Bohr's Complementarity and Kant's Epistemology

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Abstract. We point out and analyze some striking analogies between Kant's transcendental method in philosophy and Bohr's approach of the fundamental issues raised by quantum mechanics. We argue in particular that some of the most controversial aspects of Bohr's views, as well as the philosophical concerns that led him to endorse such views, can naturally be understood along the lines of Kant's celebrated 'Copernican' revolution in epistemology.

1 Introduction

Contrary to received wisdom, Bohr's views on quantum mechanics did not gain universal acceptance among physicists, even during the heyday of the so-called 'Copenhagen interpretation' (spanning approximately between 1927 and 1952). The 'orthodox' approach, generally referred to as 'the Copenhagen interpretation', was in fact a mixture of elements borrowed from Heisenberg, Dirac, and von Neumann, with a few words quoted from Bohr and due reverence for his pioneering work, but with no unconditional allegiance to his ideas [Howard2004][Camilleri2009]. Bohr's physical insight was, of course, never overtly put into question. Yet many of his colleagues found his reflections about the epistemological status of theoretical schemes, as well as his considerations on the limits of the representations employed by science, obscure and of little practical moment – in a word: too philosophical.[1] In addition, it proved somehow uneasy to reach definite conclusions as to the true nature of this philosophy.

Although Bohr's views have occasionally been criticized for their alleged positivistic leaning,[2] a number of commentators have more aptly pointed out their pragmatist aspects, especially in view of Bohr's apparently operationalist definition of microphysical phenomena, and of his documented interest for William James [Stapp1972][Murdoch1987]. We know that Bohr had a lifelong friendship with the Danish philosopher Harald Høffding (who was a close friend of his father, and taught a course at the university of Copenhagen, which Bohr attended as a student)

[1] See, *e.g.*, Holton [1978, p.162], Osnaghi [2009, pp.101-2].
[2] [Bunge1955]. See also the discussion in Howard [2004] and Faye [2009].

[Faye1991]. Through Høffding, Bohr was exposed to Kantian influences (partly reshaped by Høffding's own rather pragmatist views). Even though Bohr himself did not bother to pinpoint his debt towards Kant, such influences are arguably responsible for the Kantian pattern that can be discerned amidst Bohr's characteristic mixture of philosophical styles, and more specifically in his epistemological reflection on quantum mechanics.

Unsurprisingly, therefore, early neo-Kantian analyses of quantum mechanics, such as Carl-Friedrich von Weizsäcker's [Heisenberg1971, Ch. X], Grete Hermann's [1996], and Ernst Cassirer's [1956], took advantage of Bohr's position, instead of distantiating themselves from it. The Kantian element in Bohr's thought was subsequently recognized by a number of historians and philosophers of physics,[3] while being minimized or denied by others.[4] The reasons for such disagreement are easy to understand: on the one hand, the Kantian component of Bohr's epistemology is buried in his idiosyncratic remarks about the role of measuring devices and the boundaries of theoretical domains; on the other hand, after more than three centuries of erudite commentaries, the gist of Kant's philosophy remains a matter of debate. Any attempt to bring out the affinities and differences between Bohr and Kant can, therefore, hardly avoid engaging in a twofold process of clarification.[5]

In the present paper, we will in particular be concerned with showing that some of Bohr's crucial moves, while seemingly conflicting with the letter of Kant's work, are in fact very much in tune with its spirit. The first section sorts out the various dimensions of Kant's theory of knowledge, and identifies what was retained and what was left out by Bohr. We insist in particular on the striking analogy between, on the one hand, Kant's strategy to 'disentangle' the object and the subject from the cognitive relation which lies at the heart of our experience, and, on the other hand, Bohr's endeavor to come to grips with the 'indivisibility' of quantum phenomena. In the subsequent sections we analyze in turn Bohr's 'principal distinction' between the measuring instrument and the measured object (which we relate to Kant's general reflection upon the subjective conditions of possibility of knowledge), Bohr's concept of *complementarity* (which we relate to Kant's theory of the object), and the peculiar role of classical concepts within Bohr's approach (which we relate to the *a priori* forms that, according to Kant, enable the subject to constitute the objectivity of knowledge).

2 Kant's and Bohr's 'Copernican' turns

As a way to characterize what he regarded as a radical rupture with previous philosophical traditions, Kant described his epistemology as a 'Copernican revolution'. By this term, Kant meant to emphasize the analogy between his critical approach and Copernicus' decision to base the explanation of the apparent motion of the planets on the *relations* between the motion of the Earth and the orbit of the planets, instead of sticking to a theory of their *intrinsic* kinematics. Rather than remaining exclusively fascinated by his object of study (the planets), Copernicus focused on the situation *of the astronomer* on planet Earth, and addressed the problem of how this particular situation contributes to shaping cosmological knowledge. The gener-

[3] [Hooker1972], [Honner1982], [Murdoch1987], [Chevalley1991], [Kaiser1992], [Brock2003].

[4] [Folse1978,1985], [Pais1991].

[5] [Held1995], [Pringe2007], [Cuffaro2010], [Kauark-Leite2012].

alization of this reflective stance to scientific knowledge in general is described by Kant in a famous passage:

> Thus far it has been assumed that all our cognition must conform to objects. Let us try to find out by experiment whether we shall not make better progress, if we assume that objects must conform to our cognition. [Kant1996, BXVI, p.21]

This does *not* mean that objects are so to speak *created* by our cognition, but (i) that one cannot dispense with a proper analysis of our own faculties of knowing, if knowledge is to be understood at all, and (ii) that the form of objects is predetermined by a set of cognitive conditions enabling us to overcome the variegation of fleeting subjective appearances, and to circumscribe some invariant phenomena which can be intersubjectively recognized and designated. The term 'object' is accordingly understood as referring to such experiential invariants, rather than to something beyond experience. Kant then undertook to spell out what, in the structure of our cognition, makes the identification of unified invariant phenomenal patterns possible. He found two classes of such structures. The first one is the continuum of our sensory givenness, namely space and time. The second one is the table of the general concepts of our understanding (or categories), which are used to bring the manifold of sensory appearances under a common organization. Among the latter, we find: (i) the category of *substance*, which permanently unifies a set of attributes, and (ii) the category of *causality*, which enables us to differentiate between unruly subjective successions and law-like sequences of phenomena that any subject can identify.

