Kant's co-relational metaphysics, reality was finally detached from scientific knowledge and replaced by the subject's capacity to account for objects of experience. The circular co-relation between subject and object had lost its foundation. Realism had been deathly wounded. Kant argued that the sum of all objects, the empirical world, is a complex of appearances whose existence and connection occur only in our *representations*. Reality, renamed as a beast, *das Ding an sich* (the Thing-in-Itself), had survived but only as a monstrous paradoxical creature hiding beyond empirical sensibility, impossible to be known. As Kant would write in the *Prolegomena to Any Future Metaphysics*: "And we indeed, rightly considering objects of sense as mere appearances, confess thereby that they are based upon a *thing-in-itself*, though we know not this thing as it is in itself, but only know its appearances, viz., the way in which our senses are affected by this unknown something." Kant had introduced the un-knowable within his metaphysical system, limiting the scientific knowledge of physics to that of *objective reality*—a reality restricted by his list of *categories* (grounded on Aristotelian metaphysics) and *forms of intuition* (Newtonian space and time) common to all human subjects. Thus, *noumenic* reality or reality-in-itself could not be considered anymore as the main goal of the scientific project. Friedrich Jacobi [1787: 223] famous remark would expose the problem in all its depth: "Without the presupposition [of the 'thing in itself,'] I was unable to enter into [Kant's] system, but with it I was unable to stay within it." Furthermore, Arthur Schopenahuer would make clear that the category of *causality* could not be applied within Kant's system to *noumenic reality* and consequently, the disconnection from the categorical representation of objective phenomena was complete. Kant had introduced an essential separation between *reality* and *representation*. Reality had been cut into pieces and its essence finally captured and isolated. But it was still too soon for anti-realism to claim victory. Anti-realists would still have to wait two more centuries in order to rise as the supreme indisputable power of Western thought. It is in our postmodern age, during the 20th Century, that realism would be finally defeated by anti-realism. And the main field of this final battle —between realists and anti-realists— would be no other than a new physical theory called quantum mechanics.

2 Anti-Realist Realism, Inconsistency and Quantum Mechanics

As described by Bas van Fraassen [49, p. 2]: "Kant exposed the illusions of Reason, the way in which reason overreaches itself in traditional metaphysics, and the limits of what can be achieved within the limits of reason alone. But on one hand Kant's arguments were not faultless, and on the other there was a positive part to Kant's project that, in his successors, engaged a new metaphysics. About a century later the widespread rebellions against the Idealist tradition expressed the complaint that Reason had returned to its cherished Illusions, if perhaps in different ways." By the end of the 19th Century the Austrian physicist and philosopher Ernst Mach would produce a vigorous attack against the realist metaphysical presuppositions of classical mechanics. Through a return to empiricism, Mach developed a new positive scheme for physics which —grounding itself on empirical observability alone— would attempt to erase metaphysics from physics. The attack was focused in the Newtonian notions of space, time —which acted as *a priori* concepts within the Kantian architectonic— and atom. The Austrian physicist and philosopher was breaking the walls of the modern spatiotemporal atomist cage in which physics had been confined. But for him, the destruction of this prison implied the necessary demolition of metaphysics itself.[2] The deconstruction of classical Newtonian mechanics and Kant's metaphysical architectonic produced a major crisis in the foundations of science during the 20th Century which Wolfgang Ernst Pauli —the godson of Mach— would recognize in his own terms:

> "In many respects the present appears as a time of insecurity of the fundamentals, of shaky foundations. Even the development of the exact sciences has not entirely escaped this mood of insecurity, as appears, for instance, in the phrases 'crisis in the foundations' in mathematics, or 'revolution in our picture of the universe' in physics. Indeed many concepts apparently derived directly from intuitive forms borrowed from sense-perceptions, formerly taken as matters of course or trivial or directly obvious, appear to the modern physicist to be of limited applicability. The modern physicist regards with scepticism philosophical systems which, while imagining that they have definitively recognised the *a priori* conditions of human understanding itself, have in fact succeeded only in setting up the *a priori* conditions of the systems of mathematics and the exact sciences of a particular epoch." [43, p. 95]

Mach's subversive deconstruction had broken physics from its space-time atomist chains.[3] And it was certainly this liberation which would become essential for the development of both Quantum Mechanics (QM) and relativity theory. While Albert Einstein applied Mach's positivist ideas in order to critically address the definition of *simultaneity* in classical mechanics, both Max Planck and Werner Heisenberg were able to advance new non-classical mathematical postulates and formalisms which could explicitly escape —thanks to Mach's work— the modern space-time representation of classical physics and in this way provide a quantitative operational account of a new field of (quantum) phenomena. However, even though positivist ideas were becoming popular in Europe —specially among physicists— Mach had lost a kernel battle against metaphysical atomism. Regardless of their endorsement to Mach's criticisms, physicists simply could not give up on the modern spatiotemporal representation of reality. As a consequence, even the new theory of quanta which had been developed through a radical departure from classical ideas and presuppositions was anyhow pictured as related to a microscopic realm constituted by elementary particles. The fact that Planck's *quantum postulate* precluded a continuous description did not seem to matter. The hope was that —sooner than later— this discreteness would be —somehow— explained in terms of the classical continuous representation. It is in this crossroad between quantum and classical that Niels Bohr —maybe the most influential physicists of the 20the Century— would play an essential role establishing a new scheme for physics where both Mach's positivist ideas and metaphysical space-time atomism would co-exist. We will call this inconsistent but highly effective approach created by Bohr: anti-realist realism.

The first spectacular appearance within the physics community of Bohr dates back to 1913 with his proposal of a new model for the hydrogen atom —essentially an abstract set of rules capable of predicting spectral lines. Even though the model was essentially quantum, the proposal was framed as close as possible to the modern space-time atomist representation of physical reality. The image created by Bohr was simple and comforting to most physicists: electrons moved in quantized orbits around the nucleus just like planets orbited the sun. The microscopic realm was nothing but a simple reflection of our own planetary system. However, the price to

[2] It is interesting to note that concomitant with Mach's deconstruction of the metaphysics of classical physics, Friedrich Nietzsche would also produce a major attack to metaphysics within philosophy.

