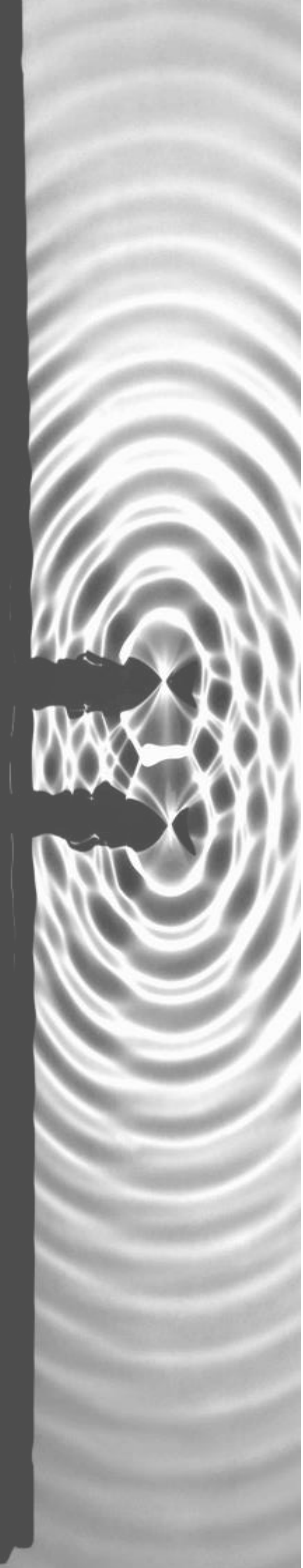

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THE STATUS OF BOHR'S COMPLEMENTARITY TODAY

A study of the nature of knowing and being

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Vivere est Cogitare

To Live is to Think

Bohr, quoting Cicero

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Part 3

The Status of Bohr's Complementarity Today

A study of the nature of being and knowing

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Introduction

In the 1930s, Danish physicist Niels Bohr (1885-1962), aware of the challenges brought about by German physicist Werner Heisenberg's (1901-1976) 'uncertainty' relations in the field of quantum physics[1], formulated his famous complementary principle. In a nutshell, the complementarity principle describes the unavoidable and irreducible situation in which two ontologies (wave and particle) or features of a physical description (space-time coordination and causality) are mutually exclusive but equally necessary actors in the explanation of physical phenomena. The importance of Bohr's work lies in two independent yet connected facts. In the first place, even though he was not the first physicist to pinpoint a breakdown of causality in physics and metaphysics,[2] he repeatedly stressed such observation and raised awareness of the implications it had in atomic physics and beyond. In the second place, he was the one who introduced a 'complementary way of thinking' in the physical sciences, aimed at dealing with such breakdown of a traditional account of causality in quantum phenomena.

In the first part of this thesis, consisting of chapters I and II, I examine how Bohr's complementarity informs some dichotomies that have traditionally characterized the nature of knowing and being, namely those Cartesian or quasi-Cartesian divides of object/subject, human/non-human, knower/known and microscopic/macroscopic. With regard to the methodology, I chronologically assess some of Bohr's papers and discussions, insofar as they are relevant to this research project, and analyse what these tell us in relation to the aforementioned dichotomies and derived debates. In chapter I, I introduce and contextualize his complementarity principle, as first presented in 1927. In chapter II, I discuss Einstein-Podolsky-Rosen's famous 1935 paper and Bohr's response to it,[3] which mark the pinnacle of Bohr's and Einstein's intellectual confrontation, crucial in shaping Bohr's notions of physical reality and phenomena and essential in order to revisit the observations made in chapter I.

In recent years a few science studies scholars have argued that 'complementary epistemology' supports the postmodern turn connecting science and society. American scholar Karen Barad (1956-) is one of these postmodernist theorists, in her case extending

[1] This was actually a development out of joint efforts in Copenhagen, although Heisenberg published these results independently.
[2] The first physicist to do so was presumably Heisenberg in the uncertainty paper. Born also pointed it out in the collapse papers.
[3] Einstein, Podolsky, Rosen, "Can Quantum-Mechanical Description" (1935)
Bohr, "Can Quantum-Mechanical Description" (1935)

postmodernism to a posthumanism, and she is probably the one with the clearest and most exciting theory: Agential Realism (AR). AR is an epistemological-ontological-ethical framework that, building upon Bohr's notion of phenomena, tries to provide an understanding of the active and co-constitutive role of human and non-human, material and discursive.[4] In chapter III I engage with her theory of AR while drawing relations to Bohr's work. Chapter IV is devoted to her faulty notion of temporalization, which has further consequences for accounting for the notion of change. Therefore, in this chapter I examine the temporalization of change through the lens of complex systems theory, a methodological choice justified by the theory's similarities with AR and the further fact that complex systems are often theoretically employed by new materialists as examples of their theories. The other inspiring reading of Bohr comes from Russia-born and America-based scholar Arkady Plotnitsky (1949-), who links complementarity to French philosopher Georges Bataille's (1897-1962) general economy and also to French philosopher Jacques Derrida's (1930-2004) deconstructive economy, concepts which I shall duly introduce in chapter V. Staying closer to a postmodern canon than Barad, Plotnitsky draws relationships between quantum mechanics, modern mathematics and Continental philosophy in order to argue that it is not only knowledge, but also the unknown (the *un*knowable) that pushes the boundaries of our thought and challenges those of disciplinarity. In the second section of my thesis, consisting of chapters III, IV, and V, although most extensively concerned with Barad's AR, I critically assess both approaches to Bohr's ideas in order to try to generate what I believe is a meaningful but unfortunately small debate. Bohr's commentators have up to the date only concerned themselves with labelling the physicist's thought according to given philosophical positions. Although this assessment may bring new aspects into play, it does not add much to previous biographies or commentaries. What we need is an answer to the question of how core –but yet not sufficiently deeply discussed– ideas such as those of subjectivity, objectivity or causality can be historically and philosophically assessed, and insight in how such an assessment may inform a critical examination of our knowing practices and of the status of Bohr's complementarity. This is the main question that has motivated this thesis, which as a whole must therefore be seen as a plea for more attention to the content of some of the most important insights gained from quantum mechanics and their contextualization in nowadays' most daring philosophical views about the nature of knowing and being.

Although Bohr is mainly known for his complementarity in physics, it is lesser known that he also discussed a complementary view of natural and social phenomena in other fields of knowledge (biology, psychology and anthropology), a fact that only reinforces the idea, underlying his writings, that he had a larger project to extend complementary epistemology beyond the horizons of physics. Therefore, in the third part of my thesis, which consists of chapters VI and VII, I research the status of complementarity in the aforementioned fields through a close reading of Bohr's papers, transcriptions of conferences and letters, and as a general theoretical matrix that

[4] Barad, *Meeting the Universe Halfway*, p. 26

constrains and enables knowledge, in the sense of Bataille's use of general economy.[5] Hence, while in part II I widely discuss Barad's AR, in this part I mostly engage with Plotnitsky's work. As a second research question, I try to answer to what extent it is feasible to 'apply' complementarity to other fields of knowledge and, given that Bohr's, Barad's and Plotnitsky's works try to move away from Representationalism (the traditional way of producing knowledge, which breaks the world down into objects, representations of such objects, and human knowers which create such representations), whether we should even be speaking of 'applicability'. The 'question of application' is a pressing one in many humanities disciplines, scholars of which rightly complain that a mere mirroring of the methodologies of the natural sciences does not take into account the theoretical apparatuses of the fields being researched but only uncritically "displace the same everywhere."[6] While both Barad and Plotnitsky –the one more directly, the other in a more indirect manner– discuss it, I argue that neither succeeds in reading Bohr accurately; Bohr is not speaking of application in a strict sense.

Both Barad's Agential Realism and Plotnitsky's analysis of quantum phenomena prove to be fruitful elaborations on Bohr's work, which allow us to explore the profound and revolutionary nature of the lessons of quantum mechanics, especially those provided by complementarity. Nonetheless, I would like to emphasise that at no point I draw a linear argument suggesting that their respective interpretations of Bohr are preferable to Bohr's own interpretation. They are novel, exciting, interesting insofar as they help us evaluate from multiple perspectives what quantum experiments tell us about the validity of physics, as classically understood, but also about these dichotomies that have characterized not only scientific knowledge but human knowledge at large. This is precisely why part II necessitates part III. The dichotomies object/subject, human/non-human, knower/known and microscopic/macroscopic are not exclusive of physics; they have structured modern intellectual history since the Enlightenment's exaltation of reason. We thus return to Bohr's work in part III of this thesis, in order to examine how this generalization of Bohr's complementarity is deployed, at both a descriptive and normative level, and to come to a general conclusion about its status.

Last, I would like to mention a methodological feature of the present thesis. Concerning the writing style, even if I introduce the chapters' content and fundamental concepts, I leave the fathoming of other more implicit ideas and terms up to the reader. For this reason, the writing might be perceived as lacking clarity. Note that this is not the case, for the exploratory and almost-literary style is intentionally so. Lines of argumentation are thought so as to be unfolded as the reading goes. The same applies to the chapters' structure. I hope that this initiative becomes, rather than a discouraging and dense experience, a pleasant and stimulating one.

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[5] I shall define 'theoretical matrix' and 'general economy' in chapter V.
[6] Haraway, *Modest_Witness@Second_Millenium*, p. 16.

Ch. I. The Advent of Quantum Mechanics
Heisenberg's *Uncertainty* Relations
Bohr's Complementarity

Even if linearity has never been a trend in history, until the XX century physics had followed a more or less linear development. Linearity in the sense that, despite occasional inconsistencies, no major issues had deeply threatened the foundations of the physical sciences. À la Kuhn, science, or to be precise, physics, had been explained by more or less cumulative and commensurable episodes.[7] A grand-narrative of progress. However, the appearance of the quantum of action changed the course of the events, and linearity completely broke down.

First recognized by German physicist Max Planck (1858-1947) in 1900, the quantum of action (Planck's constant h or reduced Plack's constant $\hbar$) was originally the proportionality constant between the minimal increment of energy E of a hypothetically charged oscillator in a black body, and the frequency f of its associated electromagnetic wave. In 1905, German physicist Albert Einstein (1879-1955) theoretically associated the value E with a 'quantum' or minimal element of the energy of the electromagnetic wave itself, eventually called 'the photon'. This resulting relation ($E = h \cdot f$) was consequently baptised as 'the Planck-Einstein relation'. In 1924, French physicist Louis-Victor de Broglie (1892-1987) presented his PhD thesis,[8] in which he generalized the Planck-Einstein relation by extending its applicability to any material particle. De Broglie's hypothesis was afterwards confirmed for electrons by both George Paget Thomson's cathode ray diffraction experiment and the Davisson-Germer experiment, and later also proved for elementary particles, neutral atoms, and even molecules.[9] In what nowadays is called 'the old quantum theory', that is, the view mainly developed by Niels Bohr and German physicist Arnold Sommerfeld (1868-1951) that real particle trajectories are constrained by quantum laws, energy and matter are released in packages, quantized.

With Planck's quantum of action, the 'old quantum theory'[10] had been born. It was a very special theory; for the first time in the history of modern physics, a 'theory'[11] violated commonly accepted principles of classical physics such as continuity or causality.

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[7] Kuhn, *The structure of scientific revolutions* (1962)
[8] De Broglie, *Recherches sur la théorie des quanta* (1925)
[9] Thomson, "Experiments on the Diffraction of Cathode Rays."
Davisson & Germer, "Diffraction of electrons by a crystal of nickel."
[10] 'Old quantum mechanics' is commonly used to refer to quantum theory before Heisenberg and Schrödinger developed their formalisms. The 'new quantum theory' was then born, and it is what we nowadays refer to as 'quantum mechanics'.
[11] The emphasis wants to remark the fact that there is no such thing as one perfectly coherent account of 'quantum theory'. Do keep reading for an explanation of what the singular (the theory, the Copenhagen interpretation) refers to.

Consequently, it had far-reaching implications for traditional epistemology; it was of utmost importance to furnish quantum theory with a consistent metaphysical framework. Here is where the so-called 'Copenhagen Interpretation' made its appearance. Briefly introduced, the Copenhagen Interpretation was the group of theories proposed by some renowned physicists: Niels Bohr (often referred to as its founding father), Werner Heisenberg, Wolfgang Pauli (1900-1958), Rudolf Peierls (1907-1995), Léon Rosefeld (1904-1974) and John Archibald Wheeler (1911-2008), to name some of them. They were the first who attempted to make sense of atomic phenomena in the new light of quantum mechanics. The conceptions of these physicists differed in many respects; famous are Heisenberg's and Bohr's somehow diverging views on the uncertainty relations derived by the former, or the opposing viewpoints of Einstein and Bohr on the completeness of quantum mechanics, also known as the Einstein-Podolsky-Rosen paradox debate, held within the Copenhagen Interpretation. Nonetheless, there were also many commonalities. In fact, the expression 'Copenhagen Interpretation' was, rather than a unified and consistent logical structure, a label introduced by people confronting Bohr's idea of complementarity to identify what they saw as the common features behind the Bohr-Heisenberg interpretation as it emerged in the late 1920s. Nowadays, the expression is mostly regarded as an umbrella term for indeterminism, Bohr's correspondence principle, Born's statistical interpretation of the wave function, and Bohr's complementarity interpretation of atomic phenomena.[12]

The history of quantum mechanics and the Copenhagen interpretation is complex and full of nuances. Due to the topic and length constraints of the present thesis, I will be unable to give a thorough account of this long and intricate story. For these reasons, I will only chronologically assess its papers and discussions, insofar they are relevant to this thesis. The analysis will be performed through Niels Bohr, a central figure in this chapter and, by extension, in the whole thesis. It will be no easy journey, for Bohr's style of argumentation is sometimes obscure and permeates "an unaccustomed wilfulness,"[13] which yet suggests precision and profundity of insight. At the same time, there is a natural evolution of his argument over time, so careful attention should be given to dates and historical context.

In this chapter, I will introduce his complementarity principle as initially formulated in 1927. Before that, I will *internally*[14] contextualize the evolution of quantum mechanics since Planck's recognition of the quantum of action until then. A more detailed account of his earlier notion of complementarity will already give us some indications of the sense in which Bohr's ideas are important for the new metaphysical framework that quantum mechanics urged. Specifically, I will analyse the divides of object/subject, knower/known and micro/macro which have characterized Newtonian physics and, more generally, our

[12] Stanford Encyclopedia of Philosophy. "Copenhagen interpretation of Quantum Mechanics," accessed 18-01-2017, https://plato.stanford.edu/entries/qm-copenhagen/
[13] Scheibe, *The Logical Analysis of Quantum Mechanics*, p. 12.
[14] Internal as in relating Bohr's thought to earlier physical theories and ideas.

approach to knowledge since the Enlightenment. For that, special attention will be devoted to Bohr's notions of 'phenomenon' and the measurement context.

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The essence of the quantum theory is contained in Planck's quantum of action. The idea that the energy of light (and material particles) could not be made arbitrarily small had deeper implications than the mere fact that its release had an inferior limit. First, it introduced an essential discontinuity, or rather individuality[15], even wholeness –a feature that Bohr named 'the quantum postulate'[16]– completely foreign to the classical theories. Resulting from this first observation was the fact that the interaction between the object and the measuring apparatus –interchangeable labels, as we will see further on in this chapter– could not be assumed to be negligibly small[17]:

> The quantum postulate implies that any observation of atomic phenomena will involve an interaction with the agency of observation not to be neglected. Accordingly, an independent reality in the ordinary physical sense can neither be ascribed to the phenomena nor to the agencies of observation.

These two interconnected consequences demanded that the whole ontology of the object and the context of measurement had to be thought anew.

A quarter of century after Planck's quantization of light and matter, Heisenberg was the first to formulate a mathematical formalism for quantum theory. It was 1925, and together with German physicist and mathematician Max Born (1882-1970) and theoretical and mathematical physicist Pascual Jordan (1902-1980), he realised that matrix calculus, relatively unknwon by then, could become an excellent tool to account for atomic transitions, that is, the observational data obtained from spectroscopy techniques. It was basic to the theory that only those quantities in principle observable were meaningful; any treatment of possible unobservables was left out. The main idea of the formalism was to represent these physical quantities or 'observables', as commonly referred to in the physics terminology, by matrices that evolve in time. For those versed in the topic, he defined these matrices as infinite Hermitian matrices, which later on would be identified as self-adjoint operators on a Hilbert space.[18] In order to build the formalism, he postulated fundamental relations between canonical conjugate quantities.[19] Take for example the case of the matrices $\mathcal{Q}$ and $\mathcal{P}$, which respectively

[15] Individuality understood as indivisibility and the unanalysable character of the whole.
[16] Bohr, "The Quantum Postulate and the Recent Development of Atomic Theory" (1928)
[17] Bohr, Ibid., p. 580.
[18] Encyclopedia of Mathematics. "Hilbert Space," accessed 10-02-2017, https://www.encyclopediaofmath.org/index.php/Hilbert_space
[19] Wikipedia. "Conjugate variables," accessed 10-02-2017, https://en.wikipedia.org/wiki/Conjugate_variables

represent the canonical position and momentum of a particle. They should satisfy the following rule, known as the canonical commutation relation CCR:

$$\mathcal{Q}\mathcal{P} - \mathcal{P}\mathcal{Q} = i\hbar$$

Only one year later, in 1926, Austrian physicist Erwin Schrödinger (1887-1961) propounded a rivalling formalism, that of wave mechanics. He wrote down an equation, nowadays known as 'time-dependent Schrödinger equation', which had the following general form:

$$\hat{H}\psi(q,t) = i\hbar\frac{\partial}{\partial t}\psi(q,t)$$

The symbol $\frac{\partial}{\partial t}$ indicates a partial derivative with respect to time t, $\psi(q,t)$ is the wave function of the quantum system and $\hat{H}$ is the Hamiltonian operator, which characterises the total energy of any given wave function and takes different forms depending on the situation. The equation's solution is a wave that describes the changes over time of a physical system significantly affected by quantum effects (such as the wave-particle duality). In particular, the equation was used to find the allowed energy levels of quantum mechanical systems such as atoms.

Heisenberg, confronted by Schrödinger's more attractive formalism, which seemed to provide the *Anschaulichkeit*[20] –using Kantian terminology– he had failed to attain with his own, destroyed but not defeated, started to work on this lacking feature of his theory.[21] For that, the easiest was to redefine *Anschaulichkeit*. He found the answer in the operational assumption that measurement is what gives meaning.[22] For *Anschaulichkeit,* he thought, it was sufficient that theories were internally consistent so that one could draw comprehensible experimental results from them. The fact that measurements always involve a certain inaccuracy secured his CCR, the basis of matrix mechanics. The first formulation of his so-called uncertainty principle appeared in a 1927 article,[23] where he considered the measurement of the position of an electron by a microscope, thought experiment known as 'Heisenberg's microscope'. As discussed there, the shorter the wavelength of the light used to illuminate the electron, the more precise the measurement of the electron's position. However, the shorter the light beam's wavelength, the more energetic it is; in this case the Compton effect, that is, the scattering of the light by a charged particle (i.e. an electron), cannot be ignored. The beam

[20] Kantian terminology, *Anschaulichkeit* means 'immediately given to the perceptions'. This German term has no official translation to English, although it has often been translated as 'visualisability'.
Jo Nye, *The Cambridge History of Science*, p. 197.
[21] Stanford Encyclopedia of Philosophy. "The Uncertainty Principle, Heisenberg, Heisenberg's road to the uncertainty relations," accessed 19-01-2017, https://plato.stanford.edu/entries/qt-uncertainty/#Heis
[22] He called it 'the measurement-meaning principle'. It is an operational assumption through which terms like 'position of a particle' only have meaning if one specifies a suitable experiment by which it can be measured.
[23] Wheeler & Zurek, *Quantum Theory and Measurement* (1983)

loses part of its energy during the collision, which is then transferred to the electron, that recoils. Hence, the shorter the wavelength, the larger is the change in the electron's momentum. In Heisenberg's words[24]:

> At the instant of time when the position is determined, that is, at the instant when the photon is scattered by the electron, the electron undergoes a discontinuous change in momentum. This change is the greater the smaller the wavelength of the light employed, i.e., the more exact the determination of the position. At the instant at which the position of the electron is known, its momentum therefore can be known only up to magnitudes which correspond to that discontinuous change; thus, the more precisely the position is determined, the less precisely the momentum is known, and conversely.

He estimated these imprecisions in the electron's position and momentum to be of the order $\delta p \delta q \sim h$. He analysed other experiments, involving other physical quantities, from which he also obtained relations for the pairs energy-time ($\delta p \delta q \sim h$) and action-angle ($\delta w \delta J \sim h$), and re-wrote them using his CCR.

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Although the formal mathematical result of Heisenberg's thought experiment remains valid, the experiment per se was soon afterwards proved wrong by Bohr. The main problem with Heisenberg's presentation of the argument was that it provided an argument for the uncertainty principle on the basis of the principles of classical optics. That is, it started from the assumption that an electron is a classical particle, whose position can be measured by an optical instrument, provided radiation of sufficiently short wave-length is used for illumination. However, as Bohr pointed out in 1927 in his famous *Como lecture*[25] in Italy, in quantum mechanics electrons do not have determinate positions before measurements are performed in order to measure their positions. In "The Quantum Postulate,"[26] Bohr thoroughly described, analysed and commented upon Heisenberg's microscope experiment.