Like Kant, Bohr was thoroughly concerned with the inherent structures of our cognitive apparatus, and he thought that we cannot dispense with studying them, if we want to make sense of the objectivity of scientific knowledge. Bohr's notion of experience is definitely Kantian in that he takes 'the boundary of our concepts' to be 'exactly congruent with the boundary to our possibilities of observation.'[6] According to Bohr, 'all knowledge presents itself *within a conceptual framework*', where, by 'a conceptual framework', Bohr means 'an unambiguous logical representation of relations between experiences.' [Bohr1934, pp.67-8, our emphasis] In his reflective analysis of the structure of our capability to know, however, Bohr did not address, as Kant did, mental faculties such as sensibility and understanding. Instead, he focused on a technological counterpart of sensibility, namely the measuring apparatus, and on an intersubjective counterpart of understanding, that is, language. On the one hand, he foregrounded the link between the phenomena and the experimental context in which they occur. On the other hand, partly following (and even anticipating) the linguistic turn of the philosophy of his time, he saw in the conditions for unambiguous communication an essential feature of scientific objectivity [Bitbol1996b, pp.263-9].

Bohr's 'Copernican turn' can naturally be understood in the context of the quantum revolution that took place in the first decades of the twentieth century. As long as a scientific paradigm [Kuhn1962] is generally accepted, science can be taken to pursue an increasingly precise characterization of its purported *objects*. However, when the paradigm is crumbling, the ontological status of these very objects becomes suspicious, and the standard procedures for extracting invariant phenomena are also

[6]Niels Bohr, letter to Albert Einstein, 13 April 1927, quoted in Honner [1982, p.7].

put into question. One then falls down onto the only firm ground left, which is 'ordinary' experience along with the results of experimental inquiry, in so far as the latter have recognizable implications within the former. Bohr's view that 'the task of science is both to extend the range of our experience and to reduce it to order' [Bohr1934, p.1] enables him straightforwardly to deal with such a situation. This instrumentalist attitude (which was all but uncommon among the physicists involved in the creation of quantum mechanics) is however decisively supplemented, in Bohr's case, by a careful analysis of the conditions of possibility of experience. He is, in other words, concerned with precisely the sort of reflective knowledge that Kant called *transcendental*, and regarded as the fundamental subject-matter of 'post-Copernican' metaphysics.

Like the more common term 'transcendent', the adjective 'transcendental' applies to something that 'exceeds experience'. This 'excess', however, can be realized in two antithetical ways. A transcendent *object* exceeds experience in so far as it is said to exist *beyond* experience, as a remote (and intellectually reconstructed) external cause of experienced phenomena. Conversely, a transcendental structure exceeds experience because it is a *precondition* of experience: it shapes experience without being part of experience. Moreover, as long as the act of knowing develops, such a transcendental structure is bound to remain in the silent background of this act. We bump here into the extraterritorial status of the precondition of knowledge - a status that Kant, who created the very concept of a transcendental epistemology, regarded as a strong logical requirement. In his own terms, the question of how the condition of possibility of knowledge '...is (itself) possible, will not admit of any further solution or answer, because we invariably require [such a condition] for all answers and for all thought of objects.' [Kant1994, §36] In other words, what plays the role of the knower cannot be known in the very process of knowing.

As we will see in Section 3, Bohr held very similar views with regard to measurement. In particular, he took the attempts to include the act of observation of a quantum phenomenon in the description of the phenomenon itself, to be fundamentally misguided. Echoing Kant, we could say that what preconditions the possibility of a quantum description cannot be described quantum-mechanically in the very process of describing. This is not to deny that quantum mechanics, as one of the most accomplished realizations of the ideal of universal description pursued by the natural sciences, could indeed describe any phenomena. Yet, in doing so, it could not avoid leaving *the preconditions for description* outside its scope. As a well-known article about the measurement problem of quantum mechanics puts it: the quantum theory can describe *anything*, but not *everything* [Peres1982][Fuchs2000]. Bohr's argument for such a conclusion is that the 'indivisibility of the quantum of action' precludes the description of the measurement interaction [Murdoch1987, Ch. 5]. This is so because, if the measuring instrument is to serve as a *measuring* instrument, at least part of it cannot obey the uncertainty relations, and this precludes its representation *qua measuring instrument* within the quantum-mechanical account of the phenomenon under study. Instead, the instrument is to be identified with the conditions that make it possible to observe and to describe the phenomenon in the first place. As such, it is placed 'in the background', and referred to using 'common language supplemented with the terminology of classical physics.' [Bohr1998, pp.142-3] This implies that a 'cut' must be introduced somewhere in our mental picture of the measuring chain, in order to separate the object-system to be described by the quantum symbolism from the measuring instrument, which is described in classical terms. Characteristically, in Bohr's writings, this issue is often related to what he calls the 'subject-object separation' [Bohr1963, p.12].

Our analysis of the term 'transcendental' has thus far focused on the subjective term of the cognitive relation. Let us now turn to the other, objective term of the relation. Beyond the horizon of experience, in the region denoted by the term 'transcendent', lies, according to Kant, the ideally conceived 'thing in itself', that is, the thing as it is independently of any relation with our faculties of knowledge. Things in themselves are to be contrasted with the objects of experience, which, according to Kant, are intrinsically relational:

> Things ... are given in intuition with determinations that express mere relations without being based on anything intrinsic; for such things are not things in themselves, but are merely appearances. Whatever [characteristics] we are acquainted with in matter are nothing but relations (what we call its intrinsic determinations is intrinsic only comparatively); but among these relations there are independent and permanent ones, through which a determinate object is given to us. [Kant1996, B341, p.340]

What we call the 'properties of material objects' are only the expression of the cognitive relations that we establish with our environment; they are not 'proper' to some object, but rather arise as an unanalyzable byproduct of our interaction with 'it' (the quotation marks surrounding the word 'it' are justified by the fact that, in Kant's approach, there are no such things as preconstituted objects placed before a passive sensorial or experimental apparatus). What exists beyond these cognitive relations and independently of them is *in principle* unreachable, since reaching it would precisely mean establishing a cognitive relation with it. So much so that some commentators concluded that, by the term 'thing in itself', Kant merely refers to the impossibility of disentangling ourselves completely from the content of our knowledge, thereby drawing a sharp distinction between the bulk of what we know and our own contribution *qua* knowers.[7]

