UNIVERSIDADE FEDERAL DE SANTA CATARINA
CENTRO DE FILOSOFIA E CIÊNCIAS HUMANAS
PROGRAMA DE PÓS-GRADUAÇÃO EM FILOSOFIA

Raoni Wohnrath Arroyo

Discussions on physics, metaphysics and metametaphysics: Interpreting quantum mechanics

Florianópolis
2020

Raoni Wohnrath Arroyo

Discussions on physics, metaphysics and metametaphysics: Interpreting quantum mechanics

Tese submetida ao Programa de Pós-Graduação em Filosofia da Universidade Federal de Santa Catarina para a obtenção do título de Doutor em Filosofia.
Orientador: Prof. Décio Krause, Dr.
Coorientador: Prof. Jonas R. B. Arenhart, Dr.

Florianópolis
2020

Ficha de identificação da obra elaborada pelo autor,
através do Programa de Geração Automática da Biblioteca Universitária da UFSC.

Arroyo, Raoni
Discussions on physics, metaphysics and metametaphysics : Interpreting quantum mechanics / Raoni Arroyo ; orientador, Décio Krause, coorientador, Jonas Arenhart, 2020.
165 p.

Tese (doutorado) - Universidade Federal de Santa Catarina, Centro de Filosofia e Ciências Humanas, Programa de Pós-Graduação em Filosofia, Florianópolis, 2020.

Inclui referências.

1. Filosofia. 2. Metafísica. 3. Ontologia. 4. Mecânica quântica não-relativista. 5. Epistemologia. I. Krause, Décio. II. Arenhart, Jonas. III. Universidade Federal de Santa Catarina. Programa de Pós-Graduação em Filosofia. IV. Título.

Raoni Wohnrath Arroyo

Discussions on physics, metaphysics and metametaphysics: Interpreting quantum mechanics

O presente trabalho em nível de Doutorado foi avaliado e aprovado por banca examinadora composta pelos seguintes membros:

Prof. Christian de Ronde, Dr.
Universidade Federal de Santa Catarina (UFSC)
Universidad de Buenos Aires (UBA)

Prof. Jerzy Bzozowski, Dr.
UFSC

Prof. Osvaldo F. Pessoa Júnior, Dr.
Universidade de São Paulo (USP)

Prof. Otávio Bueno, Dr.
University of Miami

Certificamos que esta é a **versão original e final** do trabalho de conclusão que foi julgado adequado para obtenção do título de Doutor em Filosofia.

Documento assinado digitalmente
Ivan Ferreira da Cunha
Data: 03/04/2020 14:31:39-0300
CPF: 325.359.838-18

Prof. Ivan Ferreira da Cunha, Dr.
Coordenador do Programa

Documento assinado digitalmente
Decio Krause
Data: 09/04/2020 10:40:57-0300
CPF: 202.235.369-20

Prof. Décio Krause, Dr.
Orientador

Florianópolis, 09 de Março de 2020.

Para Ananda.

ACKNOWLEDGEMENTS

I wouldn't have been able to write this thesis without the love and support of these wonderful people:[1]

My parents, Koiote and Raquel;

My supervisor and co-supervisor, Décio and Jonas;

The staff at CSC, Decibel, Desembargador, La Khalo, Pacheco, PPGFil and Taliesyn;

The professors who kindly helped me, Adonai, Alexandre, Anjan, Cezar, Christian, Evandro, Frederico, Nazareno, Newton, Ivan, Jerzy, Osvaldo, Otávio, Patricia, and Peter;

My friends and colleagues at the Research Group in Logic and Foundations of Science (CNPq): Félix, Joanne, Lauro, Kherian, and Paola; my friends and colleagues at UFSC, André (both), Diego (both), Eduardo, Gustavo, Hiago, Jaaziel, Julio, Kaue, Karine, Luizinho, Márlon, Matheus, Ítalo, Renato, Robson, Sofia, Valdenor, Vinicius, Wu; my friends at Florianópolis: Alice, Aline, Billy, Bruna, Bruninho, China, Clóvis, Fernando, Fran, Gil, Gui, Lika, Lucas, Luli, Ismael, Jeca, Jonathan, Ju, Jupi, Karina, Karol, Mari, Maria Clara, Monka, Nelito, Päülïnhö, Pedro, Priscila, Rebeca, Rodrigo, Surivan, Suzi, Thiago, Turko, Vicente, Xiquinho;

My friends elsewhere: Adom, Alan, Alex, Allan, Aliny, Amanda, André (both), Anita, Ariel, Barbara (both), Barth, Bola, Brunão, Bruno, Buzina, Cainã, Camila, Carol, Carlão, Catarina, Cauê, Ceci, CH, Chapolla, Clara, Dandan, David, Deco, Diana, Digo, Du, Éderson, Emerson, Érika, Estêvão, Felipinho, Fernando, Fernanda, Ferraz, Foca, Funari, Gaba, Gary, Germano, Gilson, Giorgia, Giovana, Gui, Henrique, Herick, Iago, Iuri, Julia, Juliana, João Paulo, Jonas, Jorge, Jow, Katia, Kleber, Laura, Letícia, Luli Francez, Luiz, Luiza, Leo, Lucas (both), Luckas, Mabel, Malfoy, Mamá, Marcelo, Marcela, Maka, Marião, Math, Monteiro, Nahuel, Nick, Nikolas, Nuno, Pablo, Paulo, Paulinho, Pedrinho, Pérola, Porco, Rapha, Renan, Robinho, Rod, Rustuk, Salomone, Samuel, Sasaki, Scott, Sérgio, Shara, Silvinho, Thales, Thais, Thaynã, Tiago, Tito, Thiaguinho (*in memoriam*), Ton, Tox, Vincent, Vini, Vitão, Wagner, William (both), Xand, Xebek, Yasmin, Zumbi;

My lovely partner, Maju;

My lovely daughter, Ananda.

Thank you all!

É nóis!

Raoni
Florianópolis, 2020

---

[1] This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior – Brasil (CAPES) – Finance Code 001.

“τὸ τί έστι”

(“the what it is”)

ARISTOTLE, Metaphysics, Z, 1030a.

RESUMO

Esta tese investiga o significado de interpretar a mecânica quântica não relativista e os limites filosóficos de tal interpretação. Buscando uma postura realista científica, um método metametafísico é expandido e aplicado na avaliação de interpretações rivais da mecânica quântica, com base na distinção conceitual entre ontologia e metafísica, para a escolha objetiva de teoria em discussões metafísicas relativas à mecânica quântica. Três casos são examinados, dos quais o método metametafísico determina quais são as alternativas *erradas* para interpretar a mecânica quântica em termos metafísicos. Os dois primeiros casos foram considerados como falhas por diferentes tipos de subdeterminação. No terceiro caso, diferentemente da subdeterminação, onde há muitas escolhas a serem feitas, uma “determinação nula” é proposta, de acordo com a qual não é possível haver escolhas metafísicas na literatura metafísica disponível. Considerando o que foi discutido, uma posição filosófica agnóstica é mantida, considerando a possibilidade de interpretar QM a partir de um ponto de vista do realismo científico.

Palavras-chave: Metafísica. Metametafísica. Ontologia. Realismo científico. Mecânica quântica não-relativista.

RESUMO EXPANDIDO

Introdução

Esta tese investiga o significado de interpretar a mecânica quântica não relativista e os limites filosóficos de tal interpretação. Diferentemente das abordagens lógicas às teorias científicas, nas quais a noção de “interpretação” é ligada às visões sintática e semântica, é argumentado que a mecânica quântica é um caso *sui generis* na qual o termo “interpretação” relaciona-se com a resolução de problemas nos fundamentos da teoria. Interpretar a mecânica quântica, sob essa perspectiva, gera teorias quânticas distintas, com contrapartidas ontológicas distintas, que podem ser interpretadas de modos metafisicamente distintos.

Objetivos

Buscando uma postura realista científica, um método metamafafisico é expandido e aplicado na avaliação de interpretações rivais da mecânica quântica não-relativista, com base na distinção conceitual entre ontologia e metafísica, para a objetiva escolha de teorias em discussões metafísicas relativas à mecânica quântica. Tendo em vista um objetivo sobretudo metodológico, o foco recai sobre duas interpretações da mecânica quântica não-relativista consideradas casos “fáceis” do ponto de vista da análise filosófica, por serem explícitas quanto aos seus comprometimentos ontológicos. As interpretações utilizadas como exemplos na tese são: a interpretação da consciência causal, pouco popular do ponto de vista da adoção por parte da comunidade científica, e a interpretação dos muitos mundos, bastante difundida. É importante lembrar que a mecânica quântica *não implica* na existência de universos paralelos ou consciências causais. Mesmo em casos nos quais interpretações da mecânica quântica são consideradas teorias científicas, é defendido que *a* mecânica quântica, entendida como uma única teoria científica independente de interpretações, é algo sem sentido.

Metodologia

Após uma breve revisão bibliográfica, são buscadas inovações conceituais para tratar problemas antigos de novas maneiras. Uma questão metodológica central é a distinção entre ontologia e metafísica, segundo a qual a primeira trata de questões existenciais e a segunda explica o que são as entidades encontradas na ontologia. O método metametafísico desenvolvido na terceira parte da tese exemplifica os limites do projeto de naturalização da filosofia com a ontologia, e mostra como é possível conhecer negativamente as opções metafísicas para interpretar a mecânica quântica. A principal estratégia para a aplicação do critério metametafísico é importar certas credenciais epistemológicas das teorias científicas para julgar quais teorias metafísicas não são aplicáveis na interpretação de conceitos científicos.

Resultados e Discussão

Três casos são examinados, nos quais o método metametafísico consegue determinar quais são as alternativas *erradas* para interpretar a mecânica quântica em termos metafísicos, isto é, quais são os perfis metafísicos incompatíveis com a teoria científica em questão. Os dois primeiros casos foram considerados como falhas por diferentes tipos de subdeterminação: no primeiro, perfis metafísicos fisicalistas são considerados incompatíveis com a formulação da mecânica quântica na qual a consciência do observador é causal, ao passo que encontra compatibilidade em alguns tipos específicos de dualismo metafísico. No segundo, a formulação fenomenológica da mecânica quântica é determinada compatível com somente um tipo de redução fenomenológica. No terceiro caso, diferentemente da subdeterminação metafísica, onde há muitas escolhas a serem feitas, é proposta uma “determinação nula”, de acordo com a qual não é possível escolhas metafísicas na literatura metafísica disponível. Com isso, propomos que um dos papéis da metafísica analítica contemporânea seja o de desenvolver novas teorias metafísicas que considerem diretamente para as teorias científicas as quais interpretam.

Considerações Finais

Ainda que teorias metafísicas feitas sob medida para a mecânica quântica cumpram o papel de explicar melhor certas abordagens de fenômenos microfísicos, não é possível livrar-se da subdeterminação na mecânica quântica. Há uma subdeterminação teórica quanto metafísica. Considerando o que foi discutido, uma posição filosófica agnóstica é mantida, considerando a possibilidade de interpretar a mecânica quântica a partir de um ponto de vista do realismo científico.

Palavras-chave: Metafísica. Metametafísica. Ontologia. Realismo científico. Mecânica quântica não-relativista.

ABSTRACT

This thesis inquires what it means to interpret non-relativistic quantum mechanics (QM), and the philosophical limits of this interpretation. In pursuit of a scientific-realist stance, a metametaphysical method is expanded and applied to evaluate rival interpretations of QM, based on the conceptual distinction between ontology and metaphysics, for objective theory choice in metaphysical discussions relating to QM. Three cases are examined, in which this metametaphysical method succeeds in indicating what are the *wrong* alternatives to interpret QM in metaphysical terms. The first two cases failed in doing so due to different kinds of underdetermination. In the third case, unlike underdetermination, where there are many choices to be made, a “null-determination” is proposed where there may be no metaphysical choices in the available metaphysical literature. Considering what has been discussed, an agnostic philosophic position is adopted concerning the possibility of interpreting QM from a scientific-realistic point of view.

Key-words: Metaphysics. Metametaphysics. Ontology. Scientific realism. Non-relativistic quantum mechanics.

LIST OF FIGURES

LIST OF ABBREVIATIONS AND ACRONYMS

CBI	Consciousness-based interpretations
CCCH	Consciousness causes the collapse hypothesis
CRCH	Consciousness recognizes the collapse hypothesis
FAPP	For all practical purposes
MMI	Many minds interpretation
MWI	Many worlds interpretation
OSR	Ontic structural realism
QM	Non-relativistic quantum mechanics
RS	Relative state interpretation

LIST OF SYMBOLS

QM^{bas}	Basic quantum theory
QM_{col}	Collapse quantum theory
QM_{bra}	Branching quantum theory

CONTENTS

INTRODUCTION: A “SMOKY DRAGON”

> “I think I can safely say that nobody understands quantum mechanics”
>
> RICHARD FEYNMAN
> *The Character of Physical Law*

This thesis focuses on the philosophy of non-relativistic quantum mechanics (hereafter, just “Non-relativistic quantum mechanics (QM)”).[2] But why QM? As Laura Ruetsche (2018, p. 293) remarks, QM is *the* perfect contender for contemporary metaphysical debates concerning scientific realism because of its empirical success. To point a few of its achievements:[3]

> [. . .] it explains the stability of the stable atoms and nuclei and predicts the decay rates of the unstable ones; it accounts for the different manifestations of matter such as gaseous, liquid and solid, metallic and insulating, magnetic, superfluid and superconducting; it forms the basis of our chemical knowledge; and it provides the conceptual framework of all contemporary models for the fundamental constituents of matter. (FRIEDERICH, 2014, p. 3).

Roughly speaking, scientific realism claims that science provides information concerning how the world is. Judging by its applications and the precision of its theoretical predictions for experimental phenomena yielded by QM, the theory can be market as one of the most empirically successful physical theories in the history of modern science. Thus, it makes sense to expect QM to tell us what the world is like, right? But yet, Richard Feynman (1965, p. 129) said that “[. . .] nobody understands quantum mechanics”. Why is that so? Curious as it may sound, the empirical success of QM does not lead to a single worldview. It has been argued instead that it leads to *plenty* of them. We fully disagree with such a position: QM is *compatible* with several worldviews but leads to none of them. In this sense, QM contradicts intuition even in relation to the most basic commonsensical conception that best scientific theories are epected to provide a worldview (for starters, this kind of expectation is the most basic scientific-realist stance). Operationally, QM is almost uncontroversial; its meaning, though, is not.

Let us (literally) draw the big picture. Wheeler (1986, p. 314) once famously characterized QM as a “[. . .] great smoky dragon whose tail is sharply defined, whose

---

[2] It should be clear from start that this study does not engage in any other scientific theory: relativistic theories, such as quantum field theories, are not even addressed. The focus here lies exclusively in non-relativistic quantum mechanics, since it suffices for the philosophical discussion presented, which can be extended (with due qualifications) to the relativistic domains.

[3] We quote below Friederich’s (2014) list of *actual* applications of QM. The interested reader may also consult the list, made by Professor Newton da Costa (2019, pp. 91–92), of *possible* applications of QM.

bite is also well marked, but which in between cannot be followed". It is not by chance that Wheeler's smoky dragon resembles the famous Mach-Zehnder experiment, which illustrates one of the greatest problems in the foundations of QM: the measurement problem.

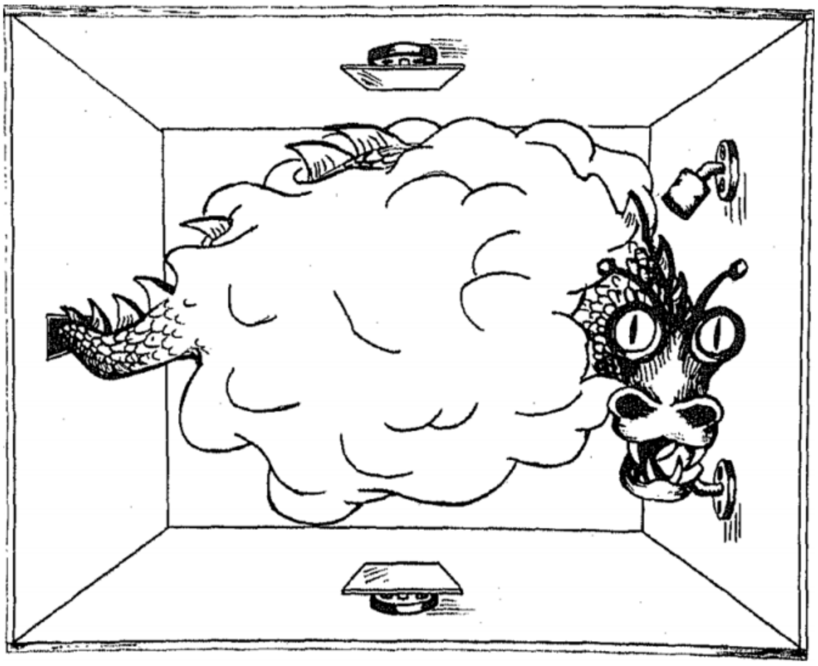

Figure 1 – The "great smoky dragon", extracted from Miller and Wheeler (1983)

The dragon's tail resembles the source of signals, while its head alludes to the detectors that capture the signals emitted by the quantum objects. These are uncontroversial parts: if one launches an electron, one can expect to capture a signal emitted from an electron, considering the experimental setup to be correct. However, what happens in the middle is not so simple. Which path did the quantum object take? What it is like? Was the detected object the same one that was launched? And one of the most controversial questions of all: what happens during a measurement process?