Long before Heisenberg's matrix mechanics and Schrödinger's wave mechanics came out, Bohr had been troubled by the perplexing wave-particle duality: sometimes light exhibited material properties and sometimes particles showed a wave nature. Yet apparently paradoxical, Bohr regarded this bizarre behaviour as a fundamental fact of

[24] Stanford Encyclopedia of Philosophy. "The Uncertainty Principle," accessed 20-01-2017, https://plato.stanford.edu/entries/qt-uncertainty/#Heis
Heisenberg, *Quantum Theory and Measurement* (1983)
[25] The content of what Bohr delivered at the International Congress of Physicists on the Occasion of the Centenary of the Death of Alessandro Volta, held in Como (Italy) in 1927, was captured in his paper 'The Quantum Postulate and the Recent Development of Atomic Theory,' published a few months later, in 1928.
[26] Bohr, "The Quantum Postulate" (1928)

nature. He used Heisenberg's thought experiment as a way of the apparent contradiction that these pictures (wave, particle) refer to an exterior, static physical reality. The essence of the consideration that the position and momentum of the radiation scattered by the electron can be determined with accuracy but then each measurement inevitably alters the precision of the other non-commuting variable, is the inevitability of the quantum postulate in the estimation of the possibilities of measurement.[27] As Bohr insisted, the uncertainty relations were not a manifestation of the limited accuracy of measuring instruments, because they would be valid even if we had perfect measuring instruments.[28] Rather, the consideration mentioned above brought out "the complementary character of the description of atomic phenomena."[29] I was 1927, and Bohr had introduced the term 'complementarity' for the first time in the Como lecture.[30] The first excerpt where complementarity is mentioned goes as follows[31]:

> The very nature of the quantum theory thus forces us to regard the space-time coordination and the claim of causality, the union of which characterises the classical theories, as complementary but exclusive features of the description symbolising the idealisation of observation and definition respectively.

The space-time and dynamical descriptions of phenomena –the latter, description in which the conservation laws for energy and momentum are applicable, was frequently referred to by Bohr as 'causality'– are not contradictory but "complementary pictures of the phenomena, which *only together* offer a natural generalisation of the classical mode of description."[32] This complementarity theory, "the consistency of which can be judged only by weighing *the possibilities of definition and observation,*"[33] is presented to us, in the context of the description of atomic phenomena, the quantum postulate, and was "already clearly brought out by the much-discussed question of the nature of light and the ultimate constituents of nature."[34] There is a vast amount of information contained in the previous quotations, so let us pause for thought. The first thing we acknowledge is that Bohr's complementarity was motivated by the difficulties presented by the wave-particle duality, which under his new framework became a 'wave-particle complementarity'. Second, complementarity did not only allow to account for the wave-particle 'paradox', but it also reconciled space-time coordination (the measurement of

[27] Bohr, "The Quantum Postulate," p. 582.
[28] Plotnitsly, "On the Character of Quantum Law," p. 1131.
[29] Bohr, Óp. cit., p. 584.
[30] The content of what Bohr delivered at the International Congress of Physicists on the Occasion of the Centenary of the Death of Alessandro Volta, held in Como (Italy) in 1927, was captured in his paper 'The Quantum Postulate and the Recent Development of Atomic Theory', published a few months later, in 1928.
[31] Bohr, Óp. cit., p. 580.
[32] Ibid., p. 581.
Italics mine.
[33] Ibid.
Italics mine.
[34] Ibid.

position) and the claim of causality (the measurement of momenta), as well as the conditions for observation and definition.

Bohr introduced several 'types of complementarity', a question to which we shall return in chapter VI. Be it one or many, however, all complementary features or modes of description are characterized as 'mutually exclusive but equally necessary', a characterization of which we shall not lose sight, as well as of the absent hierarchy between 'mutual exclusivity' and 'equal necessity'. In the case of the wave-particle duality, the concept of mutual exclusivity must be understood as the impossibility to visualize in one picture how something can be both a particle with a definite location in space and time and a wave dispersed over space and time. That is, mutual exclusivity should be viewed "vis-à-vis visualization"[35] Following this characterization, equal necessity should be viewed "vis-à-vis conceptualization."[36] Now take the example of the measurement of both the position and the momentum of a particle. Either variable can be measured with full precision (available to us) and be well-defined at any given point. However, under the constraints of the uncertainty relations and complementarity, and in contrast to classical theories, it is impossible to measure the values of both variables with full precision at the same time. That is, the *fully precise measurements* of both particle and momentum are mutually exclusive insofar as we have in mind a *simultaneous joint* measurement *within the same* experimental arrangement. This impossibility prohibits the definition of the state of a physical system as ordinarily understood –this point is central to Bohr's analysis of the Einstein-Podolsky-Rosen argument, which I shall examine in the following chapter. Nonetheless, both concepts are equally necessary to describe the state of the system; causality alone is insufficient, just as space-time coordination is.

Next, note the importance of the concepts of 'measurement' and 'phenomenon'. Wherea, after having read Bohr's works a measurement process can safely be defined as an actualisation of the possibilities of observation and definition, Bohr did not initially use the concept of phenomenon with enough clarity and consistency. In 'The Quantum Postulate'[37], he equated phenomena with the 'object of observation'.[38] It wasn't until his reading of the EPR paper that he included the agency of observation,[39] besides the object, and their mutual interaction.[40] Concisely, for Bohr (that is, post-1935-Bohr) a phenomenon is the result of a physical system S, a preparation apparatus P, a measuring apparatus M and their mutual interaction in a concrete experimental situation.

$$phenomenon = S + P + M + interaction(SP) + interaction(SM)$$

[35] Bala, *Complementarity Beyond Physics*, p. 2.
[36] Bala, Ibid.
[37] Bohr, "The Quantum Postulate and the Recent Development of Atomic Theory" (1928)
[38] Ibid., p. 584.
[39] That is, the instrument, apparatus.
[40] Scheibe, *The Logical Analysis of Quantum Mechanics*, p. 20

As already discussed, in classical physics these interactions between the system and the apparatuses can be disregarded. As a result, the measuring object is endowed with an exteriority capable of accounting for the 'objectivity' of phenomena. In quantum physics, on the contrary, the quantum of action entails both a discontinuity and an unavoidable *entanglement* of the object and the apparatus.[41] Unless we disentangle the quantum state through decoherence[42], there is no way to have information about the object per se.

However, Bohr somehow *saved the object* by turning to another idea, what German philosopher of science Erhard Scheibe (1927-2010)[43] has called 'the buffer postulate' because of its function "to use classical physics as a buffer against the quantum-mechanical treatment of a phenomenon."[44] That is, although the physical system S is quantum-mechanical, the description of the apparatus and the results of observation must be expressed in the language and concepts of classical physics and ordinary life – our only means to describe the world– in order to be accounted for unambiguously. The interaction between parts of the phenomenon is indescribable, but we can, and have to, use classical concepts to describe our experimental set-up and to present the results of our observations. The results of our observations can be seen as an amplification of the quantum phenomena to which we are trying to have access. As we will see in chapter V, Plotnitsky argues that we can talk about the *effects* of quantum-mechanical experiments. Although appeal to classical concepts in interpreting quantum phenomena is indispensable, classical concepts are never sufficient to properly account for them. While certain parts can, and have to, be described classically, classical concepts cannot account for the indivisibility of quantum phenomena and the interaction between quantum objects and measuring instruments[45].

Besides these appreciations, for a theoretical treatment of a quantum phenomenon a decision has to be made as regards which is S and which is M, for there is no fundamental cut between the two, it is just an arbitrary divide dependent on the setup. The result of the combination of the quantum and the buffer postulates is then that the interaction between the 'object' and the 'agencies of observation' cannot be characterized in classical terms, and is therefore non-analysable and not separately accountable. Precisely because of this interaction, descriptions of an object obtained under different measurement arrangements cannot be combined in to one single picture[46]. These interactions arising from different experimental arrangements cannot be subsumed or cancelled. It is their multiplicity that is fundamental to nature.

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[41] See Howard, "What makes a classical concept classical?" (1994) on Bohr's use of classical concepts in terms of *appropriate mixtures* for an account of how joint quantum states can be decomposed, disentangled.

[42] Quantum decoherence is the loss of quantum coherence, a fundamental property of quantum systems. It takes place when a system is not perfectly isolated, and has traditionally been used to explain wave function collapse.

[43] Professor at the university of Heidelberg (Germany), his works discuss the philosophy of physics and the interpretation of quantum mechanics.

[44] Scheibe, *The Logical Analysis of Quantum Mechanics*, p. 24.

[45] Plotnitsky, "On the Character of Quantum Law," pp. 1131-1132.

[46] Dieks, "Foundations of Quantum Mechanics," p. 6.

At this point an issue that necessitates separate analysis is that of the role of the human observer in Bohr's account of the process of measurement. In a sense, Bohr presupposes the prior existence of a human observer in some exterior position, securing the condition for the possibility of *objective* knowledge.[47] In line with his account of phenomena, objectivity equates to the unambiguous communication of the results of reproducible experiments.[48] In his picture, the human observer is the one who decides what kind of setup to build. The experimental arrangement chosen by the experimenter *frames* what we can know about the world, equivalent in this case to what the world is. In this sense, a measurement within a certain experimental arrangement is what gives meaning to our epistemology-ontology. The experimenter is also in charge of reading the recordings of measurements –a reading which she can only do through the use of classical language. Quantum physics' measurements thus entail subjective elements, which enter into the physical considerations by way of their embodiment in apparatuses. Nonetheless, it is important to point out that Bohr's account diverges from the von Neumann-Wigner interpretation of quantum mechanics, which postulates consciousness to be necessary for the completion of the process of quantum measurement. Note as well that here the human is not the traditional subject of Cartesian epistemology, completely detached from the object of study. She influences the measurement, but does not fix its outcome. Similarly, she is in charge of unambiguously communicating the outcome, but since the measurement is subject to an inherent indeterminacy she does not know which will be the exact outcome, but is only aware of the probabilities for different outcomes of pre-specified observations. The human is not the traditional knower of Cartesian epistemology either, in possession of deterministic physical laws.

In Bohr's account of phenomena, the human subject loses its privileged role, and conversely the interactions between measuring systems and agencies of observation gain importance. The fact that he used the terminology 'agencies of observation' to refer to measuring apparatuses indicates some sort of will to demand a change of focus from the experimenter to these interactions within phenomena. We will return to Bohr's view of the role of the experimenter in chapter III when we discuss the dichotomies subject/object and human/non-human in relation to Karen Barad's account of them in Agential Realism.

As a last remark to this introduction to Bohr's thought, I would like to highlight that throughout his writings Bohr continuously speaks of the "failure of the forms of perception adapted to our ordinary sense impressions."[49] In his book *Niels Bohr's Philosophy of Physics* philosopher Dugald Murdoch argues that Bohr's forms of perception of space and time resemble the German philosopher Immanuel Kant's (1724-1804) *Anschauungsformen*, to which Bohr also adds causality: "causality may be

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[47] Barad, *Meeting the Universe Halfway*, p. 169.
[48] I will return to the topics of the role of the language of classical physics and Bohr's account of objectivity in the coming chapter –see chapter II.
[49] Murdoch, *Niels Bohr's philosophy of physics*, p. 72.
Bohr, *Atomic theory and the description of nature,* p. 93.
Bohr, "The Quantum of Action and the Description of Nature," p. 96.

considered as a mode of perception by which we reduce our sense impression to order."[50] For Kant, however, causality was a category, a concept of the understanding rather than a 'form'. It is interesting to note that Kant's influence on Bohr is nonetheless improbable; Murdoch suggests that Bohr's usage of the phrase 'forms of perception' rather derives from Danish philosopher and theologian Harald Høffding (1843-1931)[51], who talked of the 'forms of the understanding', contrary to Kant's use, and labeled causality, continuity, space and time as 'forms'. According to Høffding, the notions of space, time and causality are forms of perception in the sense that whatever is perceptible by means of the senses is presented in space, time and in a causal relation with other objects of perception. The forms of perception are the means by which we organise our perceptual experience; if they break down –as happened with continuity after the introduction of the quantum of action— *Anschaulichkeit* ('visualisability') fails.[52] This failure brings about a linguistic handicap. As soon as the presupposition of continuity no longer applies, ordinary language, designed for our ordinary sensory experience, including the models in terms of which we interpret physical theory, becomes ambiguous, ill-defined.[53] If continuity fails, visualisability, pictoriality fail too, and ambiguity in language cannot be avoided.

Many authors –John Honner, Henry Folse, Jan Faye[54] among them– have criticized Murdoch's reading of Bohr, especially the aforementioned transcendental idealist reading of the Danish physicist,[55] a criticism I share. Nonetheless, one thing is clear: although quantum phenomena cannot be *directly* described along classical lines, in the same way as general relativity theory cannot be formulated with the absolute notions of space and time, these forms of perception –or however we want to refer to 'space' and 'time'– are essential to make sense of the world. However, it is also clear that they need to be understood differently, as Bohr's complementarity points out, a principle which, contrary to what some may think, "does indeed not involve any arbitrary renunciation of customary demands of explanation but aims at an appropriate dialectic expression for the actual conditions of analysis and synthesis in (atomic) physics."[56] In fact, the approach to the problem of explanation that is embodied in the notion of complementarity "suggests itself in our position as conscious beings and recalls forcefully the teaching of ancient thinkers that, in the search for a harmonious attitude towards life, it must never

[50] Bohr, *Atomic Theory and the Description of Nature* (hereafter ATDN), pp. 116-117.
[51] Bohr attended lectures by Harald Høffding during his first year as a student at the University of Copenhagen.
Bohr, *NBCW*, Vol. 10, p. xliii.
[52] Murdoch, *Niels Bohr's philosophy of physics*, pp. 72-73.
[53] Murdoch, Ibid., p. 73.
See for instance Bohr's letter to Dirac from 24-03-1928. Bohr, *NBCW*, vol. VI, pp. 44-46.
[54] Honner, *The Description of Nature* (1987)
Folse, *The Philosophy of Niels Bohr* (1985)
Faye, *Niels Bohr: His Heritage and Legacy* (1991)
[55] Recently Guido pointed me to a memorial book he recently co-edited about the German mathematician and philosopher Grete Hermann. See Crull & Bacciagaluppi's *Grete Hermann –Between Physics and Philosophy* for a fresh neo-Kantian reading of Bohr.
[56] Bohr, "On the notion of Causality and Complementarity," p. 54.

be forgotten that we ourselves are both actors and spectators in the drama of existence."[57] Time and space are not external categories; neither is causality.

As a preliminary conclusion, it seems sound to assert that with his conception of quantum phenomena and complementarity Bohr calls into question the Cartesian belief in the inherent distinction between subject and object, knower and known. There is one wholeness, one whole world that *inter*-acts. Nonetheless, this whole is not composed of complementary parts. Complementarity's conceptual specificity –which is not always respected– requires that an ascertainable part is the only 'whole' at a specific moment of time, and there is no overall wholeness that encompasses these local 'wholes' in the history of the system.[58] The referent of such wholeness changes at every moment of time. Things do not have inherently determinate boundaries or properties, and words do not have inherently determinate meanings.[59] With Bohr's complementarity principle, Cartesian epistemology and its triadic structure of words, knowers and things is put at stake.[60]

[57] Bohr, "Discussion with Einstein," p. 25.
Bohr, "On the notion of Causality and Complementarity," p. 54.
[58] Plotnitsky, "On the Character of Quantum Law," p. 1130.
[59] As Bohr emphasises in "On the notion of Causality and Complementarity," p. 54: "Our task can only be to aim at communicating experiences and views to others by means of language, in which the practical use of every word stands in a complementary relation to attempts of its strict definition."
[60] Barad, "Posthumanist Performativity," p. 813.

Ch. II: The Completeness and Locality of QM
The Nature of the Wave Function
Complementarity Revisited

In this chapter, the idea is to devote some time to the 'EPR' paper and Bohr's reply to it, articles which basically discuss the nature of physical reality, the wave function and the so argued 'completeness' of quantum mechanics. The discussion started by physicists Albert Einstein, Boris Podolsky (1896-1966) and Nathan Rosen (1909-1995) is crucial in many respects, but especially in shaping Bohr's notion of phenomena, as we will soon see. After the presentation of both articles, the divide between the classical and the quantum (macro/micro divide) will be assessed and the role of complementarity revisited. I will also re-examine complementarity more thoroughly in view of Bohr's *after*-1935 papers and connect it to the just mentioned macro/micro discussion.

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In May 1935, Einstein, Podolsky and Rosen (EPR hereafter) presented a paper which has become one of the centerpieces in the debate over the correct interpretation of quantum mechanics. The paper, entitled 'Can Quantum-Mechanical Description of Physical Reality Be Considered Complete?'[61] and often shortly referred to as 'EPR', featured the case of two interacting systems and analyzed the results of their entanglement; determining either position or momentum for one system would respectively fix the position or momentum of the other. According to the authors, this mental experiment threatened both the locality and the completeness of quantum thought. As a matter of historical relevance, the EPR paper was the basis of Bohr's great confrontation with Einstein.

The EPR article starts by pointing at two essential assertions concerning the nature of quantum mechanics. Given that in the case of two physical quantities described by non-commuting operators one precludes the knowledge of the other, then either (1) the description of reality given by the wave function in quantum mechanics is not complete, or (2) these two quantities cannot have simultaneous reality. According to the authors, these assertions are logically connected, for if (1) fails, so does (2). In order to assess them, EPR start by formulating a necessary condition for theoretical completeness, that is, "that every element of the physical reality must have a counterpart in the physical theory."[62] We shall label this 'the condition of completeness'. Although the authors nowhere specify what '(physical) reality' means, a task they deem unnecessary[63], they do offer the following sufficient condition: "if, without in any way disturbing a system, we

[61] EPR, "Can Quantum-Mechanics" (1935)
[62] EPR, Ibid., p. 777.
[63] EPR, Ibid.

can predict with certainty (i.e. with probability equal to unity) the value of a physical quantity, then there exists an element of physical reality corresponding to this physical quantity."[64] This sufficient condition for an 'element of reality' is often referred to as 'the EPR criterion of reality'.

EPR wanted to show that the usual assumption that the wave function does contain a complete description of the physical reality of the system in the state to which it corresponds, together with the criterion of reality, leads to a contradiction.[65] For this purpose, they propounded the following thought experiment: suppose that we have two systems, I and II, which we permit to interact during a time T. Their states before t=0 are known, but after t=T the situation is of a completely different nature. They have been interacting during a time T, so they have become entangled. After T, we separate them widely so that they cannot be said to any longer interact (locality condition, justified by special relativity). Schrödinger's equation allows us to calculate the state of the composite system, but the individual state in which each of the systems is left after the interaction cannot be calculated unless we perform further measurements. This process reduces the wave packet given by an infinite series to a single term –reason why it is called 'reduction of the wave function'. However, since the set of eigenfunctions[66] is determined by the choice of the physical quantity that we want to measure, as a result of two different measurements performed upon system I, system II may be left in states represented by different wave functions. Thus, apparently, it is possible to assign two different wave functions to the same reality.[67]

What happens if these two wave functions are eigenfunctions of two non-commuting operators corresponding to, say, the physical quantities position and momentum (being then the operators P and Q in this case)? We can measure the eigenvalues p or q without in any way disturbing the system, but in accordance with our criterion of reality we must then consider P and Q elements of reality; if we measured the momentum P1 of system I, then we could predict the value of P2 with certainty without disturbing system II. According to the condition of completeness, both P1 and P2 must correspond to elements of physical reality. However, if instead of measuring P1 we measured Q1, we would have the analogous situation to P1 and P2 for Q1 and Q2. Since the systems do not longer interact, then it results that system II must have both elements of physical reality. But this simultaneous assignment of exact position and momentum has no counterpart in the quantum mechanical formalism: there are no wave functions which are simultaneous eigenfunctions of position and momentum.[68] Hence, starting with the assumption that the wave function does give a complete description of reality we are led to the assertion that two physical quantities with non-commuting operators can have simultaneous reality. Thus, the negation of (1) leads to the negation of (2), and we are forced to conclude

[64] EPR, "Can Quantum-Mechanics," p. 777.
[65] EPR, Ibid., p. 778.
[66] Wikipedia. "Eigenfunction," accessed 11-06-2017, https://en.wikipedia.org/wiki/Eigenfunction
[67] EPR, Óp. cit., p. 779.
[68] Dieks, *Foundations of Quantum Mechanics*, pp. 10-11.

that the quantum-mechanical description of physical reality given by the wave functions is not complete.

EPR also advanced a possible way out. The objection is that their criterion of reality is not sufficiently restrictive. If one adopted, for instance, the condition that two or more physical quantities can be regarded as simultaneous elements of reality only when they can be simultaneously measured or predicted, since either one or the other could be measured or predicted at a time, both elements could not be simultaneously real. Nonetheless, EPR replied to the self-raised objection to their argument with the observation that, be it the case, the reality of these quantities would depend upon the process of measurement carried out on the first system, while the system was devised such that this would not disturb the second system. This would lead to the establishment of an *experientially-dependent* criterion of reality, of profound strangeness and dislike to them, but to which Bohr was –as one may advance– evidently sympathetic.