[3] Mach's positivist scheme for science can be resumed in four main principles. The first is the naive empiricist idea that observation is a self evident *given* of "common sense" experience. Second, that physics should be understood as an economy of such observations. Third, that metaphysics, understood mainly as narratives about the unobservable, should be completely erased from scientific theories. And fourth, that physics does not talk about an "external reality" that would describe things beyond empirical observation.

pay for introducing this planetary narrative was that the model became essentially inconsistent and incoherent —something that has been acknowledged and extensively discussed within the specialized literature (see e.g., [51] and references therein). The inconsistencies were both formal and conceptual. From a conceptual perspective, it is clear that the existence of *discrete* quantum orbits within a *continuous* space simply did not make sense. How could continuous space be described in discrete terms? Why did electrons follow trajectories within confined orbits but where unable to reach the outer regions of space? How could they actually disappear from a position in space and reappear in another one without describing a trajectory? Where were electrons supposed to go in the meantime of this apparently magical process? Furthermore, given that charged electrons were describing circular orbits, why didn't they irradiate, loose energy and collapse to the nucleus? None of these questions had any answer. From a formal perspective the inconsistency was even more explicit. Planck's discrete representation of energy implied, through the formula $E = \frac{m}{2}v^2$ (where $v = \frac{dx}{dt}$), that space and time could not be represented in continuous terms. If *energy* was —according to Planck— fundamentally *discrete* (ΔE) then *velocity* had to be discrete as well, and consequently, also *space* and *time* ($v = \frac{\Delta x}{\Delta t}$). Quantum discreteness was everywhere. Since the idea of a *discrete* space or time is in itself inconsistent, an *oximoron*,[4] Planck's *quantum postulate* implied the birth of a new physics detached from the continuous space-time representation imposed by modern science. Unfortunately, this departure, in part due to Bohr's influence, would be never fully accepted neither by physicists nor philosophers. Against the radicalness of Planck's postulate, Bohr would still apply classical images and pictures to his model gaining the sympathy of many conservative physicists who were not ready to give up on their "commonsensical" space-time atomist way of thinking. Bohr's model did not actually provide any mathematical representation of any of these particles, but for him this was "just a way of talking", a useful fiction with no direct reference to an underlying reality. But that is what physicists wanted to hear, and that is exactly what Bohr was giving them. As Alisa Bokulich [7] has recently remarked: "As we know well today [...] Bohr orbits are fictions —according to modern quantum mechanics the electron in an atom does not follow a definite classical trajectory in a stationary state and is instead better described as a cloud of probability density around the nucleus." The strength and persistence of Bohr's images is reflected in the fact that even though QM only makes reference to probability transitions and says nothing about elementary particles this has not stoped contemporary physicists and philosophers from —still today— referring to the existence of microscopic entities (e.g., see [56]).

Apart from classical images, Bohr would also apply principles —in fact, *ad hoc* rules— which allowed him to justify why certain transitions between stationary states occurred and others did not. The *correspondence principle*, as Bohr called it [4, p. 86], imposed an ambiguous relation between the quantum realm and classical physics which characterized "the asymptotic approach of the description of the classical physical theories in the limit where the action involved is sufficiently large to permit the neglect of the individual quantum."[5] Once again, even though there was no theoretical account of this limit between quantum and classical the image was powerful enough to serve its purpose. At the time, Arnold Sommerfeld [8] was not impressed by the proposal of the young Danish physicist: "Bohr has discovered in his principle of correspondence a magic wand (which he himself calls a formal principle), which allows us immediately to make use of the results of the classical wave theory in the quantum theory." Some years later his criticism would grow stronger: "The magic of the correspondence principle has proved itself generally through the selection rules of the quantum numbers, in the series and band spectra? Nonetheless I cannot view it as ultimately satisfying on account of its mixing of quantum-theoretical and classical viewpoints." As remarked by Alisa and Peter Bokulich [8]: "Sommerfeld's critical attitude toward the correspondence principle would prove influential on Wolfgang Pauli and Werner Heisenberg, both of whom were his doctoral students." Pauli would write to Bohr in a letter dated December 31st, 1924: "I personally do not believe, however, that the correspondence principle will lead to a foundation of the rule? For weak men, who need the crutch of the idea of unambiguously defined electron orbits and mechanical models, the rule can be grounded as follows: If more than one electron have the same quantum numbers in strong fields, they would have the same orbits and would therefore collide." Heisenberg, who was at first clearly impressed by Bohr's correspondence program, would also end up following in 1925 —thanks to Pauli— exactly the opposite line of investigation. By detaching himself completely from the classical attempt to describe the trajectory of electrons between atomic orbits and applying instead Mach's observability principle

[4] We might recall that the essential step for the development of the classical space-time representation of Newtonian mechanics was the creation of *infinitesimal calculus* which allowed for a rigorous mathematical definition of the *continuum*.

[5] It is interesting to note that, in consonance with Alisa Bokulich's interpretation of Bohr's approach, one might regard the correspondence principle as an attempt to produce a rational generalization of classical mechanics [6]. As Bohr [4, p. 87] himself would remark: "the aim of which [of the correspondence principle] was to let a statistical account of the individual quantum processes appear as a rational generalization of the deterministic description of classical physics."

to the intensive line-spectra observed in the lab, Heisenberg was finally able to construct a closed mathematical formalism that he would call "quantum mechanics". Unfortunately, Heisenberg's unfinished theory would be very soon replaced by Dirac's axiomatic re-formulation in which Bohr's correspondence principle as well as his atomist narrative would be essentially restored as part of the new orthodoxy.[6]

INCONSISTENCY OF QUANTUM AND CLASSICAL (CORRESPONDENCE PRINCIPLE): *Quantum mechanics makes reference to a microscopic realm constituted by irrepresentable quantum particles. There exist a limit between this quantum microscopic realm and our classical macroscopic realm represented by classical physics.*

At this point, some obvious questions might pop up to the attentive reader. First, how could it be possible to make reference to a realm which cannot be represented? If it cannot be represented, how do we know that this realm talks about microscopic entities? And how can there exist a limit between a realm that cannot be represented (i.e., the quantum) and one that is actually represented (i.e, the classical) in terms of bodies existing within space and time? There are no answers.

An essential addition for the effectiveness of Bohr's matrix is the creation of inconsistent dualities justified through the famous principle of *complementarity*. A principle shaped during his famous debates with Albert Einstein during the 1920s where Bohr had already introduced a dualistic reference to 'waves' and 'particles' in order to account for the famous double-slit experiment. Bohr would apply these two inconsistent representations[7] to essentially the same experimental situation and argue that: "We must, in general, be prepared to accept the fact that a complete elucidation of one and the same object may require diverse points of view which defy a unique description." As explained by Jean-Yves Béziau [1]: "[Bohr] argues that there are no direct contradiction: from a certain point of view 'K is a particle', from another point of view 'K is a wave', but these two contradictory properties appear in different circumstances, different experiments. Someone may ask: what is the absolute reality of K, is K a particle or is K a wave? One maybe has to give away the notion of *objective reality*." In turn, Bohr would also extend his notion of complementarity to quantum observables (e.g., position and momenta).[8] This latter extension is explicit in Bohr's reinterpretation of Heisenberg famous inequality as *uncertainty relations* —i.e., as a limit to the accuracy of quantum measurements [35]— as well as in his famous reply to the EPR paper [2] —something that would end up being known in the contemporary literature as quantum contextuality.