Here too a close analogy with Bohr can be drawn. Starting from the observation that 'the properties of atoms are always obtained by observing their reactions under collisions or under the influence of radiation', Bohr showed that the quantum of action compels us to acknowledge the existence of a fundamental 'limitation on the possibilities of measurement' [Bohr1934, p.95]. Unlike Heisenberg and others, however, Bohr did not endorse the interpretation according to which the 'disturbance' introduced by the measuring agent prevents us from having complete knowledge of the properties of the object under study. Nor did he suggest that we should regard those properties as intrinsically fuzzy or unsharp. Rather, he pointed out that, given the 'impossibility of a strict separation of phenomena and means of observation' (*Ibid.*, p.96), the very notion of attributes that would be *proper* to the atomic object becomes unworkable. Since '... interaction forms an inseparable part of the phenomena' [Bohr1963, p.4], any discourse about phenomena going on in nature independently of any measuring interaction appears to be meaningless. In his later writings, Bohr took a further step: he advocated the 'interactionality conception of microphysical attributes', according to which properties can only be meaningfully

[7] [Hintikka1991]. See also the discussion in Allison [2004, Ch.3].

defined in certain experimental contexts, and not in others [Jammer1974, p.160].[8]

The consequences of Bohr's inseparability thesis are exactly the same as those of Kant's thorough relationism. Like the latter, the former leaves us two options: either (i) accepting that there is something like a 'micro-object in itself' that we can know only obliquely, by means of successive interactive approaches; or (ii) declaring that any term referring to some such obliquely knowable 'micro-object in itself' is a fake name for the impossibility of breaking up the wholeness of the phenomena. Arguably, Bohr's concept of *complementarity* (which we discuss in Section 4) was, at least to some extent, intended to make option (i) viable. Like the 'cut' that keeps the measuring instrument separated from the phenomenon under study, also complementarity is meant as a conceptual tool for extracting objective results from the quantum symbolism. Bohr takes it to be essential for that purpose that we can refer the measurement results to the properties or the behaviour of some *object*. And since it is only within a specific set of experimental situations (in which compatible observables are measured) that certain classes of predicative sentences can be employed without inconsistency, Bohr restricts his definition of 'phenomenon' to 'observations obtained under specified circumstances, including an account of the whole experimental arrangement' [Bohr1958, p. 64]. The task of complementarity is then to bring phenomena occurring in *incompatible* situations together, as if they referred to the same object.

The last feature of Kant's epistemology that we want to consider is the organic articulation of what he regarded as the two sources of knowledge, namely sensibility and understanding. Since Kant considered that the unity brought by concepts could only concern the data of sensory intuition, he looked for a proper locus of connection between the forms of understanding and the contents of intuition, which he found in what he termed the 'schematism of pure imagination' [Kant1996, B177, p.210]. Schematism can be conceived of as the ability to devise pictures that guide our possible actions in so far as such actions purport to anticipate certain contents of sensory intuition in a systematic way. An example of such a connection is causality. As a concept of pure understanding, causality applies, according to Kant, to sensory contents pre-ordered by a spatiotemporal structure. And its application is mediated by the scheme of succession according to a rule (a generic term for the trajectories of a dynamics), which allows one to anticipate later phenomena based on the knowledge of an appropriate set of earlier ones.

It is precisely at this point that Bohr parts company with Kant. Being faced with the puzzling phenomena of atomic physics, Bohr became increasingly diffident of some components of Kant's account of the constitution of experience. At an early stage of the development of quantum mechanics, he questioned the universal applicability of the category of causality, deeming that it might preclude the possibility of providing a 'pictorial' spatiotemporal description of the trajectories (see Section 5). Subsequently, he endorsed the view that no single 'picture' could be meaningfully used to represent atomic processes: pictures were to be viewed as purely 'symbolic', not to say 'poetical', devices for accounting of the atomic processes [Heisenberg1971, Ch. 3]. Eventually, Bohr came to regard the category of causality and the spatiotemporal coordination of phenomena as mutually exclusive (see Section 4). It was, at this point, no longer possible to understand the anticipation of phenomena on the basis

[8] See Murdoch [1987, Ch. 7]. For a discussion of the analogy between Bohr's and Kant's respective notions of phenomenon, see Kaiser [1991].

of a continuous spatiotemporal representation. Anticipation was rather achieved by means of '. . . a purely symbolic scheme permitting only predictions . . . as to results obtainable under conditions specified by means of classical concepts.' [Bohr1963, p.40] Thus, a major keystone of Kant's theory of knowledge had been removed, and, to many physicists of the time, the entire building looked like it was doomed to crumbling.

The point of disagreement between Bohr and Kant can be characterized in a few words. Kant claimed that the forms of sensibility and understanding he had identified were *a priori* conditions of possibility of objective knowledge in general. This suggested that these forms, as well as their articulation, were fixed for ever by way of necessity, and that no scientific knowledge might be conceived which would *not* fit within such a scheme. As for Bohr, he accepted the typically Kantian idea of 'subjective forms' that constitute experience. He stressed that '. . . in spite of their limitations, we can by no means dispense with those forms of perception which colour our whole language and in terms of which all experience must ultimately be expressed.' [Bohr1934, p.5] But Bohr also considered that, in view of these limitations, '. . . we must always be prepared to expect alterations in the points of views best suited for the ordering of our experience.' (*Ibid.*, p.1) The idea of modifying the so-called '*a priori*' forms of human knowledge according to the advances of scientific research was so averse to Kant, that this alone sufficed for some philosophers of science to rule out any deep similarity between Bohr's and Kant's respective theories of knowledge [Folse1978]. However, even in this particular respect, the relation between the two theories is more complex than it at first sight appears.

To begin with, Kant's epistemology need not be viewed as the static articulation of the ideas displayed in Kant's own system. One can also regard it as a *research program*. Such a program was developed by an entire school of neo-Kantian philosophers, whose major move was to historicize and relativize the *a priori* forms of knowledge,[9] by suggesting that their function (namely, to unify, and extract invariants from, the manifold of appearances) could be ascribed, for instance, to plastic 'symbolic forms' [Cassirer1965] or to historically relative 'principles of coordination' [Reichenbach1965]. Philosophical pragmatism itself can, to some extent, be traced to a Kantian framework, provided that the latter's emphasis on the absolute *a priori* is attenuated [Putnam1995]. These examples show that Kant's epistemology, when conceived as a research program, might indeed prove flexible enough to account for quantum knowledge.