First, it is important to keep in mind that there are at least two types of measurement problems: (i) what happens in a measurement (Maudlin's problem), and (ii) what happens while the object is not being measured. Problem (ii) is tackled by Pessoa Junior (2003, p. 4), who presents a taxonomy that divides interpretations in four main groups:

Wave interpretations states that quantum systems are *waves*, and thus have wave-like behavior such as manifesting interference patterns.

Corpuscular interpretations states that a quantum object is a *particle*, which is manifest when detected.

Dualist/realist interpretations states that quantum systems are simultaneously waves *and* particles.

Complementarity interpretations which states that quantum objects manifest physical aspects (wave-like or particle-like) according to the experimental setup.

This thesis implicitly adopts a wave-interpretation stance, and therefore the problem (ii) of interpretation is not discussed here. I am concerned with problem (i), which relates to the stories that are told concerning what happens from the beginning to the end of experiments. Therefore, this study is driven not only by the smoky part, but by *the whole dragon!*

The main reason for the existence of a nine decades-old debate on the meaning of QM is centered around the concept of “measurement” in QM. For many, the controversy lies in the detection element. I resist this idea, arguing that detection is common ground in every approach to QM: all views lead to the same experimental outcomes. The reasons why it happens, however, remain non-consensual. In this work, the interest lies particularly in the *in between*, considered the backbone of quantum mechanics interpretation:[4] there is no certainty regarding what happens in such a smoky area.

This is no reason to discourage scientists and philosophers, as there is no need for a *unified theory of everything* in order to legitimate speculate about scientific theories. We can fight with what we have, and we have QM. Numerous attempts to *understand QM* were developed, and here we will present and try to evaluate some of these attempts using philosophical standards.

There are no established ways to compared different interpretations of QM using purely scientific criteria (physical, mathematical, or else): all interpretations of QM considered in this work account for experimental phenomena in the same equivalent manner. Therefore, there is no experimental reason for believing in one interpretation instead of another. This familiar worry is called “underdetermination”. In this thesis, I am concerned with the here called “*interpretational underdetermination*”: QM does not determine its interpretation. In this sense, this work discusses theoretical, ontological, metaphysical *and* structural underdetermination.

As means to address interpretational underdetermination in its completeness, this thesis employs an increasingly common – but by no means standard – distinction between “ontology” and “metaphysics”.[5]

The main motivation for employing such a distinction lies in metaphysical and methodological debates on the relationship between philosophy and science, as well as in metaphysical debates concerning scientific realism. In order to launch us at the head of the debate, it is possible to follow Thomas Hofweber in general lines, who distilled such a distinction in its essence.

---

[4] That is, the term “interpretation” as in the sense (i) that we began to define in the previous paragraph.

[5] See Arenhart (2012, 2019), Berto and Plebani (2015) and Tahko (2015).

> In metaphysics we want to find out what reality is like in a general way. One part of this will be to find out what the things or the stuff are that are part of reality. Another part of metaphysics will be to find out what these things, or this stuff, are like in general ways. Ontology, on this quite standard approach to metaphysics, is the first part of this project, i.e. it is the part of metaphysics that tries to find out what things make up reality. [. . .] Ontology is generally carried out by asking questions about what there is or what exists. (HOFWEBER, 2016, p. 13).

Thus, this is a matter of disciplines. Metaphysics is the widest one, dealing with the most comprehensive questions about reality. Ontology, in turn, is a part of metaphysics related to that what exists. Under the risk of stating the obvious, ontology poses the ontological question: "*what there is?*" while metaphysics asks "*what are those things that there are?*" – hence, "the *what* it is" (ARISTOTLE, Z, 1032a).

Therefore, the role of philosophy needs to be analyzed in order to better understand QM. This does not imply an attempt to solve the problems of interpretation that plague QM from its foundations. Instead, the focus lies on finding legitimate venues for philosophy in the debate and seek available options for interpreting – and thus understanding – QM in philosophical terms.

This work focuses on evaluating metaphysical theories associated with QM, through the proposal of a metametaphysical method focusing on relatively "simple" cases. The choice of almost unpopular interpretations of QM in terms of adherence by the physics community was founded in the sheer array of philosophical problems existing around them. Perhaps, if it is possible to apply the method presented here to seemingly easier cases, it might be possible to apply it to increasingly difficult cases in the future.

In this sense, the interpretation that posits human conscious action in quantum systems and the interpretation that posits infinite branchings of the universe seem to constitute fitting candidates for a metametaphysical evaluation. Nevertheless, the reader of this thesis should bear in mind that the cases analyzed in the QM *are not* the only possible cases, but cases in which the philosophical problematic is evident (perhaps more so than in other solutions more accepted by the scientific community). This work attempts to simply compare between the cases, thus focusing in the methodology of interpretation of QM and its philosophical perspectives.

In order to do so, this thesis is structured in three parts. Part I deals with problems in logic, mathematics and physics. 1 attempts to provide a precise account of what it means to interpret QM, following the traditional characterization of scientific theories following syntactic and semantic views. Chapter 2 presents a characterization of QM using set theory as a tool, showing how QM leads to the measurement problem and how interpretations are essentially solutions of such foundational problem. The terminology and examples adopted in Chapter 2 are employed throughout the thesis.

Part II deals more directly with philosophical issues. Chapter 3 explicitly confronts such issues with the debate concerning scientific realism. Chapter 4 deals with the characterization of the place and necessity for ontology and metaphysics in the interpretational debate within QM related to scientific realism. I also present considerations regarding the philosophical aspects of interpretations presented in Chapter 2

Finally, Part III deals with the evaluation of ontological and metaphysical possibilities that raises interpretational underdetermination in QM. Chapter 5 expands the “meta-Popperian” method by Jonas Arenhart (2012) to a metametaphysical method for theory choice in metaphysics related to science – which is now labeled as the method of “Unavailable Metaphysical Stories”. The next chapters present applications of this method. Chapter 6 the focus falls on narrowing the metaphysical options in order to interpret Wigner’s (1983) interpretation of QM, as well as more precisely present kinds of metaphysical options that are not compatible with such interpretation. Chapter 7 concentrates on London and Bauer’s (1983) interpretation, dismissing a phenomenological approach as an incompatible metaphysical profile for their formalism. Lastly, Chapter 8 presents another application of the method, considering DeWitt’s (1971) interpretation of QM, showing that there are no metaphysical options available for metaphysically profiling it thus far. In this chapter, a new problem is posed for scientific realism: contrary to metaphysical underdetermination, which occurs when there are numerous metaphysical options for interpreting a theory, it was identified the lack of metaphysical options also poses a problem to scientific realism: after all, without saying what are the objects with which the theory is existentially committed, what is its realism is about?

Since the measurement problem is crucial to this discussion, this work adopts the strategy of diluting its formulation instead of condensing it in one place, so that several chapters deal with different aspects of this foundational problem. In Chapter 2, the problem is presented in Maudlin’s (1995) standard taxonomy; in Chapter 4, we state the problem by describing a famous experiment, the Mach-Zehnder interferometer; in Chapter 5, we briefly state the famous thought experiment of Schrödinger’s cat, revisited in more detail in Chapter 8; in Chapter 6 we state the problem via Heisengerg’s cut; the same formulation of the problem is revisited in Chapter 7 through von Neumann’s chain.

This thesis is concluded with a somewhat detailed revision of what was achieved (and what was not). Finally, we return to the “smoky dragon” analogy in order to draw some speculative reflections concerning the efforts of interpreting QM in metaphysical terms.

Part of the material presented here was previously published in the following events, papers and chapters:

- Part of Chapter 1 was presented in the III Colóquio de Pesquisa em Filosofia da

UFSC, held in Florianópolis, Brazil, in 2019, by the title of “Da Lógica à Física: Interpretando a Mecânica Quântica” (ARROYO; FLAUSINO, 2019); written and presented in co-authorship with Joanne Flausino.

- Part of Chapter 2 was presented in the VI Workshop on Quantum Mechanics and Quantum Information: Identity and Individuality, held in Florianópolis, Brazil, in 2019, under the title “Building Quantum Theories” (ARROYO; GRACHER, 2019); written and presented in co-authorship with Kherian Gracher.
- Part of Chapter 4 was presented in the 11th Principia International Symposium, held in Florianópolis, Brazil, in 2019, under the title “Floating free from physics? The metaphysics of quantum mechanics” (ARROYO; ARENHART, 2019b);[6] written and presented in co-authorship with Jonas Arenhart.
- Part of Chapter 5 was presented on the IV International Workshop on Quantum Mechanics and Quantum Information, held at the Federal University of Santa Catarina in 2017, under the title “On physics, metaphysics and metametaphysics” (ARROYO; ARENHART, 2017b), written and presented in co-authorship with Jonas Arenhart.
- A modified version of Chapter 6 appeared in the volume called “Quanta and Mind”, edited by José Acácio de Barros and Carlos Montemayor, as a chapter entitled “Between physics and metaphysics: a discussion of the status of mind in quantum mechanics” (ARROYO; ARENHART, 2019a) that was written in co-authorship with Jonas Arenhart.
- An early draft of Chapter 7 was presented in the 10th Principia International Symposium, held in Florianópolis, Brazil, in 2017, by the title of “Underdeterminations of Consciousness in Quantum Mechanics”. Later, part of the chapter was published in the Principia: an international journal of epistemology by the title of “On Quantum Mechanics, Phenomenology, and Metaphysical Underdetermination” (ARROYO; NUNES FILHO, 2018), written and presented in co-authorship with Lauro Nunes Filho.
- An early draft of Chapter 8 was presented on the 1st Colloquium on Image and Imagination, held in Florianópolis, Brazil, in 2017, by the title of “Quantum mechanics, many worlds and fiction” (ARROYO; ARENHART, 2017a), written and presented in co-authorship with Jonas Arenhart.

I am very grateful to my co-authors and relevant publishers for permission to use and re-write this material. One last thing: from now on, the pronoun “we” will often be used in place of the pronoun “I”, except when expressing the author’s own opinion.

---

[6] To appear in the World Scientific book edited by Christian de Ronde.

Knowledge is a product of humanity, and therefore collective. There is no “I” in “team”.[7]

---

[7] Except for any errors that may be contained herein. These are entirely my responsibility.

Part I

ON PHYSICS

1 INTERPRETING SCIENTIFIC THEORIES

What is a scientific theory? In principle, if one desires to inquire about the interpretation of quantum *theory*, this seems a good place to start. Redhead (1987, p. 69) stressed that "[. . .] the word 'interpretation' is used with a number of different senses in philosophy of science". We begin our work, then, by revisiting the syntactic-semantic debate in order to present a more precise account for the endeavor of *interpreting* QM.

The search for a characterization of scientific theories has occupied much of the debate in contemporary philosophy of science. Since the 20th century, it is widely accepted that the quandary revolves mainly around two formal characterizations of the concept of a "scientific theory": a *syntactic* and a *semantic view*. Simply put, the debate unfolds as follows: in syntactic approaches, scientific theories are identified as sets of formalized sentences and some connection rules; in semantic approaches, scientific theories are identified as classes of models. The main question is: which view is best?[1]

Historically, the syntactic view ascended and declined along the Logical Empiricist program, while the semantic view flourished with the development of model theory (mainly due to Tarski's work). Semantic views, then, are considered to be the current *new orthodoxy*,[2] even though the syntactic approach still gathers numerous followers to this day.

Unfortunately, the transition in the dominant view took place based on somewhat misleading standards regarding the syntactical approach.[3] The whole endeavor of the syntactical approach was identified by a *straw man* version of it – that is, frequently attaching several highly implausible theses to it.[4] This fact can be characterized as a case of "Received View on scientific theories", as termed by Putnam (1966, p. 240), which is a sort of *automatic identification* of any approach to scientific theories, in particular, the syntactic approach. A similar situation is frequently happens with the semantic approach, in such a manner that Krause and Arenhart (2016b, p. 1) state that "there was not really a debate". Therefore, distinguishing between straw man aspects of each approach and their fundamental characteristics seems to pose as a good warm up for this discussion. In order to do so, we divide the approaches in two further groups:

1. *radical* and *moderate* syntactical approach;

2. *radical* and *moderate* semantic approach.

As we shall see, contemporary debate shows that the radical versions of both approaches are untenable, while their moderate versions converge, thus regarding them

---

[1] For early prospects on the debate, see Suppe (1977).
[2] See Contessa (2006).
[3] See Lutz (2015) and Krause and Arenhart (2016b, §1).
[4] See Lutz (2012).

as complementary rather than rivals.[5] This statement somewhat sketches our commitment to a theoretical stand in such debate. However, before focusing on this matter, let us present the discussion in more detail, starting from the syntactical approach.

1.1 THE SYNTACTICAL APPROACH

Among the main tenets of the syntactical approach is the formal treatment of scientific theories as an axiomatic calculus. The broader sense of the syntactical approach, however, is characterized in numerous ways according to the radical and moderate approaches.

The radical syntactical approach

As mentioned before, the syntactical approach has been wrongly identified exclusively with regards to the *radical* syntactic approach in the past. Mainly rooted in the theses put forth by several members of the Vienna Circle (such as Carnap and Hempel), the radical syntactic approach to scientific theories is characterized by five main requirements, succintly presented by Krause and Arenhart (2016b, p. 4):

Language: The non-logical vocabulary of the scientific formal language is divided in two parts: the *theoretical terms* (V_T) and the *observational terms* (V_O), being the latter related to empirical phenomena and the former *prima facie* not.

Logic: The formal language has a set of logical axioms, which gives rise to its underlying logic.

Theoretical axioms: A set of V_T sentences that are taken as axioms.

Semantics for V_O: Empirical entities are informally connected to V_T, which is related to a theory of meaning based on a criterion of verifiability.

Correspondence rules: A partial interpretation connects V_T to V_O, that is, relates purely theoretical parts of scientific theories with empirical data.

From this perspective, the radical syntacticist answer to the million-dollar question of “what is a scientific theory?” is: *an axiomatic calculus with theoretical axioms connected to empirical observation by means of correspondence rules*. This also explains the meaning of interpreting a theory: to *interpret*, then, is to connect the theory with entities in the world according to specific rules. As the name suggests, the *theoretical* vocabulary V_T corresponds to non-observable objects, while the *observational* vocabulary V_O relates to objects that can be directly observed by an experimental arrangement. This is, perhaps, the most intuitive way to see the distinction within the use

---

[5] See Halvorson (2012, 2013), Lutz (2015), and Krause and Arenhart (2016b, §1).

of a formal language: whereas the entities designated by V_O can, at least in principle, be *observed*, the entities designated by V_T can only be obtained by means of a mathematical formula. Consider, for example, the concept of "density" (D): in basic chemistry textbooks, it is said that *density is the ratio of the mass* (m) *to the volume* (v) *of a given material (solid, liquid or gaseous)*, yielding the following equation: $D = \frac{m}{v}$. Notice that the physical quantities m and v can be measured by means of measuring devices, thus counting as *observational terms*,[6] whereas D can be indirectly obtained through the equation, therefore constituting an example of a *theoretical term*.

These features were subject to criticism, inasmuch as the radical syntactic approach has historically been closely linked to the Logical Empiricist program.[7] Suppe (2000, p. S103) forged a very succinct list of six reasons that led to the decline of the radical syntactic view. According to the authr, the two most serious objections related to the view are the untenability of its observational-theoretical distinction and a "[...] confusion of meaning relationships, experimental design, measurement, and causal relationships some of which are not properly parts of theories" concerning the correspondence rules.

The most criticized, if not the most controversial, aspect of the radical syntactic approach lies on the proposed division of vocabulary between observable V_O and non-observable (theoretical) V_T terms, a fundamental point for the effective application of correspondence rules. As pointed out by Dalla Chiara and di Francia (1979, pp. 148–149), a simple observation of a fish through an aquarium, per example, may be considered a *theoretical term* to some extent, inasmuch the lens precludes a *direct observation* required for V_O. Similarly, Krause and Arenhart (2016b, p. 5) point out that a purely theoretical term, such as "electric current", could be, in principle, directly experienced simply by putting one's finger inside an electric socket (something that no one should do!). Therefore, this distinction seems to be highly implausible, and as such does not seem fit to serve as foundation for scientific theories.

These aspects, responsible for bringing issues to the syntactic approach, are entirely *exclusive* of the radical approach, while also being somewhat disposable. Thus, it can be said that they do not configure essential traits of the syntactic view *per se*.

However, as one of the main tenets of syntactic approaches is the formalization of scientific theories according to a logical language, there is a line of criticism that encompasses the syntactic view as a whole: the restrictions made upon the very use of formal languages.

---

[6] We will try to clear up a confusion related to the terms "language" and "meaning". Terms are the linguistic representations for certain quantities – for example, the term "mass" designates the physical quantity known as mass. Measuring, thus, is related to quantities, not their linguistic representations. In this sense, terms cannot be measured.

[7] There is a huge literature discussing the matter. For the classical exposition an criticism of the "Received View", (here referred to as the radical syntactic approach) the reader should be referred to Suppe (1977). As we mentioned earlier, this work is retained to the most recent debate.

Such aforementioned *formal language* may be considered to be a *first-order* language.[8] This point is easily accepted to what concerns *formal theories* such as mathematics or logic, however, seems inadequate when considering formal description of scientific theories,[9] given that most contemporary scientific theories, such as QM, involve more than simple relations among elements of the domains.[10] Generally, order-1 structures encompass a non-empty domain D and distinguished elements of D, n-ary relations on D and n-ary functions on D. An order-n structure, $n > 1$, may encompass elements, relations and operations of higher orders, not only dealing with the individuals of D, but also with collections or properties of such individuals, and so on.