Besides threatening the completeness of quantum mechanics, EPR also seemed to allow the violation of spatial separability (absolute exteriority), often referred to as the locality premise. Apparently, the EPR experiment involved some sort of 'spooky action-at-a-distance'; one could obtain instantaneous information about the state of the other particle with no restriction in the speed of light, so without any speed limit in the transmission of information. For Einstein, spatial separability was the condition of objectivity; spatial separation between observer and observed is what guaranteed their ontological separability and consequently secured the possibility of objectivity.[69] Spatial separability was a condition of objectivity in the strong, metaphysical sense. But, if action-at-a-distance was possible, where did EPR leave us with respect to a presumed objectivity of the physical world? Given that one considers the objections raised by EPR seriously, is there any way to secure a condition for objectivity different from that of absolute exteriority? Let us now move to Bohr's reply to the EPR paper to discuss these and other questions in more detail.

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Bohr begins his reply to the EPR paper by appealing to the inadequacy of EPR's line of argumentation in order to meet the actual situation with which we are faced in atomic physics. To him, physical reality cannot be deduced from a priori philosophical conceptions, but must (quite pragmatically) be founded on a direct appeal to experiments and measurements.[70] Obviously, Bohr disagrees with EPR's criteria of completeness and reality, and therefore does not support the logical connection between completeness and the simultaneous reality of non-commuting variables. Once again, he feverously defends a contextual understanding of the measurements of physical phenomena and, consequently, suggests his complementarity epistemology as the right approach to

[69] Barad, *Meeting the Universe Halfway*, pp. 173-174.
[70] Bohr, "Can Quantum-Mechanics," p. 696.

disclose the nature of physical reality. As a further consequence of these views of physical phenomena and measurement, Bohr understood the wave function as *symbolic*: not a mere tool, but neither a *real* entity. The wave function was something else, something *in between*, which helped the physicist represent certain elements of physical reality, not in the classical sense of representation –since the wave function can only be written once the macroscopic recordings of a phenomenon had been obtained– but still as some sort of instrumentalistic device. Bohr's notion of 'symbolic' is up to the present still unclear, but as said, its meaning undoubtedly lays somewhere in between the two aforementioned interpretations.

The first criticism Bohr raises in his reply is that EPR's criterion of reality is ambiguous when it is applied to "the actual problems with which we are here concerned"[71], namely the atomic phenomena. To show it, he considers two versions of the famous two-slit diffraction or interference experiment. In the first arrangement, that we shall call 'fixed diaphragm two slit experiment', the solid parts of the apparatus, serving as diaphragms and plate-holder, are firmly bolted to a common support. In the second setup, the 'movable diaphragm two slit experiment', a modification of the original experiment, the top slit is attached by springs to the support and the bottom slit is attached to the frame.

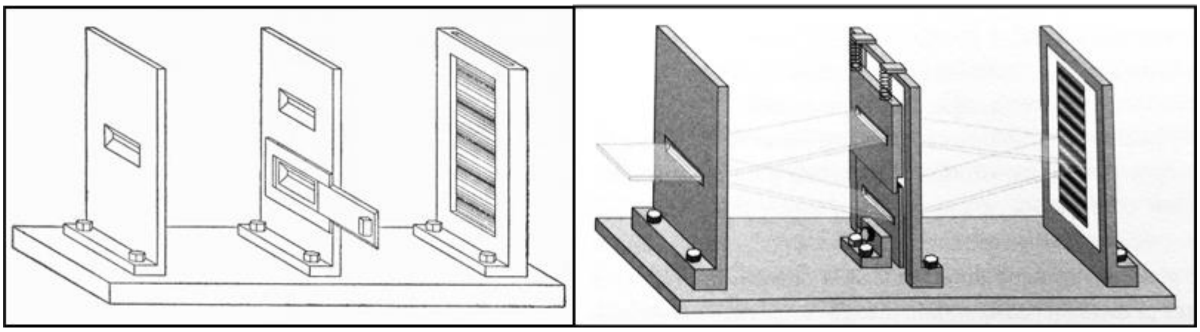

Fig. 1*:* On the left, fixed diaphragm two slit experiment, picture taken from Bohr, "Discussion with Einstein," p. 13. On the right, movable diaphragm two slit experiment, taken from Barad, *Meeting the Universe Halfway*, p. 82

The principal difference between the two experimental arrangements is that what is considered the measuring instrument and what is considered the object changes depending on the setup. As already discussed in the previous chapter, it is crucial to discriminate in each measuring procedure between those parts of the physical system treated as measuring instruments and those which constitute objects under investigation. This is a significant yet –again– contextual, relative distinction. Through these two examples, Bohr wants to remark the futility of incorporating simultaneity in the condition of completeness of the quantum description. There is an inherent indivisibility in the quantum phenomena that does not allow to make simultaneous measurements. Since there is no inherent distinction between object and instrument, the

[71] Bohr, "Can Quantum-Mechanics," p. 697.

measurement value is neither attributable to an observation-independent object nor it is a property created by the act of measurement. Therefore, the values obtained in measurements can be said to somehow *emerge*[72] during the measurement process; in this sense it is measurement, the interplay between the components of a given phenomenon itself, that gives meaning to what we can know and say about the world.

After this first more descriptive examination of the experiments, Bohr moves on to a more philosophical analysis of the measuring procedure and its implications, for which he has two main arguments. First, he asserts that EPR's criterion of reality is ambiguous as regards the meaning of the expression: "without in any way disturbing the system". Although he agrees with EPR that there is no mechanical disturbance during the last critical stage of the measuring procedure, he remarks that there is *an influence* on the very conditions which define the possible types of predictions regarding the future behaviour of the system.[73] Bohr wants to emphasise that "in the phenomena concerned we are not dealing with an incomplete description characterized by the arbitrary picking out of different elements of physical reality at the cost of sacrifying [sic] other such elements, but with a rational discrimination between essentially different experimental arrangements and procedures which are suited either for an unambiguous use of the idea of space location, or for a legitimate application of the conservation theorem of momentum."[74] Quantum mechanical descriptions are as complete as they can be under the available experimental, technological, and theoretical conditions involved in any quantum experiment. Second, he propounds complementarity as a viewpoint that allows quantum mechanics to fulfill all rational demands of completeness; the renunciation of the one or the other of two aspects of the description of physical phenomena depends on the impossibility of accurately controlling the reaction of the object on the measuring instruments and consequently defining these quantities in an unambiguous way. Appealing to atomic physics, Bohr insists that the mutually exclusive character of the concepts of position and momentum in quantum theory *entails* the complementary relationship between any detailed time account of atomic phenomena and unclassical features of decaying atoms.[75] Hence, complementarity –the word itself suggests a degree of completeness of descriptions, as Plotnitsky points out[76]– appears as a unique and necessary approach to this novel feature of natural phenomena.

Closely related to the aforementioned examination of the experimental conditions and the necessary complementarity epistemology, in 'Discussion with Einstein on epistemological problems in atomic physics'[77] Bohr recalls the transcendental role the notion of 'phenomena' plays. He insists on the application of the word 'phenomenon' exclusively to refer to the observations obtained under specified circumstances, including

[72] Emergence here should be read as emphasising the fact that we cannot attribute a value to the position or momentum of a particle before a measurement has been carried out.
[73] Bohr, "Can Quantum-Mechanics," p. 700.
[74] Bohr, Ibid., p. 699.
[75] Bohr, Ibid., p. 701.
[76] Plotnitsky, *Reconfigurations: critical theory and general economy*, p. 13.
[77] Bohr, "Discussion with Einstein" (1949)

an account of the whole experimental arrangement.[78] That is, after 1935 Bohr starts including the interaction between the system and the agencies of observation in his account of phenomena; 'phenomena' is from then on used to designate particular instances of wholeness.[79] As seen in the previous chapter, the interaction that occurs between apparatuses and objects during a measurement process is unanalysable. Therefore, as also said, our only means to have access to the phenomenon is confined to the recordings of observations such as marks on a photographic plate or marks of water drops around ions in a Wilson cloud-chamber.[80] We can only unambiguously describe quantum phenomena through their irreversible amplification effects; an unambiguous description of physical phenomena can only be given when the element which is foreign to the classical theories, that is, the quantum of action, can be disregarded, when we can use the language of classical physics. Here we have a hint of Bohr's clearly post-Newtonian –contrarily to Einstein's very classical spatial separability– notion of objectivity: 'objective' means reproducible and unambiguously communicable, in the sense that "permanent marks… [are] left on bodies which define the experimental conditions."[81] In relation to reproducibility, objectivity is thus enclosed in the traces left in the experiential world, and closely linked to the processes of experimenting and measuring. As regards communicability, objectivity can only be attained as long as we use a language we all understand –thus reinforcing the social nature of scientific practice.[82]

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Bohr's subsequent papers of 1937, 1939 and 1948[83] analyse the implications of the quantum postulate and complementarity in atomic physics more thoroughly. Especially he recurrently emphasises the idea that quantum mechanics should be seen as a natural or rational generalization of the classical theories, as well as a "more general [and comprehensive] viewpoint"[84] used to replace the ideal of causality –or the "usual so-called visualization."[85] It is this line of argumentation that quantum theory is a rational generalization of classical theories that led to the formulation of the so-called correspondence theory.[86] With regard to the notion of 'correspondence', classical theories

[78] Bohr, "Discussion with Einstein," p. 26.
[79] Barad, "Meeting: Realism and Social Constructivism," p. 170.
[80] Bohr, Óp. cit., p. 16.
[81] Barad, "Meeting: Realism and Social Constructivism," p. 172
[82] See Longino's "Values and Objectivity" for a more detailed argument defending the objectivity of science as secured by the social character of inquiry.
[83] Bohr, "Causality and Complementarity"' (1937)
Bohr, "The causality problem in atomic physics" (1939)
Bohr, "On the Notions of Causality and Complementarity" (1950). The paper was originally published in 1948, but I could only find the 1950's version.
[84] Bohr, "Causality and Complementarity," p. 291.
Emphasis mine, although the adjective 'comprehensive' was part of quotation 23.
[85] Bohr, Ibid., p. 294.
[86] In coining such an expression, Bohr might have been aware of Kant's agenda to delimit the realm within which the concept of causality makes sense.
Bohr, "The Quantum Postulate," p. 584.

are for Bohr approximations in the sense that they hold under the ideal assumptions of the infinitely large value of the velocity of light and the infinitely small value of the quantum of action.[87] However, that's it: they are approximate theories. As hinted in a footnote of last chapter's concluding remarks, German mathematician and philosopher Grete Hermann (1901-1984) provided an interesting Kantian interpretation of Bohr' correspondence principle. In Hermann's understanding, the correspondence principle becomes a means to bridge the gap between data of sensation and the formal statements of the theory, between intuitive classical concepts and unintuitive quantum mechanical concepts,[88] similarly to the way that Kant's symbolic mode of *Darstellung* (representation) works.[89] In this case classical concepts serve to interpret the quantum data of experience. Despite recognising the limitation of our forms of perception, it by no means implies that we can dispense with our customary ideas or their verbal expressions when we try to order our sense impressions. Nonetheless, as Bohr says "[the] hopes of avoiding the essentially statistical character of quantum mechanical description by the assumption of some causal mechanism underlying the atomic phenomena and hitherto inaccessible to observation would indeed seem to be as vain as any project of doing justice to the increased profundity of the picture of the world achieved by the general theory of relativity by means of the ordinary conceptions of absolute space and time"[90]. Note that he wittingly referred to Einstein in order to catch people's attention. In light of the above quote he seemed to truly believe that a renunciation of causality alone was as necessary as a renunciation of absolute notions of space and time, abandonments which would increase the profundity of the picture of the world –he was not only putting at stake causality within physics, but also within the metaphysics behind it. Nonetheless, what was Bohr's position towards the symbolism of quantum mechanics, as said, remains unclear.

As a last point, I would like to investigate the relationship between the post-Heisenberg's cut between the 'micro' and the 'macro' world. Taking into consideration his view of classical theories as only approximations that hold under ideal conditions and his view of knowledge as a unified whole, I have come to read Bohr as a quantum fundamentalist. Quantum fundamentalism, the prevailing position today within the physics community due to mesoscopic or macroscopic quantum experiments such as SQUIDS, gravity wave detectors, Josephson junctions or buckyballs, defends an understanding of the world as fundamentally quantum. In such understanding, all phenomena are subject to quantum indeterminacy and, therefore, the divide between micro/macro becomes meaningless, it is only artificial. These labels are used to deal with the complexity we encounter. At scales higher than the quantum of action, this indeterminacy gets masked by higher-scale regularities and behaviours. It is tempting to succumb to the belief that this divide is fundamental, but we should not forget that this 'loss of sight' of h is only an effect of the complexity that characterizes our world –of which

[87] Murdoch, *Niels Bohr's philosophy of physics*, p. 42.
[88] Crull & Bacciagaluppi, *Grete Hermann-Between Physics and Philosophy*, p. 157.
[89] Crull & Bacciagaluppi, Ibid., p. 156.
[90] Bohr, "Causality and Complementarity," p. 294.

we are part. I will engage in a more thorough discussion of this divide in chapter IV, where I study complex systems in the natural and social sciences in relation to Karen Barad's notion of time and temporality.

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This contesting of Cartesian or quasi-Cartesian divides resulting from Bohr's ideas bear some resemblance to the postmodernist project. Interestingly enough, a few scholars have seen in Bohr either a support or a starting point for their own epistemological/ontological/(ethical) projects. These are physicist and gender theorist Karen Barad's, proponent of Agential Realism, and mathematician and literary studies scholar Arkady Plotnitsky, who has an anti-epistemological view of Bohr's complementarity. While Plotnitsky basically uses concepts from Continental philosophy –Georges Bataille's general economy and Derrida's deconstructive economy–Barad puts forth her own theory which, rather than deploying complementarity, focuses on re-working the notion of causality on the basis of her innovative concept of *intra*-action. What is interesting about these two most full-fledged attempts to articulate a postmodern interpretation of complementarity is that they go beyond the Realism and Antirealism (Scientific Realism-Social Constructivism) debates that characterized the science wars of the 1990s, and in that sense they at the same time exceed postmodernism. Let me clarify that I do not use 'postmodernism' here in a general cultural sense; rather, its usage is theoretical. My interest is the status of postmodern knowledge, that which is sceptical of grand narratives and metanarratives. I believe this moving away from unification and categorisation should let us assess Bohr's ideas within a more flexible theoretical scheme.

Ch. III. Intra-actions from *within*
Matter comes to Matter
Knowing *in* Being

Karen Barad's Agential Realism[91] is a theory contained in what nowadays in feminist epistemology is called 'New Materialisms'. New Materialisms are a bunch of critiques emerging across the humanities and social sciences that demand new relations between the social and the natural, the cultural and the natural, as well as a posthumanist conception of matter as lively or exhibiting agency.[92] Contrary to previous feminist theories such as standpoint theory, New Materialisms do not only place humans in the world as if they were external to it, but study the ways humans produce, reproduce and consume the material world they are part of. What is in the world and what we know about things-in-the-world are constantly shaping each other. Thus, for new materialists, ontology and epistemology should not be conceived separately; their separation is only a reverberation of a metaphysics that assumes an inherent difference between human and non-human, subject and object, mind and body, matter and discourse.[93]

In this fashion, Barad defines her AR as a framework which is supposed to provide an understanding of the co-shaping role of the human and non-human, material and discursive, and knower and known. In opposition to Bohr, whom according to Barad does not explore the crucial ontological dimensions of his insights but rather focuses on their epistemological import, Barad's goal is to develop a full epistemological-ontological-ethical position. In order to do that, Barad takes Bohr's physics-philosophy[94], which involves a detailed examination of observation and measurement processes, as a fruitful starting point."[95] Crucially, she borrows from him the notion of 'phenomena', which will become the epistemic units and building blocks of reality, the *things-in-phenomena* in her AR. As we will further on see at great length, this change of referentiability is what secures a condition for objectivity. Barad also reads Bohr's physics-philosophy as an argument for the necessity of including practice within theory, something scholars Sharon Traweek,[96] Peter Galison (1955-) and Andrew Pickering (1948-) have been long defending in their sociology of science analyses of high-energy physics.[97] As it will become

[91] Hereafter referred to as AR.
[92] Coole & Frost. *New Materialisms: Ontology, Agency, and Politics* (2010)
[93] Barad, "Posthumanist Performativity," p. 829.
Here it must be remembered that since the work of the French philosopher Simone de Beauvoir (1908-1986), all binary oppositions are deemed 'gendered' by feminist theorists and hence in need of both unpacking and change. See De Beauvoir, *The Second Sex* [1949] (2010).
[94] Barad's term. She sees Bohr's work as having physical and metaphysical consequences, none derivable form the other. She calls it physics-philosophy to emphasise this absence of hierarchy between the two bodies of knowledge.
[95] Barad, "Meeting the Universe Halfway," p. 166.
[96] I have tried to provide all the sets of dates but, unfortunately, in a few cases it has not been posible.
[97] Traweek, *Bedtimes and lifetimes: the world of high energy physicists* (1988)
Galison, *How experiments end* (1987)
Pickering, A. *Constructing quarks: a sociological history of particle physics* (1984)

clear once we dwell on Barad's theory in more detail, being is threaded through with mattering (from 'to matter'). This is why epistemology, ontology and ethics are inseparable; an inseparability that makes for a world that is always already an ethical matter. Within AR, ethics should not be viewed as a concern we add to the questions of matter, but rather as the very nature of what it means to matter.[98] Yet aware of this unity, given our research's direction and length's constraints of a thesis, I will mostly focus on onto-epistemological questions. As I will explain in the conclusions section, the present thesis could also be seen as a proto-research for further ethical study of how scientific research sensitive to the category of 'gender' should ideally be conducted. For now, as said, due to scope restrictions, I will assess AR's onto-epistemological demands.

Finally, AR is an account of technoscientific[99] and other practices that take feminist, anti-racist, poststructuralist, queer, Marxist, science studies and scientific insights seriously, building on important insights from, on one side, contemporary theorists such as Judith Butler (1956-), Michel Foucault (1926-1984) or Donna Haraway (1944-), and on the other, as said, physicist Niels Bohr.[100]

Before we exhaustively immerse ourselves in Barad's AR, let us first examine its structure, which is the following:[101]

Relational ontology → *Posthumanist performativity* → *Re-thinking of materiality*

In the first place, AR is a relational ontology because it claims that what distinguishes subject from object are mutual relations rather than substance. The relations between entities, be them any kind of entities, are ontologically more fundamental than the entities themselves.[102] That is, in AR *relata* follow relations: the entanglement of beings precedes their separate existence as individuals. The world is thus a relational (entangled) structure rather than a set of pre-existent or autonomous individuals, human and non-human. In this way, agencies are only distinct from each other in a relational, not an absolute sense –that is, agencies are only distinct from each other insofar as they are part of different entanglements. Clearly, a relational ontology is then a critique of Representationalism. In order to explain why, Barad turns to philosopher Ian Hacking's (1935-) Entity Realism, which defies the belief in the objective truth of schemes of representation and explanation (scientific theories) and instead asserts the independent existence of objects, said to be real when used to experientially 'intervene' in the world. That is, in Baradian language, Hacking's view of experimenting and theorising practices is one of dynamic practices that play a co-constitutive role in the production of objects

[98] Dolphijn & Van der Tuin, *New Materialism*, pp. 69-70.
[99] In this chapter we will use 'technoscience' as defined by Gaston Bachelard in *Le matérialisme ratinonel* (1953).
That is, technoscience here refers to the technological and social context of science –scientific knowledge is not only socially coded and historically situated, but sustained and made durable by material networks.
[100] Barad, "Posthumanist Performativity," p. 811.
[101] Barad, Ibid., p. 814.
[102] Wildman, *An Introduction to Relational Ontology*, p. 1.

and subjects and matter and meaning. Nonetheless, Barad introduces a distinction in the following respect: theorising and experimenting should not be about intervening –which implies a sense of 'outside'– but about *intra-acting from within*. This notion of 'intra-action' is the central pillar of the intricate theoretical apparatus of her AR. Finally, I would like to emphasise that a relational ontology is a precondition of a posthumanist performative account[103] of bodies, which is precisely what enables the shift of focus from linguistic representation to discursive practices.[104] This shift will also allow us to re-think the notions of matter, materiality and materialization, and will hopefully become evident as we engage in Barad's theorising of discursive practices, matter, agency and the like. As presented, AR entails a reworking of the notions of discursive practices, materialization, agency, knowing, objectivity and causality, among others.[105] We are now in the position to, slowly but steadily, go deep into these concepts which articulate the scaffolding of AR. Nonetheless, do not expect a beautiful logical introduction, since linearity is not a party in this story. Do not expect either to be taken by the hand, since passivity is neither. As Barad would suggest, do immerse yourself in the narrative and read *with* the text and *with* me.[106]

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The first set of ideas we will examine are the philosophical position of Representationalism, performativity and discursive practices. Representationalism, also known as Indirect Realism or Epistemological Dualism, takes the Cartesian divide of the world into words and things as its starting point. It is a foundational divide; in Representationalism the world exists independently of the human mind. That is, theories of representation foreground the thinking human, the subject, over the material and make distinctions between subjects and objects. Consequently, it has been significantly criticised by mainly feminist, poststructuralist, postcolonial and queer theorists who have risen awareness about the power dimension of such seemingly neutral foundational divides (who can speak, who can be objectified?).[107] Concerning science more specifically, as said, it was Hacking's 1983 *Representing and Intervening*[108] that first begged questions about the limitations of representationalist thinking, immediately followed by Andrew Pickering's ideas on the symbiosis between experimental practices and natural phenomena –so against 'putting the phenomena first'. Later, philosopher of science and science studies scholar Joseph Rouse (1952-)[109] thoroughly criticised Representationalism, calling it 'a Cartesian by-product', a consequence of the division

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[103] Posthumanism not understood in a sense of 'after humans' but as ousting humans from their privileged position.
[104] Barad, "Posthumanist Performativity," p. 807.
[105] Barad, Ibid., p 811.
[106] Barad employs a diffractive reading of texts, a concept that will be briefly defined later in this chapter.
[107] See Roof & Wiegman, *Who Can Speak?* (1995)
[108] Hacking, *Representing and Intervening* (1983)
[109] Rouse, *Engaging Science: How to Understand Its Practices Philosophically* (1996)

between 'internal' and 'external' that breaks along the line of the knowing subject.[110] As said in the introductory section of this thesis, Representationalism, seen as the traditional way of producing scientific knowledge, breaks the world down into objects, representations and knowers that produce knowledge;[111] that is, it takes for granted the idea that representations reflect reality and it situates the knower back *in* the world – but always at a certain distance *from* it. The knower is the sole active agent in this process, the agent that unidirectionally conducts and shapes the research in question. However, *realness* does not necessarily imply *thingness*. It is clear that Barad is not a realist in the representationalist sense. Hers is a Realism that, in her own words, "is not about representations of an independent reality but about the real consequences, interventions, creative possibilities, and responsibilities of intra-acting within and as part of the world."[112] There is no room for Representationalism's dualism in her account. By emphasizing the power of discursive practices, performativity is the tool that allows us to eliminate it. Performative approaches in cultural, feminist, multicultural, antiracist science projects and science studies –these being the knots of the process of making sense of the worlds of technoscience[113]– have been prompted by the search for fruitful alternatives to Social Constructivism and Scientific Realism, both imbued with representationalist traces. As Rouse pointed out, although they differ in the referent –in Scientific Realism scientific knowledge represents things in the world as they really are (i.e., 'nature), in Social Constructivism it represents it as the product of social activities (i.e. 'culture') – both subscribe to the belief that scientific knowledge mediates our access to the material world.[114] In philosophy and gender studies, some theorists, notably Derrida, Butler, and later on Haraway, have argued that even commonplace communication and speech acts are performative, in that they serve to define and maintain identity. In this way, performativity reverses the idea that an identity is the source of more secondary actions such as speech and gestures and enquires into the construction of identities as they are caused by performative actions, behaviours, and gestures. It is this political historicity that Barad borrows from the poststructuralist understanding of performativity and unites with Pickering's use of the word, which embraces non-human entities. In this line, Barad propounds a posthumanist notion of performativity that aims at getting rid of the supremacy of 'the human' and incorporate material/discursive, social/scientific, human/nonhuman, natural/cultural factors, non-dualistically defined.