INCONSISTENCY OF CLASSICAL REPRESENTATIONS (COMPLEMENTARITY PRINCIPLE): *Quantum objects require contradictory classical representations provided through the notions of 'wave' and 'particle'. Complementary quantum properties (e.g., position and momentum) as well as measurement outcomes also require complementary experimental arrangements which are necessary as a prerequisite for their consideration.*

To sum up, the unity, consistency and coherency of theoretical representation, essential to the Greek scientific paradigm, developed also in modern times through the notions of *invariance* and *objectivity*, would become completely subverted within Bohr's matrix. The constitution of inconsistent dualities framed through *ad hoc* unjustified rules, principles and pseudo-explanations would allow Bohr to create a new foundation for physics, shaky and unstable, constantly moving back and forth between waves and particles, position and momenta, between causal mathematical representation and space-time events, between microscopic and macroscopic, subjective observations and objective interactions, between reality and fiction. David Deutsch has characterized this system simply as 'bad philosophy':

> "Let me define 'bad philosophy' as philosophy that is not merely false, but actively prevents the growth of other knowledge. In this case [i.e., QM], instrumentalism was acting to prevent the explanations in Schrödinger's and Heisenberg's theories from being improved or elaborated or unified. The physicist Niels Bohr (another of the pioneers of quantum theory) then developed an 'interpretation' of the theory which later became known as the 'Copenhagen interpretation'. It said that quantum theory, including the rule of thumb, was a complete description of reality. Bohr excused the various contradictions and gaps by using a combination of instrumentalism and studied ambiguity. He denied the 'possibility of speaking of phenomena as existing objectively' —but said that only the outcomes of observations should count as phenomena. He also said that, although observation has no access to 'the real essence of phenomena', it does reveal relationships between them, and that, in addition, quantum theory blurs the distinction between observer and observed. As for what would happen if one observer performed a quantum-level observation on another, he avoided

[6] Something that has been exposed in contemporary quantum physics through the development of the principle of decoherence in 1970 by Dieter Zeh and popularized during the early 1980s by Wojciech Zurek.

[7] For a detailed discussion of the inconsistency present within the complementarity principle see [16].

[8] For a detailed analysis of the complementarity principle see [38].

> the issue. [...] For decades, various versions of all that were taught as fact —vagueness, anthropocentrism, instrumentalism and all— in university physics courses. Few physicists claimed to understand it. None did, and so students' questions were met with such nonsense as 'If you think you've understood quantum mechanics then you don't.' Inconsistency was defended as 'complementarity' or 'duality'; parochialism was hailed as philosophical sophistication. Thus the theory claimed to stand outside the jurisdiction of normal (i.e. all) modes of criticism —a hallmark of bad philosophy." [23, p. 308-310]

3 A Smoky Dragon in the Quantum Realm

Maybe the most clear exposition of Bohr's approach to QM can be found in a paper by John Archibald Wheeler, not only a prominent figure in the post-war physics commanded by the U.S. but also one of his closest students and followers. In 1983 Wheeler co-authored with one of his students, Warner Miller, a paper titled "Delayed-Choice Experiments and Bohr's Elementary Quantum Phenomenon" where, together, they argued that the notion of *elementary quantum phenomenon* had to be regarded as the most important concept within the general scheme proposed by the Danish physicist.

> "What one word does most to capture the central new lesson of the quantum? 'Uncertainty', so it seemed at one time; then 'indeterminism'; then 'complementarity'; but Bohr's final word 'phenomenon' —or, more specifically, 'elementary quantum phenomenon'— comes still closer to hitting the point. It is the fruit of his 28 year (1927-1955) dialog with Einstein, especially as that discussion came to a head in the idealized experiment of Einstein, Podolsky and Rosen. In today's words, no elementary quantum phenomenon is a phenomenon until it is a registered ('observed' or 'indelibly recorded' phenomenon), 'brought to a close' by an 'irreversible act of amplification'." [41, p. 72]

Wheeler was right to point to the elementary phenomenon as one of the main elements within Bohr's scheme. And even though at first sight this notion might have seemed as just a fancy way to talk about observations of 'clicks' in detectors or 'spots' in photographic plates, Wheeler had recognized that there was something deeper, still unveiled. An elementary quantum phenomenon was in fact a monstrous creature:

> "The elementary quantum phenomenon is a great smoky dragon. The mouth of the dragon is sharp, where it bites the counter. The tail of the dragon is sharp, where the photon starts. But about what the dragon does or looks like in between we have no right to speak, either in this or in any delayed-choice experiment. We get a counter reading but we neither know nor have the right to say how it came. The elementary quantum phenomenon is the strangest thing in this strange world." [41, p. 73]

Of course, a smoky dragon —contrary to Wheeler's description— does not actually bite the counter, instead —as shown in figure 1— it produces fire in order to generate a 'click' in the detector. Regardless of this obvious inaccuracy, Wheeler's dragon encapsulates perfectly well Bohr's approach to QM. An inconsistent scheme of thought which has the main purpose of justifying effectively operational models through fictional concepts which even though have no theoretical nor experimental support are —anyhow— capable of upholding the most amazing illusions and narratives. A smoky dragon is a concept that cannot be (consistently) represented in theoretical terms, that has no experimental support but is anyhow regarded as part of an inconsistent reality that becomes indistinguishable from fiction.

Smoky Dragon (Inconsistent Concept): A smoky dragon is an irrepresentable meaningless concept which provides a pseudo-picture of a physical situation or process and, consequently, the illusion of understanding. Such inconsistent concepts have no mathematical representation nor posses any operational testability procedure.

Maybe the best example of a smoky dragon is Bohr's famous *quantum jump* of electrons between quantized orbits. For those acquainted with the theory, this notion generates a strange motion picture in our minds allowing us to imagine a process that is not described by the mathematical formalism nor observed in the lab. Of course, hiding beneath these quantum jumps we find another smoky creature, namely, *quantum particles* themselves. Microscopic entities which must exist, since they are "small", within space and time. However, it is also claimed that quantum objects cannot be actually represented and that their existence can be only witnessed through 'clicks' in detectors and 'spots' in photographic plates. Obviously, these two statements are contradictory. If a quantum object is un-thinkable, irrepresentable, than it cannot be "small" nor can it inhabit space and time —which are of course part of the modern metaphysical representation of classical physics. Since

Figure 1: Niels Bohr's smoky dragon generating a 'spot' in a photographic plate.

both quantum jumps and particles are part of the "standard" account of the theory of quanta, an obvious question rises: How could such inconsistent fictional creatures been able to endure within a —supposedly— rational field like physics? Essential to the survival of smoky dragons is Bohr's outstanding use of misdirection. Managing audience attention is the aim of all theater, and the foremost requirement of all magic acts. In theatrical magic, misdirection is a form of deception in which the performer draws audience attention to one thing to distract it from another. This is the key to understand the effectiveness of Bohr's matrix. As we pointed out, in order to complete his trick Bohr did not only rely on the well known atomist images that physicists where expecting to recover, he would also tell everyone that the electrons orbiting the nucleus were capable of performing "quantum jumps" which allowed them to magically disappear from their orbits and immediately reappear in another one. The story was spectacular and physicists were immediately captured. How could this happen? What were these fantastic "quantum jumps"? Are they actually real? How can particles disappear and reappear at will? Where are these particles going in the meantime? The complete lack of answers did not matter. The trick had been already completed. The Danish conjurer had succeeded in drawing the focus of attention away from the critical consideration of atoms, electrons and protons —something that Mach had criticized just a few decades before— to the fictional existence of —unobserved and irrepresentable— quantum jumps. With great confidence a young charismatic Bohr would wispear to his audience: "It is weird because it is quantum!"