Moreover, the attempt of applying this kind of formalization to relatively complicated scientific theories would be impractical. Consider, example, a scientific theory such as QM: before formalizing the theory itself, one would first need to formalize several general ideas related to set theory, as well as the required mathematics (such as several topics of standard functional analysis, *e.g.*, Hilbert spaces, differential calculus, etc.). This kind of criticism makes the ideal of formalization useless for real scientific purposes, since this situation proves itself to be far from actual scientific practice – which is a serious constraint.

Nevertheless, as Lutz (2015) pointed out, there seems to be *no* textual evidence that the proponents of the radical syntactic approach restricted the language of formalization to order-1 structures. In fact, as Krause and Arenhart (2016b, p. 7) argue, order-n languages are frequently employed by proponents of syntactic approaches such as theory of types – see Carnap (1958). In addition, the alleged obligatory requirement of preliminary formalization from scratch seems not to exist – notably, there is no documentation of such requirement made by proponents of the radical syntactic approach, as Lutz (2015) remark. Therefore, this criticism seems to configure yet another straw man attack on the radical syntactic approach (LUTZ, 2012).

Lastly, it is relevant to address the criticism of the radical syntactic approach termed the "individuation problem". This objection states that the radical syntactic approach *identifies* a theory with regard to its *linguistic formulation*. But if theories are not linguistic entities (which does seem to be the case), the conclusion that follows is that theories are individuated incorrectly by the radical syntactic view. Similarly to several of the criticisms briefly presented in this section, the individuation problem would represent a severe drawback of the radical syntactic approach, were it legitimate, since it would render impossible to formulate the *same theory* using different vocabularies.

This, however, appears not to be the case, insofar as there seems to be *no evidence* that the radical syntactic approach is committed to this sort of individuation

---

[8] From this point forward, we will adopt the notation presented by Krause and Arenhart (2016b), who call first-order structures as "order-1", and high-order structures (*e.g.*, with $n > 1$) as "order-n".

[9] See, for instance, Suppes (2002, p. 4).

[10] See Krause and Arenhart (2016b, §6.1).

of theories based on formal vocabulary. It seems, in fact, that the radical syntactic approach does not necessarily promises to provide an explication of the concept of "scientific theory" in general. This seems to be yet another widespread misunderstanding concerning both syntactic and semantic approaches to characterization of scientific theories (KRAUSE; ARENHART, 2016b, p. 8). If it were to do so, such attempt would be made to fall since *not every scientific theory* is well developed to the point that allows it to be axiomatized as a formal system.

Following Lutz (2015, §5) and Krause and Arenhart (2016b, p. 9), proposals of the radical syntactic approach should be seen as a rational reconstruction of particular scientific theories (thus avoiding the individuation problem). This formal reconstruction, in turn, should be understood as an *ideal* rather than as a *criterion* of which theories *ought* to meet in order to be considered scientific theories.

The preliminary discussion here presented allow u to proceed to a more sensible conception of syntactical approaches, here referred to as a "moderate syntactical approach".

The moderate syntactical approach

As pointed out by Krause and Arenhart (2016b, p. 6), it is possible to refrain from most controversial aspects of the radical syntactical approach without forfeiting the syntactical approach: one is not obliged to adhere to a verificationist theory of meaning, per example, neither to accept the relation between theories and experience via specific rules of correspondence or the division of vocabulary between V_T and V_O in order to employ a syntactic view of scientific theories. As argued by Krause and Arenhart (2016b, p. 77), the radical syntactic approach is nothing but a "folklore", which has been "demystified" mainly by Lutz (2012, 2015).

This demystification of the syntactic view is not, however, widely known. The effort to rule out the most problematic features of the radical syntactic approach, while sticking to basic tenets of the syntactic view is precisely what constitutes the "moderate syntactical approach". Following Lutz (2015, p. 5) and Krause and Arenhart (2016b, p. 10), the main traits of the view can be presented as follows:

Formal language: A scientific theory can be presented in a formal language of order-n.

Theoretical equivalence: An equivalence between theories can be put forth, so that different formulations could count as the same theory.

Partial Interpretation: Some sentences of the formal language must be *partially interpreted* in the sense that the theoretical language of the theory refers to empirical objects, thus granting that the theory is an empirical theory.

The theoretical equivalence feature seems act as a clarification of the individuation problem allegedly presented in the radical syntactic view. Accepting the commitment to individuation of a theory as formulated in one unique language makes it possible to accept equivalent formulations of a theory.[11]

One does not need to commit to order-1 structures in order to present an axiomatization of a scientific theory – this can also be achieved in order-n structures, *e.g.* type theory. Before advancing in direction to the main goal of this work, however, it is fit to digress towards the notion of "axiomatization", which plays a central role within this discussion. So far, "axiomization" and "formalization" have been terms used interchangeably. However, as pointed by Suppe (1977, p. 110), that does not seem to be the case, thus being important for the discussion to distinguish both terms from this point forward.

Following Charles Parsons (1974, p. 27), "axiomatization" may be defined as an organization of a body of knowledge (such as a scientific theory) in order to clarify its structure, by singling out certain concepts as "primitive" (or "undefined") and others as "defined" or "derived". The main point achieved by such definition is the possibility of presenting the theory as a deductive system, in which certain propositions singled out as axioms may provide the deductive derivation of all other propositions. It should be remarked that the matter of axiomatization is marked by several misunderstandings concerning its corrigibility. In the traditional sense, named "concrete axiomatization", axioms are taken to be *sacred truths*, immutable by their own nature. Fortunately, this is not relevant to the current situation of mathematical development, which conversely defines axioms as expressions of tacit assumptions, in order to make them explicit. Quoting Dalla Chiara and di Francia (1979, p. 134): "[t]o *axiomatize* is not to *dogmatize*!". Once a theory is properly axiomatized, it can be interpreted within its axiomatic constrains, that is, the domain of interpretation is restrained to the situations in which the axioms are true. This observation leads to the *formalization* of a theory: for such an interpretation to be considered precise, one must replace its language by a formal (artificial) syntax – and that is the meaning of *formalize*.

As for partial interpretation, it is noteworthy to reiterate that this concept carries *no commitment* to specific correspondence rules, differently from the radical syntactic approach. Moreover the criticism to which this notion was subjected seems to disappear when the dichotomy between V_T and V_O is abandoned (SUPPE, 1989, §1). This line of thought renders the criticisms of Putnam (1966, pp. 244–248) and Achinstein (1968, pp. 85–91) regarding the Received View's *partial interpretation* inaccurate with concern to the *moderate* approach. The notion of *partial interpretation* shall be used here in the

---

[11] See Halvorson (2012, p. 191) for a development of this trait.

sense of attributing partial meaning to propositions,[12] *e.g.*, physical meaning.[13]

Moreover, as argued by Suppe (1989), this particular feature of the moderate syntactical approach makes sense *only* when attached to semantical concepts such as metalanguage:

> Since it would appear that little more can be said syntactically in the way of characterizing partial interpretation, if we are to find an adequate analysis of the concept, we must turn to semantic considerations. (SUPPE, 1989, p. 43).

In this sense, a physical theory can be said to be a *metatheory* inasmuch as it assigns physical meaning to a purely mathematical language that is not necessarily connected to anything but mathematics. The plot thickens right here, since this position corroborates the thesis enunciated previously: moderate versions of syntactic and semantic approaches converge, rather than compete with each other.

Let's take this hook to move on to the analysis of the semantic approach.

1.2 THE SEMANTIC APPROACH

The elemental aspect of the semantic approach is the identification of a scientific theory as a class of models. However, unlike syntactical approaches, there is no unified view called *the* semantic approach. Rather, there are several accounts on what "models" are, how they can relate to reality, and the role of formalized language in the characterization of scientific theories. For instance, according to Suppes (2002, §2.1), there are numerous ways to understand the concept of "model", *e.g.*, *iconic* models, *analogy* models, *logical* models, and others. Moreover, the followed question can be posed: is it the role of models to *represent* something? If so, *what* should them represent: phenomena, data, theories, or something else? Yet, what is the *ontological status* of models, that is, *what* are models? Are they physical objects, fictional, or purely formal set-theoretical entities?

Such debate is not part of the scope of this work,[14] but, notwithstanding, it focuses on a specific approach regarding models. Given this plurality, we adhere to the Suppesian set-theoretical development of models, called by Krause and Arenhart (2016b, p.11) the "hegemonic version of the semantic approach"; This choice is made mainly due to the fact, as put by da Costa and French (2000), "models" are said to be structures (of one kind or another) in all these accounts, and as such this notion may

---

[12] It is noteworthy to mention that the terminology of "partial interpretation" is employed here in a non-standard way. It shall not to confused with its standard meaning: if every elementary statement in a theory T has a correspondent in its models, then it is considered to be a "full interpretation"; otherwise, it is a "partial interpretation" (see HASKELL (1963, p. 48)).

[13] But not *philosophical* meaning. This matter shall be discussed in more dept in the following chapters.

[14] The interested reader may be referred to a general account of these problems in Frigg and Hartmann (2017).

configure a better path to the philosophical purposes of this study due to its generality.[15] Moreover, the goal here is to inquire about the semantic approach to scientific *theories* in general, and so it would be prudent to keep this inquiry self-contained in regard to the role of models as models of scientific theories.

Therefore, mentioning the concept of a "model", it should be assumed the acceptance of a set-theoretical entity, typically built in a set theory. In this context, this work proceeds by supposing a development inside the usual Zermelo–Fraenkel set theory. The following sections present the *radical* and the *moderate* version of this view of semantic approaches, beginning with a more *radical* stance.

The radical semantic approach

Considering such set-theoretical approach to models the following fundamental tenets the *radical* semantic approach are, according to Krause and Arenhart (2016b, p.11):

Reification: A scientific theory *is* a class of models.

Language independence: A scientific theory is language-independent.

Set theoretical structures: Models are understood as set theoretical structures.

According to say the radical semanticists, "scientific theories are classes of models", which, in the terms of van Fraassen (1980, p. 222), means to "reify" a theory. But from there arises the question: what, then, is a model? Traditionally, mostly due to Tarski (1956), a "model" $\mathcal{M}$ is defined as an ordered pair such as

$$\mathcal{M} = \langle D, \mathcal{I} \rangle$$

where the domain D is a non-empty set and $\mathcal{I}$ is the *interpretation function*. Intuitively, the interpretation function $\mathcal{I}$ involves the interpretation *of a language* $\mathfrak{L}$ (the object-language), which means assigning the function truth-values *in a metalanguage* trough mapping of the non-logical elements of a formal language, relating each symbol to an *element* in D, the domain of interpretation: individual *constants*, *functions* and predicate *symbols*. In this sense, to interpret a theory is to correlate a language with set-theoretical elements of a structure, in a purely mathematical manner.

More specifically, the standard textbook approach of this matter (CHANG; KEISLER, 1990, pp. 18–36) goes as follows: order-1 models are defined as structures in the form of the ordered pair $\langle D, \mathcal{I} \rangle$ (with the domain $D \neq \varnothing$), where the interpretation

---

[15] We must not lose sight of the main goal here, which is to make sense of the *interpretation(s)* of QM. Thus, the more general the approach of models, the better.

function $\mathcal{I}$ maps each one of the constant symbols c to a constant $x \in D$, each m-place function symbols F to an m-place function $G : D^m \longrightarrow D$ on D, and each n-ary relation symbols S to an n-ary relation $R \subseteq D^n$ on D. Constants and relations on D are *extensional* concepts, and thus two relations $\{R, R'\}$ are identical if they have the same extension, that is, if $\forall x\big[(x \in R) \leftrightarrow (x \in R')\big]$, then $R = R'$.[16] However, the existence of two different relation symbols $\{S, S'\}$ with the same extension of their interpretation is possible. If a structure $\langle D, \mathcal{I}\rangle$ contains an exclusive interpretation for multiple relation symbols $\{S_i\}_{i\in I}$ that maps every S to the same R, there would be only one relation, so its image would lead to $\langle D, \{R\}\rangle$. As remarked by Hodges (1993, pp. 1–4) and Lutz (2015, p. 11), this extensional account of relations is precisely the involvement with language. From now on, these kinds of structures, formalized with a vocabulary, will be called “labelled structures”.

As famously stated by van Fraassen (1989, p. 366), however, the independence of a specific language (*i.e.*, a syntax) should be a *fundamental* trait of the semantic view: without it, its motivation is lost when “[. . .] models are defined, as in many standard logic texts, to be partially linguistic entities, each yoked to a particular syntax.” Thus, the requirement of *language independence* seems to seriously constrain this traditional Tarskian-like account of models, since it is precisely “yoked to a particular syntax”. In fact, Halvorson (2012) argues that any appeal of language, *e.g.* the labelled-structure account of models, could reduce the semantic approach into a syntactic approach.

Moreover, the traditional characterization of ‘models’ via labelled structures is, very restrictive. Since it quantifies over *elements* of D, it only functions when considering order-1 structures, which are not able to comprise most of the best contemporary scientific theories. Thus, when adopting models for the characterization of scientific theories, this definition presents itself as problematic. As Bueno and Krause (2007) argued, the literature on models is elusive in this aspect, and any semantic approach which attempts to characterize scientific theories needs some sort of re-conceptualization when intending to characterize contemporary physical theories such as quantum mechanics. The major drawback presented by this stance is that a proper *model theory* needs to be comprised exclusively in order-1 structures: *strictly speaking, there is no model theory for order-n structures*,[17] since fundamental theorems of standard model theory (such as the Löwenheim-Skølem theorem)[18] only holds for systems of order-1 logic.

According to Krause and Arenhart (2016b, p. 12), the set-theoretical characterization of structures poses as the most common alternative for the traditional, language-

---

[16] Although Chang and Keisler (1990) work only with order-1 structures, the idea can be generalized.

[17] This is also the case for non-standard semantics, such as *Henkin semantics*, see Henkin (1950) and Enderton (2015, §3). Nevertheless, we will stick with the standard case.

[18] Roughly speaking, the Löwenheim-Skølem (1879) theorems state that order-1 theories have a countable ($\aleph^0$) model, implying that the theorems are unable to control the cardinality of their transfinite models. Thus, no order-1 theory (with transfinite models) can have a unique model (*up to* isomorphism).

dependent, account of models as labelled structures. Following this characterization, $\mathcal{M}$ is defined as a n-tuple such as

$$\mathcal{M} = \langle D, R_i \rangle_{i \in I}$$

where D is a non-empty set and R_i[19] stands for a *family of relations* on the elements of D. Note that R_i does not relate *only* elements of D, therefore it could give rise to order-n structures (with $n > 1$). As for the language-independence criterion, this type of structure is defined independently from a specific vocabulary when written as n-tuples containing a domain and a family of relations (comprised of functions and constants). This can be seen clearly in order-1 structures, trough the definition of the algebraic structure of "group". A group G may be written as $\langle G, \circ, e, - \rangle$, where: "$G$" is a non-empty set; "$\circ$" is a binary operation (the composition function on G); "e" is the neutral (identity) element; and "$-$" is the inverse (opposite) operation. As an example of an order-n structure there is the case of "topological space", written as the structure $\langle D, \tau \rangle$, with $\tau \in \mathfrak{P}(\mathfrak{P}(D))$, since τ is a family of subsets of D. In cases such as this, the family of relations R_i is interpreted as an *indexed structure*, so the structure could be written as $\langle D, R_0, \ldots, R_n \rangle$ and the position of the relations of D in the structure takes the role of the index, so that it could be read as $\langle D, \{R_i\}_{i \in \{1,\ldots,n\}} \rangle$. It should be noted that indexed structures contain more information than the image of an interpretation of labelled structures.

After clarifying the main tenets of the set-theoretical semantic approach, it is possible to present its application, based on the example made famous by van Fraassen (1980, pp. 41–44)[20] called the "seven point geometry", also known as the *Fano plane* (Figure 2). Suppose the need to present a theory T of a projective plane, where we take "point" and "line" are taken as primitive concepts presenting the following sentences as axioms:

1. For any two lines, there is at most one point lying in both.
2. For any two points, there is exactly one line containing both.
3. On any line there are at least two points.

Let $\{x, y, z, \ldots\}$ represent individual variables of a domain D, and $\{L, P\}$ represent unary predicates in a universe U consisting of lines and points, so that $L(x)$ means that x is a line, and $P(x)$ means that x is a point. It is possible, then, to present an unique metalinguistic scheme of order-1 comprising all three axioms as follows:

---

[19] Decomposed as $R_i = \langle R_1, \ldots, R_n \rangle_{n \in I}$, with $1 \leqslant i \leqslant n$.

[20] See also van Fraassen (1989, pp. 218–220).

$$\forall x \forall y \Big(L(x) \land L(y) \land x \neq y \to \exists ! z \big(P(z) \land z \in x \land z \in y \big) \Big)$$

This theory T can be presented as the ordered triple $\langle D, L, P \rangle$. Suppose a model $\mathcal{M}_1$ of T as the following sentence: “a single line with two points in it”. This assertion renders the axioms true, so $\mathcal{M}_1 \vDash T$. Subsequently, consider a second model $\mathcal{M}_2$, which comprises the Fano plane picture in Figure 2: it interprets and makes true the whole set of axioms of the theory T true, so that it is possible to write, also, that $\mathcal{M}_2 \vDash T$.

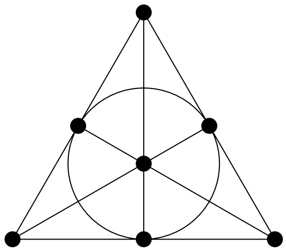

Figure 2 – The Fano plane ($\mathcal{M}_2$)

This example illustrates a central characteristic of semantic approaches in a very intuitive manner: if a theory is true with respect to a model, then it is possible to say that this is a model of the theory. In other words, a model is that which makes the axioms true.This example, then, indicates the manner in which a geometric model provides a semantics – or, concerning the case of interest here, an *interpretation*) – for the axioms of a theory.