Let me now discuss discursive practices more specifically. According to Foucault, discursive practices are defined as ways of constituting knowledges,[115] the local sociohistorical material conditions that enable and constrain disciplinary knowledge

[110] This rejection of the Cartesian distinction is precisely the reason why Barad can be considered an ally of the object-oriented philosophy variant of Speculative Realism, although not a supporter of other forms of the latter.
[111] Barad, *Meeting the Universe Halfway*, p. 86.
[112] Barad, Ibid., p. 37.
[113] Haraway, 'A Game of Cat's Cradle' (1994)
[114] Orr, *Belief, Bodies, and Being,* p. 14.
[115] Remember that for Foucault, knowledge and power are inextricably connected.

practices such as speaking, writing, thinking, calculating, measuring, filtering, and concentrating. That is, discursive practices constrain and enable what can be said, they define what counts as meaningful statements.[116] Discursive practices produce, rather than merely describe, the 'subjects' and 'objects' of knowledge practices. Barad makes use of a Foucaultian notion of discourse, which she implements in her AR. As introduced by her, "discursive practices are specific material (re)configurings of the world through which local determinations of boundaries, properties, and meanings are differentially enacted within the phenomenon produced. Discursive practices are causal intra-actions –they enact local causal structures through which one 'component' (the 'effect') of the phenomenon is marked by another 'component' (the 'cause') in their differential articulation."[117] This is a very complete yet complicated definition, worth dissecting in shorter statements. Let us try to do that. To begin with: discursive practices are specific material (re)configurings of the world. That is, discursive practices are already material, which consequently means that matter is not prior to discourse, but always already discursive. The world is material, and so is everything that is part of it, even our ways of constituting knowledge. At the same time, the world is constantly becoming, and we are becoming-*with* it, hence the 'reconfigurings'. Through these reconfigurings of the world local causal structures are differentially enacted. Both 'locality' and 'causality' are very important terms in the previous sentence, but let us continue with our articulation of AR and return to them after I have introduced 'materialization' processes.

As noted, performativity is deeply intertwined with matter. Butler's account of 'materialization' and Haraway's notion of 'materialized refiguration' suggest such a performative understanding of matter. Butler elaborates Derrida's notion of performativity through Foucault's understanding of the productive effects of regulatory power in theorising the notion of identity performatively.[118] It is in *Bodies That Matter*[119] that Butler argues for a linkage between gender performativity and the materialization of sexed bodies. There, she presents matter as a process of materialization that stabilizes over time to produce the (illusory) effect of boundary, fixity and surface.[120] Materialization is a process of sedimentation, a kind of citationality, "the acquisition of being through the citing of power, a citing that establishes an originary complicity with power in the formation of the *I*."[121] Reworking the notion of matter as a process of materialization brings to the fore the importance of recognising matter in its historicity. At the same time, it challenges Representationalism's construal of matter as a passive blank slate awaiting the active inscription of culture and the representationalist positioning of the relationship between materiality and discourse as one of absolute exteriority.[122] In Butler's understanding, to be material means to materialize, where the principle of that materialization is precisely the very intelligibility of the body. In this

[116] Barad, *Meeting the Universe*, p. 148.
[117] Barad, Ibid., pp. 148-149.
[118] Barad, "Posthumanist Performativity," p. 808.
[119] Butler, *Bodies that Matter* (2011)
[120] Butler, Ibid., p. xviii.
[121] Butler, Ibid., p. xxiii.
[122] Barad, Óp. cit., pp. 821-822.

sense, to know the significance of something "is to know how and why it matters, where *to matter* means at once *to materialize* and *to mean*."[123] That is how matter *comes to matter*, how matter makes itself felt.[124] Similarly, Haraway demands a reworking of matter as a process of materialization through her notion of 'materialized refiguration'. As defined by her in 'A Game of Cat's Cradle'[125], "the point is to refigure what counts as knowledge in the interests of reconstituting the generative forces of embodiment"[126], where 'to refigure' means "to trope and knot together"[127] –to give a new meaning or use by placement in this cat's cradle. Basically, Haraway urges an implosion of metaphor and materiality in the culturally specific apparatuses of bodily production, a *thinking-together* of the material, discursive and linguistic. Even though Barad takes on Butler's and Haraways's ideas on matter and materialization, there are some points of divergence, especially between Butler's and Barad's accounts –as concerns Haraway, who can be considered one of the precursors of the new (feminist) materialist turn, not much more can be added; Barad basically elaborates on her ideas. Hence, let me now briefly clarify the dissimilarities between Butler and Barad. First, AR's relational ontology provides an understanding of materialization that goes beyond the anthropocentric limitation of Butler's theory –not only human but also non-human bodies materialize. Second, Barad defends that in an AR account matter has dynamism, contrary to Butler's theory, which ultimately re-inscribes matter as a passive product of regulatory power and discursive practices rather than as an active agent participating in the very process of materialization.[128] Matter does not refer to a fixed substance; rather, matter is a substance in its intra-active becoming –not a thing, but a doing, a congealing of agency. Matter is a stabilizing process of iterative intra-activity, and phenomena precisely come to matter through this process of ongoing intra-activity. 'Matter' does not refer to an inherent, fixed property of abstract, independently existent objects; rather 'matter' refers to phenomena in their ongoing materialization,[129] where materialization ('to matter') is never a closed process, but a radically open one. Matter is never a sealed matter.[130]

This conceptualisation of matter allows to address the relationship between technoscientific practices and human –and non-human– bodies. Discursive practices and material phenomena do not stand in a relationship of externality to each other; rather, "the material and the discursive are mutually implicated in the dynamics of intra-activity."[131] This is why the discursive is already material, and the material already discursive. This is why all bodies, human and non-human, come to matter through the world's iterative intra-activity, the world's performativity. Matter(ing) is a dynamic

[123] Butler, *Bodies that Matter*, p. 7.
[124] Expressions Barad uses in Dolphijn's and van der Tuin's *New Materialism*.
[125] Haraway, "A Game of Cat's Cradle" (1994)
[126] Haraway, Ibid., p. 61.
[127] Haraway, Ibid., p. 60.
[128] Barad, "Posthumanist Performativity," pp. 821-822. In the same article, Barad makes the same comment about Foucault.
[129] Barad, *Meeting the Universe Halfway,* p. 151.
[130] Barad, "On touching," p. 7.
[131] Barad, Óp. cit., p. 152.

articulation of the world.[132] Hence, Barad contends that naïve Empiricism is not the only option left for matter's conceptualisation:[133] AR offers a portrayal of matter neither as a passive surface awaiting to be endowed with meaning by culture (such as in the sex-gender discussion), nor the end product of cultural performances. In this sense, AR rises as a promising reconciliation of the contentious nature-culture divide.[134]

As seen, both human and non-human bodies materialize. Agency serves as a link to materialization –the reason why I suspect Barad keeps the word. Nonetheless, in her AR agency is not aligned with human intentionality or subjectivity. There are no human agents who have agency or grant agency to non-humans. Agency is not held; it is not a property of persons or things. Rather, "it is an enactment, a matter of possibilities for reconfiguring entanglements."[135] It is about the possibilities of mutual response, of worldly reconfigurings.[136] Once more, agency is a matter of intra-acting. Barad found inspiration in Bohr's phrase 'agencies of observation' to delineate her notion of 'agency'. Nonetheless, Bohr used it to refer to the measuring instruments, while 'agents' for Barad refer to any kind of body –human and non-human. Also, the role the (human) observer plays is different for Bohr and Barad. While in Barad humans and non-humans are on the same causal plane, Bohr did not attribute any ontological significance to the observer during the *actual* measurement process. Still, in Bohr's account the human observer is the one who chooses an appropriate apparatus for the investigation in question and notes down the results after measurements have been performed. Hence, quantum physics' measurements do entail subjective elements, which enter into the physical considerations by way of their embodiment in apparatuses. Barad is worried about this last part and its implication that the very possibility of objectivity of science is put at stake. Of course, she is presupposing a different definition of objectivity than Bohr's –agential separability, a concept which I will shortly introduce.

What she proposes is to move away from Bohr's "epistemic human-based"[137] notion of objectivity to her posthumanist account of objectivity, which is posthumanist in the sense that it establishes a horizontal relationship among human and non-human bodies. Everything materializes, human and non-human bodies alike. AR completely blurs the distinction between subject and object. Then, the subsequent question is: what is the role of the 'human' in Barad's theory? The human, as well as the non-human, has a constitutive role, as in *it is part* of the phenomena. Unavoidably, this answer should not satisfy us, for even if it solves certain epistemological-ontological problems, it creates new ones. What should we do with free will, subjectivity, responsibility? In an AR account,

[132] Barad, *Meeting the Universe Halfway,* p. 151.
[133] Barad, "Posthumanist Performativity," pp. 827.
[134] In Western philosophical discussions, nature and culture have often been portrayed as dichotomous irreconcilable domains. For feminists this has meant that nature was passive (feminized) and culture active (masculinized).
See Lloyd & Genevieve. *The Man of Reason* [1984] (1993)
[135] Dolphijn & Van der Tuin, *New Materialism*, p. 54.
[136] Dolphijn & Van der Tuin, Ibid., p. 55.
[137] Barad, *Meeting the Universe Halfway*, p. 173.

they need to be re-defined. Subjectivity is no longer an attribute of the thinking human. Therefore, questions about free will framed within the traditional dichotomies render obsolete. Subjectivity is about *accountability*. We, human and non-human, are all agents, so we are subjective beings insofar as we are aware of our entanglement with everything else. Responsibility is again accountability, awareness of these entanglements, these connections and our commitments to them. In Barad's words, we, 'we all', not only 'we humans', "are always already responsible to the others with whom or which we are entangled, not through conscious intent but through the various ontological entanglements that materiality entails."[138] Therefore, ethics should not be viewed as an external framework we impose upon matter, but as "responsibility and accountability for the lively relationalities of becoming of which we are part."[139]

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Nonetheless, back to phenomena, Bohr and Barad coincide when it comes to defining apparatuses. In Barad's eyes, Bohr succeeded in conferring agency to devices by proposing contextual divides between parts of the setup and treated apparatuses as material-discursive practices, to use Harawayian/Baradian, where concepts like 'particle' or 'wave' can only become intelligible through specific material arrangements. Similarly, in an AR view apparatuses are themselves phenomena, specific material-discursive practices, dynamic reconfigurings of the world, agential (open-ended) practices, intra-actions through which specific exclusionary boundaries are enacted.[140] Apparatuses are also boundary-making practices that are formative of matter and meaning, productive and part of the phenomena produced.[141] It is precisely in this last point where Foucault's influence on Barad manifests most evidently.

Turning now more specifically to how intra-actions work: intra-actions enact agential cuts –different from Cartesian cuts[142]– that effect local separations between subjects and objects, where 'local' here means *within* phenomena. Crucially, intra-actions enact agential separability within phenomena. Agential separability does not lead to subjective knowledge: this agential separability is a local condition of exteriority, some sort of exteriority-*within* which replaces the classical notion of absolute exteriority and becomes our new condition of objectivity, foundered on a shift in referentiability toward phenomena. The agential cut enacts a local causal structure among 'components' of a phenomenon in the marking of causes and effects.[143] However, these causes and effects differentially make themselves intelligible to each other, they *emerge*; causality is in

[138] Barad, *Meeting the Universe Halfway*, p. 393.
[139] Barad, Ibid., p. 393.
[140] Barad, "Posthumanist performativity," p. 820.
[141] Barad, Óp. cit., p. 146.
[142] The inherent distinction between subject and object.
[143] Barad, "Posthumanist Performativity," p. 815. The original quote goes "in the marking of the 'measuring agencies' ('effect') by the 'measured object' ('cause')". I deem this sentence confusing, since it gives the impression that measuring agencies should always be understood as the effects of measured objects (causes), completely missing the point for which she is arguing: that causes and effects are differentially enacted.

Barad's sense of a non-linear kind. It is equally important to acknowledge that the agential cut is a constructed/agentially positioned/movable/local/Bohrian divide.[144] Barad often uses the famous example of the two-slit experiment[145] to show how an agential cut works, but for the sake of simplicity we will now focus on the case of light scattered by a particle.

In this scenario, the scattered light may be directed towards a photographic plate rigidly fixed in the laboratory and used to record the position. Alternatively, the light might be directed towards a piece of equipment with movable parts used to record the momentum of the scattered light. While in the first case the light is part of the measuring apparatus, in the latter the light's momentum is being measured, so it is treated as part of the object in question.[146] Each of the setups affords a specific constructed cut which serves to define 'object' and 'agencies of observation' in a particular context. Each of the setups affords the configuration of a particular instance of wholeness, a particular phenomenon. Moral: these re-workings of both the traditional notions of causality and objectivity are possible due to the two basic ingredients of intra-actions and the use of phenomena as epistemic(-ontological) referents. It is in the context of the analysis of this condition of objectivity that we 1) feel its extremely Bohrian inspiration 2) grasp the posthumanist sense of AR's performativity and 3) better understand AR's place within New Materialisms. Under the condition of agential separability the human does not stand in a relation of exteriority to the natural world; there is no exterior observational point of view. Humans are not outside observers of the world. Humans do not have any kind of supremacy. Rather, we are part of that nature that we seek to understand. We are part of the "world-body space in its dynamic structuration." [147] That is, a full-blown posthuman perspective.

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As an onto-epistemology, AR invites us to think in terms of processes of entanglements, processes of an ongoing co-constitutive co-existence of all kinds of bodies. We are part of the world-body space in its dynamic structuration, which entails that practices of knowing cannot be about locating ourselves in any perspective; rather, they can only be about knowing *in* being. Becoming and knowing are understood as in a state of interdependence. As previously explained, knowing is material-discursive intra-activity, a matter of enacting agential cuts through which a part of the world makes itself intelligible to another. Let us exemplify it with Dutch science studies scholar Annemarie Mol's (1958-) beautiful case study of 'the I who eats an apple' as a contribution to theorising subjectivities:[148] we grab and approximate an apple to our mouth. The apple

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[144] Barad, "Meeting the Universe Halfway," p. 171.
[145] See Ch. II, p. 20 for a brief explanation of the two-slit experiment.
[146] Barad, Ibid., p. 171.
[147] Barad, *Meeting the Universe Halfway*, pp. 184-185.
[148] Hillevi, "A diffractive and Deleuzian approach," p. 271.
Mol, "'I Eat an Apple": On Theorizing Subjectivity" (2008)

makes itself intelligible to our bodyminds as it is examined by our hands or mouth when eating. The same goes for our hands, mouth, teeth and saliva, that simultaneously make themselves intelligible to the material body they encounter. It is obvious that this Harawayian process of reading and becoming-*with* demands a different kind of research methodology. Here is where diffractive analysis, the study of the entangled effects differences make[149], comes to the rescue.[150] Diffractive reading is seen as an alternative to reflective methodologies, which are not generally sensitive to the entanglement of matter and ideas. Contrarily, diffractive practices treat theories and texts not as pre-existing entities, but as intra-action.[151] The idea of the approach is to put the knowledge generated from different interdisciplinary practices –such as eating an apple– *in conversation* with one another[152], to read these texts intra-actively through one another, enacting new patterns of engagement, attending to how exclusivity matters.[153] This is precisely what Barad does in her AR: she reads physics and poststructuralist theory not as statically opposed to each other, but rather as dynamically intra-acting –the knowledge production being the result of this intra-action. In a sense, we could say this is a putting-together of interdisciplinary practices pointing towards the generation of transdisciplinary knowledge.

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Finally, let me recall that at the beginning of the chapter I introduced AR as providing an understanding of the role of the human and non-human, the material and discursive and the knower and known. At this point, it should be clear how each of these dichotomies gets blurred by AR. Nonetheless, let me recapitulate how AR configures each of these relationships. In the first place, both human and non-human bodies are situated in the same causal plane. It is in this sense that Barad's understanding of performativity is posthumanist. Second, Barad's ontology is material and she presents her position as onto-epistemological. Therefore, the material and discursive are not intertwined but one and the same whole. Finally, AR does not follow a traditional subject/object distinction. In the practices of knowing in being, we are simultaneously knowing and being known.[154]

This experience unavoidably alters our notion of space and time. Spacetime is no longer a combination of the notions of space and time into a single continuum, but should be viewed as spacetimemattering (space-time-matter), where spacetimemattering is everything there is, constantly becoming and making itself intelligible. There is nothing behind the events through which components of phenomena intra-act, nothing behind

[149] Barad, *Meeting the Universe Halfway,* p. 71.
[150] Barad borrows the term 'diffraction', understood as a critical social practice, from Donna Haraway, who started using it in her 1992's and 1997's works, that is, respectively "The Promises of Monsters" and *Modest_Witness@ Second_Millenium*. Diffractive methodology is taken as a metaphor, an analogy from the physical phenomenon of diffraction.
[151] Dolphijn & Van der Tuin, *New Materialisms*, p. 57.
[152] Barad, Óp. cit., p. 93.
[153] Barad, "Quantum Entanglements and Hauntological Relations," p. 243.
[154] Such as in Mol's example of the apple's knowing.

their phenomenal character or performative articulation. An unnerving wholeness resonates through Barad's account; given that there is a continuum and an agentiality throughout –so no generative force of this intra-activity– the nature of change has to be deeply re-thought. How can change be explained on the basis of these (im)possibilities, these (dis)continuities? There was nothing before change occurred, and nothing ceases to be changing. But at the same time intra-actions are presented as dynamic enactments, have a sense of movement, performativity, and potentiality. Change happens at every intra-action. Change is a "dynamism that operates at an entirely different level of existence from that of postulated brute matter situated in space and time […]; rather, what comes to be and is immediately reconfigured entails an iterative intra-active becoming of spacetimemattering."[155] However, according to this wording of change its directionality collapses, and here is where AR's main problem lies. There is no before and after. Past, present and future are open, so no time arrow can be drawn, and this is problematic because as French philosopher Henri L. Bergson (1859-1941) contends concerning the nature of time, *duration* is the deeper form of time[156]:

> Everyone will surely agree that time is not conceived without a *before* and an *after* –time is succession.

Though lived, duration is difficult to define. It is something other than what can be measured or thought. We experience the duration of time when we wait, that is, when time is not exactly calibrated to the will and we experience it differently than how we thought it should run. When discussing his famous example of the mixing of a glass of sugar and water,[157] Bergson notes that his experience of waiting is of a time that "I cannot protract or contract as I like."[158] There, he is saying that such experience of duration is no longer a relation, but an absolute. Time is not something external, and duration is intensive –not extensive–, felt –not thought– and embodied –not applied.[159] We somehow *learn* that time unfolds.