Conversely, one might argue that Bohr's epistemology is itself characterized by a sort of *a priori* component, namely 'classical concepts'. As we have seen, Bohr's account of quantum phenomena relies on classical concepts in two different contexts: the description of the measuring apparatus and that of the complementary features of a given atomic 'object'. This is no accident. Bohr was always sceptical towards the idea that atomic phenomena demanded the dismissal of the classical conceptual framework. In his reply to a letter in which Schrödinger urged 'the introduction of *new* concepts' (though, as he said, this would entail a 're-organisation involv[ing] the most profound levels of our knowledge, space, time and causality'), Bohr remarked: 'I am scarcely in complete agreement with your stress on the necessity of developing 'new' concepts. . . . The 'old' experimental concepts seem to me to be inseparably

[9] [Friedman1992], [Bitbol1998], [Pradelle2013].

connected with the foundation of man's powers of visualizing.' [10] He reiterated the same point in his writings, arguing that it was '. . . [un]likely that the fundamental concepts of the classical theories will *ever* become superfluous for the description of physical experience.' [Bohr1934, p. 16, our emphasis]

The need to retain classical concepts can be generically related, as Bohr repeatedly did, to the conditions of possibility of unambiguous communication. As we will see in Section 5, however, Bohr's lack of enthusiasm for any project involving the *replacement* of classical concepts stems less from his attachment to those particular 'forms of perception' than from the conviction that what quantum mechanics demands is not so much a new set of concepts as a deeper understanding of the way concepts *in general* enter the construction of objective knowledge. This, once again, sounds like a distinctly Kantian concern. Bohr's suggestion that we should think of 'the viewpoint of complementary forms' as 'a consistent *generalization* of the ideal of causality' [Bohr1958, p.27, our emphasis] can be understood along these lines.

In so far as we confine our analysis to the measuring apparatuses and other massive objects *as considered within ordinary experience*, Bohr thinks that we are allowed to rely on 'our accustomed forms of perceptions', in spite of having learned from quantum mechanics that these are mere '*idealizations*' (*Ibid.*, p.5). In this sense, Bohr can be thought to acknowledge the enduring pragmatic value of Kant's *a priori* forms. The empirical domain to which such forms apply is nevertheless severely hampered [Bitbol2010]. It does not extend to the whole field of microphysics, but only to ordinary experiences. Kant's *a priori* forms are taken as an anthropological condition of possibility for the technological conditions of possibility of microphysical research. Therefore, as Heisenberg pointed out, they can be viewed as a second-order condition of possibility of microphysical knowledge: 'What Kant had not foreseen was that these *a priori* concepts can be the conditions for science and at the same time have a limited range of applicability.' [Heisenberg1990, p.78] The forms that directly precondition our familiar experience and the phenomena of classical physics have a limited range of applicability; yet they indirectly precondition all empirical knowledge beyond that range. This may be seen as Bohr's simultaneous vindication and confinement of Kant's *a priori.*

3 The 'agency of measurement' and the cut

By stipulating that we should use a classical mode of description to account for the measuring instruments, the measurement outcomes, and the experimental procedures, Bohr seems to grant them a sort of 'extraterritorial status'. It is important to realize, however, that Bohr's prescription in no way presupposes or implies an ontological distinction between macroscopic and microscopic systems. There is nothing in the *physical* nature of macroscopic objects that distinguishes them from the microscopic ones, and which rules out the possibility of describing them as quantum systems.[11] Bohr's concern is rather to emphasize the specific *function* that the measuring apparatuses accomplish in the system of knowledge: that of ensuring

[10] Erwin Schrödinger, letter to Niels Bohr, 5 May 1928, and Bohr's reply, 23 May 1928, both quoted in Murdoch [1987, p. 101].

[11] This point is often overlooked. Rovelli [1996, p.1671] remarks for example that 'the disturbing aspect of Bohr's view is the inapplicability of quantum theory to macrophysics', and he understands such a view as implying that 'the classical world is physically distinct from the microsystems'. See also, *e.g.*, Zurek [2003], Weinberg [2005], as well as Hugh Everett's analysis of Bohr's position in Osnaghi [2009].

the intersubjective agreement about experimental results and procedures, thereby fulfilling a condition of possibility of objective experience. The functional status of the 'principal distinction' between measuring instruments and object-systems [Bohr, 1998, p.81] is confirmed by Bohr's emphasis on the fact that the boundary between the classical and the quantum domain is by no means fixed, and we are left the 'free choice' to locate it at one or the other point of the measuring chain [Bohr1998, pp.73-82]. By choosing to describe the measuring apparatus in classical terms, Bohr cuts the measurement problem off at its root [Murdoch1987, p.114]. On the one hand, in so far as a classic-like actualistic description of the relevant part of the measuring instruments is taken as the fundamental presupposition of any quantum account of the phenomena, there is no need to figure out a mechanism for the transition between potentialities and actuality. On the other hand, since the quantum description is prevented from extending to the totality of the measurement chain, there is no such thing as a superposition of pointer macrostates.

While dissolving the traditional measurement problem, Bohr's strategy is nevertheless faced with an issue of consistency. The same system can alternatively be seen as a measuring instrument (in which case it is described classically) or as an object-system (in which case the quantum symbolism applies). As Bohr hinted, the issue can in principle be fixed by thermodynamic considerations, in so far as the macroscopic number of degrees of freedom of real measuring apparatuses is taken into account [Daneri1962][Rosenfeld1965]. Although no unitary process can bring the quantum account exactly to *coincide* with a classical distribution of definite pointer positions, one may argue that the two become practically indistinguishable soon after the measurement has taken place. Despite its practical effectiveness and arguable consistency, saying that Bohr's approach is not very popular among physicists would be an understatement.[12] For, by preventing in principle the quantum theory from accounting (at least retrospectively) for the experimental conditions of its own assessment, it seems to imply that any physical description is fundamentally incomplete [Omnès1992, pp.340-1][Weinberg2005].

In the late 1950s, the preceding objection was raised and intensely debated with Bohr and his collaborators by Hugh Everett, then a PhD student at Princeton under the supervision of John Wheeler [Osnaghi2009]. It is, however, only after Bohr's death that the issue started to receive increasing attention. The growing dissatisfaction with Bohr's approach culminated in John Bell's [1990] 'manifesto' *Against 'measurement'*. In this article, Bell criticized the idea that we should content ourselves with propositions that are valid only 'for all practical purposes', and he argued that a mature quantum theory should at once get rid of the 'shifty split' and 'refer to the world as a whole'. Elsewhere, Bell [2004] discussed Bohm's [1952] hidden variable and Everett's [1957] 'relative state' formulations of quantum mechanics as two possible ways of 'completing' the Copenhagen interpretation along these lines. More recently, the same program has received a strong impulse by the theoretical and experimental study of decoherence. As a way to get rid of Bohr's alleged 'dualism', it has been suggested that it might be sufficient to prove that the classical behavior of macroscopic systems is predicted by quantum mechanics itself, provided that the effects of decoherence are taken into account [Zurek2003][Joos2003].