Moderate semantic approach

In the light of the foregoing, it seems reasonable to drop the “language independence” requirement from the basic traits of the semantic approach to scientific theories. Call, then, the semantic approach following this decision a *moderate* semantic approach. Is it, however, enough to fix an answer for the question of “what is a scientific theory?” in indexed structures? As it will be argued, not quite so. Consider the discussion of group theory previously presented, written as the ordered quadruple $\langle G, \circ, e, - \rangle$: is this an exhaustive answer to the inquiry on what *is* a class of groups? No. Alternatively, one can argue that a group can be represented by the triple $\langle G, \circ, - \rangle$, the triple $\langle G, e, \circ \rangle$, or, yet, the pair $\langle G, \circ \rangle$.[21] None of these structures are the same, and therefore language seems to be important here.

The dilemma established by Krause and Arenhart (2016b, p. 13) is then given: in one hand, models comprise a vocabulary when identified as labelled structures which yields a not so different result from the syntactic approach (HALVORSON, 2012).

---

[21] For simplicity, from this point forward the description of these structures’ components shall be fixed as defined in the previous paragraph.

Moreover, if such a language is of order-n, then it is not covered by any model theory at all. Alternatively, models identified as indexed structures do not result in much of semantics in stake, insofar as the models does not make anything true. Furthermore, considering a language-free ideal scenario, there shall be no language according to which the structures are interpreted: the semantic approach to scientific theories, then, in agreement with this fairly general characterization, would refer solely to purely formal set-theoretical structures – which are unsound point, since scientific theories must relate to empirical data in some manner (LUTZ, 2015, p. 14).

1.3 TOWARDS A UNIFIED APPROACH

A fairly well-accepted settlement to this so-called “dilemma” has been presented by Craver (2008), Krause, Arenhart, and Moraes (2011), Lutz (2015) and Halvorson (2016). That is precisely the recognition that issues concerning the “labelled structure” and the “indexed structure” views on the semantic approach arise only when one accepts the ideal of *identifying* scientific theories with something (*e.g.*, these formulations). As soon as this ideal is abandoned, it becomes clear that both views are attempts to apprehend aspects of scientific theorizing, in the sense that they are distinct *representations* of scientific theories – and thus do not provide the essence of scientific theorizing itself. In this sense, these views must not be considered as competitors, which is perhaps the major upshot of recent debate.

Following the adaptation made by Lutz (2015, §5.3) of the argument presented by Halvorson (2016, §2), it is possible to interpret an indexed structure (semantic) as a labelled structure (syntactic). Consider the structure A as follows:

$$A = \big\langle D, R_1 \big\rangle,$$

where $D = \{a, \langle a, a\rangle\}$ and $R_1 = \{\langle a, a\rangle\}$. Presented as such, it is not clear in this indexed structure whether R_1 describes a relation over *a set of elements* or over *a set of tuples of elements of the domain*. As a result, it is also unclear what this structure *is*. If one understands a mathematical structure solely as a set of mathematical entities endowed with mathematical relations, it is not possible to advance from this point. To push the argument a little further, consider now the structure A':

$$A' = \big\langle D', R_1' \big\rangle,$$

where $D' = \{a, b, \langle a, b\rangle\}$ and $R_1' = \{\langle a, b\rangle\}$. A question arises: are A and A' isomorphic structures? This information is not provided by the description. The answer lies in the *arity* of relations R_1 and R_1', that is, in their classification as unary or binary relations.

Thus, if a bijective function $f : D \to D$ and if $\langle l, m\rangle_{\in R_1}$, then $\langle f(l), f(m)\rangle_{\in R_1}$. This crucial information is not explicitly given: if the relations have the same arity, yes; otherwise, no. However, to explicitly provide information regarding non-logical terms of the structure (*e.g.*, a mapping from the index set of the indexed structures to the elements or types of elements of the structure) *is to transform the indexed structure into a labelled structure*, since the result carries the indexed set's index taken as a vocabulary (CHANG; KEISLER, 1990, p. 19).[22] In other words, the *indexed structure* may be converted to a Tarskian-like structure when the index set I is defined as the non-logical vocabulary of a language, thus transforming the indexed set into a labelled set with concern to the indexation status of interpretation. Therefore, as Krause and Arenhart (2016b, p. 16) argue, "[. . .] an isomorphism may be defined both in the presence as well in the absence of a language in which the structures are interpreted", rendering both approaches to models meaningful.

As Lutz (2015, §7) states, [. . .] the syntax-semantics debate was about a distinction that marks no difference", to the extent that one approach can be freely translated into another. Similarly, as noted in the pictorial analogy of the "duck-rabbit", made famous by Wittgenstein (1953, II §xi), one can see, in the same image, either a duck or a rabbit, thus making it pointless to identify the picture with solely one of these complementary points of view. Moreover, Krause and Arenhart (2016b, p. 17) remarked that, specifically within the semantic approach, the discussion related to whether or not to include the requirement for language independence is unimportant considering that both structures (language-dependent and "independent" are convertible into one another). In fact, that is precisely what Suppes (1967) means when distinguishing between the complementary *intrinsic* and *extrinsic* approaches to theories: the former consists in the axiomatization via linguistic resources (*e.g.*, via *labelled structures*, or *syntactically*); when no such axiomatization is viable, one can proceed with the latter by characterizing the class of models of the theory directly in set theory.

Ultimately, it seems that philosophers of science have not provided a satisfying answer to the question of "what is a scientific theory?", as its most plausible answer would be, after all, "I don't know". Although an answer concerning what a scientific theory *is in its essence* could not be provided, we may say in which ways it could be *represented for philosophical purposes*. In that sense, both syntactic and semantic *tools* can be employed in philosophical inquiry.

Based on the discussion presented so far, it is relevant to notice that both the syntactic and the semantic approaches are *live options* in current practice of philosophy of science. Even if both approaches are viable, they are not considered to be equally adequate to treat scientific theories philosophically. For instance, notice that models are models of *something*: when they are models of some axiomatic, it would only make

---

[22] See also Lutz (2015, §5).

sense to call it “model” as if there if a set of axioms modeled by the structure. Then, it would be necessary to provide an axiomatics of the theory before modeling it in a set theoretical structure. Is not that, however, a major shortcoming of the radical syntactic approach mentioned earlier? Recall the syntactic approach: the goal is to axiomatize a theory, by describing it from its underlying logic to its specific axioms. Therefore, this seems to be an inconvenient for the semantic approaches. Naturally, this is a simple matter when the theory in question is a simple as well, such as the theory concerning the projective plane. Suppose, however, that the theory to be modeled requires several “sub-theories”, which must all be axiomatized. Consider QM, which encompasses several underlying theories such as the tensor calculus, theory of differential equations, vector spaces, and so on. This would render the axiomatization impracticable.

In this sense, Zahar (2004) and Worrall (2007) seem to pursue a *syntactic* kind of axiomatization, relating the use of set theory to axiomatization – either its vocabulary (WORRALL, 2007) or set-theoretical axiomatization of parts of theories (ZAHAR, 2004). According to Suppes (1967), this categorizes an “extrinsic approach”. Nevertheless, we consider the criticism of Krause and Arenhart (2016b, §5.1) to this kind of approach (in their vocabulary, the “external axiomatization”) to be crucial when considering the matter models. Krause and Arenhart (2016b, p. 79) argue that this kind of approach either (i) cannot provide its models, in the sense that if a set-theory (such as the standard Zermelo–Fraenkel, or any other known set theory) is supposedly *consistent*, it cannot provide its own models in the object language, but only in a metalanguage in which it is constructed. This leads to the objection that (ii) this fact would render axiomatization impracticable due to the need for axiomatizing its models entirely, which involves huge structures. The argument made by Krause and Arenhart (2016b, p. 79) is therefore accepted here, in what concerns their affirmation that states that “[t]hat goes beyond what any philosopher of science would be willing to take into account.”

This point, however, is not entirely correct, as *not any* philosopher of science would decline this kind of axiomatization. In fact, this is precisely how da Costa and Chuaqui (1988) lead their axiomatization process.[23] It should be remarked, though, that this kind of detailed axiomatization is fairly distant from the working scientific practice; by contrast, it is fundamentally the logician’s approach, which proves to be more useful to the philosopher of science than to the working scientist. Call this approach “rigid axiomatization” – which is also a *formalization* of scientific theories.

At the same time, Suppes’ (2002) argues that, ideally, all “step-theories” (axiomatized in the *rigid* approach) can be *presupposed* as obtainable within a set theory.

---

[23] It should be remarked that both Suppes (2002) and da Costa and Chuaqui (1988) consider their approaches to be part of the so-called “Suppes’ predicate”, but their approach clearly differ. Krause and Arenhart (2016b, §5, §6) present a detailed discussion on these differences, surpasses kinds of axiomatization. However, for the purpose of this work, a superficial account on their differences based on different methodological approaches to axiomatization suffices.

This yields that only the specific axioms of the theory must be presented. The important point, then, are its set theoretical structures, which model the theory's axioms, *i.e.*, the *models of the theory*. Therefore, this it is a *less rigid* axiomatization, yet properly semantic in the sense that the elements of the theory are defined in its satisfiability in relation to the axioms.

A brief commentary on some authors discussed in this chapter: Lutz reduces the syntactic approach to the semantic approach applying set theory in order to demonstrate a certain equivalence. Note, however, that such equivalence is made in a set theory! Thus, it is not a neutral way of assessing an equivalence between theories. In a way, this "begs the question". These are tacit assumptions that commonly go unnoticed but can be questioned. Something similar could be said of Halvorson, who presents this equivalence in a stronger theory, namely in a category theory. *Mutatis mutandis*, category theory faces the same problem stressed when addressing set theory: the semantic approach is already bought in advance by the authors who claim to establish an equivalence between the syntactic and semantic approaches. However, it is still possible to question whether it is conceivable to establish a theoretical equivalence from a "cosmic exile".

We believe it is not.

1.4 INTERPRETATION: FROM LOGICS TO PHYSICS

Since apparently some crucial aspects of the previous debate are needed in order to discuss the efforts of interpreting QM, an assessment of the matter shall be provided, even if in passing. Syntax is needed to better specify some concepts, as well as semantics, in order to interpret scientific theories – recall that a purely syntactical approach is rigid enough to preclude this possibility.[24]

As discussed above, to interpret a scientific theory (according to the syntactic and semantic views) is an issue mainly concerned with concepts in logics.[25]

In the syntactic approach, to interpret is to connect an axiomatic system with empirical data. Take as a rough example the following: suppose a formal system $\mathfrak{A} = \langle \mathfrak{F}, \mathcal{A}, \mathcal{R} \rangle$, where $\mathfrak{F}$ is the set of formulas, $\mathcal{A}$ are the axioms, and $\mathcal{R}$ are the rules of inference. To interpret $\mathfrak{A}$ is to add a "physical counterpart". In order to do so, consider the language $\mathcal{L}_{\mathfrak{A}}$ of the system $\mathfrak{A}$; consider also the addition of new symbols to its primitive alphabet (which may be denominated after "theoretical terms"), as well as the addition to $\mathfrak{A}$ of a set (not necessarily finite) of "specific axioms" of the new system $\mathfrak{A}^*$. The rules in $\mathcal{R}$ remain the same. Evidently, there is now an extended axiomatic system, which may be denominated as a "theory". In this manner, $\mathfrak{A}^* = \langle \mathfrak{F}^*, \mathcal{A}^*, \mathcal{R} \rangle$, where $\mathfrak{F}^*$

---

[24] As will be presented in Chapter 4, it is also essential to move away from formalization in order to discuss several aspects of metaphysics. These questions are aside until Part II of this thesis, however.

[25] See Shapiro and Kouri Kissel (2018, §4) for a comprehensive guide to interpretation in logics.

represents the new set of formulas obtained by the application of the grammatical rules of $\mathcal{L}_{\mathfrak{A}}$ to the finite sequence of the extended alphabet, and $\mathcal{A}^*$ is the union of $\mathcal{A}$ with the new specific axioms. Thereby, one may go from mathematics to physics.

As stated by Wallace (2012, p. 17), to do so is to surpass the “bare formalism” to an empirically adequate theory, which, in the specific case of QM, is the introduction of the concept of measurement: “[. . .] if we are to extract empirical content from the mathematics, we seem to have to introduce the notion of measurement as a fundamental concept”. As will be discussed in detail in the next chapters, such introduction leads to the (in)famous *measurement problem*, one of the backbones of interpreting QM.

As for the semantic approach, all that one is required to do in order to *interpret* a physical theory such as $\mathcal{A}^*$ is to find the models in which its axioms $\mathcal{A}^*$ are true (as indicated in the Fano plane example).

But is that the case with regard to QM? *In case* there was a single method to axiomatize QM, then to interpret QM would mean finding the models in which its axioms were true. However, were it not the case, both the syntactic and the semantic approach present an relevant issue, and an *interpretation* of QM does not have the same meaning as an interpretation in logics.

Unfortunately, this seems to be precisely the case. Different interpretations of QM have different axioms. For the sake of argument, take as example only two “families” of interpretations of QM: the collapse interpretations and the no-collapse interpretations. They have different axioms (*i.e.*, the collapse). How to proceed, then? If it is not as in logics, what does it mean to interpret QM? The next chapter provides a discussion concerning what is QM and what it means to interpret it, utilizing both syntactic and semantic concepts.

2 BUILDING QUANTUM THEORIES

> "[. . .] physicists come up with interesting results but are not sufficiently literate as philosophers to articulate the broader significance of their discoveries for our conception of physical reality, so the philosophers come in afterward as a sort of cleanup crew to sanitize the messy metaphysics of the physicists. This division of labor relegates the philosopher to a rather boring and sterile role."
>
> JEFFREY BUB
> *Elegance and Enigma: The Quantum Interviews*

THE PROBLEM

What is QM? It is a settled fact that QM can be formulated in several ways.[1] Since the seminal work of von Neumann (1955) on the axiomatization of QM, developments and debates on QM employ, predominantly, the Hilbert space formulation.[2] However, when adhering to such formulation, one can still be bothered with the problematic question: *what is quantum mechanics?*

It is a widespread belief that *the* formalism of QM can be *interpreted* in numerous ways (JAMMER, 1974; LEWIS, P., 2016), as if a single theory, *The* QM – with a capital "T" – exists, from which various interpretations emerge as solutions to the measurement problem (FRIEDERICH, 2014, §2). The work of Ćirković (2005) challenges such a picture, stressing that different "interpretations" of QM, such as collapse and no-collapse interpretations,[3] yield *different experimental outcomes*, and, therefore, be considered

---

[1] See Styer et al. (2002).

[2] According to Auyang (1995, p. 16), "[. . .] Despite their mathematical sophistication, all rivals [formulations of QM] have to make contact with the Hilbert space formulation, which yields almost all experimentally verifiable results. Hence it is fair to say that the Hilbert space formulation has a special status". For a critical summary of various formulations of QM, see Wightman (1976), Gudder (1979), Styer et al. (2002), and references therein.

[3] This topic is even more problematic when considering other theoretical developments on quantum phenomena which *modifies* the formalism, such as the hidden variable theories (BOHM, 1952). This subject is briefly covered in Appendix A.

different quantum theories.[4]

The so-called "interpretations of QM", then, are claimed not to consider the same set of axioms (regarding the collapse axiom) neither the same set of equations (regarding the Schrödinger equation), so that interpretations do not depart from the same point in order to "interpret" a single theory. Along these lines, Maudlin (1995, p. 7) stresses that "[a]ny real solution [to the measurement problem] demands new physics". This explains the followed statement made by Sklar (2003, p. 281): "I doubt that one can draw any principled line between replacing a theory and 'merely interpreting' it". Closely examine the arguments put forth by Ćirković (2005, pp. 821–822), as follows. Consider that theory T and T' are different theories if at least one of the three following criteria is fulfilled:

1. T predicts new phenomena, nonexistent in T', subject to empirical verification (even if only in principle);
2. The formal parts of T and T' are different;
3. T and T' differ in the description of *observed* phenomena.

It is important to recall that undisputed cases, such as spontaneous-collapse theories (GHIRARDI; RIMINI; WEBER, 1986)[5] and hidden-variable theories (BOHM, 1952), must be set aside from the discussion.[6] The most difficult cases, represented by collapse and no-collapse versions of QM, constitute the cases of interest here. It is safe to state that these cases do not satisfy item 1. Item 2 may be disputed, as collapse and no-collapse versions of QM can be placed in "external" descriptions as different structures, with different axioms (*e.g.*, one structure *with* the collapse axiom, and another structure *without* it). Since other mathematical aspects of both approaches (*e.g.*, the equations) remain the same, it becomes easy to see how item 2 is traditionally considered unfulfilled in this case. Although we disagree with such assessment, we will not put it in dispute at this moment, in accordance with the standard practice. Therefore, the debate shall move onto item 3.

Thus far, collapse and no-collapse approaches to QM are empirically indiscernible, meaning that both leads to the same set of laboratorial consequences. Maintaining the analogy of Wheeler's (1986) smoky dragon made in the Introduction, the content of the head remains the same – For all practical purposes (FAPP). However, what to say of *conceivable* experiments, even those not forthcoming in the near future? As

---

[4] Indeed, as Ćirković (2005) stated, there are many thought experiments that, in principle, yield different results depending on whether one accepts or abandons the axiom of collapse. These results cannot, in fact, be currently tested in practice, contributing to the unfeasibility of opting for a theory.