From the point of view of both physics and our human inner experience, it is clear that the notion of change is deeply challenged by AR. Even though we could take this challenge as an opportunity to revise our inheritances, I am convinced that despite the many inspirational insights AR provides in terms of materiality and performativity, it gives a flawed account of change. When examining change, AR's main challenge is the symmetry between past and future, both open and thus suspiciously reversible temporalities. This is troublesome, for duration is asymmetrical, irreversible. Undoing the knot, we stumble upon the simultaneity and/or absence of hierarchy between matter and discursive practices. In order to address these intricate difficulties, in the next

[155] Barad, "Quantum Entanglements and Hauntological Relations," p. 248.
[156] Bergson, "Duration and Simultaneity," p. 218
[157] "If I want to mix a glass of sugar and water, I must, willy nilly, wait until the sugar melts. This little fact is big with meaning."
Bergson, "Creative Evolution," p. 178
[158] Bergson, Ibid., p. 176
[159] Schweizer, *On Waiting*. pp. 16-17.

chapter I will deconstruct AR through the lens of connectionist complex systems (neural networks), which have precisely often been used by new materialists as examples of the materiality and intra-activity of natural and social phenomena.

Ch. IV. On the Symmetry of (Space)time
The Temporalization of Intra-Actions
Complex systems and Non-Reductionist Phenomena

In this chapter, I will analyse AR's faulty notion of change through complex systems, often used as theoretical examples by new naterialist scholars. While Barad does not pay enough attention to the temporalisation of AR's intra-actions and how such a theory explains how memory –essential for the endurance of time– can be retained, complex systems, understood as non-linear collective phenomena, do.

Complex systems can be defined as ensembles of large numbers of elements that dynamically interact. These interactions do not necessarily need to be physical; they can also be thought of as the transference of energy or information, e.g. the electrical synapses in the brain. The most important feature of complex systems is the non-linearity of their *inter*-actions. That is, there is a correlation between causes and effects, but it is not a linear one. Non-linear causality. It is this non-linearity that precisely constitutes the essential pre-condition for complexity,[160] through which complexity emerges as the result of a rich range of patterns of interactions between elements where the global behaviour of a system cannot be expressed as a sum of the behaviour of its parts. Using familiar terminology, we could say that the behaviour of complex systems cannot be *reduced* to the behaviour of its components.[161] Rather, methodologically speaking, holism has to be embraced.

Intimately related to non-linearity, there are questions concerning the triad of uncertainty, predictability and determinism. In order to investigate them, we shall be aware that not all non-linear systems are chaotic systems.[162] Chaos, as applied to complex systems, refers to the sensitive dependence on initial conditions.[163] In chaotic systems, even minuscule uncertainties in measurements of initial position and momentum can result in huge errors in long-term predictions of these variables.[164] As the famous butterfly effect manifests, there is no direct proportionality between causes and effects, so small perturbations may cause large effects. Nonetheless, as said, it is important to bear in mind that only a subgroup of complex systems can be deemed chaotic.

In general terms, the phenomenology induced by complex systems can be manifested in two ways.[165] First, as the emergence of properties manifested by the creation of self-

[160] Cilliers, *Complexity and Postmodernism*, p. 4.
[161] Mitchell, *Complexity*, p. 23.
[162] Note however that the reverse is always true.
[163] Sensitivity to initial conditions is not the only requirement for a dynamical system to be classified as chaotic, although it is the most important one. It is a necessary but not sufficient condition.
[164] Mitchell, Ibid., p. 20.
[165] Scholarpedia. "Complex systems.," accessed 15-06-2017,

organized states of a hierarchical type, where a bottom-up mechanism ensures order. While in the natural sciences we speak of self-organization (self-assembly)[166], in the case of social sciences this appearance of unplanned order is called ‘spontaneous order’. Most of the complex systems are of this unplanned kind. Among archetypical complex systems which show collective emergent behaviours we find fluids under stress, cellular automata and the global symmetry of certain crystals, like snowflakes. Second, complex systems can be manifested as the intertwining of large scale regularities and seemingly erratic evolutionary trends; that is, a coexistence of order and disorder. Typical examples of these are weather forecasts, extreme geological phenomena such as earthquakes and floods, stock markets and herds. In the former case some sort of predictability can be ensured, but in the latter scenario, we find ourselves on ‘the edge of chaos’, in this domain between deterministic order and randomness, this transitioning between the regimes of order and disorder that engenders a constant dynamic interplay between the two. À la Barad, there is a sense of knowability from within in complex systems’ description and functioning, but to what extent are they predictable, deterministic given that they have a chaotic component? After such a short introduction to complex systems it is difficult to elucidate an answer to this question. Therefore, I would like to turn our attention to the first assertion made at the beginning of this paragraph that not all complex systems are chaotic, for this point will later be crucial in our argumentation of why Barad’s notion of change collapses.

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Interestingly, some complex systems are adaptive. This means that they have the capacity to *spontaneously* develop collective properties or patterns that allow them to change *and learn* from experience. Examples of these are the biosphere and the ecosystem, the brain and immune system, and any human social group-based endeavour such as the economy. In the case of adaptive systems, matter is clearly recognized as “exhibiting self-organizing properties subtended by an intricate filigree of relationships.”[167] Here, matter is “always something more than *mere* matter: [it is] an excess, force, vitality, relationality or difference that renders matter active, self-creative, productive, unpredictable.”[168] The auto-regulation, the agency of phenomena such as weather patterns or the body’s immune system is thus a characteristic of complex phenomena. Just as in Barad’s AR, non-human bodies and systems are also agential.

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http://www.scholarpedia.org/article/Complex_systems

[166] As a curiosity, in poststructuralist studies the term *assemblage* comes from Deleuze’s and Guatarri’s term of *agencement*, translated as *assemblage* in Brian Massumi’s English translation of *A Thousand Plateaus* (1987).
Brian Massumi translated, in 1987, Deleuze’s and Guatarri’s term of *agencement* as *assemblage*.

[167] Coole, *New materialisms*, p. 13.

[168] Coole, Ibid., p. 9.
Brackets mine.

Another closely connected feature of complex systems is that they are open, unbounded systems.[169] Boundaries between systems and their environments are blurry, arbitrarily enacted by the observer who *frames* the system –just as the physicist in Bohr's account of phenomena, who does not directly influence the measurement but nonetheless fixes the conditions of observation by her choice of setup. That is, inter-actions (intra-actions) between (within) phenomena are enabled and the exchanges can take the form of matter, energy or information. It is these exchanges that characterize complex systems as dynamic. Had complex systems been isolated and closed, flow of matter and energy would be strictly forbidden, and the systems would eventually reach equilibrium, symmetry and complete stability –in other words, death. Emphasis has to be put on flow and movement as essential for complexity, as well as on processes rather than states. Through a postmodern understanding of complexity, systems are self-organizing processes of networks in which "meaning is generated through dynamic processes and not through the passive reflection of an autonomous agent."[170] As concerns the multiplicity of possible outcomes allowed by the phenomenology of complex adaptive systems, which endows the system with the capacity to choose, to explore and to adapt, attention inevitably has to be paid to the *flow* of time, as South-African philosopher Paul Cilliers' (1956-2011) points out:[171]

> Complex systems have a history. Not only they evolve through time, but their past is co-responsible for their present behaviour. Any analysis of a complex system that ignores the dimension of time is incomplete, or at most a synchronic snapshot of a diachronic process.

That is, in the study of complexity the dimension of time cannot be neglected. Complex systems' evolution *through* and *in* time has to be duly explored:[172]

> Complex systems unfold in time, they have a history that co-determines present behaviour and they anticipate the future.

It is clear that a study of complexity sensitive to the temporal evolution of the system brings to the fore another notion: that of its 'history' or, in more technical terms, its 'memory'. In complex systems we have to understand 'history' as referring to a collection of traces distributed over the system,[173] similar to Barad's reconfigurings (spacetimematterings), written in the flesh of world. At first sight, there seems to be no difference between the account of complex systems so far presented and Barad's AR. Complex systems have a non-linear causal basis, just like her reworked notion of causality. Similarly, all components of complex systems actively participate in the configuration of its collective dynamics. However, I will continue to use Cilliers' expertise

[169] Cilliers, *Complexity and Postmodernism*, p. 4.
[170] Cilliers, Ibid., p. 116.
[171] Cilliers, Ibid., p. 4.
[172] Cilliers, "On the importance of a certain slowness," p. 107.
[173] Cilliers, Óp. cit., p. 117.

on the topic of complexity, both as an engineer and scholar that defended the relevance of poststructuralism for the study of complex systems,[174] to argue that there is a difference, and it is a crucial one.

As defined by Cillers, we should think of *remembering* as the past being active in the present. Memory is something *embodied* in the system; in many respects one could say that "the system *is* its memory."[175] Given a relational understanding of complexity such as the one we are presupposing, where systems are viewed as networks of elements (nodes) and connections between nodes, the nature of these connections "is a result of which states of the network are 'retained'; thus the structure of the system is a result of the sedimented history of the system."[176] The memory of the system takes time to develop. Note that using a non-reductionist discourse to describe complex systems is not incompatible with materialist principles.

As Canadian psychologist Donald O. Hebb (1904-1985) formulated in 1949,[177] the connection strength between two neurons should increase proportionally to how often it is used. Despite being only a qualitative rule, this use-principle –later on mathematized by several authors[178]– provided the clue to where the values of the weights that mediate connections come from. The states that are significant are repeated more often and therefore form more permanent links in the network; this is how the network gains robustness, and can be said to have a history. The history or memory of a system is what allows it to anticipate the future, where anticipation is a non-linear process through which the system tries to cope with unforeseen situations on the basis of that which it has already experienced. Consequently, and as has been commonly accepted within the field of complex system studies since the work of Belgian physical chemist and Nobel laureate Ilya R. Prigogine (1917-2003),[179] the behaviour of complex systems is not symmetrical in time; "they have a past and a future that are not interchangeable."[180]

In a nutshell, non-chaotic –this is where the difference between types of complex systems comes to matter– connectionist complex systems can explain why AR is unable to account for change. Once the system has been framed to a certain level of detail, that is, a boundary between system-environment has been enacted, we can locally speak of discrete components and the relationships between them. Nonetheless, we should not forget that this understanding is not reductionist, for it is collective or system-wide behaviours that are our objects of study. Complex systems must be understood in their

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[174] Cilliers believes that the traditional rule-based and analytical approaches to complex systems are flawed, and that insights from postmodern and post-structural theory can inform our study of complexity at both a theoretical and experimental (experimenting as in 'modelling') level.
Cilliers, *Complexity and Postmodernism,* p. 25 & p. 37.
[175] Cilliers, "On the importance of a certain slowness," p. 108.
[176] Cilliers, Ibid., p. 108.
[177] Cilliers, *Complexity and Postmodernism,* p. 17.
[178] Grossberg, *Studies of Mind and Brain* (1982)
Grossberg, *Neural Networks and Natural Intelligence* (1988)
[179] Prigogine, *Order out of Chaos* (1985)
[180] Cilliers, "On the importance of a certain slowness," p. 108.

totality. Taking the neuronal tissue in the brain. Our components are neurons and glial cells. Since the system is open, cells can be created/destroyed and connections may arise/disappear. In a sense our system is boundless. However, some of these basic components and connections remain unaltered, a fact which ensures that the most recurrent patterns of activity can be encoded in the system's structure, what we call the system's memory. The framing of the system delineates a conventional cut, a divide between an interiority (the system) and an exteriority (the environment). As blurry as the cut may be, once we have set a boundary, we can confidently talk about relations, *inter*-actions between entities. Given that it is the behaviour of the system that is our object of study, following Barad it would seem legitimate to call this exteriority 'exteriority-*within*' and talk about *intra*-actions instead of *inter*-actions. However, constant becoming, spacetimemattering, appears irreconcilable with matter's history and asymmetrical temporality. Even if meaning is not reducible to matter, in a sense matter is prior to meaning –Relationism[181] does not necessarily imply a relational ontology. As learnt from complex systems studies, even if our objects of study are the emergent global behaviours of a system, locally, the material existence of (semi-fixed) nodes precedes any patterns of activity and meaning is generated through the recurrence of *inter*-(*intra*-)actions between nodes. And yet, matter is not a sealed matter,[182] a substance confined in a body. This is how historicity sediments, can be retained, and how it becomes meaningful to secure a notion of identity and a direction *of* and *in* time. The past is past, gone, but still inscribed in the traces of the systems, influencing the present. The future is, to some extent, open. Past and future are not symmetric, so a directionality can be assigned to time. In opposition, AR's past is un-retainable, as well as its future, both absolutely open. There seems to be some sort of unnerving symmetry, thus intuitively killing the possibility of flow, of change. If we cannot hold on past and future is a *yet-to-become* completely unknown, aren't we trapped in an eternal present? This is problematic because it means there cannot be a *before* and an *after*; "there is one or the other, not both, and both are needed to constitute time."[183]

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Barad insists that "space and time are intra-actively produced in the making of phenomena,"[184] that we should not construe time "as a succession of evenly spaced moments or as an external parameter that tracks the motion of matter in some pre-existing space"[185] but rather as a dynamic variable with its own history. Intra-actions are temporal in the sense that the properties reconfigured in each intra-action are part of the very "making/marking of time."[186] Time changes at every intra-action. Note that Barad's making of time is similar to French anthropologist of science Bruno Latour's (1947-), for

[181] The doctrine that an entity cannot be considered independently of its relations to other entities and that these relations have a real existence in themselves.
[182] Barad, "On touching," p. 7.
[183] Bergson, "Duration and Simultaneity," p. 218
[184] Barad, "Quantum Entanglements and Hauntological Relations of Inheritance," p. 261.
[185] Barad, *Meeting the Universe Halfway*, p. 180.
[186] Barad, Ibid., p. 180.

whom actors create their respective relationships, transformations, sizes and also mark their measures of time; they even decide what comes before that.[187] Time is clearly relative. Sure. And many would agree that time should not be reduced to a parameter of continuous functions that describe the motions of bodies. However, I fail to see how we should understand Barad's notion of temporality, how intra-actions 'make time'. Even if we don't let change be caught up in the notion of continuity, even if we engage in talks of fluidity and non-linearity –certainly dynamic concepts– Barad's notion of temporality does not explain how 'past' and 'future', intra-actively reworked and enfolded, are connected. Therefore, it is difficult to see how matter can have a historicity,[188] and change remains a mysterious concept.

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Astrid Schrader, who earned her PhD under Barad's mentorship, realised that AR's account of temporality was insufficient and therefore propounded to nuance or –better phrased– broaden the idea of causality as a "matter of cutting things together and apart."[189] In Schrader's account, developed to explain the importance of timing in fish bioassays, this 'cutting-together and apart' becomes, apart from a process of differentiation between 'object' and 'measuring agencies', one of *temporalization*, where temporalization is understood as a sine qua non condition of possibility of appearance of the phenomenon, a process that "extends a phenomenon through 'time.'"[190] To provide the reader with some context: in her paper 'Phantomatic Ontologies, Indeterminacy, and Responsibility in Toxic Microbiology,'[191] Schrader uses the scientifically unsettled question of whether the dinoflagellates *Pfiesteria piscicida* (better known as 'fish killer') can be regarded as the causative agent of massive fish kills in the estuaries of the US mid-Atlantic "to investigate how criteria for what counts as evidence get built into the experimental apparatuses and suggest that the joint possibilities of causality and responsibility vary within the temporalities of the objects enacted."[192] There, Schrader follows the 'Koch Postulates', a series of criteria developed in the late 19th century by the German bacteriologist Robert Koch (1843-1910) that have since then been used to establish when a microorganism can be considered the cause of a specific disease. The two main requirements of causality as postulated by Koch are repetition of the infection and stability of identity between iterations.[193] But what does repeatability mean? How does identity get configured?

In discussion of experiments that focus on the repeatability of *Pfiesteria*'s toxic activities that the importance of temporalization becomes apparent. Since repetition of toxic phenomena modifies the boundary between potential fish killer and 'its'

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[187] Latour, "Technology is society made durable," p. 119.
[188] Butler's term. See Butler, *Bodies That Matter* [1993] (2011)
[189] Barad, *Meeting the Universe Halfway*, p. 394.
[190] Schrader, "Phantomatic Ontologies," p. 295.
[191] Schrader, "Phantomatic Ontologies" (2010)
[192] Schrader, Ibid., p. 275.
[193] Schrader, Ibid., pp. 292-293.

environment, we cannot base repeatability on the existence of fixed boundaries. A repetition of a toxic phenomenon renders an unambiguous differentiation between *Pfiesteria* and their environment impossible. The crucial point of this impossibility is that the microorganism has a history; there is not only an entanglement between 'bodies' and 'environment' but also one between 'past' and 'future'. Therefore, differentiation has to be understood next to what she calls *temporalization*, "the establishment of a relation between 'past' and 'future'."[194] In these experiments what turned out to be repeatable is a certain temporal pattern of continued deadly activity of fish under specific environmental conditions such as water temperature, pH, etc. A successful repetition of these experiments ensures that there is a link, a correlation, between *Pfiesteria*'s toxic response to fish and the nutrient pollution of water.[195] Nothing else. In view of the previous assertions, it seems difficult to delineate what identity may mean in this context –unless we think of it in terms of the phenomenon *Pfiesteria*-fish killed. What is clear is that the notion of 'identity' needs a history, and consequently a 'memory'. In the case of the fish killer, just as in the case of neuronal responses or T cells in our immune system, 'memory' is understood as a 'biochemical memory', which can only manifest itself in response to fish. Memory, like agency, is not something someone or something has, but rather a mechanism that recreates a past each time it is invoked. The concept of 'memory' is only meaningful when all actors which co-constitute a certain phenomenon are present.

Schrader's argument is not that far from my afore-given example of Hebb's rule, which explains how a neuronal network gains robustness through repeatability. Despite the differences, connectionist complex systems and Schrader's modified version of AR give similar accounts of how 'memory', an 'organic' memory, may be configured, a process which allows us to speak of a 'directionality' of time and constitutes a requirement for change. Although the traditional notion of time as future-oriented, teleological and described in terms of an arrow has been –especially in the last decades– questioned by many scholars from different fields, I would still like to defend the necessity of some sort of *succession*, in order to be able to explain change. Time is relational, relative –as also learnt from Einstein's relativity of simultaneity– and not uniform, but still moves forward. There is no such thing as a perspective-independent 'present', but in each relative framework time unceasingly flows from *no-longer-now* to *now* to *not-yet-now*.[196]

This succession should be understood as *duration*. That is, it is not merely that one instant replaces another –in that case there would be no prolonging of the past into the actual, no evolution. As Bergson writes, duration is the continuous progress of the past which "gnaws into the future and which swells as it advances."[197] The apparent discontinuity of our psychical life is due to our attention being fixed on a series of separate

[194] Schrader, "Phantomatic Ontologies," p. 293.
[195] Schrader, Ibid., p. 295.
[196] Kant's used these expressions for time's uniform succession in the transcendental aesthetic (*Critique of Pure Reaso*n). Although I use them, not that I am not defending a Kantian approach to space-time.
[197] Bergson, "Creative Evolution," p. 173

acts that catch our attention because change has become significant,[198] but continuity is the underlying trend. Change is continuous, characterized by an endless self-sufficient[199] flow of time, time which co-constitutes phenomena.

Even if in a sketchy fashion, I hope to have provided enough reasons to defend the claim that in any explanation of how a system develops its 'history', a directionality *in* and *of* time is needed. The past is closed in the sense that any recreation of a past state will only be an approximation, an alteration, for its temporality will not be the same. That is, the past is closed in the sense of irreversibility. The future is open but constrained by the foreseeing capacity of the system's memory, which connects the *befores* with the *afters*.

Last but not least, I would like to conclude the chapter with a brief discussion about the micro/macro relation in view of the connectionist complex systems theory presented above. One would at first be tempted to distinguish between a micro level (the nodes) and a macro one (the collective behaviours resulting from the connections among nodes). But as we expand a system's boundary with its environment –as spacetimemattering grows in size– more information, more relations, more actors inevitably co-constitute the complex systems we are part of. Therefore, what constitutes the micro-world and what could be called the macro-world shifts. I hope it is evident by now that complex systems theory stems from the acknowledgement that complexity governs nature –all humans and non-humans being part of it. Hence, the idea of a fundamental divide between a 'micro' and a 'macro' world that obey different laws and different physical descriptions (respectively, quantum and classical) is ungrounded and totally unproductive. I suggest we speak of local and global behaviours, only different in degree of complexity, but not in kind –since all obey the same physical laws. A divide between a micro and a macro world is pragmatic, arbitrary, but not ontologically significant.

[198] Bergson, "Creative Evolution," p. 172
[199] The flow of time being self-sufficient as opposed to the flow implying a thing that flows.