The complete lack of justification within Bohr's inconsistent scheme was clearly exposed during a meeting in 1926 that took place in Copenhagen where the Danish physicist had invited Erwin Schrödinger to discuss about the existence of 'quantum jumps'. Under the attentive gaze of Heisenberg, Bohr's young apprentice, the Austrian physicist would present several arguments exposing not only the lack of theoretical and experimental support for the existence of quantum jumps but also the serious inconsistencies reached when introducing this fantastic process within the theory. Schrödinger [34, p. 73] would then conclude that "the whole idea of quantum jumps is sheer fantasy." However, with great mastery, without even confronting the strong arguments of his enemy, making use of his powerful rhetorics Bohr would turn things completely upside-down in a single move:

> "What you say is absolutely correct. But it does not prove that there are no quantum jumps. It only proves that we cannot imagine them, that the representational concepts with which we describe events in daily life and experiments in classical physics are inadequate when it comes to describing quantum jumps. Nor should we be surprised to find it so, seeing that the processes involved are not the objects of direct experience." [34, p. 74]

Reversing the burden of proof Bohr was asking Schroödinger either to grant him the existence of quantum jumps or prove their non-existence.[9] After his meeting, in a letter to Wilhelm Wien, Schroödinger would expose his suspicions about Bohr's rhetorics:

> "Bohr's [...] approach to atomic problems [...] is really remarkable. He is completely convinced that any understanding in the usual sense of the word is impossible. Therefore the conversation is almost immediately driven into philosophical questions, and soon you no longer know whether you really take the position he is attacking, or whether you really must attack the position he is defending." [42, p. 228]

In modern times philosophers engaged in a process of dissection of the Greek notion of *physis* (section 1). As a culmination of this process, reality was effectively separated in three distinct realms: subjective reality, objective reality and reality-in-itself. Kant had limited physics to the circular interrelation between subjective and objective realities; distancing this co-relational form of knowledge from *reality-in-itself* which —according to him— would then remain unreachable, unknowable, unthinkable. Reality had been torn apart and detached from physics. Three centuries later, in post-modern times, Bohr was ready to generate a new system, more complex, stable and powerful than its predecessor. It is the introduction of *fictional reality* as a constitutive element of physical representation itself that would allow to replace the need of mathematical invariance, conceptual objectivity and operational testability —to which we shall return in section 5— by narratives and interpretations with no connection whatsoever to any theoretical formalism nor experimental evidence. The Bohrian matrix could be pictured as a highly effective Möbius strip machine generating motion through the constant creation of dualistic poles applied within a never-ending line of reasoning. Going back and forth between contradictory statements and principles, Bohr was able to create a never-ending progression of rhetorical self-justification. Scrambling epistemology (i.e., gnoseology) with ontology he would argue that the fictional consideration of a quantum object imposed a limit to representation [5, v. 2, p. 62]: "In quantum mechanics, we are not dealing with an arbitrary renunciation of a more detailed analysis of atomic phenomena, but with a recognition that such an analysis is in principle excluded." It was the *quantum of action* which —according to the Danish physicist— was to be blamed for this impossibility [3, p. 79]: "not being any longer in a position to speak of the autonomous behavior of a physical [quantum] object, due to the unavoidable interaction between the [quantum] object and the [classical] measuring instrument." However, proposed by Max Planck in 1900, the discrete quantum theoretical representation of energy, $\Delta E = h.n$, was not only imposing a limit to the possibilities of representation, it was also —according to Bohr— describing something truly real, something going on in each and every interaction between a quantum particle and a classical apparatus. As he would explain in his famous reply to EPR [2, p. 701]: "The impossibility of a closer analysis of the reactions between the [quantum] particle and the [classical] measuring instrument is indeed no peculiarity of the experimental procedure described, but is rather an essential property of any arrangement suited to the study of the phenomena of the type concerned, where we have to do with a feature of [quantum] individuality completely foreign to classical physics." Thus, (quantum) physics could not represent objective reality as described by quantum objects due to the (real) interaction between the (fictional) quantum object and the (real) classical measuring device. But turning things upside-down, once again, this epistemological limit had to be understood —according to Bohr— not as a technical limit of our instruments or our human capabilities but rather as an ontological feature of reality-in-itself, namely, its own irrepresentability! This typical scrambling of gnoseological and ontological claims, of realist and fictional statements, is part of Bohr's incredibly effective pendular rhetorics. The Borian Möbius strip of reasoning is an amazing device, a never ending process which forces us to remain in constant motion always between two poles: between waves and particles, between the objective interaction of systems and subjective observations, between microscopic and macroscopic, between theory and measurement, between ontology and epistemology, between reality and fiction...

4 Smoky Dragons in the Interpretations of Quantum Mechanics

Bohr's pendular rhetorics about microscopic particles, classical apparatuses and measurement outcomes remains the discursive basis of what is known today in physics as "Standard QM" (SQM), a general set of (inconsistent) rules framed under the Dirac-von Neumann axiomatic formulation sometimes referred to as "the Copenhagen

[9] This sort of proof is known in jurisprudence as the *probatio diabolica* [the diabolical proof], namely, the legal requirement to achieve an impossible proof. Such Devil's Proof is the logical dilemma that while evidence will prove the existence of something, the lack of evidence fails to disprove it.

interpretation" or —by philosophers— as the "minimal interpretation".[10] Regardless of the many difficulties within the field, there are two main points of profound consensus between physicists about the standard account of the theory of quanta which expose the penetration of Bohr's anti-realist realism. The first point of absolute consensus is the unquestionable fact that SQM makes reference to a microscopic realm constituted by elementary particles [56]. As explained by the Richard Feynman [28, Chap. 37]: "Quantum Mechanics is the description of the behavior of matter and light in all its details and, in particular, of the happenings on an atomic scale." However, strange as it might seem, there is another point of generalized agreement between contemporary physicists when questions begin to pop up, namely, that "nobody understands QM" —a phrase also made popular by Feynman [29, p. 129]. These statements are clearly contradictory. If we do not know what QM is talking about then we cannot know that it talks about atoms. Period. As a result, still today Bohrian rhetorics are commonly applied by physicists who do not even recognize the inconsistent jumps they perform when going from metaphysical claims such as "QM is a theory that talks about microscopic particles" to purely instrumental ones such as [31, p. 70]: "[...] quantum theory does not describe physical reality. What it does is provide an algorithm for computing probabilities for the macroscopic events ('detector clicks') that are the consequences of experimental interventions." A common way out of this conundrum is to argue that quantum particles are "fundamental". But as recognized by Xiao-Gang Wen [56], a theoretical physicist at the Massachusetts Institute of Technology: "We say [electrons, photons, quarks] are 'fundamental'. But that's just a [way to say] to students, 'Don't ask! I don't know the answer. It's fundamental; don't ask anymore'." The attempt to answer these questions has been indeed banished from theoretical physics and replaced under the jurisdiction of philosophy where —to our complete surprise— we can also find the profound influence of Bohr's anti-realist realism. In fact, the creation of philosophy of QM can be easily related to the creation of a smoky dragon analogous to the one created by Bohr in 1913.