[5] Following the common practice in this field (FRIEDBERG; HOHENBERG, 2018, p. 321), non-standard collapse theories are not analyzed in this work.

[6] For those cases, see the references cited in Ćirković (2005, p. 821).

Ćirković (2005, §3) emphasizes, there are several thought experiments available in the literature that should not go unnoticed.[7] Considering that *thought experiments* demonstrate experimental differences according to the adoption of collapse or no-collapse approaches to quantum phenomena, item 3 could be considered the epistemologically weakest of the three items.

This situation seems to amount to one's definition of "quantum theory", arising the following dilemma. First off, if the accepted definition is excessively *narrow*, one is unable to comprise several theoretical programs for investigating the phenomena on a quantum level, commonly referred to as QM. This appears to pose a pragmatical drawback for the narrow definition of "theory", as numerous working physicists inclined to different solutions of the measurement problem could work in various subjects without ever disagreeing, even without realizing that they are working with distinct physical theories.

On the other hand, if one's definition is too *wide*, one may substantially conflate different nuances of several theoretical approaches to quantum phenomena, such as different predictions of experimental outcomes, or different ways of calculating the motion of a quantum object. In this sense, QM presents a unique case in which the theory's very axioms depend on a choice of interpretation.

This chapter proposes a characterization of a "quantum theory" considering a modification of the semantic approach, that is, by stating basic requirements in order to obtain the theory's specific axioms, offering a basic formulation of QM that can serve as a common ground for several theoretical programs on the study of quantum phenomena. Collapse (VON NEUMANN, 1955) and no-collapse (EVERETT, 1957) theories are the examples that serve as focuses of this discussion.

The offering of a basic schema, considering convenient set-theoretical tools, allow for further definition of the differences among several approaches to quantum phenomena. Furthermore, in addition of additional assumptions traditionally made upon such basic schema clarifies the modifications resulting from each response to a foundational problem concerning the basic structure in order to obtain the axioms of the theory at stake.

This basic structure is here called "QM^{bas}". With these efforts, This work seeks to advance towards a more accurate account of what QM could be and what it means to interpret it. In our terms, QM is formed by a basic mathematical structure QM^{bas} with General Principles that result in the measurement problem To interpret QM, then, means to instantiate the General Principles of QM^{bas} in order to solve the measurement problem, often at the cost of creating new quantum theories. In this sense, the notion of "interpretation" of QM is introduced here as the very axiomatic structure of each

---

[7] For a brief analysis of *seven* thought experiments that show the differences in experimental results between collapse and no-collapse approaches versions of QM, see Ćirković (2005, pp. 823–834).

subsequent “quantum theory” that solves the measurement problem.

The subject is delicate and deserves some comment. When referring to axioms, it may seem that the subject is that of *formal* theories. However, stating that theories may be different if their formal parts are different, as Ćirković (2005) does, may be quite confusing. Indeed, theories may have distinct axioms and yet be equivalent. For example, take T and T' to be axiomatic formal theories. Provided that the translation of the axioms of T into T' are theorems of T' and vice versa, T and T' are equivalent theories. By stating that theories may be different when nonexistent predictions regarding one of them are made in the other, the situation grows even more puzzling, as it is not believed to exist a concept of “prediction” among formal theories. The literature is elusive at this point. For instance, Dalla Chiara and di Francia (1979) mention “formal physical theories” (sic). It seems strange to discuss empirical predictions within a purely formal schema. Therefore, the concepts of “physical systems”, “observables” and “properties” in some of the General Principles shall be carefully introduced so to grant a degree of “physicality” to the scheme.[8]

2.1 WHAT *IS* QUANTUM MECHANICS

We present a semantic characterization of QM, briefly explained as follows. Assuming that a semantic axiomatization can be done *at least in principle*, the adequate manner to axiomatize parts of present-day physics, such as the Standard Model of particle physics, is still unknown. Moreover, it should be noted that this study works exclusively at the broader, informal level, for simplicity of presentation. For the sake of precision, if the reader thinks necessary, the Zermelo–Fraenkel set theory with the axiom of Choice (ZFC) can be assumed.[9] “Axiomatize”, then, simply means that non-trivial assumptions are at stake. Therefore, this chapter does not present a *complete* axiomatization of QM, as this would be a Herculean task, beyond the scope of this work. It is assumed, though, that this can be done – even if not here. Following the lead of Krause and Arenhart (2016b, §5.8.1), this work proposes, as for heuristic objectives, answers to the question of so-called “interpretations of QM” as well as aims to explicit their differences.

A major problem of presenting QM according to the semantic approach is the fact that a quantum theory depends on its axioms. Simultaneously, the theory’s axioms largely depend on the chosen interpretation, since QM can be presented with different axioms motivated by a given choice of interpretation. Consequently, as previously stated, the frontiers between replacing a theory and interpreting it are blurred, and this

---

[8] I would like to thank professor Adonai Sant’Anna for this point.

[9] The debate between the syntactic and semantic approaches to scientific theories (SUPPE, 1977; LUTZ, 2015) is not of interest here, because, as we saw in Chapter 1, it can be considered as a case of two complementary approaches, not competing ones – see Halvorson (2013), Lutz (2015), and Krause and Arenhart (2016a, §1).

seems to be a *sui generis* case of QM: if the focus were to lie only on the axiomatic structure of QM, it could be presented with *different* axioms, resulting in *different QMs*, without a common starting point.

For instance, von Neumann (1955) presents QM with the so-called “collapse axiom”, whereas Everett (1957) drops this axiom in his approach. As Ćirković (2005) argues, however, adopting collapse axiom entails *in principle* that a particular set of experimental predictions divergent from those in which such axiom is dropped.

Thus, to present an axiomatic structure for each quantum theory does not seem to result in a path towards a unified view on QM. The discussion here presents, then, precisely this common starting point. For instance, a recent effort to present an axiomatization of QM conducted by Krause and Arenhart (2016b, §5.8.1) is also committed with collapse as an axiom of QM, thus appearing to be an axiomatization of an *interpretation* of QM, and not of QM *per se*. In order to encompass a wider variety of approaches to QM, we propose a different definition of a quantum theory with an emphasis on the metalanguage. So, instead of presenting its axioms, something similar to the role played by axiom schema in systems of logic is attempted. In essence, *axiom schemata* generalize the notion of axiom by stating the rules by which axioms are generated. Here, the set of “axiom schema”, in QM^{bas} is labelled as “General Principles”, denoted as $\mathcal{P}$. These General Principles may establish a common ground that can be instantiated in specific axioms of each quantum theory. As stated above, this work conceives each formalized interpretation of QM as a physical theory (MAUDLIN, 1995; ĆIRKOVIĆ, 2005), in order to allow for the examination of theories as different extensions or formulations derived from the same fundamental General Principles: hence, a basic schematization for QM.

In our proposal, modifying the semantic approach, to present QM is to present its (specific) *General Principles*. In this way, our definition of QM is a *basic schematization*, in the meta-level, of a common ground to several independent research programs towards quantum phenomena, known as “QM”. Each General Principle, on its turn, can be instantiated as a theory’s specific axiom.

With these instruments in mind, the basic schematization of QM, labelled “QM^{bas}”, is now presented. It should be clear that there is no claim that this structure is adequate for all cases; rather, limit cases of the standard Hilbert-space formulation of QM are being considered, hoping to extract some philosophical lessons from it.[10] For instance, only pure states and observables with discrete, non-degenerate spectra are being con-

---

[10] In this sense, it should be clear that the semantic approach to scientific theories, which states that a scientific theory *is* a mathematical structure, is not being followed here. For references and criticism, see Krause and Arenhart (2016b, §1) and Lutz (2015). Here, the theory is simply *represented* by such structure for philosophical purposes. Moreover, the emphasis on the structure’s *metalanguage* (*i.e.*, to present its *General Principles* instead of already-instantiated *axioms* of the theory) is not a standard attitude within the semantic approach.

sidered here.[11] Following the previous discussion, it is possible, then, to elaborate a structure that furnishes the tools for representing a QM^{bas} as a schema for the construction of quantum theories, based on the standard (orthodox) formulation of QM. So, QM^{bas} is a structure presented as a n-tuple of the form:

$$\mathrm{QM}^{bas} = \langle \mathfrak{F}, \mathcal{P}, \mathcal{R} \rangle \tag{1}$$

where:

1. $\mathfrak{F}$ is the set of formulas of the language of QM^{bas}. $\mathfrak{F}$ is obtained from a basic language $\mathcal{L}$ consisting of a primitive vocabulary and rules of formation[12] of well-formed formulas or expressions – which in turn are finite sequences of such symbols. So, in $\mathfrak{F}$ there is a set of purely mathematical, uninterpreted symbols, which composes the formal (both logical and non-logical) *vocabulary* of the theory.

2. $\mathcal{P}$ is the set of General Principles of QM^{bas}. The General Principles of $\mathcal{P}$ are stated in the language of $\mathfrak{F}$. Since we are dealing solely with the Hilbert-space formulation of QM, the mathematical axioms of QM^{bas} are the axioms of standard functional analysis, while the logical axioms and rules of inference of QM^{bas} are the axioms and the rules of classical logic.[13] The logic is assumed in the background. Thus, listing rules of inference is not necessary there is the desire to introduce some rule as one of the principles of QM^{bas} – which is not the case. Therefore, the essential matter to be stated here relates to the specific General Principles of the theory, which will be *informally* presented. Again, dealing with the standard Hilbert-space formulation of QM implies a commitment to a specific set of the theory's General Principles. This presentation follows mainly von Neumann (1955), Jammer (1974, §1), Auyang (1995), Krause (2016), Krause and Arenhart (2016b), and Takhtadzhian (2008). The General Principles of $\mathcal{P}$ are:

---

[11] The description of *rigged* Hilbert spaces will not be presented, albeit it being necessary to describe observables with continuous spectrum. Statistical mixtures are not covered here either, which requires to treat systems in which the knowledge of its initial state is not available. Nevertheless, a description is provided in order to consider the measurement problem, a fundamental aspect of the interpretations of QM.

[12] See $\mathcal{R}$ ahead.

[13] There is an ongoing debate raised from the seminal work of Birkhoff and von Neumann (1936), to whom the logic of QM *is not* the classical logic. This discussion will not be covered here. Rather, following Dalla Chiara (1977, 1981), this work accepts that the role of the so-called "quantum logic" is *not* played within the domain of rules of inference. As a consequence, as Dalla Chiara (1981, p. 337) argues, the general logic of QM is not quantum logic, but classical logic; quantum logic is to be introduced as "[...] a particular physical sub-language of [QM]". An interesting point concerns the nature of S. Since quantum objects may be indiscernible without turning to be the same object, S should not be viewed as a set. Quasi-set theory can formalize such situation, being enough to substitute Zermelo–Fraenkel set theory with the axiom of Choice; see French and Krause (2006) and Dalla Chiara and di Francia (1993).

$\mathcal{P}_1$ [*Hilbert Space*]: A Hilbert space $\mathcal{H}$ is a linear space with inner product, complete in relation to the norm introduced by the inner product comprising a set of *vectors* denoted as $\{|\psi\rangle, |\varphi\rangle, |\psi_1\rangle, \ldots\}$. The field is usually taken to be that of complex numbers, where elements are termed "scalars" and denoted by Latin lower-case letters, occasionally with indexes. When $\mathcal{H}$ is infinite-dimensional, it is assumed to be separable (*i.e.*, it has an enumerable orthogonal basis).

The states of quantum-mechanical systems S are represented by vectors $|\psi\rangle$ in a complex, infinite-dimensional, separable Hilbert space $\mathcal{H}$. A pure quantum state $|\psi\rangle$ is a summary of the physical characteristics of S in a specific instant of time t. The description of S employing $|\psi\rangle$ consists of constant characteristics (such as mass, charge, spin, etc., of the system) and variable characteristics changing over time. A state of a quantum system can be represented by a unitary vector $|\psi\rangle$ (also called "state vector"), which norm is unity, up to a phase factor. If $|\psi\rangle$ represents a state, then $e^{i\theta}|\psi\rangle$ also represents the same state, where θ is the phase factor (an arbitrary number).

The set of all states permissible for a quantum system to assume is theoretically represented by the concept of "state space", a complex $\mathcal{H}$. $|\psi_i\rangle$ and $|\psi_j\rangle$ are orthogonal if $\langle\psi_i|\psi_j\rangle = 0$ and orthonormal if $\langle\psi_i|\psi_j\rangle = \delta_{ij}$, where $\delta_{ij} = 0$ if $i \neq j$ and $\delta_{ij} = 1$ if $i = j$.

Vectors can be represented as a linear combination (sum) of other vectors. In the same sense, a state can be represented as a linear combination of other states. A set of vectors $|\alpha_i\rangle$ forms a basis of $\mathcal{H}$ if every vector in $\mathcal{H}$ can be written as a linear combination of its members and this set of vectors is linearly independent. So $|\psi\rangle$ can be written as a set of basis states $\{|\alpha\rangle\}$ in the form:

$$|\psi\rangle = \sum_i \langle\alpha_i|\psi\rangle|\alpha_i\rangle = \sum_i c_i|\alpha_i\rangle, \tag{2}$$

where $c_i \in \mathbb{C}$ are the *Fourier coefficients* $c_i = \langle\alpha_i|\psi\rangle$, where the basis is composed by orthonormal vectors. According to the theorem of Gram–Schmidt, every vector space with an inner product has an orthonormal basis. This is the *superposition principle*. Intuitively, the *sum* of quantities *of the same type* is also a quantity of that same type. Thus, as the sum of two lengths is a length, the superposition principle asserts that the sum of states of a quantum system is a state of such a quantum system.

$\mathcal{P}_2$ [*Quantization Algorithm*]: The physical observables A are represented by self-adjoint operators in $\mathcal{H}$. The quantization algorithm introduces a set of basis states in which the states of observables can be revealed upon measurement. Observables embody quantum-dynamical variables (position, *momentum*, non-relativistic spin, and so on), and can be *incompatible* in the sense of the theoretical impossibility of simultaneously obtaining the values of two incompatible observables (such as position and momentum). In addition to describing the state, an observable also yields the possible outcomes of measurements.

An observable associated with a quantum system is represented by a self-adjoint operator $\hat{A}$ on its Hilbert space. The spectrum of the operator $\hat{A}$ indicates the possible values that can be found when the observable in question is measured. There are many operators in QM, but only operators in the class of $\hat{A}$ represent observables.

A self-adjoint operator is a linear transformation of a Hilbert space $\mathcal{H}$ into itself, and its spectrum consists only of real numbers. Therefore, for an observable $\hat{A}$, the spectrum $\Lambda(\hat{A})$ of its representing self-adjoint operator stipulates all possible values that the measurements of the physical observables represented by $\hat{A}$ may obtain. As this work focuses only on observables within the discrete spectrum, the spectrum of an observable $\hat{A}$ is $\Lambda(\hat{A}) = \{a_i\}$, where $\{a_i\}_{\in\mathbb{R}}$ are real numbers named *eigenvalues*, which represent the possible results of experiments, or measurement outcomes. The self-adjoint operator maps one state into another. Thus, a state $|\alpha_i\rangle$ for an observable $\hat{A}$ is written as $\hat{A}|\alpha_i\rangle = a_i|\alpha_i\rangle$. The states $|\alpha_i\rangle$ are called the *eigenstates* of $\hat{A}$; they are invariant under the operation of $\hat{A}$, as $\hat{A}$ multiplies the state $|\alpha_i\rangle$ by a numerical factor a_i. From the set of eigenstates $\{|\alpha_i\rangle\}$, in the non-degenerate case, it is possible to obtain a basis of $\mathcal{H}$, such that any state $|\psi\rangle$ can be expressed by a linear combination called "superposition of states". Since the interest here lies in observables with *non-degenerate spectra*, each eigenvalue is associated with a single eigenstate.

$\mathcal{P}_3$ [*Statistical Algorithm*]: The statistical algorithm does not mention the probability of a state *to have* a specific eigenvalue; contrarily, probability and eigenvalue are concepts related to measurement outcomes. The concept of probability is used since the observed result of a single pure state is at stake.

The squared norm of the Fourier coefficients $c_i = \langle\alpha_i|\psi\rangle$ is a numerical factor $|c_i|^2$ which gives the probability for a measurement made upon an observable S to yield the eigenvalue a_i when the system is in the eigenstate $|\psi\rangle$. Therefor, for the discrete and non-degenerate state:

$$\mathrm{Prob}_S^{|\psi\rangle}(a_i) = |\langle\alpha_i|\psi\rangle|^2 = |c_i|^2 \tag{3}$$

The statistical algorithm states that the measurement values are probably found in an interval of $\mathbb{R}$. This is frequently called the “Born rule”.

$\mathcal{P}_4$ [*Dynamics*]: The motion of quantum states through time is governed by the unitary operator $\hat{U}$, which maps the states from $|\psi(t_0)\rangle$ to $|\psi(t_{x\neq 0})\rangle$ in the form of $\hat{U}(t)|\psi_0\rangle = |\psi(t)\rangle$. Such temporal evolution is represented by linear, differential equations of motion. The linearity feature of $\hat{U}$ implies that $|\psi_1\rangle$ evolves to $|\psi_1'\rangle$, and $|\psi_2\rangle$ evolves to $|\psi_2'\rangle$, then $a|\psi_1\rangle + b|\psi_2\rangle$ evolves to $a|\psi_1'\rangle + b|\psi_2'\rangle$.