Ch. V. The nature of the Unknowable

Complementarity as a General Economy

On the *efficacity* of Quantum Phenomena

Interdisciplinary scholar Arkady Plotnitsky has for many decades now researched the status of nonclassical theories and how they redefine the nature of knowledge. He presents nonclassical theories as those that embrace the unknowable as an irreducible part of knowledge. As employed by Plotnitsky, the word 'nonclassical' may be related to and deployed alongside such terms as 'poststructuralist', 'deconstructive' and 'postmodernist'.[200] In contrast to classical thinking, which does indeed not deny that there may be things beyond theory or observation, the irreducible *un*knowledge of nonclassical theories is beyond conception, while still affecting what is knowable.[201] Bohr's complementarity principle, which has eventually come to designate Bohr's overall interpretation of quantum mechanics, is an example of nonclassical theory in Plotnitsky's sense.

In this chapter I will mostly engage with Plotnitsky's first major work, *Complementarity: Anti-Epistemology after Bohr and Derrida*,[202] while incorporating later refinements in his argument. In the aforementioned book, Plotnitsky gives his own account of the resonance between deconstructionist theory and certain ideas of quantum mechanics. Among others, he uses Bataille's concept of general economy to examine Derrida's work on *différance*, as well as to characterise Bohr's complementarity principle, an analysis on which I will focus. As a historically remark relevant to the content of this chapter, Bataille developed and nuanced his theoretical ideas more or less simultaneously with Bohr's development of complementarity.[203]

As we know well, complementarity describes the unavoidable situation in which two mutually exclusive ontologies or properties are required to explain a single phenomenon: e.g. light is not simultaneously both wave and particle, although no synthesis of the two is possible. Also, none is dispensable, for both are equally necessary to explain phenomena.

In an analysis of how economy works,[204] Bataille flips German philosopher Karl Marx's (1818-1883) views to argue that economy is not only about coping with scarcity but also with excess. Our contemporary marketplace as we know and live it –we humans only consume to survive in order to labour more– is a 'restrictive economy'. Nonetheless,

[200] Plotnitsky, *The Knowable and the Unknown,* p. 13.
[201] Plotnitsky, Ibid., pp. xiii-xiv.
[202] Plotnitsky, *Complementarity* (1994)
[203] Plotnitsky, Ibid., p. 18.
[204] Bataille, *The accursed share* (1988)

the excessive and non-recoverable part of any economy also plays an important role in it. This excess, which he calls 'the accursed share', is destined to one of two modes of economic and social expenditure. This must either be spent luxuriously and knowingly without gain in the arts, in non-procreative sexuality, in spectacles, etc., or it is obliviously destined to an outrageous outpouring in war. 'Sovereignty' is the wasteful consumption or expenditure of resources, this transgressive domain of non-utility, and 'sovereigns' are those who do the expending. An economy that pays attention to this consumption, this luxurious expenditure, is a 'general economy'. General economy designates, thus, "a science –a rigorous theory– which accounts for or relates to the operation of sovereignty and analogous forms of loss and expenditure."[205]

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In quantum mechanics we can only capture 'elementary particles' through their *traces,* in a literal reading of the word, as also employed by Derrida. We observe photographs, or at best, traces left by ions in cloud chambers. That is, in quantum mechanics "one still observes classically by 'reading' –in terms of classical physics– measuring devices."[206] In this sense, Bohr's complementarity is a realisation of the complexities arising in these classical readings with respect to quantum events. Plotnitsky argues that such complexities demand a general economy, and Bohr's principle can be seen as such. Quantum mechanics, and more specifically Bohr's complementarity, always entail general economic theories that redefine the relationships between the concepts of experimental finding and of the product of theorising. In other words, the general economies of quantum mechanics and, more specifically, complementarity redefine the relationships between 'event' and 'observation, 'practice' and 'theory'.[207]

Additionally, Plotnitsky is extremely aware of the material implications of complementarity, so he labels Bohr's complementarity 'a general economy of matter'. Bohr was a visionary in fully grasping that we can no longer speak of matter as a separate reality, independent of the concepts of experimental finding (observation, measurement) and those referring to the product of theorising (interpretation, theory), although matter affects and constrains all observation. As known, complementarity stems from an essential indeterminacy and how this indeterminacy presupposes an indivisible quantum of action, an irreducible interaction between measuring instruments and objects. Since this is a material interaction, Bohr's complementarity can be seen as a general economy of matter. Let me now recall the enunciation of the quantum postulate once more:[208]

> The very nature of the quantum theory thus forces us to regard the space-time coordination and the claim of causality, the union of which characterises the classical theories, as complementary but exclusive

[205] Plotnitsky, *Complementarity,* p. 21.
[206] Plotnitsky, *Reconfigurations*, p. 7.
[207] Plotnitsky, Óp. cit., p. 66.
[208] Bohr, "The Quantum Postulate," p. 580.

> features of the description symbolising the idealisation of observation and definition respectively.

And also the following consequence that:[209]

> 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.

Bohr was the first to pinpoint that, in the light of the novel features shown by quantum phenomena, not only classical physics has to be abandoned but also classical metaphysics, which crumbles with it. Quantum mechanics, as shown by Heisenberg's relations, can be characterized by 'losses' in the content of observation or measurement, thereby prohibiting the strict continuity and causality upon which the classical theories –restricted economies– are based. That is, we cannot understand reality in the ordinary sense –that is, classically– and, as a result and as indicated in the quote above, "there can be no question of causality in the ordinary sense of the word". As also known, Bohr verbalised this problematic and proposed, as an alternative, a complementary approach to physical (and psychological and anthropological) phenomena. The fundamental feature of these ontologies or modes of description/observation, which have to be complementarily viewed, is that they cannot be observed and measured simultaneously, or even unambiguously defined so as to be applied simultaneously. This impossibility to simultaneously observe and/or measure prohibits the definition of the state of a physical system as ordinarily understood, a point that was central to Bohr's argument against EPR's paper on the completeness of quantum mechanics.[210]

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Due to the fact that it concerns loss and waste, Plotnitsky argues that a general economy has to be seen as an anti-epistemology: "general economy makes *apparent* that unutilizable excesses of energy are produced and unrecoverable losses in representation take place."[211] In the case of complementarity, these losses in representation of all the processes involved are signaled by the uncertainty relations, which condition complementarity.[212] The implications of the quantum postulate are anti-epistemological precisely because of these losses, losses *with respect to* classical theories. Plotnitsky remarks that general economy must relate its theoretical knowledge to such losses,[213] something which according to him can only be done by means of a general economy.[214]

[209] Bohr, "The Quantum Postulate," p. 580.
[210] Plotnitsky, *Complementarity,* p. 71.
See chapter II for further detail.
[211] Plotnitsky, *Complementarity,* p. 22.
[212] Plotnitsky, *Reconfigurations,* p. 12.
[213] Plotnitsky, Óp. cit., p. 22.
[214] Plotnitsky, Ibid., p. 72.

Knowledge and *un*knowledge[215] are excluded by each other, but they are also irreducibly linked. As Bataille himself says in *Conférences sur le non-savoir*, "it is impossible to speak of unknowledge, while we can speak of its effects."[216] But what effects does he refer to?

For Bataille, the irreducible loss of meaning is the *efficacity* of all possible meaning –it is a necessary condition of interior experience[217] and sovereignty. The quantum situation forces us to the recognition that, at a certain point, an irreducible interaction excludes further analysis of such interaction. And it is impossible to scrutinise it further because the behavior of quantum objects alone is beyond visualisation, beyond representation. Nonetheless, for Plotnitsky the key realisation is that this situation does not preclude but enable a rigorous analysis of these effects, unique as the many occurrences of such phenomena, which are irreducibly unformalisable –while still accessible[218]. Using Plotnitsky's terminology, all the phenomenology within the wave and particle pictures are wave-like or particle-like effects or sets of effects. This is the step where his argument may be disputed: the behavior of quantum objects is not only beyond visualisation and representation, but also beyond conception, beyond thought. As he vehemently states in his latest article 'On the Character of the Quantum Law':[219]

> Our understanding of quantum phenomena and quantum mechanics may need to involve something, a deeper reality of nature, that is beyond understanding or even thought itself, something that is literally unthinkable –un-thinkable.

The fact that the quantum object per se is unthinkable is what motivates Plotnitsky to introduce Bataillian 'efficacity'. Since no conceivable term can be used to describe the nature of this efficacity of the irreducibly unknowable itself, which is ultimately an inaccessible process, Bataille appeals to the word 'unknowledge'. The nature of *un*knowledge is itself *inaccessible* because we cannot know how we ultimately know any more than what is ultimately responsible for what we can know. Indeed. It is also in this sense that we say that *un*knowledge thus places an *irreducible* limit upon all knowledge.

Nonetheless, at the same time *un*knowledge brings into play the limits of both the knowable and the unknowable, the possible and the impossible, the thinkable and the unthinkable, and so forth.[220] It enables relationships between these apparently exclusive pairs and also between concepts from different pairs. However, the nature of these

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[215] The use of this term shall be explained in short.
[216] My translation of: "Du non-savoir lui même, il y aurait en somme impossibilité de parler, tandis que nous pouvons parler de ses effets."
Plotnitsky, "Effects of the Unknowable," p. 16.
[217] For Bataille, inner experience is the mystical experience of the sacred founded on the absence of god. The search for inner experience begins where religion, philosophy, science, and literature leave off, where doctrines, dogmas, methods, and the arts collapse.
Bataille, *Inner Experience* (1988)
[218] Plotnitsky, "Effects of the Unknowable," p. 19.
[219] Plotnitsky, "On the Character of the Quantum Law," p. 1116.
[220] Plotnitsky, Ibid., p. 20.

relationships is not one of absolute exteriority,[221] or one of binary opposition.[222] Bataille's radical epistemology conceives of these pairs not as excluded from each other's domains or systems –that is, not as absolute *others*– but, once again, as irreducibly linked to each other.[223]

As a final remark, I would like to evaluate the usage of the term 'loss'. Although aware of the central role the concept of *un*knowledge has in Plotnitsky's analysis –as he argues, it is this loss that *always* demands complementarity in the first place[224]– and independently of the tenability of such concept, the word 'loss' reinforces a rhetoric of progress. The insights gained from quantum mechanics, and more specifically Heisenberg's relations and Bohr's complementarity principle, may constrain our (un)knowing practices, but it is not an undesirable result. Quantum indeterminacy is structural, irreducible, a fundamental fact of nature. For Bohr, Heisenberg's principle is not one of uncertainty but one of indeterminacy. Hence, it is an ontic/semantic issue, which is only derivatively epistemic[225]: what there is, is everything we can say about the world. Quantum indeterminacy should be seen as a pressing demand to radically deconstruct the concepts of observation, measurement, theory and interpretation under quantum conditions. Nothing more, nothing less. Although this is how we secure knowledge, in principle one would not necessarily have to comparatively assess the status and explanatory power of quantum mechanics with respect to that of classical physics. Following Plotnitsky's analysis, quantum indeterminacy constrains and inhibits, but as crucially emphasised, it also produces new configurations. Therefore, why not merely say that it is the *in*efficacity[226] of classical physics and metaphysics that demands complementarity in the first place, without any reference to 'losses'? Of course, this is just an observation, a suggestion which would need further unpacking. Yet aware of the essential role the concept of 'loss' plays in Bataille's and, derivatively, Plotnitsky's rhetoric, I inquiry whether it would be possible to replace 'loss' by another less charged word.

Because such a concept is crucial to the relationship between the knowable and the unknowable, I believe Plotnitsky's analysis becomes extremely insightful in relation to Bohr's correspondence principle. The knowable equals the classical; that is, that which is conceivable and representable. The unknowable is situated beyond conceptualisation, beyond representation –it is a capacious term that subsumes denominations such as inaccessible, unrepresentable, unconceptualisable, and so forth.[227] Therefore, how can we have access to *un*knowledge? We cannot, but as said, we can speak of its effects. We can

[221] Term used to describe Einstein's condition of objectivity in the physical sciences.
[222] Derrida criticised the structuralist idea of binary oppositions by arguing that these were arbitrary and inherently unstable. Deconstruction rejects binary oppositions on the grounds that such oppositions always privilege one term over the other, that is, à la Swiss linguist Ferdinand de Saussure (1857-1913), the signified over the signifier.
[223] Plotnitsky, "Effects of the Unknowable," p. 22.
[224] Plotnitsky, *Reconfigurations: critical theory and general economy*, p. 12.
[225] Barad, *Meeting the Universe Halfway*, p. 118.
[226] Invented word, aimed at exploring the playfulness of Bataille's and Plotnitsky's terminology.
[227] Plotnitsky, *The Knowable and the Unknown,* p. 5.

speak of photographs or traces of ions left in cloud chambers, which we examine with a classical mindset. Indeed, classical theories provide a pathway –or rather, the only– pathway to the unknowable. Nonetheless, they only help us conjecturing its existence. The unknowable cannot be properly understood by classical means; here's where nonclassical theories come to the rescue. Thus, since classical theories lead the way to *un*knowledge, Plotnitsky employs a comparative rhetoric, in which nonclassical theories are defined as implying losses of representation and meaning, losses which justify the origin of the unknowable, the impossible, the unthinkable, and so forth. Going backwards, it is also the existence of such losses that gives meaning to Bataille's notion of general economy. Despite fully grasping the justification for the use of such terms, I cannot get rid of the feeling that there should be another more neutral way to approach the interplay and refer to such ontological and epistemic limits. Of course, such a suggestion would need to be further explored, but also duly considered.

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Throughout his work, Plotnitsky continuously refers to 'Bohr's matrix' and complementarity as a 'framework.'[228] These characterizations are closely linked to the question of application that I shall discuss in the following two chapters. Hence, let me now introduce and carefully examine these terms in a Plotnitskyian key.

Bohr's matrix is a structure compounded of complementary relations which are interactive and correlative to each other. They are the now already familiar complementarities between 1) wave and particle, 2) kinematic and dynamic explanations and 3) space-time coordination and causality. That is, Bohr's matrix is a framework, a framework which functions by means of a general economy that is conditioned by the dependence of quantum processes on both the experimental arrangements and the mathematical formalism that accounts for the quantum effects observed. So far so good.

Then Plotnitsky tries to employ complementarity in a more extended sense. He proposes to broadly conceive complementarity as characterised by heterogeneity and multiplicity, an interconnectivity not only consisting of double configurations but also multiple ones. That is, there can be pairs of concepts (or metaphors) but also "clusters of concepts, metaphors, or of conceptual and metaphoric networks"[229] which exceed the binary way of thinking; note that in such a framework mutual exclusivity is not always a required characterisation. With such an extension, Plotnitsky wants to emphasise that, while complementarity is always a general economic theory, the opposite is not necessarily true: in principle not all general economic theories need to appeal to or entail complementarity.[230] Be them part of the theory, they would then constrain and even define them in a particular way. Having remarked that the relationship between

[228] Note that Plotnitsky uses the words 'matrix' and 'framework' as synonyms.
[229] Plotnitsky, *Complementarity*, p. 73.
[230] Plotnitsky, e-mail message to author, July 2017 –see acknowledgements section.

complementarity and general economy is not bi-conditional, we will omit the opposite direction –general economies are not necessarily governed by complementary relations– and focus only on the characterisation of complementarity as a general economy. To sum up, complementarity is the kind of relationality that defines Bohr's matrix functioning. Bohr's matrix is configured by complementary pairs, which are mutually exclusive but equally necessary. In a sense, we could say that complementarity functions *as* and *in a* matrix –a theoretical economy– that has a branching structure in which complementary relations may give birth to other complementary relations. Complementarity is a then matrix, but also a general economy, "two characterisations that demand each other and may be said to be parts of the same economy."[231]

*

At this point, an interesting question is what is the added value of complementarity as formulated in the physical sciences. As Dutch-born American physicist and science historian Abraham Pais (1918-2000) observes, "complementarity can be formulated without explicit reference to physics, to wit, as two aspects of a description that are mutually exclusive yet both necessary for a full understanding of what is to be described."[232] *Touché*. To give an example, French Continental philosopher Gaston Bachelard (1884-1962) had a non-reductionist view of perfect knowledge as that which had to be both minutely detailed and universal.[233] These two requirements were seen as complementary. Detailed and universal were equally necessary characterizations of an idealised notion of knowledge, but at the same time they were mutually exclusive, that is, simultaneously incompatible. Bachelard's account bears some resemblance to AR in the sense that his view demands a move from a static to a dynamic view of scientific knowledge and it allows for discontinuities, which nonetheless do not block progress, defined as an ongoing refinement of approximate, inexact, incomplete knowledge. Bachelard's view of scientific knowledge also bears some resemblance to Connectionism, in that he views reality as hierarchically structured by orders of physical magnitudes, so basically a nested order of complex systems. Complexity is actually the reason why we should speak of interactiveness and complementarity rather than synthesis.[234]

One more time, let me insist on the most crucial idea of Plotnitsky's analysis of Bohr: the insights Bohr's complementarity gives are related to the fact that matter constrains and enables meaning, generated through the inter-actions between components of phenomena. Plotnitsky defends that the general economy of matter emerging in quantum mechanics generates powerful constraints on general economic theories,[235] although he does not clarify which are these constraints and how they are generated. Although the answer has to do with the unexplored direction of the bi-conditional mentioned between

[231] Plotnitsky, *Complementarity*, p. 75.
[232] Pais, *Niels Bohr's Times*, p. 24.
[233] Gutting, *Continental Philosophy of Science*, pp. 157-183.
[234] Plotnitsky, Óp. cit., p. 22.
[235] Plotnitsky, *Complementarity,* p. 74.

complementarity and general economy, as far as I am concerned he nowhere elaborates on such constraining by the quantum mechanical general economy of matter. Clarification of such strong statement would have been much appreciated, especially in view of the content of the following two chapters.

Notwithstanding this small critique, as well as my reluctance towards the employment of the term 'loss' in his discourse, I find Plotnitsky's analysis of complementarity as a general economy stimulating, especially as regards the anti-epistemological conclusions he draws from such analysis[236] and his talk of efficacity

[236] Although according to my above-expressed suspicion concerning his (and Bataille's) terminology, I would not embrace it.

Ch. VI. Complementarity Beyond Physics

Conceptual vs. Experiential Complementarity

Teaser: The Question of Application

In chapters I and II we saw that Bohr's notion of complementarity, far from having a fixed meaning, evolved through the years and was used to refer to different kinds of relationships between pairs of concepts. In the present chapter we are going to devote time and attention to this evolution and to how Plotnitsky and philosopher Arun Bala, author of the recently published book *Complementarity Beyond Physics*[237], have labelled these types or phases through which complementary has passed. Although from different perspectives, both scholars have thoroughly studied Bohr's complementarity: while Bala offers a detailed defence of Bohr's complementarity in the biological and social sciences by explaining such parallels as responses to the omnipresence of 'grown properties' in nature,[238] as seen in the previous chapter, Plotnitsky explores the potential of Bohr's complementarity as a general economy. Hopefully, their characterisations will enlighten the understanding of complementarity beyond the horizons of physics. Furthermore, the aforementioned attempt at extending complementarity beyond physics will naturally lead us to the sensitive discussion of the potential 'use' or 'application' of complementarity beyond such horizons, a topic which I will develop conscientiously in the subsequent chapter.

As seen, Bohr coined the term complementarity to refer, in the first instance, to the dual nature of light and matter, sometimes better described through the notion of particle, sometimes through that of wave. It was 1927, and he made the concept public in his by now already familiar Como lecture. There, he also emphasised the mutual exclusivity of space-time coordination and the claim of causality in the quantum theory, "exclusive features of the description symbolising the idealisation of observation and definition respectively"[239] which according to him should be understood as complementary modes of description of physical phenomena. In his following papers, this is the flavour complementarity acquired: there is an essential indivisibility of atomic processes, which translates into the non-commutability of certain pairs of variables (position and momentum, energy and time, etc.), impossible to measure simultaneously. As Bohr expresses:[240]

> Any attempt at locating atomic objects in space and time demands an experimental arrangement involving an exchange of momentum and

[237] Bala, *Complementarity Beyond Physics* (2017)
[238] I will not engage in his own position but will only limit myself to his analysis of Bohr. For an explanation of the term 'grown properties', see Bala, *Complementarity Beyond Physics* (2017)
[239] Bohr, "The Quantum Postulate," p. 580.
[240] Bohr, "On the Notion of Causality and Complementarity," p. 52.

> energy, uncontrollable in principle, between the objects and the scales and clocks defining the reference frame. Conversely, no arrangement suitable for the control of momentum and energy balance will admit precise description of the phenomena as a chain of events in space and time.

These experimental limitations can be brought back to the philosophical domain through the realisation that space-time coordination (the idealisation of observation) and causality (the idealisation of definition), although incompatible features of the description of physical phenomena, are complementary. There is none prior to the other, and the result of their interplay is not fixed, but configured by the experimental conditions selected.

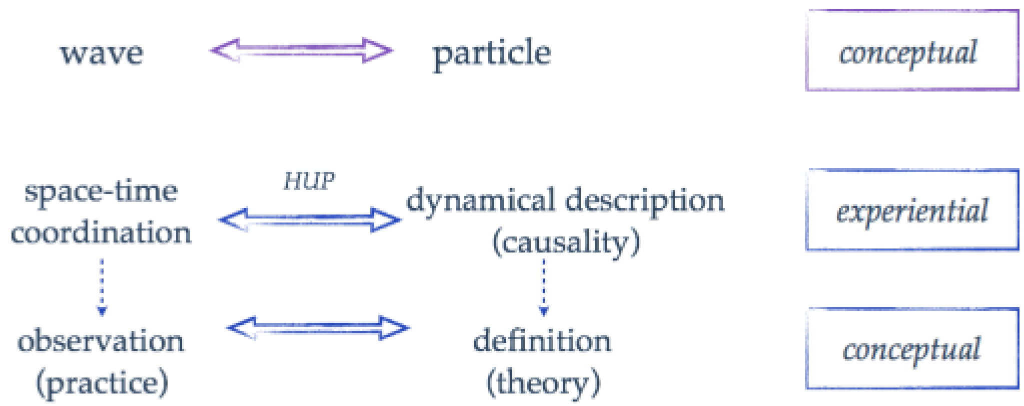

Fig. 2: Scheme of Bohr's 'types' of complementarity.