The story begins in the year 1930 when a young English engineer and mathematician called Paul Dirac —following Bohr's teachings— would give to birth a dragon so powerful it could turn an abstract mathematical formula into a real empirical observation —or in more technical terms, a quantum superposition into a single measurement outcome. This would become to be known between physicists as the "collapse" of the quantum wave function —also called *projection postulate* or *measurement axiom*. The introduction of this fantastic process which would soon become an essential cornerstone of the standard understanding of the theory was presented within the first chapters of *The Principles of Quantum Mechanics*. In a typical Bohrian fashion, making reference to the polarization measurement of photons, Dirac would describe the real effect of observations:

> "When we make the photon meet a tourmaline crystal, we are subjecting it to an observation. We are observing wether it is polarized parallel or perpendicular to the optic axis. The effect of making this observation is to force the photon entirely into the state of parallel or entirely into the state of perpendicular polarization. It has to make a sudden jump from being partly in each of these two states to being entirely in one or the other of them. Which of the two states it will jump cannot be predicted, but is governed only by probability laws." [24, p. 9]

Dirac argued explicitly that "science is concerned only with observable things" [24], however, he was less explicit about the fact that observations —according to him— had to be necessarily restricted to a binary representation. In this respect, the introduction of the collapse had the sole purpose to do away with quantum superpositions and in this way restore his presupposed narrow understanding of (binary) observability. Quite ironically, this restriction was doing away with the positivist observational rule which had allowed Heisenberg to come up with QM in the first place just five years before —in a nutshell, forget about fictional orbits and classical trajectories, forget about particles and consider instead what is actually observed in the lab, namely, a list of intensive values that can be represented by matrices. Dirac's formulation reinforced by the influential mathematician John von Neumann with his 1932 *Mathematical Foundations of Quantum Mechanics* [52] would become orthodoxy and the newborn jumping dragon would be soon ready to give birth to another monster baptized as "the measurement problem of QM". The fact that this process created a serious inconsistency within the mathematical formalism, that it had never ever been observed nor measured within the lab, or that it was not even necessary from an operational perspective —for Heisenberg's matrix mechanics already provided a consistent operational account of experiments [18]— did not seem to matter to most instrumentalist physicists. However, a few of them —with clear philosophical inclinations— would not let go and begin to desperately try to come up with stories that

[10] As the U.S. physicist John Clauser [13, p. 70] would stress: "given Bohr's strong leadership, the net legacy of their arguments is that the overwhelming majority of the physics community accepted Bohr's 'Copenhagen' interpretation as gospel, and totally rejected Einstein's viewpoint."

would attempt to —somehow— justify Dirac's quantum jump. This could not be so difficult. After all, Bohr had already showed physicists how narratives could be introduced and justified with confidence and creativity by making reference, in ambiguous ways, to the —still modern— metaphysical prejudices everyone shared in silence.

The presence of Bohr's anti-realist realism within Dirac's axiomatic re-formulation is exposed in the fact that even though the reference to atoms and elementary quantum particles continued to play an essential role, Dirac would simultaneously argue against the possibility to imagine what QM was really talking about: "it might be remarked that the main object of physical science is not the provision of pictures, but the formulation of laws governing phenomena and the application of these laws to the discovery of phenomena. If a picture exists, so much the better; but whether a picture exists of not is a matter of only secondary importance." This typical inconsistent conjunction of instrumentalism and fictional realism has remained an essential part of the discourse applied by contemporary physicists who are taught since students that QM is a "recipe" to compute measurement outcomes which are consequence of microscopic entities. But, as Tim Maudlin [39, pp. 2-3] has recognized, "if a physics student happens to be unsatisfied with just learning these mathematical techniques for making predictions and asks instead what the theory claims about the physical world, she or he is likely to be met with a canonical response: Shut up and calculate!" As it is well known, this response which has become completely widespread in physics all around the world, finds its origin in the development of physics in the U.S. during the 1950s and 1960s (see [32, 37]).[11] Sean Carroll [12] has recently unveiled the mystery of what actually happens to those students that simply won't shut up: "Many people are bothered when they are students and they first hear [about SQM]. And when they ask questions they are told to shut up. And if they keep asking they are asked to leave the field of physics." It is in this context that the debates about the measurement problem that begun very slowly during the 1950s might have seemed like an oasis for the young rebels still wondering about reality. Today, things do not seem to have changed a lot. As Maudlin [45, p. 52] —a former physics student expelled from the field— explains: "The most pressing problem today is the same as ever it was: to clearly articulate the exact physical content of all proposed 'interpretations' of the quantum formalism is commonly called the measurement problem, although, as Philip Pearle has rightly noted, it is rather a 'reality problem'." But is the measurement problem a secure refugee for true realists or is it in fact a trap carefully designed by anti-realists themselves in order to avoid the construction of a meaningful theoretical reference to reality?

The anti-realist collapse introduced by Dirac in 1930 had soon become not only a cornerstones of SQM, but also a great exemplification of the way in which empirical science could always impose the reference to actual observations. During the following decades as the influence of Bohr and positivism would grow stronger physics would be reframed in an instrumentalist fashion. As Karl Popper [44] would describe during the 1960s: "Today the view of physical science founded by Osiander, Cardinal Bellarmino, and Bishop Berkeley, has won the battle without another shot being fired. Without any further debate over the philosophical issue, without producing any new argument, the *instrumentalist* view (as I shall call it) has become an accepted dogma. It may well now be called the 'official view' of physical theory since it is accepted by most of our leading theorists of physics (although neither by Einstein nor by Schrödinger). And it has become part of the current teaching of physics." Popper argued that this result had been a direct consequence not only of the successful technical applications obtained in the U.S., "some of them with a big bang", but also of Bohr's complementarity approach.[12] In the context of the U.S. post-war anti-realist program of science questions about reality and foundations had no place, but the unease and pressure of those who still wanted to actually understand the theory could be felt in the classrooms. Trying to deal with this conflictive situation, during the 1970s, a new field of research was specifically created in order to contain the few subversive students and even fewer Professors that were still willing to make questions. Young realist physicists who wanted to destroy their academic careers were given the opportunity to have a new job as philosophers of physics. As such, they were given a very specific task to accomplish: try

[11] As Clauser [13, pp. 72-73] recalls from his student days in the 1960s: "Any physicist who openly criticized or even seriously questioned these foundations (or predictions) was immediately branded as a 'quack'. Quacks naturally found it difficult to find decent jobs within the profession. [...] Religious zeal among physicists prompted an associated powerful proselytism of students. As part of the 'common wisdom' taught in typical undergraduate and graduate physics curricula, students were told simply that Bohr was right and Einstein was wrong. [...] Any student who questioned the theory's foundations [i.e., SQM], or, God forbid, considered studying the associated problems as a legitimate pursuit in physics was sternly advised that he would ruin his career by doing so. I was given this advice as a student on many occasions by many famous physicists on my faculty at Columbia and Dick Holt's faculty at Harvard gave him similar advice." For very similar remarks by David Albert and Lee Smolin see [20].