$\mathcal{P}_5$ [*Measurement*]: A measurement $\mathfrak{M}$ transforms a *superposition of states* in a single *eigenstate* from $|\psi_i\rangle$ to $|\psi_k\rangle$. When the state of a physical system S described as the superposed state

$$|\psi\rangle = \sum_i c_i|\alpha_i\rangle, \tag{4}$$

is subject to a measurement process $\mathfrak{M}$, the system S ceases to be described by $\hat{U}$ and stats being described by the corresponding eigenstate in the form of

$$|\psi\rangle = \sum_i c_i|\alpha_i\rangle \xrightarrow{\mathfrak{M}} |\alpha_w\rangle, \tag{5}$$

where $|\alpha_w\rangle$ is one of the elements of the expansion, with a probability given by the statistic algorithm in $\mathcal{P}_3$, which is $|c_i|^2 = |\langle\alpha_i|\psi\rangle|^2$. It is worth remembering the following: it is agreed that the values of eigenstates are set according to measurement results. An eigenstate, however, is *not* the result of measurement.[14]

3. $\mathcal{R}$ is the set of of the inference rules of QM^{bas}, that is, a collection of relations between finite sets of formulas and formulas. Each relation has an arity $n > 0$, and are inference rules of QM^{bas}. Following common practice, we assume that the rules of inference in $\mathcal{R}$ are the standard rules of inference of classical logic.

We aim at to generalize the notion of “measurement” with the symbol $\mathfrak{M}$ defined in $\mathcal{P}_5$, whose function is to give the eigenvectors of the systems in the cases of superposition, without committing ourselves with the theoretical mechanisms by virtue of which

---

[14] There is some consensus concerning this mode of presentation of measurement results. For the sake of precision, it is essential to emphasize that this applies to *measurements of the first kind*. There are, however, measurements where this does not occur: where the eigenstate does not correspond to the eigenvalue. The position measurement satisfies the postulate presented, but, strictly, this does not apply to the measurement of energy.

this process occurs – this will vary depending on the *interpretation* of QM one adopts, *e.g.*, it can be represented by a state-vector collapse (VON NEUMANN, 1955), by a branching-recognition process (EVERETT, 1957), and so on.

The measurement problem

It is remarkable that, in order to make empirical statements, the concept of "measurement" represents a phenomenological statement about actual (laboratorial) measurement outcomes, rather than a statement buildable within the theoretical apparatus constructed so far. Moreover, the notion of measurement, here called $\mathfrak{M}$, is broad enough to be completely *neutral* regarding questions related to its *causal agent* or its *theoretical mechanisms*: instead, these questions concern the *interpretation* of QM in a broader sense.

But where does interpretation comes across? Here is the hook: even this work's definition of QM^{bas} is problematic when jointly considering assumptions made upon $\mathcal{P}_1$, $\mathcal{P}_4$ and $\mathcal{P}_5$. This difficulty is known as the "measurement problem", and interpretations of QM are essentially *responses* to the measurement problem (FRIEDERICH, 2014, §2).

There are numerous ways to define the measurement problem, one of the central issues of QM.[15] In order to keep this work self-contained, the language employed so far will be maintained, defining the measurement problem as follows. The taxonomy presented by Maudlin (1995) shall be followed, which distinguishes three instances of the measurement problem. In order to fulfill the purposes of this work, Maudlin's (1995) *first* measurement problem will be approached, defined as the conjunction of three assumptions, added to the General Postulates ($\mathcal{P}$):

1.A The (pure) state vector $|\psi\rangle$ gives a *complete description* of S.

2.A The state vector $|\psi\rangle$ is *always* governed by a linear dynamics.

3.A Measurements always have *definite* outcomes, up to probability.

While General Principle $\mathcal{P}_4$ states that the description of S is governed by $\hat{U}$, General Principle $\mathcal{P}_5$ determines that the description of S *is not* governed by $\hat{U}$ (but, at best, by a statistical algorithm). Therefore, both General Principles, when considered jointly, *seem* to contradict each other. This is, in a nutshell, a manner to perceive the measurement problem in QM. In this sense, the non-trivial role played by interpretation is precisely that of accounting for it: to save the theory's very consistency. As remarked by Peter Lewis (2016, p. 50), without an answer to the measurement problem, QM is *trivialized*; what Ruetsche (2018, p. 296) calls an "empirical contradiction".

---

[15] There are indeed authors, such as Gibbins (1987, p. 104), who consider the measurement problem to be *the* central problem of QM.

We *do not* think that a formal contradiction is involved. A closer look in the measurement problem is needed in order to explain such a view since many assumptions were made, and it is not clear whether there is a formal manner to state this so-called contradiction. Regarding *informal* proof, Esfeld (2019, p. 223), claims that Maudlin's taxonomy became the standard way of stating the measurement problem in QM:[16]

> If the entire system is completely described by the wave function [*1.A*], and if the wave function always evolves according to the Schrödinger equation [*2.A*], then, due to the linearity of this wave equation, superpositions and entangled states will, in general, be preserved. Consequently, a measurement of the cat will, in general, not have a determinate outcome [. . .]. (ESFELD, 2019, p. 223).

It is essential, however, to (at least apparently) determine measurement outcomes [*3.A*], hence the informal inconsistency. In order to state the measurement problem more precisely, consider the following case. Suppose that one wants to measure a position observable of a physical system, denoted as "$\hat{A}$", by means of a macroscopic apparatus denoted as "$\hat{M}$". This will be done, in principle, trough the interaction of these two physical systems.[17] Suppose, further, that the initial state of $\hat{A}$ in t_0 is $|\psi_0\rangle = \sum_i c_i|\alpha_i\rangle$ and that the initial state of $\hat{M}$ is $|\varphi_0\rangle$, meaning the apparatus presents no reading, *i.e.*, it is in the *reset button*. For $\hat{M}$ to fulfill its purposes as a measuring device, it must be prepared in a certain way in which it is susceptible to measure some quantities of the system of interest $\hat{A}$, to yield an eigenvector of $\hat{A}$. However, by means of $\hat{U}$ only, the state of composite system $\mathcal{H}_{\hat{A}} \otimes \mathcal{H}_{\hat{M}}$, represented by

$$|\psi\rangle \otimes |\varphi_0\rangle = \left(\sum_{i=1}^{n} c_i|\alpha_i\rangle\right) \otimes |\varphi_0\rangle \tag{6}$$

evolves to

$$\hat{U}(t)\left[\Big(\sum_{i=1}^{n} c_i|\alpha_i\rangle\Big) \otimes |\varphi_0\rangle\right] \xrightarrow{\hat{U}(t)} \sum_{i=1}^{n} c_i\Big(|\alpha_i\rangle \otimes |\varphi_i\rangle\Big) \tag{7}$$

for any $t \neq 0$. Remarkably, this result is not an eigenstate of either $\hat{A}$ or $\hat{M}$, meaning that the measurement process must be *something else* other than the application of $\hat{U}$.

---

[16] Another way of stating such problem is relating "open" and "closed" systems – see Pessoa Junior (1997). This work, however, sticks to Maudlin's taxonomy as it better relates to the here considered.

[17] The belief that *the same* system can be measured is often found in the literature. For example, according to Auyang (1995, p. 77), "[a] single observation on a single system tells us nothing; we need to observe repeated transitions of the system or use ensembles". In many cases, the measurement problem is restricted to single measurement cases, and is not so problematic if they are considered statistical ensembles. This situation is not, however, necessary. In de Barros, Holik, and Krause (2017), the authors discuss whether it is possible to perform two measurements over a same system. According to them, we neither perform a measurement twice nor over the same system. To cope with this idea, they introduced the notion of "indiscernible operators" and use quasi-set theory for considering indiscernible quantum systems.

Notice that a superposition is never actually observed. Even in quantum controlling experiments, such as the isolation of a single trapped electron as presented by Wineland (2013), the measurement outcome is *never* a vector sum, but a single definite state vector.

Following the notation adopted so far, the measurement process is described in the form

$$\sum_{i=1}^{n} c_i \Big(|\alpha_i\rangle \otimes |\varphi_i\rangle \Big) \xrightarrow{\mathfrak{M}} \Big(|\alpha_w\rangle \otimes |\varphi_w\rangle \Big), \tag{8}$$

with the probability given by the statistical algorithm stated in $\mathcal{P}_3$.

To explain *why* and *how* this change in the dynamics occurs is one of the central issues of approaches to the measurement problem, while the attempts to overcome these changes are subject to the so-called *interpretations* of QM. The central point of the matter is, then: how can one reconcile what the theory predicts with what is observed? The answer is: “by interpreting it!” However, what does it mean to interpret QM, exactly? That is where this discussion is headed.

2.2 INTERPRETATION

The variety of answers that the numerous interpretations of QM give to the measurement problem is not of concern here; instead, the inquiry on *what is to interpret QM* is at take. As it should be clear at this point, an interpretation of QM must provide, among other factors, a solution to the measurement problem, a foundational problem in the very heart of QM^{bas}.

Recall that such a solution requires the refusal of at least one of the three assumptions mentioned earlier, made in addition to the General Principles. In the language employed thus far, to solve the measurement problem is, therefore, to *instantiate* the General Principles $\mathcal{P}$ of the structure QM^{bas} (1) in specific axioms $\mathcal{A}$. Often, a solution requires the *modification* of the elements of $\mathcal{P}$, as tated by numerous examples in literature (JAMMER, 1974). As to keep this work self-contained, two examples are analyzed:[18]

i) The standard *collapse* interpretation (VON NEUMANN, 1955), that rejects assumption 2.A in the General Principle $\mathcal{P}_4$ and instantiates the General Principle $\mathcal{P}_5$ in the axiom of the state vector collapse, thus originating the collapse quantum theory QM_{col}.

---

[18] A third example is sketched in Appendix A.

ii) The *branching* interpretations (EVERETT, 1957), which rejects assumption 3.A in the General Principle $\mathcal{P}_5$ and instantiates it in the axiom of the branching process, thus originating the branching quantum theory QM_{bra}.

Collapse quantum theory

This section begins by presenting the (standard) collapse solution to the measurement problem, as stated by von Neumann (1955). It modifies (or *interprets*) the structure of QM^{bas}, instantiating some of its General Principles in specific axioms of *collapse quantum theories* by denying assumption 2.A. Therefore, in an axiomatic structure, a collapse quantum theory QM_{col} is a n-uple:

$$\mathrm{QM}_{col} = \langle \mathfrak{F}, \mathcal{A}_{\mathrm{col}}, \mathcal{R} \rangle \tag{9}$$

where:

1. $\mathfrak{F}$ is the language of QM_{col}, the same as QM^{bas};
2. $\mathcal{A}_{\mathrm{col}}$ are the specific axioms of QM_{col} (*i.e.* instance of the set $\mathcal{P}$ of QM^{bas}). The list of $\mathcal{A}_{\mathrm{col}}$ is:

$\mathcal{A}_{\mathrm{col}\,1}$ [*Hilbert space*]: The same as $\mathcal{P}_1$.

$\mathcal{A}_{\mathrm{col}\,2}$ [*Quantization Algorithm*]: The same as $\mathcal{P}_2$.

$\mathcal{A}_{\mathrm{col}\,3}$ [*Statistical Algorithm*]: The same as $\mathcal{P}_3$.

$\mathcal{A}_{\mathrm{col}\,4}$ [*Undisturbed Dynamics*]: Slightly modifies the General Principle $\mathcal{P}_4$; $\mathcal{A}_{\mathrm{col}\,4}$ states that the temporal dynamics of the set $\{A\}$ of observable obeys the linear evolution of $\hat{U}$ *only when* A is not subject to a measurement process, thus denying assumption 2.A. Moreover, $\mathcal{A}_{\mathrm{col}\,4}$ instantiates the differential equation of motion of $\mathcal{P}_4$ in the Schrödinger equation (where $i = \sqrt{-1}$, $\hbar$ is the Planck constant divided by 2π, and H is the Hamiltonian, which gives the energy of the system) as follows:

$$i\hbar \frac{\partial |\psi(t)\rangle}{\partial t} = H|\psi(t)\rangle, \tag{10}$$

where $\hbar$ is the reduced Planck constant and H is the Halmiltonian of the system.

$\mathcal{A}_{\mathrm{col}\,5}$ [*Collapse*]: Slightly modifies the General Principle $\mathcal{P}_5$. $\mathcal{A}_{\mathrm{col}\,5}$ states that a measurement $\mathfrak{M}$ takes place whenever a quantum system interacts with nonquantum-mechanical systems[19] which collapses a superposed state in a single eigenstate of $\hat{A}$. As $\mathcal{A}_{\text{col }4}$ declares the *limited* validity of $\hat{U}$, $\mathcal{A}_{\text{col }5}$ states that $\hat{A}$ is found in a single, determined state by virtue of its interaction with a other systems, enabling the application of $\mathfrak{M}$.

3. $\mathcal{R}$ are the rules of inference of QM_{col}, similar to those stated in QM^{bas}.

Branching quantum theory

Proceeding the branching solution to the measurement problem, according to Everett (1957): it modifies (or *interpret*) the structure of QM^{bas}, instantiating some of its General Principles in specific axioms of *branching quantum theories*, by denying assumption 3.A. Therefore, in an axiomatic structure, a branching quantum theory QM_{bra} is a n-uple:

$$\mathrm{QM}_{bra} = \langle \mathfrak{F}, \mathcal{A}_{\text{bra}}, \mathcal{R} \rangle \tag{11}$$

where:

1. $\mathfrak{F}$ is the language of QM_{bra}, likewise QM^{bas};
2. $\mathcal{A}_{\text{bra}}$ are the specific axioms of QM_{bra} (*i.e.* instance of the set $\mathcal{P}$ of QM^{bas}). The list of $\mathcal{A}_{\text{bra}}$ is:

$\mathcal{A}_{\text{bra }1}$ [*Hilbert space*]: The same as $\mathcal{P}_1$.

$\mathcal{A}_{\text{bra }2}$ [*Quantization Algorithm*]: The same as $\mathcal{P}_2$.

$\mathcal{A}_{\text{bra }3}$ [*Statistical Algorithm*]: The same as $\mathcal{P}_3$.

$\mathcal{A}_{\text{bra }4}$ [*Branching*]: Instantiates, also, the differential equation of motion of $\mathcal{P}_4$ in the Schrödinger equation, similarly to $\mathcal{A}_{\text{col }4}$, however maintaining its *universal validity*. By maintaining the universal validity of $\hat{U}$, every time A is described by a superposition, $\mathcal{A}_{\text{bra }4}$ says that *all terms* of such superposition exist in different *branches*.[20]

$\mathcal{A}_{\text{bra }5}$ [*Branching Recognition*]: Instantiates the measurement $\mathfrak{M}$ as the recognition of a relative branch, considering a single eigenstate of A. It is worth noting that, by virtue of $\mathcal{A}_{\text{bra }4}$, *all* other states of S are equally real in different branches. Thus, $\mathcal{A}_{\text{bra }5}$ implies the denial of assumption 3.A: S is found in a single, determined state by virtue of a recognition of a particular branch of

---

[19] This matter is further discussed in Chapters 4 and 6.

[20] It is important to say that such a specific axiom is neutral in relation to what enters the branching process: the states or the systems. This matter is discussed in Chapters 5 and 8.

the universe, which enables the application of $\mathfrak{M}$. Such determinate outcome, however, is relative to a branch, and not absolute. For all practical purposes, $\mathcal{A}_{\text{bra 5}}$ resembles the concept of collapse, as stated in QM_{col}, but no collapse really occurs – just the branching.

3. $\mathcal{R}$ are the rules of inference of QM_{bra}, similar to those stated in QM^{bas}.

2.3 FINAL REMARKS

This chapter presented new horizons to old questions: what is QM, and what does it mean to interpret it? Regarding the first question, we suggest that the structure QM^{bas} can be a first step leading, since: (i) it accounts for central issues of several empirically successful physical theory about quantum phenomena; and (ii) it is sufficiently broad, meaning it is not committed to any particular approach, but serves as common ground to several approaches. Concerning the second question, this work suggests that *to interpret QM* means solving the foundational problem of measurement by instantiating the General Principles of QM^{bas} in specific axioms. The main consequence of such suggestion is that, following Maudlin (1995), *to interpret QM* means *create new quantum theories*. Alternatively, at least, as Esfeld (2019) argues, to interpret QM is to provide a dynamics for QM in order to solve the problem as posed by Maudlin. Here, used a meta-theoretical approach that did not commit to a specific interpretation was adopted, to organize the object and content of interpretations of QM methodologically.

Considering what has been discussed in this chapter, it is possible now to enunciate the specific vocabulary that will be employed throughout this thesis. The figures that appear at the end of Chapters 6, 7 and 8 are divided in discipline levels. So far, the mathematical and physical levels has been covered. Part II of this thesis deals with the ontological and metaphysical levels, and Part III connects all levels. The “YES” and “NO” entries represents the method of Unavailable Metaphysical Stories.

Recalling the three levels of underdetermination, the theoretical underdetermination is schematically presented Figure 3.

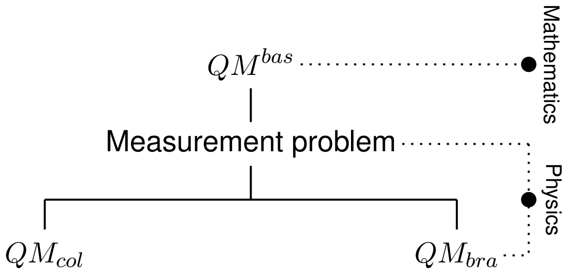

Figure 3 – QM^{bas} and its interpretations.

In the next Chapter we will begin to address questions of metaphysics and ontology.