It is interesting to frame the research program just outlined in the more general philosophical project that aims at the complete 'naturalization' of the transcenden-

[12]In a manuscript of 1955, Everett calls it 'repugnant' [Osnaghi2009, p.105].

tal. In so far as the 'cut' is supposed to separate the content of knowledge from its preconditions (which is clearly the function that Bohr attributed to it), any attempt to generalize the quantum theory for the purpose of doing away with the cut can be viewed as a step in the direction of providing a fully naturalistic account of the cognitive process. The guiding idea of such attempts is that, if the measuring apparatus is to be regarded as a natural object (as nothing seems to prevent us from doing), it should be possible to describe the measurement interaction as a standard natural process. More generally, it should be possible to consider the whole cognitive operation, including the *decision* to perform an experiment and the *realization* of the occurrence of one particular outcome, as a topic to be addressed by natural sciences such as neurobiology, biochemistry, optics etc. Wheeler and Everett made precisely this point during their discussions with the Copenhagen group: 'Thinking, experimentation and communication – or psychophysical duplicates thereof – are all taken by Everett as going on *within* the model universe.'[13]

At first sight, naturalization looks like a quite reasonable research program. Nothing seems to prevent the continuous expansion of the domain of validity of the sciences of nature towards an increasing disclosure of the cognitive process. Moreover, in so far as one considers classical physics, the indispensability of the pretheoretical level [Mittelstaedt, 1998, pp.8, 104] can go unnoticed, since the pretheoretical treatment of the measurement process can be made *isomorphic* to its theoretical description. So much so that isomorphism could in this case be conflated with identity, which would allows one to understand 'the measurement process ... as a special case of the general laws applying to the entire universe.' [Bohm1993, p.13] Nothing seems therefore to hinder the grand project of an entirely *naturalized* theory of knowledge, which would render Kant's intimation of a *transcendental* epistemology somehow superfluous.

When it comes to quantum mechanics, however, things are not as simple. Indeed, Bohr's point can be formulated precisely by saying that the *transcendental* approach of knowledge becomes unavoidable when one is concerned with quantum phenomena. Bohr has two arguments to support this claim. The first, which he develops at length, especially in his replies to Einstein's objections, is the above-mentioned *dynamical* argument that in order for measurement to be possible at all in the quantum domain, we are forced to presuppose that at least part of the instrument does *not* obey the uncertainty relations. This is a typical Kantian pattern of reasoning. Bohr assumes that we *do* have knowledge of atomic phenomena, and analyzes the conditions that must be satisfied in order for this to be possible. There is, however, another argument, which recurs in Bohr's later writings, although he never takes the trouble of spelling it out in detail. This is the *semantic* argument according to which the very possibility of *communicating* the results of an experiment, as well as the conditions under which these results were obtained, requires that they be expressed in ordinary language. This may look as a prescription stemming from a particular theory of meaning, one that privileges 'observational language'. As we will see in the last section, however, what really matters for Bohr is that *no* account of experience is possible without assuming some conceptual framework (in Bohr's sense). Consequently, the attempt to get rid of 'any presupposition', by showing that the assumed conceptual relations emerge 'spontaneously' within a suitable account *of experience*, can only bring us into a regress. As Bohr's friend and collaborator

[13]John Wheeler, letter to Alexander Stern, 25 May 1956, quoted in Osnaghi [2009, p. 118].

Léon Rosenfeld put it in a letter of 1959:

> To try (as Everett does) to include the experimental arrangement into theoretical formalism is perfectly hopeless, since this can only shift, but never remove, this essential use of unanalyzed concepts which alone makes the theory intelligible and communicable.[14]

This conclusion is illustrated by the fact that the shadow of the distinction between the predictive formalism and the elementary presuppositions needed for putting it to the test remains visible, and uneliminable, in the naturalizing approaches mentioned above. In the case of Bohm's theory, the hidden variables whose distribution is supposed to determine the result of a measurement are made epistemically inaccessible by means of an *ad hoc* postulate, which might be the shadow of the background status of the act of measuring. In the case of Everett's theory, the pretheoretical level is reflected in the deterministic description of the 'universal state vector'. This description is given from the standpoint of an ideal metaobserver, and is required in order to derive the probabilities recorded in the 'memories' of the naturalized observers who inhabit the various 'branches' of the universal state vector. Similar remarks apply to the approaches based on decoherence. Decoherence can yield quasi-classical probabilistic structures for certain 'preferred' observables, but not a full degree of classicality [Schlosshauer2011]. Moreover, in order to do so, it must rely on a deliberate selection of the relevant degrees of freedom of the system within a larger domain of environmental degrees of freedom, which can be seen as the shadow of the 'cut' between the object-system and the experimental context.

4 The 'measured object' and complementarity

According to Bohr, a crucial consequence of the fact that the experimental modes of access to phenomena cannot be separated from the phenomena themselves is *complementarity*. Let us follow Bohr's reasoning. In classical physics, where the influence of the measuring procedure can in principle be substracted from its outcome, the data obtained by using various instruments '...supplement each other and can be combined into a consistent picture of the behaviour of the object under consideration.' [Bohr1963, p.4] Conversely, in quantum physics, changing the experimental arrangement is tantamount to changing the holistic phenomenon itself, which therefore turns out to be incompatible with other holistic phenomena. 'Combination into a single picture' of various experimental data then yields contradictions. The contradictions may be overcome by adopting a new, non-pictorial method for articulating the information derived from various experimental arrangements. Bohr calls this method 'complementarity' because it takes the various pieces of information obtained in mutually *exclusive* experimental contexts to be jointly *indispensable* in order to characterize a given micro-object:

> ...evidence obtained under different experimental conditions cannot be comprehended within a single picture, but must be regarded as complementary in the sense that only the totality of the phenomena exhausts the possible information about the objects. [Bohr1958, p.40]

[14] Léon Rosenfeld, letter to Saul Bergmann, 21 December 1959, quoted in Osnaghi [2009, p.117].