[12] Karl Popper [44] saw the future with hope: "I trust that physicists will soon come to realize that the principle of complementarity is *ad hoc*, and (what is more important) that its only function is to avoid criticism and to prevent the discussion of physical interpretations; though criticism and discussion are urgently needed for reforming any theory. They will then no longer believe that instrumentalism is forced upon them by the structure of contemporary physical theory."

to solve the measurement problem through the introduction of a narrative —what philosophers would call in technical jargon an *interpretation* of the theory— that would somehow picture what was really going on when measurements were actually performed.[13] Or in other words, provide an answer to the measurement problem. Ever since, many physicists transformed into philosophers of physics —I am myself one of them— helped also by philosophers, logicians and mathematicians have been creating stories to calm their own metaphysical anxieties. As Hervé Zwirn [57, p. 639] described: "Faced to what seems a real inconsistency inside the quantum formalism, physicists have proposed many solutions largely depending on their initial philosophical inclination." However, there was a barrier left behind by anti-realists. Anyone —physicist, philosopher, logician or mathematician— attempting to add an interpretation to SQM would be faced with a serious obstacle, namely, there was no place whatsoever for any of these narratives within the anti-realist account of (empirical) theories. And with no *objective link* between theory and interpretation these metaphysical narratives would always remain in a fictional limbo floating free from physics (see for a detailed discussion [54, 55] and references therein). As John Horgan described, when attending in 1992 a symposium at Columbia University in which philosophers and physicists attempted to discuss the meaning of quantum mechanics:

> "The symposium demonstrated that more than 60 years after quantum mechanics was invented, its meaning remained, to put it politely, elusive. In the lectures, one could hear echoes of Wheeler's it from bit approach, and Bohm's pilot-wave hypothesis, and the many-worlds model favored by Steven Weinberg and others. But for the most part each speaker seemed to have arrived at a private understanding of quantum mechanics, couched in idiosyncratic language; no one seemed to understand, let alone agree with, anyone else. [...] [W]hen I revealed my impression of confusion and dissonance to one of the attendees, he reassured me that my perception was accurate. "It's a mess," he said of the conference (and, by implication, the whole business of interpreting quantum mechanics). The problem, he noted, arose because, for the most part, the different interpretations of quantum mechanics cannot be empirically distinguished from one another; philosophers and physicists favor one interpretation over another for aesthetic and philosophical —that is, subjective— reasons." [36, p. 88]

The truth is that most physicists trained today in an instrumentalist fashion do not even know that such a "realist debate" about QM even exists.[14] They simply don't care. And there is a very good reason for the complete lack of interest, namely, this "realist debate" is not regarded as a scientific one. Science today is orthodoxly understood in empirical terms which, following Bas van Fraassen [48, pp. 202-203], can be resumed in the following: "an empiricist account of science is to depict it as involving a search for truth only about the empirical world, about what is actual and observable", more specifically, "science aims to give us theories which are empirically adequate: an acceptance of a theory involves as belief only that it is empirically adequate." This is why Roberto Torretti [46, p. 367] seems correct to point out that interpretations of QM should be considered as "meta-physical ventures [...] for they view the meaning and scope of QM from standpoints outside empirical science." Taking this point into consideration Arthur Fine [30, p. 149] gives us the following very reasonable advise: "Try to take science on its own terms, and try not to read things into science. If one adopts this attitude, then the global interpretations, the 'isms' of scientific philosophies, appear as idle overlays to science: not necessary, not warranted and, in the end, probably not even intelligible." However, regardless of the sarcastic reference made by many anti-realists to interpretations, as we have argued in [19], their introduction has played an essential role for the perpetuation of their own program. In fact, the creation of narratives has created the perfect smoky shield for hiding the many dragons flying freely within the so called "minimal interpretation" of QM. But even more importantly, the introduction of interpretations has also allowed anti-realists to control and restrict the activities of realists in term of a praxis placed outside the limits of empirical science itself. But even this seems to have run out of control. The complete lack of experimental or theoretical constraints in order to come up with crazy stories —tolerated in some cases and embraced in others— has turned philosophy of QM into breeding field of smoky dragons. As David Mermin [40, p. 8] declared: "[Q]uantum theory is the most useful and powerful theory physicists have ever devised. Yet today, nearly 90 years after its formulation, disagreement about the meaning of the theory is stronger than ever. New interpretations appear every day. None ever disappear." In the last decades, the situation is becoming to be recognized as untenable and Adán

[13] Let us remark that not even "non-collapse" interpretations (e.g., many worlds and modal) reject the *projection postulate* [18].

[14] As Maximilian Schlosshauer [45, p. 59] remarks: "It is no secret that a shut-up-and-calculate mentality pervades classrooms everywhere. How many physics students will ever hear their professor mention that there's such a queer thing as different interpretations of the very theory they're learning about? I have no representative data to answer this question, but I suspect the percentage of such students would hardly exceed the single-digit range."

	ψ-Ontic	ψ-Epistemic
Type-I (intrinsic realism)	Bohmian mechanics[10,11]	Einstein[19]
	Many worlds[12,13]	Ballentine[20]
	Modal[14,15]	Consistent histories[21,22]
	Bell's "beables"[16]	Spekkens[23]
	Collapse theories*[17,18]	

	About knowledge	About belief
Type-II (participatory realism)	Copenhagen[24,25]	QBism[33–35]
	Wheeler[26,27]	
	Relational[28,29]	
	Zeilinger[3,30]	
	No "interpretation"[31]	
	Brukner[32]	

Figure 2: Adán Cabello's realist map of interpretational madness in quantum theory in [10].

Cabello —a prominent physicist in the field of quantum information— has even characterized it as "a map of madness" [10]. How did we get to this point?

Even though the boom of interpretations can be placed —with the rise of philosophy of QM— during the 1980s and 1990s, the introduction of these narratives goes back to the late 1950s with Heisenbergs', Margenau's and Popper's hylemorphic interpretations in terms of potentialities, latencies and dispositions (see [19]). All these narratives are good examples of this second layer of smoky dragons which, as Mauro Dorato [25, p. 4] has recognized, have failed to provide a consistent representation of what the theory is talking about: "In a word, the use of the language of 'dispositions' [and also 'potentialities' and 'latencies'] does not by itself point to a clear ontology underlying the observable phenomena, but, especially when the disposition is irreducible, refers to the predictive regularity that phenomena manifest. Consequently, attributing physical systems irreducible dispositions, even if one were realist about them, may just result in more or less covert instrumentalism." Exactly the same happens with the notion of 'world' or 'branching' introduced by Bryce DeWitt during the 1960s in what has become today's popular many worlds interpretation of QM —a metaphysical account of Hugh Everett's relative state formulation. There is no theoretical account of what a 'world' is according to the theory nor any way to test experimentally their actual existence, and the same counts for the 'branching process' [18]. In a typical Bohrian fashion, the contemporary justification for the complete lack of theoretical representation or experimental support for these narratives is grounded on the simple fact that "QM is weird". As Sean Carroll [11] explains: "As you learn more and more about the world, as you do more science, as you uncover more and more facts, observations become more precise, you go into realms that you hadn't yet seen —distant stars and galaxies and the subatomic world. Would you expect —that as your learn all these new things— your best description of the world would become more intuitive and everyday or more and more weird and surprising? It will become more and more weird and surprising because we are looking at things that we are not trained to experience." Unrelated to the theory they attempt to refer to the introduction of these new interpretations can be regarded as an effective misdirection which has allowed the standard account of the theory to remain safe from critical attacks. Addressing the role of interpretations, Bas van Fraassen —one of the most prominent contemporary anti-realists— explains that, regardless of the fact that any fictional story responding to the question 'what is the world like according to the theory?' could —in principle— be *true*, the interpretation does not need to be actually true in order for the theory to be good [48, p. 10]. In fact —according to anti-realists— we will never know for real if any of these fictions describes reality-in-itself.[15] Thus, it might seem far more reasonable and convenient to remain simply "agnostic" —as van Fraassen himself has called his skeptic standpoint. After all, empirical science is only meant to describe actual observations. Period. Realists are then easily portrayed by anti-realists either as "naive" or "fanatic" believers in interpretations they cannot justify nor relate to the theory. They are essentially correct.