Part II

ON METAPHYSICS

3 REFLECTIONS ON SCIENTIFIC REALISM

> “[. . .] I am not ready to take lessons in ontology from quantum physics as it now is.”
>
> DAVID K. LEWIS
> *Philosophical Papers II*

Crudely, scientific realism is the claim that science describes how the world *is*, not only regarding observable but also unobservable aspects. Eventually, the discussion presented in the previous chapters reaches the following point: how can a realist position concerning theoretical and ontological contents of QM be accepted? It is time, then, to tackle the debate concerning scientific realism and scientific anti-realism. Much of what is discussed here is textbook,[1] except for the last section, which presents the author’s impressions of the debate.

3.1 THE ONGOING DEBATE

The quarrel between realism and idealism depicts a classic debate in metaphysics. In realism, existence precedes perception, that is, the world exists independently of a subject that perceives it. Conversely, in idealism, perception precedes existence, and, therefore, the world only exists through a subject to perceive it. This debate seeks to understand how the world *really* is.

One of the main tasks of philosophy of science is to pursue the understanding of the nature of scientific enterprise, as well as to discover how to interpret what science really is. In this field, the traditional metaphysical opposition is thus translated in terms of ‘scientific realism’ and ‘anti-realism’.[2]

There are numerous forms of realism, as well as various forms of anti-realism. As a first characterization, “realism” may be compared in metaphysics to “naive realism”. Similarly “anti-realism” may be compared to “instrumentalism”. The various positions in the debate between realism and anti-realism may be referred to as a *spectrum*, where naive realism and instrumentalism are at the spectral ends of the realist and anti-realist positions, respectively.

Nevertheless, several stances have essential points in common. As Faye (1991, p. 198) suggests, the two most general metaphysical theses can be characterized according to their position in relation to the following assumptions:

---

[1] As in it can be easily found in introductory works such as Chakravartty (2017b).

[2] For the sake of simplicity, henceforth the “scientific” part of the terms will be suppressed, an the terms “scientific realism” and “realism” will be employed interchangeably. The same holds for “scientific anti-realism” and “anti-realism”.

1. The existence of the world is independent of people.
2. The notion of "truth" is independent of people.

Thereby, realism categorically accepts both assumptions, whereas anti-realism provides different answers: an agnostic position towards the first assumption, and rejection of the second. This first distinction should suffice in order to delimit the various characterizations of the realist and anti-realist spectra.

According to realism, the best scientific theories provide a faithful picture of what the world really is. From this perspective, scientific theories reveal reality. Therefore the entities assumed by theories actually exist – furthermore, they exist despite scientific theories, which merely correctly describe what was already there.

On the contrary, anti-realism argues that the best scientific theories act as tools to predict phenomena. From this perspective, scientific theories are simply explanatory models for the prediction of phenomena. Therefore the entities assumed by the theories are only convenient fictions – so that unobserved entities only exist in scientific theories.

Naturally, when scientific theories refer to objects that can be directly shown to any person endowed with full perceptual faculties, such as this text before your eyes, realists and anti-realists have little or nothing to disagree. Thus, scientific theories that work with such objects are not included in the scope of the ontological and metaphysical aspects of the debate between realism and anti-realism in philosophy of science.

However, when scientific theories address entities which cannot be observed in this sense, realists and anti-realists disagree. Therefore, the debate depends on the definition of the term "observable". Could only "objects" are perceived directly by the human senses be perceived as "observable"? Or is it legitimate to characterize as "observable" objects detected by instruments? If so, what would be an acceptable degree of the instrument's complexity?

As it is well known, the term "observable" is vague. That is, its field of application is unclear. There are, however, limiting situations in which the notion applies sufficiently well: it is safe to say that a green fungus on a Petri dish under an optical microscope is observable. Likewise, it is safe to say that a subatomic object, such as an electron, is not.

A central point distinguishing realist and anti-realist approaches relates to the ontological status of the involved entities: would it be legitimate to infer the existence of unobservable entities? While realism maintains that such entities do exist despite our knowledge or ability to detect them, anti-realism, conversely, maintains a skeptical attitude towards the matter.

3.2 THE MAIN ARGUMENTS

This section highlights three main arguments in the literature concerning the debate between these two philosophical conceptions. Firstly, the “Miracles argument” (sometimes referred to as “no-miracles argument”) is presented, favoring a realistic conception. Then, leaning toward anti-realism, the arguments of “pessimistic metainduction” and “underdetermination” are discussed.[3]

The Miracles argument

One of the main arguments in defense of a realistic approach to metaphysics for scientific enterprise lies in the explanation of the empirical adequacy of scientific theories. An intuitive attitude towards the empirical adequacy of a given scientific theory considers that the empirical success and the technological application of scientific theories attest,somehow, that theories addresses nature directly. Were that not the case, the fact that a scientific theory makes correct predictions about the world would be marked as a coincidence, and the empirical adequacy of these predictions would be considered a miracle. Moreover, it would be a constant miracle to every conceivable prediction with experimental success. As Putnam (1975, p. 73) famously states, scientific realism is “[. . .] the only philosophy of science that doesn’t make the success of science a miracle”. Thus, realism has a *positive* argument. Following Ruetsche (2015, §3.3), we will call this the “Miracles argument”.

Concerning ontology, the Miracles argument takes accepts the point of empirical success as a sufficient condition for existing entities in theory to be considered existing entities in the world. This is a powerful argument, since science, as a cultural phenomenon, shaped both the worldview and material conditions of human life. The Miracles argument argues that objects of scientific theories must correspond to objects of the world unless the idea that the application (and its empirical counterpart) is a miracle is accepted without reservations. Thus, realism expresses the idea that truth is a relation of correspondence to the world, said or thought to be either true or false under how the world really is. In fact, this is the *only* argument *in favor of* realism. The other two arguments that we will review in the next sessions are arguments *against* realism.

Pessimistic meta-induction

From a historical perspective, several scientific theories have obtained empirical success in their predictions and yet have been replaced by other theories that presented greater empirical success, and/or higher domain of explanation. That is, the history of

---

[3] Initially, the focus lies on *theoretical* underdetermination only.

science recognizes as false numerous scientific theories that were once considered to be true.

The argument is: the fact that our scientific theories are currently successful does not guarantee their success in the future; in fact, the history of science provides good reasons for not believing this will occur. This is called the “pessimistic metainduction” argument. It is an inductive reasoning (*à la* Hume) that employs the history of science when discussing science (thus being *meta*inductive) while maintaining a skeptical attitude concerning the possibility of being on the verge of a final explanation in science (thus being *pessimistic*).

Since the focus of the discussion lies in the existence of the entities to which the scientific theories are committed, the point presented by the argument of the pessimistic metainduction is as follows: the substitution and subsequent abandonment of scientific theories result in the replacement of the entities to which the theory was existentially committed. Therefore, existing entities in theory should not be extended to a real-world existence, that is, the objects associated with scientific theories should not be taken as existing outside, despite the theories that introduced them. Thus, if theories truly describe the world, the notion of “truth” concerning such entities must be regarded as an epistemic notion.

While the historical argument is also highly intuitive, it does not account for the line of criticism towards scientific realism as it presents a *subjectivistic* appeal. In this sense, one might maintain an *optimistic* attitude towards the historical perspective by conceding mistakes of the past while defending opinions like “Now we are on the verge of getting the truth!”. Ultimately, the optimistic stance lacks justification as much as the pessimistic stance, as the problem of induction (Hume’s problem) is at stake here. Even so, this line of criticism against scientific realism does not need to be further considered in order to present the point: that QM made the realists’ life difficult.

Underdetermination

The argument that scientific theories do not determine their interpretations is the most powerful one against several forms of scientific realism. It is a central argument in favor of the point made throughout this thesis, and as such, it is crucial to scrutinize it.

When two theories are equally successful in the empirical domain, that domain cannot be used as a criterion for choosing among rival theoretical conceptions. QM is a glaring example of this. As stated in Chapter 2, there are several ways of interpreting the same basic formalism.[4]

From an ontological point of view, the argument against scientific realism lies on the difficulty of asserting that the entities of one interpretation exist while entities of

---

[4] Chapter 4 presents at least two interpretations of QM that are commit to the existence of incompatible entities.

others do not, since from an empirical point of view all theories are equivalently correct.

Considering solely evidence, however, the results of predictions of phenomena and their technological applications are maintained. This suggests that QM, as a scientific theory, does not provide the elements necessary to decide which interpretation is correct. Therefore, if the interpretation of QM is underdetermined by experimental data, how can one state that one particular interpretation is a real description of the world while another is a mere construction? Put differently, how we are justified to be realists about one interpretation instead of the another?

3.3 REALISM IN THE QUANTUM REALM

Considering the arguments in favor and against scientific realism sketched above, it is now possible to address the bigger picture: how can one adopt a realist position to what concerns QM? *Should* this be done?

Consider the positive argument for scientific realism. Ruetsche (2015, §3.3) states the Miracles argument as follows.

P_1 Theory *T* is successful.

P_2 *T*'s truth is the best explanation of this success.

$\therefore$ *T* is true.

This schematization of the argument shows its abductive roots, which have been criticized.

> No support accrues to realism by showing that realism is a good hypothesis for explaining scientific practice. If we are open-minded about realism to begin with, then such a demonstration [. . .] merely begs the question that we have left open ("need we take good explanatory hypotheses as true?"). (FINE, 1986, p. 115).

There are, also, versions of the Miracles argument that are not dependent on truth-statements.

> I claim that the success of current scientific theories is no miracle. It is not even surprising to the scientific (Darwinist) mind. For any scientific theory is born into a life of fierce competition, a jungle red in tooth and claw. Only the successful theories survive – the ones which *in fact* latched on to actual regularities in nature. (VAN FRAASSEN, 1980, p. 40).

At this point in the debate, it is interesting to set that line of criticism aside and pay attention to the possible meaning of the Miracles argument as presented by Ruetsche (2015, §3.3), considering it applied to a specific scientific theory, such as QM:

P_1 QM is successful.

P_2 QM's truth is the best explanation of this success.

$\therefore$ QM is true.

As QM is *the* most successful empirical theory, the first premise is guaranteed (RUETSCHE, 2018; FRIEDERICH, 2014). *Additionally*, the deliberate setting aside of criticisms regarding abduction (or "inference to the best explanation") and truth-sentences allows for the acceptance of the following conclusion: QM is *true*. In this sense, the following argument defended by Ruetsche (2015, §3.3) is of great interest to this thesis: *what* does one believe when one believes a theory's truth? The answer is:

> What a realist believes when she believes a theory T is an *interpretation of* T, an account of what the worlds possible according to T are like. [. . .] An interpretation of QM tells the realist about QM *what* she believes when she believes QM. (RUETSCHE, 2018, p. 293).

According to this reasoning, the belief in QM's truth is the belief in *an interpretation* of QM. As stated by van Fraassen (1989, p. 226), "*Any question about content is, in actuality, met with an interpretation*". How to settle the matter, then, considering that QM underdetermines its own interpretation? Take this re-schematization of the reasoning mentioned aboce concerning the Miracles argument, employing the characterizations presented in Chapter 2. Firstly:

P_1 QM^{bas} is successful.

P_2 QM^{bas}'s truth is the best explanation of this success.

$\therefore$ QM^{bas} is true.

Assuming the interpretations of QM^{bas} represent the beliefs of scientific realists believes when they believe in QM, the schema changes slightly. It could be written as follows:

P_1 QM_{col} is successful.

P_2 QM_{col}'s truth is the best explanation of this success.

$\therefore$ QM_{col} is true.

It could, however, be presented like this:

P_1 QM_{bra} is successful.

P_2 QM_{bra}'s truth is the best explanation of this success.

$\therefore$ QM_{bra} is true.

It could, even, be presented as some something else.[5] Since both QM_{col} and QM_{bra} are empirically successful theories, their success seems to play no role in theory choice, thus causing the Miracles argument to lose its force. Presented like this, the Miracles argument must somehow respond to the argument of underdetermination and any realist account of QM should respond to the underdetermination argument. At any rate, the Miracles argument seems to be of little help for the realist. Ruetsche eloquently puts it as follows:

> Even if – maybe particularly because – a variety of contenders are available, there remain several Miracles argument-undermining possibilities. [. . .] the criteria by which the realist hopes to select the winning interpretation fail to single any such out. (RUETSCHE, 2018, p. 298).

Such argument was schematized in Brading and Skiles (2012, pp. 100–101), to voice criticism towards the so-called "object-oriented" realism concerning metaphysical underdetermination on the subject of the identity of quantum objects. Their argument is here modified in order to meet the purposes of interpretational underdetermination.

P_1 Object-oriented realists are committed to objects, and such objects may vary: (i) there is a fact of the matter about whether there are a *causal consciousness* in QM_{col} or *splitting worlds* in the world in the case of QM_{bra} and (ii) there is no fact of the matter about which one of those objects exist.

P_2 If P_1 is the case, then adopting object-oriented realism implies a commitment to the expectation that the best theories will accurately describe which objects there are.

P_3 The best theories, however, fail to offer an account of what objects there *really* are: ontology, as given by the best theories, is ontologically underdetermined.

C_1 Therefore, object-oriented realism is (probably) false.

So far, it should be clear that the support of all premises presented above has been argued for in the previous chapters. If a realist position about the *objects* postulated by QM is to be adopted, that results in (at least) two possibilities: the objects of QM_{col} or the objects of QM_{bra}[6] – and no objective criteria for deciding a correct one between them.

---

[5] See APPENDIX A.

[6] They are different. See Chapter 4.

Remarks on structural realism

It has been argued, mainly by French (2011, 2014), that a specific kind of realism may triumph over anti-realist's arguments. The author maintains that realism should be accepted only with regards to the *structures* of scientific theories. Such position, labeled as Ontic structural realism (OSR), argues that only the structures are existent – hence dismissing other less radical structural-realist stances, such as *epistemic* structural realism.[7] As so, OSR could, allegedly, provide an answer to the matters of interpretational underdetermination (FRENCH, 2014).

Following OSR, the schema presented in Brading and Skiles (2012, p. 101) may be adapted as follows:

P_4 If OSR is true, then the best theories are not infected with ontological underdetermination.

C_2 So, everything else maintained, OSR is preferable to object-oriented realism.

Therefore, an OSR-like account of QM seems to suffice: a realist position is only needed concerning *structural aspects* of QM. However, Chapter 2 presented QM as QM^{bas}: a stripped-down mathematical version of a basic formalism needed to account for the description of quantum phenomena. QM^{bas} itself is *so* basic, that it requires interpretation in order to save the theory's consistency (LEWIS, P., 2016; RUETSCHE, 2018). Then, two other structures were presented in order to interpret it: QM_{col} and QM_{bra}. Those structures are *incompatible* with each other; their axioms are different. Roughly, to raise the idea of representing QM_{col} as a formal system, say $\langle L, A, R\rangle$, where L is the language, A is its axioms, and R are its rules of inference, means that *at least* the set A will contain "collapse" as an axiom. In the same lines, if QM_{bra} is represented as $\langle L', A', R'\rangle$, then "collapse" would not be in A', differing from A *at least* in this point. This is precisely where the laws lie.

As Esfeld (2012) argues, "OSR is not an interpretation of QM in addition to many worlds-type interpretations, collapse-type interpretations, or hidden variable-type interpretations", but is *attached* to a particular interpretation of QM. Thus, when a structural realist proposes realism concerning QM, is realism concerning QM_{col} or QM_{bra} implied? Furthermre, is another interpretation of QM^{bas} included? The answer is not clear, as there is a *structural underdetermination* at sight. These questions ought to be answered as to the correct interpretation of QM^{bas} when one adopts a realist position about such interpretation's structure. Therefore, any realist account of QM seems to hold the burden of proof to solve the interpretational underdetermination. However, as decades of debate without consensus on the foundations of QM attest, this is by no means an easy task to achieve.

---

[7] There are many variations of structural realism and an extensive literature about it. A comprehensive survey of the field can be found in Ladyman (2016).

Another line of criticism may be brought up against those in favor of the OSR. Some would say that a realism about something (say, structures) lacks content *unless* a metaphysical characterization of that something is given (called here the “metaphysical profile”).[8] As acknowledged by Arenhart and Bueno (2015), there are no metaphysical accounts of what a structure may be. French recognizes such line of criticism.

> If the realist were to simply present the core equations of General Relativity and declaim “There! That is how the world is!”, the reaction would be justifiably dismissive (certainly from other philosophers or lay-folk, at least!). [...] we need to interpret these equations. (FRENCH, 2018, p. 394).

There is, then, an interpretational underdetermination concerning QM. The following chapters investigate whether such a debate could be settled within a philosophical debate. That is, by considering the ontological commitments of the two particular interpretations of QM^{bas} taken as examples throughout this thesis, these chapters asses whether it is possible to evaluate the interpretations themselves, without appealing to hard-scientific criteria (such as experimental falseability).

This scenario can be extended in the following terms. As stated by Esfeld (2019, p. 222), physics should be about Nature.[9] Furthermore, as de Ronde and Massri (2019) argue, the relation between theory and *physis* are not necessarily that of one-to-one representation: according to de Ronde (2018, §7), this representation is multiple. Therefore, instead of underdetermination, one may argue: why not embrace pluralism,[10] *e.g.*, theoretical, logical, ontological or metaphysical pluralism? The argument goes when one takes such an approach, and then any plurality of options would no longer be a problem.