Bohr's complementarity is no simple or unambiguous concept. One may list *three* (disputable) applications of the concept of complementarity in quantum mechanics:[15]

C1 – *The complementarity between incompatible variables*. 'In quantum physics ... evidence about atomic objects obtained by different experimental arrangements exhibits a novel kind of complementary relationship.' [Bohr1963, p.4] A standard example is the complementarity of the archetypal couple of conjugate variables, namely position and momentum.

C2 – *The complementarity between causation and spatiotemporal location of phenomena*. This was the first explicit formulation of complementarity, which Bohr stated in his 1927 Como lecture: 'The very nature of quantum theory... forces us to regard the space-time coordination and the claim of causality, the union of which characterizes the classical theories, as complementary but exclusive features of the description, symbolizing the idealization of observation and definition respectively.' [Bohr1934, pp.54-5]

C3 – *The complementarity between the continuous and discontinuous pictures of atomic phenomena, i.e. between the wave model and the particle model*:

> The individuality of the elementary electrical corpuscles is forced upon us by general evidence. Nevertheless, recent experience, above all the discovery of the selective reflection of electrons from metal crystals, requires the use of the wave theory superposition principles in accordance with the original ideas of L. de Broglie. ... In fact, here again we are not dealing with contradictory but with complementary pictures of the phenomena which only together offer a natural generalization of the classical mode of description. (*Ibid.*, p.56.)

C3 is at the same time the most popular and the most controversial version of complementarity, since it involves remnants of classical *representations* (as opposed to classical *variables*, or classical terminology for the description of measuring apparatuses) [Murdoch1987, p.59]. As Held [1994] points out, after 1935 Bohr '... tacitly abandons the idea of wave-particle complementarity', and starts to regard the concept of complementarity as providing only an indirect 'clarification' of the dilemma of wave-particle dualism [Bohr1963, p.25]. This suggests that the two other formulations of complementarity might in some sense be more fundamental. In the rest of this section, we will examine each of them in turn.

The C1 version of complementarity, which is likely to be close to the roots of the concept, is not without difficulties. The most benign difficulty is that the incompatibility of a pair of conjugate variables implied by C1 does not follow from that of the corresponding experimental arrangements. Indeed, from a narrowly epistemic interpretation of the uncertainty relations, one can derive that our experimental *knowledge* of the position is incompatible with our experimental *knowledge* of the momentum. Yet, this does not necessarily prevent the object from intrinsically 'possessing' both properties. As we have seen, however, Bohr's argument for the incompatibility of conjugate variables did not rest on a doubtful extrapolation from epistemic limitations to ontology. His point was rather that the experimental arrangement is not to be understood as the instrument for *revealing* the putative

[15] [Faye1991], [Held1994], [Murdoch1987], [Bitbol1996a].

intrinsic value of a given variable, but rather as an essential part of the *definition* of that very variable.

A more serious difficulty bears on the claim that the values of incompatible variables are *jointly* indispensable to exhaust knowledge about the object. This claim seems to conflict with Bohr's tenet that incompatible variables cannot *simultaneously* have definite values. As a way to bypass *simultaneous* possession, one might argue that joint indispensability refers to the values found when *successive* measurements are actually performed. But this solution is not satisfactory either, because the values can vary according to the *order* of the measurements. A more satisfactory alternative is to focus on the observations that are *possible* when only the experimental preparation, but not the measurement to be performed, has been fixed [Held1994]. Along this line of thought, one may reconcile mutual exclusion and completion of conjugate variables without logical inconsistency: mutual exclusion pertains to *actual* experimental arrangements, whereas completion (or exhaustiveness) refers to *possible* measurements.

An important question arises at this point. Given that complementary variables require incompatible experimental arrangements in order to be measured, are we compelled to think of them as attributes of one and the same *thing*? There is little doubt that, for Bohr, a complete list of conjugate variables provides exhaustive information *about an object*. This *aboutness* of experimental information is stressed again and again: '... evidence obtained under different experimental conditions ... must be regarded as complementary in the sense that only the totality of the phenomena exhausts the possible information about the objects' [Bohr1958, p.40]; '... together (these phenomena) exhaust all definable knowledge about the objects concerned' (*Ibid.*, p.90); '... such phenomena together exhaust all definable information about the atomic objects' (*Ibid.*, p.99). The emphasis on aboutness suggests indeed that Bohr conceived of complementarity as a means to provide us with the possibility of *referring* to micro-objects as if they were somehow independent of any experimental procedure – a possibility that would otherwise be precluded by the unanalyzable (or interactional) nature of quantum phenomena. The atomic objects Bohr seems to have in mind have the same general predicative structure as the objects of classical mechanics, although they are not ascribed predicates as such. Just as classical particles, 'atomic objects' are indeed construed by Bohr as points of convergence of two families of conjugate features such as position *and* momentum.

Bohr's account is not without alternatives, however. One might in particular dismiss the presupposition that the experimental outcomes are *about* objects endowed with the same predicative structure as the moving bodies of classical mechanics. That is, one could accept that position and momentum are mutually exclusive, while at the same time rejecting the idea that they are *jointly* indispensable for describing some *thing*. The interpretation of C1, therefore, places us before a dilemma similar to that of the 'object in itself': should we refer to a 'micro-object in itself', characterized by successive, but mutually incompatible, interactive probings; or should we rather look for a new mode of objectification that retains *nothing* (not even the adumbration of a predicative structure) of the classical corpuscularian concept? If we follow Bohr in adopting the first (conservative) strategy, we must ascribe a highly non-conventional status to micro-objects. Expressing this status in a Kantian idiom, we might say that Bohr's cloudy 'micro-object' is a unifying *symbol* used as a regulative-heuristic device; it is not a tangible *something*.[16] However, if we adopt the 'revolutionary' strategy of looking for novel forms of objectification, we become free to construe certain elements of the quantum symbolism as denoting previously unconceivable objects of knowledge. This is precisely how Schrödinger proposed that we should interpret the wave function [Bitbol1996a].