To sum up, the second layer of smoke created by the addition of interpretations plays a major role within the anti-realist understanding of QM hiding and protecting from critical through the first layer of fictions already introduced within the supposedly un-interpreted standard account of the theory —which refers to atoms, electrons, jumps, measuring devices, etc. While interpretations shift the focus of attention to a supposedly "realist debate" about potentialities, propensities, worlds, histories, modalities, etc., the orthodox "recipe" and its microscopic-instrumentalist narrative remains shield from criticism. Physicists can then continue to use their "recipe", while philosophers are creating new dragons. Cabello [10], who has characterized this situation as "odd

[15] As Alan Musgrave [14, pp. 1209-1210] remarks: "As usually understood, the realism-antirealism issue centers precisely on the question of truth. Positivists deny the existence of 'theoretical entities' of science, and think that any theory which asserts the existence of such entities is *false*. Instrumentalists think that scientific theories are tools or rules which are *neither true nor false*. Empistemological antirealists like van Fraassen or Laudan concede that theories have truth-values, even that some of them might be true, but insist that no theory should be *accepted as true*." It is only what anti-realists have termed "scientific realists" who argue that interpretations are true.

and is arguably an obstacle for scientific progress" has also attempted to clarify this "map of madness" through a classification in two main groups: "intrinsic realism" and "participatory realism" (Figure 2). In the following section we will argue that the introduction of interpretations in a non-starter for realists who should instead focus on the specific conditions required for the construction of adequate physical concepts.

5 How to Capture and Defeat a Smoky Dragon

It is essential to acknowledge that —even from a realist perspective— through its criticisms, anti-realism has always played an essential role for the development of science. Without sophistry, it would have been impossible for Plato and Aristotle to create metaphysics and without Mach's criticism to Newton's and Kant's metaphysical presuppositions it would have been impossible to develop QM and relativity theory. Undoubtedly, it is the balance between realism and anti-realism which has been kernel for the critical advancement of science in the history of Western thought. Unfortunately for all of us during the last century this balance has been broken and the distinction between realism and anti-realism erased. Anti-realists have been finally able to conquer both physics and philosophy producing the most outstanding re-foundation of the meaning of science itself. In this context, the main triumph of anti-realism has been to trap realists in a fictional world which they themselves have been compelled to build up. Realists slaves have become so comfortable they would certainly refuse —if given the opportunity— to escape their prison. Could we say that realism is actually dead? Is there any hope left for the reconstruction of the realist program beyond fictions, interpretations and narratives? Or in other words, would it be possible for realists to capture and defeat smoky dragons?

Smoky dragons are powerful illusions capable of creating the fantasy of an ungrounded reference with no (realist) theoretical nor experimental support. QM illustrates perfectly well the extreme dangers created by an extremist anti-realist account of science supplemented by a fake fictional realism. The annihilation of conceptual critical thought produced by smoky dragons has created a desert in which realists wonder with no compass, preaching and fighting between each other for imaginary stories that no one really cares about. The power of these creatures comes from the darkness of un-scientific mythical thought exposing the return to a dark pre-scientific rationality (section 1). However, our optimistic claim is that realists already possess the tools and weapons to fight and defeat smoky dragons. Realists simply need to remember the basic ideas that support their flag, namely, that theoretical representations are not interpretations and physical concepts are not just words in a story. According to realism, a physical theory is a unified formal-conceptual representation of a state of affairs which relates to experience coherently and consistently in a qualitative and quantitative fashion. In this respect, it is essential to note that, while physical representations are both dependent on (conceptual) subjective preconditions and (formal) reference frames, realism seeks their unity in order to make reference to *the same* (real) state of affairs through objectivity and invariance. What Einstein called repeatedly a subject *detached* account of physical reality.

Definition 5.1 Realism: *The presupposition that physis (or reality) is knowable*[16] *through the creation of theories, namely, unified, consistent and coherent formal-conceptual invariant-objective representations which provide an account of a state of affairs and experience detached from both particular subjects and reference frames.*

Definition 5.2 Anti-Realism: *The claim that realists are wrong and that even if physis (or reality) would actually exist, due to our human limitations it would anyhow remain always un-reachable, un-knowable.*

What is essential to realize is that the mathematical formalism and the conceptual system that conform a theory are constrained by a specific set of *necessary conditions* within the realist program. It is these same conditions, essential for the creation of adequate physical concepts, that could be used today as powerful weapons against smoky dragons. Let us address some of these realist conditions in some detail.

Operational-invariance and phenomenological-objectivity provide a rigorous foundation in order for a theory to refer to a state of affairs that can be considered as real; i.e., a representation completely detached from the perspectival perception of subjects or the choice of any particular frame of reference. *Operational-Invariance* points to the fact that a mathematical representation must be able to provide a consistent scheme for the

[16]It should be remarked , once again, that realism does not refer to "stuff", it refers to reality. Knowing reality does not imply the idea that representation should describe *reality-as-it-is*; i.e., the idea there should exist a *correspondence relation* between the representation of a theory and reality. This claim is actually made by many anti-realists (e.g., van Fraassen) in order to create the weakest possible form of realism and a "straw realist" easy to attack and defeat.

operational testability considered with respect to different frames of reference (or perspectives). For any realist representation to be consistent, there must always exist an operational-invariant formalism which allows us to discuss what is really going on independently of the choice of the particular reference frame —chosen in order to describe the state of affairs. A rabbit running through a field might be described from a frame of reference attached to a speed-train or to the railway station, but even though both descriptions will be different the consistency between them will still allow us to talk about *the same* rabbit.

Definition 5.3 Operational Invariance: *A physical concept must be able to provide a consistent unified account of its operational testability considered with respect to different frames of reference (or bases).*

This condition is fulfilled in classical mechanics via the Galielan transformations and in relativity theory via the Lorentz transformations. On the contrary, in QM the orthodox interpretation of probability in terms of binary measurement outcomes together with the non-invariant definition of quantum state has destroyed the operational invariance present within Heisenberg's original matrix formulation (see for a detailed analysis and discussion [21, 22]). This mathematical condition can be translated in conceptual terms as a phenomenological-objective condition which imposes the need to discuss about *the same* object of experience independently of the particular viewpoint taken by an agent. Observers from different perspectives should be able to agree about what they observe. Thus, unlike in the case of the famous story by Jorge Luis Borges, *Funes the Memorius* [9], a 'dog observed form a profile' should be considered as *the same* 'dog observed from the front' (see [17]).