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In the first chapter of his last book *Complementarity Beyond Physics*[241], Bala explores the question of whether one can extend complementarity in physics to psychology, biology and anthropology. Let me clarify that this attempt at an extension is precisely the reason why we start with Bala instead of Plotnitsky and not the other way around, as one would chronologically expect. Content-wise, this order will give the chapter more dynamism.

Before engaging in such a daunting analysis of complementarity relations in other fields different from physics,[242] Bala introduces the reader to a self-drawn distinction, that between what he respectively calls 'aspect complementarity' and 'property complementarity'. He believes that such categorisation helps making sense of the different ways in which Bohr's complementarity is employed. By 'aspect complementarity' he refers to the particle-wave duality, in which we have two conceptually mutually exclusive ontologies. At the same time there is 'property complementarity' between non-commuting properties such as position and momentum,

[241] Bala, *Complementarity Beyond Physics* (2017)

[242] I will not examine his analysis in detail. See Bala, *Complementarity Beyond Physics* (2017) for an introduction to Bala's account.

not conceptually but experimentally mutually exclusive. As noticed, property complementarity refers to the latter meaning complementarity adopted –especially after the EPR paper (1935). The fact that two variables do not commute leads to the picture of a complementary view of the space-time description and the dynamical description (that Bohr usually called 'causality') of phenomena. These two kinds of complementarity differ in that the former implies a conceptual incompatibility, whereas the second presupposes, in the first place, an experimental one. And I remark 'in the first place' because although it stems from an experimental incompatibility, Bohr frames this type of complementarity in terms of modes of description: space-time coordination as the idealisation of observation and causality as the idealisation of definition, observation and definition being the *conditions* of measurement. That is, yet not conceptually incompatible, the lesson we learn from these *CCR* somehow drives us back to the sphere of *the conceptual*.

Based on the distinction between aspect and property complementarity, Bala proceeds to analyse whether Bohr's complementarity can be extended to the psychological, biological and anthropological sciences. From 1929 onwards, Bohr publicly discussed epistemological problems in these fields.[243] It has often been argued that Bohr's speeches did not go beyond vague suggestions and illustrations on how that could be done.[244] Despite this prevalent opinion, it is fair to say that he truly seems to have wanted to shed light on the conditions for the observation and description of phenomena in the aforementioned fields. But why these fields only, if he spoke, time and again, about the 'unity of knowledge'? Well, it appears to be the case that before the publication of his complementarity principle in physics he had concerned himself with the conditions of observation and description in psychology and biology, although he never published his views on these topics before he did so in physics.[245] His interest in ethnology and anthropology came a few years later, but in no case was it motivated by his 1927's remarks on Heisenberg's relations in quantum mechanics. Therefore, as a preliminary observation I would like to encourage cautiousness when speaking of 'extending' or 'applying' complementarity beyond physics, for at least chronologically speaking that is inaccurate.

*

As concerns psychology, Bohr addressed the topic of perception. When describing our mental activity, he acknowledged that "we require, on one hand, an objectively given content to be placed in opposition to a perceiving subject, while, on the other hand, as is already implied in such assertion, no sharp separation between object and subject can be maintained, since the perceiving subject also belongs to our mental content."[246] This

[243] Bohr, *NBCW,* Vol. 10, p. xxiii.
[244] Bohr, "The Atomic Theory and the Fundamental Principles underlying the Description of Nature" (1929)
[245] Bohr, *NBCW,* Vol. 10, pp. xxvii-xxviii.
[246] Bohr, "The Quantum of Action and the Description of Nature," p. 96.
Also in *NBCW*, Vol. 6, p. 212.

assertion should not strike us, for Danish psychologist and phenomenologist Edgar Rubin (1886-1951) probably had had an influence on Bohr's thoughts.[247] In this respect, it is of historical importance to remember that Bohr had attended lectures by also Danish philosopher and theologian Harald Høffding (1843-1931) during his first year as a student at the University of Copenhagen.[248] Høffding advocated a view which he named 'the hypothesis of identity', according to which mind and matter are but two attributes or aspects of one substance, two sides of a coin, a position Bohr initially and mistakenly named 'psychophysical parallelism.'[249] Nonetheless, Bohr never spoke of parallelism as the traditional relation between the bodily and the mental, but as a parallelism in the sense that in both of these two domains observation alters the phenomenon under investigation. Concerning perception, he also explicitly discussed complementarity between thoughts and sentiments, mutually exclusive elements. A beautiful example he often used to explain it was that of listening to music: the emotional experience of a piece of music excludes conscious analysis of it, whereas analysis of the music excludes emotional experience, yet both approaches are necessary for our understanding of it.[250] In the examination of this mutual exclusivity between thoughts and emotions, rationality and instinct, Bohr repeatedly notes that "any attempt at exhaustive description of the richness of conscious life demands in various situations a different placing of the section between subject and object."[251] The line of separation between the observing subject and her thoughts is movable and depends on our approach to every situation. The demand of taking all essential features of an experimental situation into account is precisely reflected by the verbs we attach to the pronoun when we describe it. While in psychology we clearly emphasise that it is the 'I' who thinks or feels, in quantum physics it is still the 'I' who observes.

Although Bohr did not explicitly engage in talks of gestalt psychology, his thoughts on psychological complementarity do bear some resemblance to gestalt theories, especially considering the influence that Rubin may have exerted on him. In his book, Bala precisely works in this direction; that is, to read gestalt psychology according to a complementary approach. In the theory of gestalts, what we perceive depends on the external sensory stimuli we passively receive from the medium, but also on the interpretation we choose as actors when responding to such stimuli. Think now of Rubin's

[247] In his 1925 entry on "Psychology" in the major Danish encyclopaedia, Rubin defined 'psychological parallelism' in precisely the same way as would Bohr shortly after.
Salmonsens Konversations Leksikon, Bind XIX, J.H.Schultz Forlagsboghandel A/S, Copenhagen 1925, p. 683.
[248] Bohr, *NBCW*, Vol. 10, p. xliii.
[249] Bohr, *NBCW*, Vol. 10, pp. xxliii-xlv.
Høffding named Leibniz's view, based on correlation between mental events and brain processes without interaction, 'psychophysical parallelism'. He rejected Leibiniz's view on the mind-body relation, as he did with Descartes', who maintained that mind and matter are two fundamentally different forms of existence that interact in some way. Hence, considering his many admonitions on this subject, he probably found it surprising and totally wrong that Bohr called his view 'psychological parallelism'.
As known, the mind-body relation has been a long debate in philosophy. Leibniz's and Descartes' viewpoints are the two most prominent ones since the 17th century onwards.
[250] Bohr, *NBCW*, Vol. 10, p. xlvi.
[251] Bohr, "The Unity of Human Knowledge." p. 159.

vase, or the also famous duck-rabbit picture –see figure 3 on the next page[252]. Although viewing the gestalt as externally imposed upon us and viewing it as mentally constructed by us seem mutually exclusive perspectives, both are necessary to fully comprehend the way we experience gestalts. If we now recall the distinction between aspect and property complementarity introduced a few paragraphs above, Bala contends that we are able to recognise these two kinds of complementarity in this example: configuration and interpretation can be viewed as conceptually incompatible *aspects* of complementarity, just as the *properties* that arise from their interplay, which cannot be simultaneously conceived.[253] We may agree or disagree with Bala's analysis here, but as said the similarity with Bohr's talk of 'psychological complementarity' is striking.

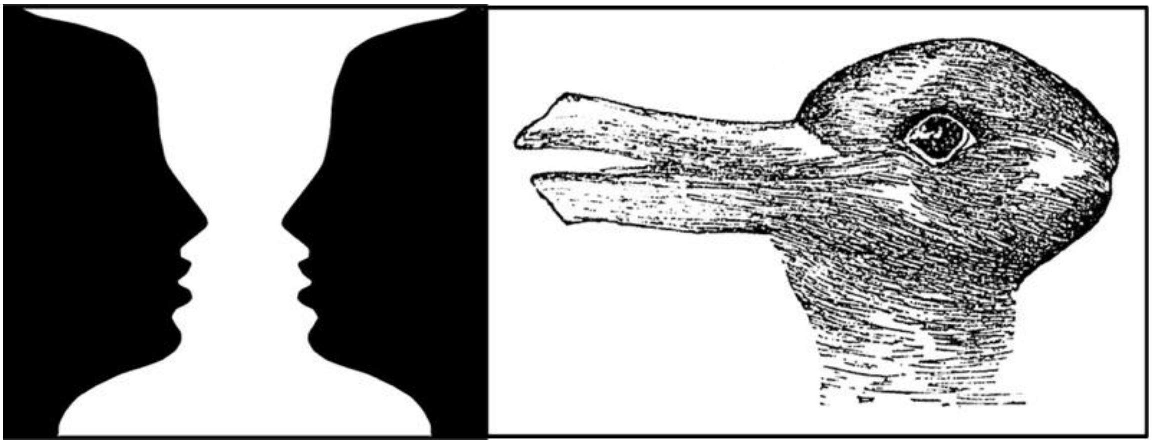

Fig. 3: Rubin's vase and duck-rabbit illusion.

Since the mental and the bodily are not separate for Bohr, let us now move to his views on biology without losing sight of the previous discussion on consciousness. In fact, in his 1932 'Light and Life' lecture,[254] delivered to a congress of light therapists in Copenhagen –and the first in which he officially discussed biological issues– Bohr stated that "any analysis of the very concept of explanation would, naturally, begin and end with a renunciation as to explaining our own conscious activity."[255] Again with respect to consciousness, Bohr opposed a purely mechanistic explanation of life, on the basis of "the fact that consciousness, as we know it, is inseparably connected with life." Such *inter-connectedness* leads to the obvious conclusion that "the very problem of the distinction between the living and the dead escapes comprehension in the ordinary sense of the word."[256] Besides that, it requires that we adopt a teleological[257] approach to living

[252] On the left: The Dress, Rubin's Vase, Yound Lady and Old Lady and famous optical illusions, acessed 16-08-2017, http://www.ibtimes.co.uk/thedress-rubins-vase-young-lady-old-lady-other-famous-optical-illusions-1489764
On the right: Weisstein, E. W. Rabbit-Duck Illusion, accessed 16-08-2017, http://mathworld.wolfram.com/Rabbit-DuckIllusion.html
[253] Bala, *Complementary Beyond Physics*, p. 39.
[254] Bohr, "Light and Life" (1933)
[255] Bohr, Ibid., p. 459.
[256] Bohr, "The Atomic Theory and the Fundamental Principles Underlying the Description of Nature," p. 119.
[257] Teleological: exhibiting purpose, especially in nature.

processes, besides our mechanistic descriptions, in which we endow them with a certain account of free will. As he also said in 1958: "a description of the internal function of an organism and its reaction to external stimuli requires the word *purposeful,* which is foreign to physics and chemistry."[258] That is, purposefulness as exhibiting agency.

Bohr also opposed vitalism, for even though he claimed that life cannot be reduced to physico-chemical processes, he fervently defended the idea that all biological results must be stated in the language of physics and chemistry in order to obtain unambiguous descriptions, just as quantum phenomena have to be accounted for in ordinary language supplemented with classical physical concepts.[259] Life did not and should not have any special ontological status, although its very existence should be taken, according to him, as a basic fact in biology in the same sense as the quantum of action had to be regarded in atomic physics as a fundamental element irreducible to classical physical concepts.[260] The discovery of the helical DNA structure in 1953 and the subsequent advancements in genetics seemed to suggest a reductionist view[261] much against that which Bohr had been advocating. Nonetheless, he remained impassible, convinced that, besides the fact that these discoveries add to our knowledge of the complexity of living organisms, "the integrity of *these*[262] and the characteristics of conscious individuals present features of wholeness, the account of which implies a typically complementary mode of description."[263]

Bala reads Bohr's comments on biology as a recommendation to treat mechanical and functional explanations of the structure and behavior of a biological system as complementary, a recommendation that he argues would, put into practice, enrich our understanding of developmental, evolutionary and ecological processes.[264] Thus, on Bala's reading, Bohr's biological remarks entail an aspect complementary relation between mechanistic (deterministic) and teleological (free will) explanations, which are mutually exclusive. He also proposes to extend 'biological complementarity' beyond the development and evolution of individual organisms and species to ecological properties of natural systems in the biosphere (e.g. ecosystems).[265] This transition from the individual to the ecosystem is the kind or approach being adopted in interdisciplinary studies, following the 'people planet profit' paradigm.[266] Nonetheless, the implementation

[258] Bohr, *Daedalus* (1958).
[259] Bohr, *NBCW,* Vol. 10, p. 11.
[260] Bohr, "Light and life revisited," pp. 166-167.
[261] That is, genes as the basic constituents of life; life seen as reducible to a mechanistic explanation of genes' functioning.
[262] Emphasis mine. Originally the quote reads 'living organisms'.
[263] Bohr, *NBCW,* Vol. 10, p. 10.
[264] Bala, *Complementary Beyond Physics*, p. 43.
Italics mine.
[265] Bala, Ibid., p. 45.
[266] Nowadays, considering factors such as climate change and the financial collapse of 2008-2009, business models have shifted from a one bottom line framework which only considers profit to a triple bottom line which considers the social and environmental impacts of a business in its pursuit of profits (people-planet-profit).

of a complementary rhetoric to describe the relation between genetic and environmental descriptions in these vast and extremely complex systems should be carefully studied.

Last but not least, let me comment on Bohr's anthropological remarks, scarcer than those related to psychological and biological issues –fields in which he developed a strong interest– but yet remarkable. As regards this topic, of special interest is his 1939 article 'Natural philosophy and human cultures'.[267] In this article, Bohr pointed out that the observational situation in the anthropological sciences had similarities to that in quantum mechanics because a complete assimilation in a foreign culture and a concise, analytic description of that culture would seem to exclude one another.[268] When studying human cultures different from our own, we are again confronted with a particular problem of observation, "which on closer consideration shows many features in common with atomic or psychological problems, where the interaction between objects and measuring tools, or the inseparability of objective content and observing subject, prevents an immediate application of the conventions[269] suited to accounting for experiences of daily life."[270] One is one's own instrument. In relation to human behavior, Bohr more specifically emphasised that "the amazing capacity of so-called primitive people to orientate themselves in forests or deserts, which, though apparently lost in more civilized societies, may on occasion be revived in any of us, might justify the conclusion that such feats are only possible when no recourse is taken to conceptual thinking."[271] In this fragment the dilemma between instinctual and rational modes of behavior of living beings is brought to the fore, since in explaining many human traits it is impossible to sharply separate them. In anthropology, as in biology, Bohr demands a view of human behavior as explained by the complementary standpoints of nature (instinctive biological inheritance) and culture (conceptual thinking), an understanding of the nature-nurture relation under the light of his complementarity epistemology.

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Like Bala, Plotnitsky also discusses two main kinds of complementarity. He introduced them in his 1994 book *Complementarity: Anti-Epistemology After Bohr and Derrida.*[272] The first kind of complementarity –that of particle-wave complementarity presented in the Como lecture – reflects the duality of the behaviour of quantum objects and relates the continuous and discontinuous representations of quantum processes, which had been traditionally dissociated in classical physics. It is philosophically crucial insofar as it not only accounts for the incompatibility between the particle and wave ontologies but

[267] Bohr, "Natural philosophy and Human Cultures" (1939)
[268] Bohr, Ibid., p. 270.
[269] Here I understand the use of 'convention' as referring to the separation between the observing subject and the *objective* content of the observation. After this fragment, Bohr enters into the discussion of the study of cultures of primitive people: contact with the ethnologists studying them corrupts their cultures and, at the same time, these studies have an impact on the ethnologists' own human attitude.
[270] Bohr, "Natural Philosophy and Human Cultures," p. 271.
[271] Bohr, Ibid., p. 270.
[272] Plotnitsky, *Complementarity* (1994)

certainly also dislocates the classical causal dynamics of objects. The second one –or ones, as we will see– is the complementarity of coordination, defining a position or a configuration of positions of a quantum object or system, and causality, classically determining the behaviour of such an object or system. Since it is directly connected to the complementarity of position and momentum –or the kinematic-dynamic complementarity as it is sometimes called– it can be seen as more empirical than the former. Space-time coordination and causality "symbolize the idealization of observation and definition respectively."[273] As already seen in chapter I, Bohr also said the following: "the very nature of the quantum theory… 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."[274] These two assertions give rise to another complementarity within the second kind, again a bit more conceptual or philosophical in nature: the complementarity of the two metaphors, symbols, idealisations in question, namely that of observation (experiment) and that of definition (theory).[275] As Plotnitsky highlights, "this understanding is crucial in defining complementarity as a theoretical matrix," and specifically, "in making it a general economy."[276] Note that, contrary to the distinction between the first and second types of complementarity, the difference between sub-kinds, which for simplification we shall call 21º and 22º, is only one of degree, not of kind or nature. Note as well that the distinction between types of complementarity bears a strong resemblance to the one drawn by Bala between aspect and property complementarity; this should not strike us, for although there is no direct mentioning of Plotnitsky in this section of Bala's book, he clearly must have been influenced by the former. Moreover, it is quite straightforward from Bohr's work that a divide between a first and a second use can be drawn.

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Considering the previous analysis of complementarity as employed in psychology, biology and anthropology, it is quite evident that it makes no sense to think of complementarity beyond physics in the most experimental sense –that is, Bala's property complementarity or what I have called Plotnitsky's 21º complementarity. Although I support a quantum fundamentalist reading of Bohr which devises the world as essentially quantum, a problem of complexity manifests here. The uncertainty implied by the quantum postulate gets masked by higher scale effects, which prevail on the macro –using here the illusory conventional divides I am contesting– level. Nonetheless, I would like to defend the idea that the conceptual apparatus of complementarity, that is, Bala's aspect complementarity or Plotnitsky's 1st complementarity kind, together with Plotnitsky's 22º, are successful epistemological attitudes towards any field of knowledge. Leaving the Realism-Antirealism debate aside, the complementary use of conceptually mutually

[273] Bohr, "The Quantum Postulate," p. 580.
[274] Bohr, Ibid., p. 580.
[275] Plotnitsky, *Reading Bohr*, p. 165.
[276] Plotnitsky, *Complementarity*, p. 7

exclusive ontologies or modes of description seems to be a sensitive approach to knowledge, inasmuch as it leaves space for comparison, contrast inquiry and equity. As Bohr says, "the complementary mode of description does indeed not involve any arbitrary renunciation of customary demands of explanation" but, on the contrary, "aims at an appropriate dialectic expression for the actual conditions of analysis and synthesis in atomic physics."[277] Although in view of the fact that Bohr only examined three fields it would be a fair criticism to question the generalization of the previous quotation to all fields of knowledge, it is also the case that on the basis of his ultimately unified view of knowledge it seems fair to accept this assumption as sound.

Once manifested my sympathy for the conceptual use of complementarity, a pressing question is whether this methodology has been and can indeed be 'applied' to fields beyond physics. Although I will specifically devote the coming chapter to this issue, let me briefly introduce it here. We have seen that, chronologically, application is inaccurate. At least, Bohr's views in biology and psychology did not develop from his quantum mechanics. Concurrently, we have also contended that although due to a scale problem it seems difficult to account for *experimental* complementarity in other fields of knowledge else than physics, at most *conceptual* complementarity holds within any field. It is a formal –formal in the sense that it does not put constraints on the content– and essential condition or requirement for a *maximally complete* –as complete as possible within this irreducible incompleteness– knowledge. Obviously, as a physicist most of Bohr's work is in this discipline, but this is certainly not a compelling reason to claim he 'applied' his 'discoveries' in physics to other domains. As I will discuss in the following chapter, he rather seemed to be asking for a certain epistemological attitude towards life.

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[277] Bohr, "On the notions of causality and complementarity," p. 54
Italics mine.

Ch. VII. The Question of Application

Parallelisms, Metaphors and Frameworks

Complementarity as Epistemological Attitude

Another interesting feature of Bohr's reply to the EPR paper –which we did not discuss in chapter II– is that throughout the paper Bohr calls for an acknowledgement of the parallels between the limitation imposed on the causal description in atomic physics and other fields of knowledge. He demands an acknowledgement of the "necessity in many domains of general human interest to face problems of a similar kind as those which have arisen in quantum theory."[278] After one of his brief comments on biological and psychological complementarities, he writes down one of his most famous sentences: "the development of atomic physics forces us to an attitude towards the problem of explanation recalling ancient wisdom*, that searching for harmony in life one must never forget that in the drama of existence we are ourselves both actors and spectators*."[279] Bohr, aware of the mysticism underlying such assertion, which has been extensively used in domains beyond rational scrutiny (e.g. by Austrian-born American physicist Fritjof Capra (1939-) in his *Tao of Physics* or American writer Gary Zukav (1942-) in *The Dancing Wi Li Masters*),[280] then gives the following important and completely undervalued piece of advice: that "each field of knowledge and interest should investigate which are its own conditions for the analysis and synthesis of experience."[281] In *Atomic Physics and Human Knowledge*[282]*,* he again insists that for objective description and harmonious comprehension it is necessary in *almost*[283] every field of knowledge to pay attention to the circumstances under which evidence is obtained. With these assertions, Bohr seems to suggest that we must analyse the experimental conditions in which knowledge is obtained in the search for the complementary variables that set the conditions for the observation and definition of a particular phenomenon.