Let us finally turn to C2, namely the complementary relation between causality and the use of space-time concepts. According to Bohr, '...the use of any arrangement suited to study momentum and energy balance - decisive for the account of essential properties of atomic systems - implies a renunciation of detailed space-time coordination of their constituent particles.' [Bohr1963, p.11] This suggests that C2, like C1, derive from combining the incompatibility of experimental arrangements with the interactionality thesis. However, other texts of the earlier period,[17] as well as Heisenberg's lucid interpretation of Bohr's position, favour another conception of the complementarity between causality and space-time coordination, which does *not* reduce it to the complementarity of pairs of conjugate variables. In his *Physical principles of the quantum theory*, Heisenberg argues that the measurement of *any* variable whatsoever involves spatiotemporal aspects. Thus, it is not only space-time coordination, as any description of phenomena in space-time, which is incompatible with causality. Indeed, one can observe *no* spatiotemporally circumscribed phenomenon without influencing it in a way that prevents the application of causal laws [Heisenberg1949, p.63]. Following this Heisenbergian interpretation, von Weizsäcker [1985] and Mittelstaedt [1976] have construed C2 as a relation of mutual exclusiveness and joint completion between the abstract deterministic law of evolution of the ψ-functions (*i.e.*, the Schrödinger equation) and any measurement result observed in space-time.

Because complementarity dismantles the articulation between the category of causality and spatiotemporally-shaped sensory experience, and because this unsettles Kant's system of *a priori* conditions of any possible knowledge, complementarity appears to challenge not only the special architecture of the *Critique of Pure Reason*, but also, more generally, Kant's global project of providing an account of how the chaos of subjective impressions is progressively ordered into an objective pattern. As we saw in Section 2, the process of objectification involves, according to Kant, two steps. In the first step, the impressions are embedded into a spatiotemporal structure, whereas in the second step, spatiotemporally located appearances are connected with one another according to a *law* of succession. How can one objectify the phenomena, if the former procedure is no longer available? Bohr's answer is daring, but in line with the spirit (if not the letter) of Kant's epistemology. It consists in turning complementarity into a connecting device that *supplants* causality (or rather *includes* causality within its own more general scheme of mutual exclusion and joint exhaustiveness). Quantum physics, Bohr says, 'forces us to replace the ideal of causality by a more general viewpoint', namely 'complementarity' [Bohr1998, p.84]. In so far as the standard (causal) connection of phenomena is prevented by the

[16] [Kant1987,§59, p.227],[Chevalley1995],[Pringe2007].

[17] Here is for example a passage from the Como lecture [Bohr1934, p.54]: '...if in order to make observation possible we permit certain interactions with suitable agencies of measurement, not belonging to the system, an unambiguous definition of the state of the system is naturally no longer possible, and there can be no question of causality in the ordinary sense of the word. The very nature of the quantum theory thus forces us to regard the space-time co-ordination and the claim of causality, the union of which characterizes the classical theories, as complementary but exclusive features of the description, symbolizing the idealization of observation and definition respectively.'

incompatibility of the various modes of experimental access, a new mode of (complementary) connection is offered as a substitute. 'Complementarity is called for to provide a frame wide enough to embrace the account of fundamental *regularities* of nature which cannot be comprehended within a single picture.' [Bohr1963, p.12] As above, we can interpret Bohr's move as aiming at extrapolating the mode of existence of standard classic-like objects beyond the domain of ordinary experience. The revolutionary mode of connection here compensates for a conservative ontology. A diametrically opposed strategy has also been proposed, which consists in sticking to the standard (causal) mode of connection at the cost of redefining the objects of microphysics [Mittelstaedt1976].

5 Classical concepts: a remnant of Kant's *a priori*?

Our last task is to explore the peculiar status of classical concepts within Bohr's philosophy, and to point out some *functional* analogies between Bohr's classical concepts and Kant's *a priori* forms. The atom model [Bohr1913] provides a telling example, from Bohr's early career, of the role that classical concepts and representations played in his approach to theorizing. The atom model is a non-conventional compromise between classical mechanics and electrodynamics on the one hand, and Planck's 'quantum rules' on the other. Because of its baroque combination of electronic stationary orbits ruled by classical mechanics, quantized transitions from one orbit to another, and overt violation of certain theorems of classical electrodynamics, the model has sometimes been regarded as incoherent. Yet, in so far as one follows the prescriptions that restrict the use of the various pieces of this patchwork to specific theoretical contexts, no inconsistency arises [Vickers2007]. In other terms, the model lacks unity rather than logical and practical consistency. And unity, as a regulative ideal of physics, was no sufficient motivation for Bohr to simply *abandon* his clumsy model and endeavor toward a fully unified non-classical theory.

During the intermediate phase that separated the old quantum theory from the advent of modern quantum mechanics, say from 1913 to 1925, Bohr was indeed looking for new ways of articulating classical physics with quantum postulates, rather than trying to eliminate the classical features altogether. The 'correspondence principle' between classical and quantum physics acted as a pivotal element of this strategy. Not only was it taken as a prospective guide for the construction of new theoretical structures (in a way that went far beyond the usual retrospective requirement that the old theory be a limiting case of the new one), but it was also used as a sort of spare wheel for predicting the value of certain variables that did not appear in the hybrid model, such as the spectral line amplitudes. The correspondence principle thus worked as a meta-theoretical structure that enabled one theoretical structure (the classical one) to serve as analogic scaffolding for the development of another theoretical structure (the quantum one) [Darrigol1992, p.81]:

> ... although the process of radiation cannot be described on the basis of the ordinary theory of electrodynamics ... there is found, nevertheless, to exist a far-reaching *correspondence* between the various types of possible transitions between the stationary states on the one hand and the various harmonic components of the motion on the other hand. ... This correspondence is of such a nature that the present theory of spectra is in

> a certain sense to be regarded as a rational generalization of the ordinary theory of radiation. [Bohr1922, pp.23-4]

Bohr's effort to improve his original model involved a permanent negotiation about which classical concepts should be retained and which should be excluded. The boundary between the classical and the quantum components of the model kept moving accordingly. In an attempt to reconcile the discontinuity of the quantum jumps with the continuous spatiotemporal orbits, in 1924 Bohr considered the possibility of jettisoning the principle of causality and the principles of conservation of energy and momentum *for individual events* [Bohr1924]. This proposal gained little support. In a letter to Bohr of December 1924, Pauli suggested to reverse the approach, and to dismiss the classical 'picture' of orbital trajectories in favor of a thoroughly 'quantum' account of the kinematic and dynamic aspects of the problem [Darrigol1992, p.208]. A first sketch of such an account had just been provided by Born, who had coined for it the name '*Quantenmechanik* (quantum mechanics)' [Born1924]. The next decisive accomplishment in this direction was, of course, Heisenberg's [1925] 'matrix mechanics', which completely dispensed with the concept of a continuous trajectory, and replaced it with a law-like structure that applied to the spectral observables. Although Heisenberg's work implied a systematic procedure of symbolic translation of classical laws into quantum laws, as well as the *replacement* of ordinary continuous variables by non-commuting matrices of measurable discontinuous quantities, Bohr [1925] hailed it as a '... precise formulation of the tendencies embodied in the correspondence principle'. Heisenberg [1929] himself referred to his theory as 'a quantitative formulation of the correspondence principle'.[18] The vestige of classical physics was then far from having been eliminated.