Definition 5.4 Phenomenological Objectivity: *A physical concept must be able to bring into unity the multiplicity of physical phenomena observed from different perspectives.*

Classical mechanics and electromagnetism are good examples of how both the formal and the conceptual parts of a theory can be brought into unity in order to consistently and coherently imagine the evolution of a real state of affairs. In these particular cases, the physical concepts that provide a consistent account of what is going on are *particles* and *electromagnetic waves*. On the very contrary, the notion of object discussed by Bohr in QM plays exactly the opposite role. Instead of providing a unified account of phenomena, it is defined as that which differs from itself in every observation. Going back to George Berkeley's dictum, *esse est percipi*, Bohr's principle of complementarity has allowed to bypass objectivity and invariance generating instead an inconsistent narrative which makes reference to the act of perception of either waves or particles, position or momenta. Bohr's empiricist standpoint, in line with positivism, contrasts radically with Einstein's theoretical realism according to which it is only the theory which decides what can be observed:

> "I dislike the basic positivistic attitude, which from my point of view is untenable, and which seems to me to come to the same thing as Berkeley's principle, *esse est percipi*. 'Being' is always something which is mentally constructed by us, that is, something which we freely posit (in the logical sense). The justification of such constructs does not lie in their derivation from what is given by the senses. Such a type of derivation (in the sense of logical deducibility) is nowhere to be had, not even in the domain of pre-scientific thinking. The justification of the constructs, which represent 'reality' for us, lies alone in their quality of making intelligible what is sensorily given." [27, p. 669]

As famously remarked by Einstein when addressing the concept of *simultaneity* within classical mechanics, a physical concept requires not only a clear mathematical and conceptual definition, it must also possess operational content:

> "The concept does not exist for the physicist until he has the possibility of discovering whether or not it is fulfilled in an actual case. We thus require a definition of simultaneity such that this definition supplies us with the method by means of which, in the present case, he can decide by experiment whether or not both the lightning strokes occurred simultaneously. As long as this requirement is not satisfied, I allow myself to be deceived as a physicist (and of course the same applies if I am not a physicist), when I imagine that I am able to attach a meaning to the statement of simultaneity. (I would ask the reader not to proceed farther until he is fully convinced on this point.)" [26, p. 26]

Thus, the development of an adequate physical concept —within the realist program— involves also the provision of a consistent link to its experimental testing.

Definition 5.5 Conceptual Operationality: *A physical concept must provide a consistent link to its operational testability.*

Most smoky dragons we have been discussing in the context of quantum theory fail to fulfill this very basic operational condition. As we have discussed, the notion of quantum jump —a cornerstone of SQM— is not testable —something that holds for almost every fiction which is part of an interpretation. In fact, since there are no theoretical nor empirical constraints, and since the field has been extremely tolerant with all possible narratives, it seems that is only the imagination of researchers —always willing to publish their stories— which has placed a limit to the proliferation of interpretations. Of course, the lack of empirical content within contemporary theoretical physics is not restricted to QM. In tune with the anti-realist program, theoretical physicists today are going as far as to argue that experience should not be regarded as a necessary ingredient of physical theories and models. The Nobel Laureate Gerard t' Hooft [47] has recently defended the idea that: "Working with long chains of arguments linking theories to experiment, we must be able to rely on logical precision when and where experimental checks cannot be provided." Following the same line of reasoning Steven Weinberg [53] has gone further: "I think 100 years from now this particular period will be remembered as a heroic age when theorists cut themselves temporarily free from their experimental underpinnings and tried and succeeded through pure theoretical reasoning to develop a unified theory of all the phenomena of nature." Recently, Richard Dawid has even defended the introduction of non-empirical arguments in order to justify mathematical theories [15].

The possibility to conceive and observe the same object of experience through time is another essential aspect of physics. Apart from providing its operational content physical concepts must also bring into unity the multiplicity of physical phenomena as observed in different subsequent tests. Repeatability is an essential condition for physical research and analysis. If every time we observe 'something' it refers to 'something *different*', it becomes then impossible to keep track of anything. Things which are observed only once are impossible to investigate from a scientific standpoint. This is a problem which is well known since Heraclitus' theory of becoming and was referred to by the Greeks as 'the problem of movement'. In short, what can be regarded as an *identity* within *difference*? Clearly, if there is no repeatability, the reference of different experiences is precluded right from the start and just like in *Funes the Memorious*, the necessary link between the observation of a 'the dog at three-fourteen' and 'the dog at three fifteen' is nowhere to be found. A meaningful physical concept must be capable of providing the conditions of its testing in different instants of time.

Definition 5.6 Operational Repeatability: *A physical concept must be able to bring into unity the multiplicity of physical phenomena observed in different subsequent tests.*

An object must be capable of bringing into unity a multiplicity of different observations. An object which can only relate itself to a single measurement outcome is not an object, it is just an 'event' which lacks the conditions required by a realist physical representation. Physics does not talk about observations or events, it talks in terms of physical formal-conceptual invariant-objective representations. In standard QM, the notion of 'quantum particle' does not fulfill *operational repeatability*, for —according to the orthodox narrative— particles are destroyed with every measurement that is actually performed (see for a detailed discussion [18]). Quantum particles are explicitly defined as non-repeatable existents, they are just 'clicks' in detectors and 'spots' in photographic plates. Such spatiotemporal events or measurement outcomes are essentially irrepeatable. Every measurement creates always a new 'click', a new 'spot', different to the ones preceding it, different to the ones to come. Of course, this goes against the very basic goal of science which in the words of Pauli refers to the attempt to account for the unity of different phenomena through concepts: "'Understanding' probably means nothing more than having whatever ideas and concepts are needed to recognize that a great many different phenomena are part of coherent whole."

It is quite clear that the standard "recipe" of QM fails to fulfill any of these basic conditions required for a realist understanding of the theory. Thus, instead of fictional narratives which have no link whatsoever with experience or the mathematical formalism, it is these general set of conditions which should guide realists in their future production of a unified, consistent and coherent representation for the theory of quanta. In this respect, the unquestionable fact that QM is "weird" should not be understood as necessarily imposing a limit to physical representation itself, but rather as exposing the limit of the very specific representation provided by classical physics. The Bohrian claim that experience can be only described in terms of classical concepts stands at the center of this widespread confusion. If we accept, as any realist should, that experience is derived from the theory —and is not the "self evident" unproblematic given which ground science—, then we will be necessary confronted not to the irrepresentability of the theory of quanta but with the need to develop a new adequate conceptual scheme that matches all the conditions we have discussed above.

6 Conclusion

In this article we have argued that interpretations and narratives attempting to justify an anti-realist fictional collapse of the quantum wave function —introduced in order to make reference to single measurement outcomes without any experimental or theoretical support— are clearly non-starters for a realist account of QM. Fictions have nothing to do with realism. Instead, the realist program should focus itself in the attempt to produce an invariant-objective representation of a real state of affairs. Something that can only be done by following the general theoretical conditions we have discussed in the previous section. From a realist standpoint, we must recognize that smoky dragons are nothin but contemporary myths which embrace contextuality instead of objectivity, preferred bases instead of operational-invariance, measurement-collapses and outcomes instead of operational repeatability. The lesson coming from this analysis is quite straightforward. It is only by staying close to the basic ideas of realism, refusing to enter the anti-realist labyrinth of interpretations and narratives, that we can hope to capture and defeat these fantastic creatures. The fight against them has just begun.

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