Many have claimed that Bohr's unfinished epistemological project was to apply complementarity to other disciplines beyond physics. Specifying known characters, these include Bala. To a certain extent, Plotnitsky's views could also be seen as siding with Bala's strict sense of application, although we will examine and nuance the former's position. Barad is critical of the application thesis, but what we see is other scholars applying Barad's AR (or even Barad herself applying Bohr's work) to other fields without

[278] Bohr, "Discussion with Einstein," p. 25.
[279] Bohr, Ibid., p. 25.
Italics mine.
[280] Capra, *The Tao of Physics* (1975)
Zukav, *The Dancing Wu Li Masters* (1979)
[281] Bohr, Óp. cit., p. 24.
[282] Bohr, *Essays 1958-1962 on atomic physics and human knowledge*, pp. 1-2.
[283] Emphasis mine. Bohr seems to refer to those fields of knowledge which obtain their evidence from experience, be it social or natural sciences.

researching the fields' apparatus. As already hinted in the introduction, Plotnitsky's and Barad's works try to move away from the Representationalism –the traditional way of producing knowledge, which breaks the world down into objects, representations of such objects, and human knowers which create such representations– which lies at the basis of reflexive practices. In the present chapter I will discuss their views on the application of Bohr's work in order to present a new, or rather compromise, stance in the debate of Bohr's extension of complementarity beyond physics. Note that since I have deemed strict application undesirable, I will not even consider Bala's position.

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As seen in the previous chapter, Plotnitsky views Bohr's framework of complementarity as a theoretical matrix, revolutionary within physics, but also as a theoretical matrix in more general conceptual terms. In chapters I and II we already discussed in which sense complementarity disrupts classical physics. But what does Plotnitsky mean by complementarity being revolutionary on a conceptual level in more general terms? He defends that complementarity can be extended to theoretical aspects of the humanities and the social sciences insofar as we do so in the spirit of an anti-epistemological general economy (of physics and metaphysics). The economy of complementarity, as he defends, "may be extended to entire theoretical matrices or fields, or other forms of enclosure."[284] But what kind of extension is he putting forth here? On the one hand, Plotnitsky believes that Bohr's complementarity provides a metaphorical model for the social sciences and the humanities that can be effectively utilized elsewhere (!). On the other hand, he contends that complementarity as a general economy of matter emerging in quantum mechanics "generates powerful, if highly mediated, constraints on general economic theories."[285]

Thinking of complementarity as a metaphor and closely examining the meaning of the word 'metaphor',[286] I have my doubts with respect to the difference between *literally* applying a framework and *metaphorically* applying a framework. It is true that metaphors suggest a less intense sense of resemblance; nonetheless, practices of mirroring are still at their –even if metaphorical– basis. But Plotnitsky does not stop here. As a metaphorical model, he claims that Bohr's theoretical matrix is also constraining. As I understand it, Bohr's matrix enables new configurations of ideas, but the losses of representation in the general economy of complementarity constrain the arising of such new configurations. Nonetheless, as concluded in the previous chapter, it is obscure how constraints on general economic theories are generated.

Barad's criticism of Bohr's work is more radical than Plotnitsky's. While Plotnitsky

[284] Plotnitsky, *Complementarity*, p. 74.
[285] Plotnitsky, Ibid., p. 74.
[286] Metaphor: figure of speech in which a term or phrase is applied to something to which it is not literally applicable in order to suggest a resemblance.
Dictionary.com. "Metaphor," accessed 09-07-2017, http://www.dictionary.com/browse/metaphor

acknowledges and endorses Bohr's 'extension project' and then continues with his own line of argument on the potential of complementarity as a general economy, Barad harshly attacks Bohr for being suspect of applying arguments made specifically for microscopic entities to the macroscopic world. That is, she accuses him of following an analogical approach. Furthermore, she contends that his analogical strategy often failed, "both because he proposed a set of variables that turned out not to be complementary, and because the implications drawn on this basis watered down the complexity and richness of the *epistemological lessons*."[287] In this respect, and as discussed in chapter VI, I agree with her that complementarity in its most experiential sense cannot serve as a basis of any kind of complementary relations. As an alternative to Bohr's presumably analogical account of complementarity, she proposes her AR as surpassing this analogical fashion, as a theory that takes on a set of epistemological commitments such as the conditions for objectivity, the appropriate referent for empirical attributes, the role of natural as well as cultural factors in techno-scientific and other social practices, the nature of bodies and identities, and the efficacy of science.[288] Funnily enough, she calls her epistemological commitments 'widely *applicable* philosophical issues'.[289] Therefore, even if her approach is –as seen in chapter III– novel and exciting, her critique of Bohr is inconsistent. As a final note, it is not only her own statements which are contradictory; many humanities and social sciences scholars have missed AR's motivation or working methodology and have, in turn, tried to use an application logic with AR.[290]

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In my view, Bohr does not speak of applicability but of parallelisms. Thus the importance of Bohr's demand that "each field of knowledge and interest should investigate which are its own conditions for the analysis and synthesis of experience."[291] The line between the two is blurry, and given his obscure language and sometimes contradictory remarks, even dangerous. Of course, due to him being a physicist much attention has been paid to his complementarity principle as formulated after Heisenberg's uncertainty relations. As a physicist, it is not strange that he was convinced of the significance of physics for "testing the foundation and scope of some of our most elementary concepts."[292] Nonetheless, in the previous chapter I have shown that, at least as regards his thoughts about consciousness, complementary views of quantum physical phenomena did not precede his views on 'psychological complementarity', to give it a name.

[287] Barad, *Meeting the Universe Halfway*, p. 70.
[288] Barad, Ibid., p. 70.
[289] Emphasis mine.
[290] To topics as random as fashion, selfies, placentations or even liberation theology. See Parkins, "Building a feminist theory of fashion" (2008), Scott, "Placentations" (2014), Mamic, "AR as a methodological foundation for a new historical Project of Liberation Theology" (2015) and Warfield, "Making the Cut" (2016)
[291] Bohr, "Discussion with Einstein," p. 24.
[292] Bohr, *PWNB*, Vol. 3, p.1.

In order to assess my claim, let me gather some of his most outstanding quotes on complementarity beyond the disciplinary silo of physics. For instance, referring to the contentious object-subject distinction in psychology, Bohr contends:[293]

> I hope, however, that the idea of complementarity is suited to characterize the situation, which bears *a deep-going analogy* to the general difficulty in the formation of human ideas, inherent in the distinction between subject and object.

Bohr is really concerned about the problem of consciousness. Concerning the relationship between the object of study and the presumed researcher of an investigation, when talking about anthropology he reminds us that we are confronted with a particular problem of observation, which upon closer consideration "*shows many features in common* with atomic or psychological problems, where the interaction between objects and measuring tools, or the inseparability of objective content and observing subject, prevents an immediate application of the conventions suited to accounting for experiences of daily life."[294] These conventions, as remarked in the previous chapter, refer to the traditional idea that a line object-subject can be unproblematically drawn. And yet in another excerpt related to biology and sociology he continues:[295]

> The epistemological lesson we have received from the new development in physical science, where the problems enable a comparatively concise formulation of principles, may also *suggest lines of approach in other domains of knowledge where the situation is of essentially less accessible character*. An example is offered in biology, where mechanistic and vitalistic arguments are used in a typically complementary manner. In sociology, too, such dialectics[296] may often be useful, particularly in problems confronting us in the study and comparison of human cultures… Recognition of complementary relationship is not least required in psychology, where the conditions for analysis and synthesis of experience exhibit *striking analogy* with the situation in atomic physics.

In this excerpt, there are a few things that are worth-mentioning. Bohr speaks of physics as suggesting 'lines of approach' to biology and sociology, which he acknowledges, are "of essentially less accessible character." That is, he admits that the problems arising in each of these fields are of different nature. Therefore, what he demands is a use of the *dialectics* of complementarity. Although it is truly complicated to draw a line between analogy and application, in view of the above quotations I would like to encourage a more

[293] Bohr, "The Quantum Postulate," p. 590.
Emphasis mine.
[294] Bohr, "Natural Philosophy and Human Cultures," p. 271.
Emphasis mine.
[295] Bohr, "On the Notions of Causality and Complementarity," p. 54.
Emphasis mine.
[296] Dialectics as in use of a complementary rhetoric.

nuanced reading of Bohr, one that turns away from the idea that his complementarity principle should be treated as a methodology to be applied everywhere and instead pays attention to Bohr's unified view of knowledge[297] and his consequently understandable search for *similarities* between areas of knowledge:[298]

> By such a comparison it is, of course, in no way intended to suggest any closer relation between atomic physics and psychology, but merely *to stress an epistemological argument common to both fields.*

That is, there is an epistemological argument underlying these fields –or physics and psychology, if we limit ourselves to the quote just presented. Note that a strict sense of application does not sit well with these two intricately linked observations, for it would imply that Bohr devised knowledge as hierarchically structured –a claim for which we have no evidence–, a structure in which physics would be attributed a privileged role. Rather, I read Bohr as proposing a formal framework based on complementary relations. The word 'formal' is of utmost importance here. Even though there are some complementary relations that have been recurrently studied in many disciplines (subject-object, knower-known, micro-macro) and therefore have higher chances of reappearance, Bohr does not presuppose a fixed model of complementary relation that should guide our (un)knowing practices. His framework is formal, not contentual. As already emphasised, he demands that we all search for each field's complementary relations that govern its theoretical apparatus –its theoretical matrix, using Plotnitsky's terminology.

Finally, I would like to assess and consider the other possibility mentioned: that of treating Bohr's complementarity metaphorically. Plotnitsky so does and, despite the fact that Barad renounces to further take on complementarity and comes up with a new theory instead, scholars in critical theory –Barad included– have resorted to another metaphor from the physical sciences: that of diffraction. Although in principle it would seem harmless to give complementarity the status of 'metaphor', the concept of metaphor still manifests traces of reflexivity. Despite all the criticism of reflexivity put forward in the name of anti-Representationalism and, in general, of the authoritative role science (especially physics) has long been attributed, we keep securing our knowledge in both the humanities and the social sciences and in public discourse about knowledge and truth through the use of (even if metaphorical) 'frameworks' from the natural sciences. Therefore, I would discourage any understanding of Bohr's complementarity principle as either a literally or metaphorically applicable framework and encourage instead, as expressed, the viewpoint of Bohr's complementarity as a theoretical framework to be duly explored in each field of knowledge.

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[297] Note that this is more of a humanist view of knowledge that nonetheless does not aim at synthesis. Remember that he conceived the whole not as composed of complementary parts; rather, he suggested that we treat the relevant parts of each experimental situation as complete.

[298] Bohr, "Natural Philosophy and Human Cultures," p. 270.

As a final remark, I would like to point out that regardless of the status we give to complementarity, Bohr was clearly and explicitly asking for a renunciation of causal explanations, incapable of successfully answering the demands of the problems of observation we encounter in many fields. The impossibility to draw sharp divides between the relations object/subject, knower/known micro/macro (which Bohr proposes to examine in a complementary way) signals a failure of traditional causality. In reverse, a failure of causality demands a re-thinking of the metaphysics behind the phenomena observed. In a more implicit way, he emphasised the need to re-think classical physics (classical thinking) and classical meta-physics (classical meta-thinking).

Summary and Conclusions

In this thesis, I have tried to show how Bohr's physics-philosophy, encapsulated in his complementarity principle, challenges the dichotomies that have underlain modern intellectual history. I have contended that its significance should not only be restricted to the domains of physics. Complementarity, as ultimately an (anti-)epistemological attitude, shall be examined within larger debates on the nature of knowing and being. Bohr, aware of the problem of perception, narrowed the distance between subject and object, the most momentous of the Cartesian divides. Although for him the observer is still, as in classical epistemology, the condition for the possibility of objective knowledge, she is not the traditional knower of classical physics and metaphysics. Within the theories that co-form the Copenhagen Interpretation of Quantum Mechanics, it is difficult to determine what constitutes an 'observer' or an 'observation'. Nonetheless, it is clear that Bohr's thought suggests an awareness of the impossibility to detach *the subjective* from *the objective*, to understand them as separate categories. The experimenter chooses the setup to be employed in a particular experiment, thus deciding on the cut between what the object and the measuring instrument will be. At the same time, the experimenter communicates the results of physical observations, thus becoming part of Bohr's notion of objectivity, defined as reproducibility and unambiguous communication of the experimental results of phenomena. I believe the subject/object dichotomy to be still underexplored in physics and therefore I suggest that objectivity must be deeply re-thought in order to bring in subjective elements, which are an undoubtedly relevant part of scientific practice. It is in this respect that Bohr's work was visionary. The second of the divides I have assessed, that of knower/known, is inherently linked to the former, and therefore falls within the same line of argument.

EPR-Bohr's debate on the locality and completeness of quantum mechanics allows us to immerse ourselves in Bohr's ideas on the nature of reality and his view of measurements and their implications. According to these ideas, a complete description of reality need not involve simultaneity; quantum mechanical descriptions are as complete as they can be under available experimental, technological and theoretical conditions involved in the account of any phenomenon. It is in relation to this last concept that EPR-Bohr's debate is of utmost importance. Since 1935, Bohr included the interaction between the object –the physical system– and the agencies of observation –the apparatuses– in his account of phenomena. This interaction signals the insufficiency of classical concepts and classical language to explain the intrinsic indeterminacy of quantum phenomena, a novel feature of physical phenomena marked by Heisenberg's *uncertainty* relations and subsequently characterized by Bohr's complementarity principle. The language of classical physics remains necessary, our only means to describe *the world*, but we have to bear in mind that what we refer to are amplifications of quantum phenomena. Quantum mechanical *objects* are inaccessible, and therefore ontologically trifling. Our new onto-epistemological referents should be physical phenomena in their totality.

As the title of this thesis hints, my aim was not only to assess Bohr's work in isolation, but to relate it to contemporary scholars who have close-read him in order to build upon some of his work's aspects. There are many scholars who have offered their own interpretations of the physicist's insights, but only a few who have tried to go beyond the edges of physics and to explore Bohr's work's full potential from a primarily philosophical perspective, focusing on the questions of what do we know, how do we know and what it means to know in the first place instead of limiting their analysis to the superficial labelling of his position as realist/anti-realist/idealist/pragmatist/ instrumentalist or any other that has been attributed to him. In this respect, Karen Barad and Arkady Plotnitsky have offered unique and profound approaches, sensitive to the aforementioned questions. They both try to overcome positions that ultimately fall within traditional and fixed categories, reason why I have called their endeavors 'postmodernist'.

In chapter III I introduced Karen Barad's theory of Agential Realism. Barad does not endorse Bohr's notion of complementarity, for in her view it is restricted to physics, and therefore she is critical about it. Her aim is to develop a theory that may be used to explore the theoretical apparatuses of all fields of knowledge without falling into application logic. Alternatively, she inherits Bohr's notion of phenomenon and incorporates ideas from Continental philosophy and feminist theory to shape her framework. Hers is a daring and full-fledged account that aims at overcoming Cartesian epistemology. Despite the intricacies of her position, I hope to have successfully shown how it blurs the divide between subjects and objects, all actors part of *spacetimemattering*, humans and non-humans, all in the same causal plane, knowers and known, a relation which does not correlate to humans and non-humans, and material and discursive, none prior to the other. This blurring I deem insightful because it gets rid of all the inconsistencies arising from the assumption of such divides. Moreover, her condition of objectivity –agential separability– ensures that human beings do not stand in a relation of exteriority to the natural world. We are actors and spectators *in* and *of* that nature we seek to understand. We know *in* being. Nonetheless, having focused on the epistemological-ontological import of her theory, I have contended that her talk of intra-actions does not sufficiently explain the nature of change, which is no other problematic than the nature and evolution of time, one of the most central questions in philosophy ever since humans have tried to rationalise their existence.

As a consequence, in chapter IV I introduced complex systems in order to explore the notion of change in Agential Realism. Due to their non-linear causality, complex systems are often used by new materialists to support their views. Nonetheless, I believe there is a respect in which connectionist complex systems succeed in accounting for change, while AR fails. I bring in Astrid Schrader's work on Barad with the intention to back up my claim that AR does not pay enough attention to the temporal dimension of intra-actions. Moreover, I believe complexity helps us understand that there is no fundamental divide between a micro-world and a macro-world, the last divide with which I am concerned, and therefore I encourage a quantum fundamentalist view of Bohr. Quantum indeterminacy is only visible at very small scales of the size of Planck's constant. But that does not mean it is not at the basis of all matter of which we are also made of. We are actors and spectators *in* and *of* that nature we seek to understand.

Next, I have familiarised my readers with Arkady Plotnitsky's work. Plotnitsky defends that Bohr's complementarity should be viewed as a general economic theory in Georges Bataille's sense. He argues that general economies are anti-epistemological theories concerned with the losses of representation and meaning of quantum mechanical theories with respect to classical theories, losses which are the *efficacity* 'of all possible meaning.' In contrast to classical theories, quantum mechanics –and complementarity more specifically– are nonclassical theories, that is, theories about both knowledge and the irreducible unknowledge of everything that is beyond conception and representation. Furthermore, they are material theories, in the sense that they are attentive to the realisation that matter cannot be treated independently from the concepts of experimental finding (observation, measurement) and theorization (interpretation, theory). Finally, Plotnitsky's work is crucial with respect to the question of application, to which I have devoted in the last part of my thesis. As a general economic theory, Bohr's complementarity can be seen as a framework or matrix that provides a metaphorical model for the social sciences and the humanities, as well as a theory constraining other general economies.

In order to better evaluate whether Bohr aimed at applying complementarity to other fields of knowledge beyond physics, in chapter VI I have analysed his sketchy remarks on complementarity in psychology, biology and even anthropology –as we name these fields nowadays. As can be gleaned from the assessment of this literature, and as also stated by some other authors (Plotnitsky and Bala among them), Bohr seemed to speak of complementarity in two different senses. First, he referred to the complementarity between wave and particle, a type of complementarity I have called *conceptual*. Second, and especially after the debate with EPR, he talked about the complementarity between non-commuting variables, a type of complementarity I have deemed *experiential*. Even though in view of a quantum fundamentalist reading of Bohr this experiential kind of complementarity affects all matter in the universe, in chapter IV we have seen that the world we live in suffers from a problem of complexity. Therefore, at scales higher than the quantum of action it is meaningless to speak of this most experiential kind of complementarity. Nonetheless, although not exclusive from physics, complementarity as a mutually exclusive but equally necessary kind of relationality might be a good theoretical tool with which to explore philosophical matrices.

Last, I have discussed the question of whether Bohr talked about application. Although many have argued that he had an incomplete project to apply complementarity elsewhere, while not harshly denying it I would like to suggest a more nuanced reading of Bohr's complementarity. The existence of the quantum of action had become a clear example of the failure of causality, but prior to that he had been aware of the impossibility to causally describe certain aspects in psychology. We cannot confidently offer a strong conclusion in this respect, the only assertion we can make is that he spoke of parallelisms between fields of knowledge. Moreover, given the obscurity of Bohr's writings, I suggest cautiousness when speaking of application, a practice that, given its representationalist basis, and convinced by Barad's arguments, I have condemned. As a conclusion, Bohr demands that we all search for the complementary relations that govern each fields' theoretical apparatuses –their theoretical matrices, using Plotnitsky's terminology.

As a further line of research, I would like to explore the potential of Bohr's complementarity as a theoretical matrix that pays attention to each field of knowledge's assumptions and needs. This ties in with the initial research question of my thesis: whether complementarity can inform the field of feminist science studies. Complementarity has often been misconceived as regards the relation between the whole and its parts, but appropriately employed as a kind of mutually exclusive but equally necessary relationality, it may help understand other relations between apparently opposite pairs of concepts. In relation to feminist science studies, at this historical moment what we have are feminist critiques of existing science, but I am inclined to believe that we rather need to make the search for a *feminist science* our endeavor. What that would look like constitutes the nature of this vaster project. Nevertheless, it should undoubtedly start by the re-examination of the subject-object relation and the consequent re-definition of objectivity, just as complementarity does. In words of historian of science Elizabeth Fee, a feminist science would need that in the first place "we overcome the dualisms that feminists have identified as being associated with sexual dichotomies, such as the subject/object relation."[299] A feminist science would not create artificial distinctions between the theorization and practice of knowledge, between thought and feeling, between subject and object. A feminist science would be an alternative epistemological tool, one that would liberate science from the habits of thought inscribed by the separation of human experience into fixed realms.[300] In that respect, I see the insights gained through Bohr's complementarity (anti)epistemology, just as well as Karen Barad's Agential Realism, as a preliminary stage in the search of how a feminist science should look like.

[299] Fee, "Women's Nature and Scientific Objectivity," p. 25.
[300] Fee, Ibid., pp. 22-25.

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