The reasons for the stubborn presence of classical concepts within the new theoretical structures might be sought in Bohr's non-conventional approach to theorizing. This approach has cogently been compared to the methodology that Kant discusses in his *Critique of Judgment*, which prescribes to bring seemingly heterogeneous theoretical structures into a unique *system* irrespective of their differences, through a hypothetical use of reason [Pringe2009]. However, it would be misleading to ascribe Bohr's motivation for retaining classical concepts to his methodology of research alone. Neither had such a motivation anything to do with ontological considerations. Rather, as Bohr himself explained in 1934, the crucial point was the peculiar role that classical concepts play *within* language:

> ... it would be a misconception to believe that the difficulties of the atomic theory may be evaded by eventually replacing the concepts of classical physics by new conceptual forms. ... It continues to be the application of these concepts alone that makes it possible to relate the symbolism of the quantum theory to the data of experience. [Bohr1934, p.16]

Bohr's emphasis on this argument came to occupy an increasingly important place in his later writings. In 1949, he summarized it as follows:

> *However far the phenomena transcend the scope of classical physical explanation, the account of all evidence must be expressed in classical terms.* The argument is simply that by the word 'experiment' we refer to a situation where we can tell others what we have done and what we have

[18] Quoted in Darrigol [1992, p.276].

> learned and that, therefore, the account of the experimental arrangement and of the results of the observations must be expressed in unambiguous language with suitable application of the terminology of classical physics. [Bohr1958, p.39]

Bohr's explicit reference to the conditions of possibility of communication contributes to further clarifying the relation between phenomenon and context. In Section 3, we saw that the *transcendental* status that Bohr attributed to classical concepts was linked to their role in implementing the separation between the measuring instrument and the measured object, in a context in which such a separation appears to be precluded by the 'essential wholeness' resulting from the measurement interaction [Bohr1958, p.72]. Since the object-instrument separation is, for Bohr, demanded by the very *concept* of observation, classical concepts could be said to be essential in order to make observation possible. This argument, however, is not devoid of ambiguities, since Bohr does not clearly (or at least, not always) distinguish the semantic and the dynamical aspects involved in it.

In the preceding quotations, however, *all* the emphasis is placed on the conditions for communication. This should come as no surprise, given Bohr's well-documented interest in language. Bohr was always much concerned not only with clarifying and circumscribing the rules for the valid use of particular concepts, as in the atom model, but also with reaching a deeper understanding of the conditions for objective description *in general*.[19] His scattered remarks cannot of course be taken as outlining, or presupposing, a definite theory of concepts. Yet, some general ideas emerge if one considers his reflections as a whole (and in particular the post-EPR papers). When adopting this standpoint, Bohr's classical 'conceptual framework' may be thought as a system of 'conceptual' inferences which is presupposed by empirical inferences, in order for experience to have the constitutive features that we ascribe to it. While the cut can accordingly be understood as a way to stress the transcendental role of the classical conceptual framework, complementarity appears as a (rather rudimentary) attempt to generalize such a framework, in a context in which *intrinsically probabilistic* (*i.e.*, non-causal) inferences are allowed.

Why, then, must we rely specifically on classical concepts in order to 'tell others what we have done and what we have learned'? Why, in other words, should ordinary language and classical physics (which we use to express experimental results and to provide instructions on how to build and calibrate measuring instruments) embody the most elementary conditions of possibility of intersubjective agreement *in general*? It might be thought that Bohr is here dogmatically assuming a positivistic theory of meaning, according to which theoretical statements only have meaning in so far as they can be translated into observational reports that refer 'directly' to the objects of our immediate environment. Nothing, however, would be more foreign to Bohr's conception of language than the idea of privileging a class of 'atomic' propositions, based on the alleged immediacy of the link between those propositions and their putative referents. What motivates Bohr's prescription is, arguably, quite the opposite view, namely that linguistic expressions acquire meaning only as part of a web of inferential *relations*. The classical conceptual framework is in no way more 'objective' than other conceivable, and more general, systems of inferences. Yet, by

[19] [Petersen1985]. See Murdoch [1987, Ch. 7] for a discussion of the pragmatist features in Bohr's views on meaning, particularly in so far as his partial endorsement of verificationist criteria is concerned.

instantiating the logical two-valued *structure* required for unambiguous communication, it *makes objectivity possible* in the first place.

6 Conclusion

In the *Critique of Pure Reason*, which addressed our interest in *nature*, Kant explained how, without truly disentangling ourselves from what there is, we can nevertheless elaborate a form of knowledge that works *as if* we were separated from nature. Our role in this picture mimics that of an external *spectator* of nature, and the knowledge thus acquired qualifies as objective. By contrast, in the *Critique of Practical Reason*, which deals with the issues of freedom, action, and morals, any such separation is precluded and we are ascribed the role of true actors of our own deeds [Beck1963, p.31]. This dialectic of actor and spectator was later taken over by Schopenhauer in *The World as Will and Representation*. According to Schopenhauer, the will is experienced from the point of view of a living actor, whereas the representation of the world is obtained from a point of view that superficially resembles that of a spectator. But the latent lesson of both Kantianism and post-Kantianism is that there is no *true* spectator's standpoint (except in a minimalist 'as if' sense). And that in view of our insuperable entanglement with what there is, the standpoint of a spectator of nature is extrapolated out of the only available standpoint, which is that of the actor.

This is exactly what Bohr concluded from his reflection on quantum mechanics, with some additional radicality though. He soon became aware that our apparent disentanglement from nature in classical knowledge is only the limiting case of a more general situation, in which it is not even possible to conceive of ourselves *as if* we were spectators. This, however, does not entail that we can entirely dispense with the role of the classical pseudo-spectator, if we are to make sense of experience *qua objective* knowledge. 'We are both onlookers and actors in the great drama of existence': this is 'the old truth' of which 'the new situation in physics . . . has so forcibly reminded us' [Bohr1934, p.119].

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