A possible answer would be based on the subjectivity of such choices. In essence, pluralism would imply a more optimistic attitude toward the multiplicity of options, while underdetermination would betoken a more fatalistic one. However, even if pluralism is adopted, the kind of *Physis* described by physical theories would still be questioned: would it be one with or without collapse? An objection to pluralism could arise related to the unity of truth: there is only one truth about a single universe; in that sense, there is only one true description of reality. Thus, pluralist or not, scientific realism still seems to be in trouble.

---

[8] This is Chakravartty’s challenge, presented in more detail in Chapter 4.

[9] The ancient Greek term is “Φύσις” (“*Physis*”), also commonly translated by “Reality”.

[10] See de Ronde (2018, note 11) and references therein, since the author in question is developing a new kind of realism that does not necessarily correspond to the present terms of the debate, which in themselves are orthodox to his point of view. However, the the debate here is carried on according to the tradition established for the time being.

4 METAPHYSICS AND SCIENTIFIC WORLDVIEWS

> “Reality resists imitation
> through a model.”
>
> ERWIN SCHRÖDINGER
> *The Present Situation in*
> *Quantum Mechanics*

Chapter 2 presented a definition of QM as a stripped-down mathematical and physical *structure*. QM^{bas} is the best option an instrumentalist can get, as it adopts a ‘quietist’ attitude towards ontology and metaphysics: it is well-known that the standard approach for the measurement problem is to “shut up and calculate” (MERMIN, 2004). Any realistic approach, then, must solve the measurement problem and such solutions, defined as *interpretations of QM* (more specifically, QM^{bas}), *in principle* may be represented by set-theoretical structures – just as QM^{bas}.

Thus, if the interpretations of QM^{bas} yield the realist contents of the theory (RUETSCHE, 2015), what is an interpretation such as QM_{col} or QM_{bra} realist about? Sets? As argued in the next session, $\mathcal{A}_{\mathrm{col}\ 5}$ states that *consciousness* must play a causal role in the measurement process, in order to solve the measurement problem; Similarly, $\mathcal{A}_{\mathrm{bra}\ 4}$ states that reality must somehow be included in a *branching* process.

Where do such features enter the scenario? How to approach them? Can they *be* sets, or they must be something else? This chapter deals with these questions.

4.1 QUANTUM WORLDVIEWS

This section approaches what van Fraassen (1989, p. 193) calls “the foundational question *par excellence*”: “*how could the world possibly be the way this theory says it is?*”. The question is also called “the question of interpretation”: “[w]hat does it [the scientific theory] say the world is like?” (VAN FRAASSEN, 1991, p. 242).

In order to address these questions, it is fit to explain how QM_{col} and QM_{bra} describe a famous quantum experiment known as *Mach-Zehnder interferometer*,[1] frequently used in descriptions of the measurement problem. The experimental set-up consists of one monophotonic light source, two silvered mirrors (S_2 and S_3), two half-silvered mirrors or *beam splitters* (S_1 and S_4), and two detectors D_1 and D_2.

One property of half-silvered mirrors is to split light beams into two. Thus, S_1 splits the flash $|\psi\rangle$ from the source so that the transmitted flash $|\psi_A\rangle$ goes through path A and the reflected flash $|\psi_B\rangle$ goes through path B. The two mirrors S_2 and S_3 are then

---

[1] It is well-known that QM fails to be applied in systems with relativistic mass, such as light photons. Nevertheless, this experiment is crucial for the exhibition of quantum-like phenomena and has been replicated in an *electronic* analog (JI et al., 2003), where QM undeniably applies.

arranged in a manner to deflect $|\psi_A\rangle$ and $|\psi_B\rangle$, which then rejoin at the second half-silvered mirror in S_4. The path lengths of the two half beams are set equal. Given that reflected flashes undergo phase shift of $1/4$ of wavelength ($\lambda/4$), it should be expected that *only* D_1 shows detection.

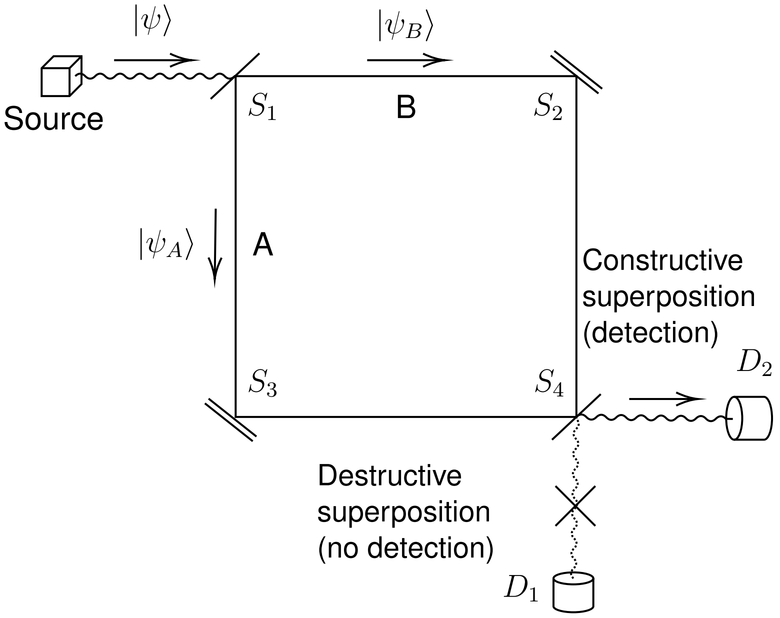

Figure 4 – Mach-Zehnder Interferometer.

Consider the following four possible cases below concerning the trajectory of the quantum system:

1. The eigenvalue corresponding to $|\psi_A\rangle$ is detected in D_1: at t_1 it is reflected by S_1 (phase shift $= \lambda/4$); at t_2 it is reflected by S_3 (phase shift $= 2\lambda/4$); at t_3 reflected by S_4 (phase shift $= 3\lambda/4$).

2. The eigenvalue corresponding to $|\psi_B\rangle$ is detected in D_1: at t_1 it is transmitted by S_1 (phase shift $= 0$); at t_2 it is reflected by S_2 (phase shift $= \lambda/4$); at t_3 it is transmitted by S_4 (phase shift $= \lambda/4$).

3. The eigenvalue corresponding to $|\psi_A\rangle$ is detected in D_2: at t_1 it is reflected by S_1 (phase shift $= \lambda/4$); at t_2 it is reflected by S_3 (phase shift $= 2\lambda/4$); at t_3 it is transmitted by S_4 (phase shift $= 2\lambda/4$).

4. The eigenvalue corresponding to $|\psi_B\rangle$ is detected in D_2: at t_1 it is transmitted by S_1 (phase shift $= 0$); at t_2 it is reflected by S_2 (phase shift $= \lambda/4$); at t_3 it is reflected by S_4 (phase shift $= 2\lambda/4$).

The difference between phase shifts in D_1 being $\lambda/2$ results in a *destructive* superposition – hence, no detection. The same is not true in D_2, as $|\psi_A\rangle$ and $|\psi_B\rangle$

shows the same phase, having a *constructive* superposition – thus enabling detection. This standard setup accounts for a probability of detection in D_2 equal to 100% and 0% in D_1. As there is always a single photon in the experiment at once, QM^{bas} yield information regarding *which path* $|\psi\rangle$ followed, which is the linear combination in the form of $|\psi\rangle = \alpha|\psi_A\rangle + \beta|\psi_B\rangle$.

Suppose, however, that the half-silvered mirror S_4 is *removed*, resulting in a case where the probability of detection is 50% for D_1 and 50% for D_2.

In this case, QM^{bas} yields the following superposition concerning the situation of a "*which-detector*" question, assuming that $|\psi_1\rangle$ is the eigenstate in which $|\psi\rangle$ is detected in D_1 and $|\psi_2\rangle$ is the eigenstate in which $|\psi\rangle$ is detected in D_2:

$$|\psi\rangle = \tfrac{1}{\sqrt{2}}|\psi_1\rangle + \tfrac{1}{\sqrt{2}}|\psi_2\rangle \tag{12}$$

The probability of measurement outcomes is given by Prob$(|\psi_1\rangle) = |\frac{1}{\sqrt{2}}|^2 = 0,5$. The same holds for Prob$(|\psi_2\rangle)$ as both detectors are in orthogonal paths; thus $|\psi_2\rangle = |\psi_1\rangle^{\perp}$ and $\langle\psi_1|\psi_1\rangle^{\perp} = 0$. A measurement will return either $|\psi_1\rangle$ or $|\psi_2\rangle$ as an outcome, and this happens when the detectors, either D_1 or D_2 respectively, responds.

At this point, Wheeler's (1986) "smoky dragon", arises again. Wheeler's analogy becomes apparent when taking the dragon's tail as the source signal, which passes through S_1. Then, there "is" its head, biting the detectors D_1 or D_2. And *which-detector* question brings along the dragon's smoky parts: one cannot be certain without the help of an interpretation as this brings the measurement problem to the surface, that is, the problem of telling a story about what happens in the whole experiment that yields the empirical result. There is extensive literature on many formulations of the measurement problem. For this chapter's purposes, it is stated as the *which-detector* question concerning the Mach-Zehnder experiment. The endeavor of solving the measurement problem is an interpretative one. The following discussion explains how the selected examples so far explains this experiment.

Take, firstly, QM_{col}. $\mathcal{A}_{\mathrm{col}\,4}$ states that Equation (12) describes the whole system until detection, when, based on $\mathcal{A}_{\mathrm{col}\,5}$ the system collapses to either $|\psi_1\rangle$ or $|\psi_2\rangle$ with equal probability. There is, however, an ontological counterpart. It has been argued that the collapse in $\mathcal{A}_{\mathrm{col}\,5}$ is somehow related to human consciousness (WIGNER, 1983; LONDON; BAUER, 1983). Therefore, QM_{col} can be argued to be ontologically committed to consciousness. Such ontological counterpart is *extracted* from the theory, and labeled here as Consciousness-based interpretations (CBI). In metaphysical terms, however, the idea that Consciousness causes the collapse hypothesis (CCCH) may be entertained.[2] It may *also* be entertained that Consciousness recognizes the collapse

---

[2] See Wigner (1983).

hypothesis (CRCH).[3] Thus, metaphysical underdetermination can be seen right from the start. This chapter, focuses on CCCH only.[4]

In ontological terms, von Neumann (1955, p. 421) argues that superposed states as in Equation (12) collapse with the interaction with the "abstract ego" of an observer. The detection in D_1 or D_2 would not be enough to cause the collapse, as linearity implies that the detectors' states are also to be described as superpositions as well. This situation occurs since the whole system described by $|\psi\rangle$ is in the same ontological domain. Thus, *physical domain*; so, in order to account for measurement outcomes, only the interaction of a *non-physical* agent can stop the superpositions and collapse the superposed state into a single-term state, which is actually observed. Wigner (1983) suggests, further, that such non-physical agent that causes the collapse is *consciousness* – hence, C*C*CH.

Focus now on QM_{bra}. $\mathcal{A}_{\mathrm{bra}\ 4}$ states that in the case described by Equation (12), the superposition is taken literally: both terms are *equally real*. Therefore, by $\mathcal{A}_{\mathrm{bra}\ 5}$, if $|\psi_1\rangle$ is as a measurement outcome, then the outcome $|\psi_2\rangle$ is also true elsewhere.

Elsewhere since QM_{bra} does not determine its ontology: according to the Many worlds interpretation (MWI), the branching splits the worlds (DEWITT, 1971), while according to the Many minds interpretation (MMI), the branching splits the minds of the observers (LOCKWOOD, 1989). This work discusses exclusively the former, although it should be noted that there is also an ontological underdetermination at this point.

An ontological counterpart of $\mathcal{A}_{\mathrm{bra}\ 4}$ is MWI, according to which the world branches itself into each possible outcome of a superposition.[5] Therefore, if $|\psi_1\rangle$ is found as a measurement outcome, then we happen to live in this branch of the world – the outcome $|\psi_2\rangle$ is still true for an orthogonal branch of the world, where such measurement outcome is found simultaneously. Thus, although the collapse is apparently happening (even if a superposition is not actually *seen*), it is not *really* occurring. What happened, in fact, is the branching of the world in two, although other worlds are not perceived. This fact also integrates the head of the dragon: determinate outcomes of measurement are perceived.

The interpretational underdetermination between QM_{col} and QM_{bra} presented in Chapter 2 leads to additional cases of underdetermination, which may be ontological and metaphysical regarding the choice of a theory, say, CCCH or MWI. Ultimately, distinct physical theories are indeed *distinct metaphysical possibilities* in the sense of

---

[3] See London and Bauer (1983).

[4] CRCH is analyzed in Chapter 7.

[5] To avoid possible misunderstandings, it is worth emphasizing that the term "world" refers to the whole universe, and not a single planet – see Putnam (1974, p. 150).

distinct proposals about the nature of the physical world.[6]

4.2 LOST ONTOLOGIES

As presented in Chapter 1, the semantic-like characterization of physical theories is literally about mathematical structures, and nothing else. At most, the matter includes a *representation* of real systems, yet not cover those directly. Now, however, mathematical structures are being related – *not* the real objects of this world, in both observable and unobservable aspects. As Frigg (2010, p. 253) remarks, this approach is metaphysically neutral concerning the nature of the objects in its domain. As so, relations on this domain are defined extensionally, hence having no properties other than formal properties (*e.g.*, transitivity, reflexivity, and so on).

This discussion, if based solely on the semantic view, leads to the conclusion that all that exists is either sets or elements of sets (atoms or "*Urelementen*"). A structure, then, does not concern anything in the current phenomenal world. Even if one were to admit that models are structures connected to physical systems by the setting up of morphisms between them, it should be recalled that a morphism is a relation *between structures*, *i.e.*, purely mathematical, not a relation between a mathematical structure and a physical object. Moreover, in order to make sense of this morphism between structures (models) and physical systems (objects), the assumption that these systems at most *exemplify* specific structures would be required. As Frigg (2010, p. 254) argues, these structures "[. . .] cannot be had without bringing non-structural features into play".[7] As long as we are dealing with empirical theories, it seems to be essential to keep empirical entities at sight.

As reported by the semantic approach, the best alternative is to assume that some structure *represents* the theory's ontology, in which the beings have set-theoretical substitutes. This issue is somewhat more straightforward in the syntactic approach (SUPPE, 1977). Once a theory is axiomatized and formalized, all that remains is attending to the *interpretation function*, which associates part of the linguistic vocabulary to entities in the model that simulates the entities – thus endowing the theory with a *partial interpretation*, which is a *physical* interpretation. Notice, however, that even this approach leaves central issues concerning the nature of these entities unad-

---

[6] Peter Lewis shall be thanked for this observation. Naturally, there could be also cases of metaphysical underdetermination *without* theoretical underdetermination. Take, for example, the problem of identity in QM. In essence, even if an interpretation is deliberately determined, QM does not yet provide an answer to whether or not there are identity and individuality, in a metaphysical sense, for the quantum domain – see French and Krause (2006).

[7] Frigg (2010) considers this line of criticism towards the semantic approach when presenting a metaphysical account of models as representing *fictional entities*, that is, hypothetical entities, rather than purely mathematical structures. As interesting as this suggestion may be, this work does not enter the metaphysical debate accounting for the concept of "models". For now, it suffice to say that the critique of the semantic approach presented by Frigg (2010, §2) is agreed almost *in totum*, concerning its lack of commitment in relation to real objects.

dressed: for instance, of entities' kinds are not described by the interpretation function. This approach to scientific theories entails, then, that the theory is silent over several philosophical questions concerning the objects that are dealt with.

This is, as Muller (2011, p. 98) declares, the "problem of lost beings". These beings, however, are not to be found within the structures, and thus the ontology of scientific theories concern something else. This point is further explained as follows.

Take, for example, CCCH and MWI: both interpretations of QM^{bas}[8] postulate different entities with fundamental (but also distinct) theoretical roles, which do not appear in formalism. Where are the (ontological) entities of theories, then? Certainly not in the formalism, but surely within the theories' scope: in CCCH's QM_{col}, for example, the causal agent of the collapse (recall axiom $\mathcal{A}_{\mathrm{col}\ 5}$) is human consciousness (WIGNER, 1983, p. 421); in MWI's QM_{bra}, the branching process (recall axiom $\mathcal{A}_{\mathrm{bra}\ 4}$) depends on multiverses. In the sense the term "ontology" was defined here, as a *catalogue* or *list* for *what there is* in the world (accordingly to a given theory), entities such as human consciousness and multiverses *should* be regarded as fundamental components of the ontology of CCCH and MWI respectively. So it appears that the mathematical approaches explored in Chapter 1 do not comprise the totality of what scientific theories are.[9]

Thus, if one gets asked something like: "Okay, but where does the discussion about the interpretation of QM, often mentioned, fit in? That is, where are the beings, say, consciousness or the many worlds, in this scheme?", the following answer must then be (awkwardly) provided: "Nowhere!" Is this a drawback of formal approaches to philosophy of QM? This answer is not quite as simple as the previous one.

According to Ruetsche (2015), the interpretations regarding QM are precisely the realist content of the theory. Thus, it is non-trivial to postulate, for instance, the causal act of the observer's consciousness (WIGNER, 1983) or the world-branching process (DEWITT, 1971). Once the semantic approach leaves the problem of clarification unanswered, it should be expected that the metaphysical aspects of the realist features of a scientific theory are not addressed *within* the theory's mathematical constructs. This very question produces an insight into the nature of the interpretation of QM: its *non-formal* characteristics.[10]

As suggested in Chapter 1, the interpretation of QM in this broader sense differs from the notion of "interpretation function" in mathematical logic, is defined as

---

[8] This chapter simply writes "QM", except when further specification is needed.

[9] That is, the semantic view and the syntactic view.

[10] Before abandoning formal aspects, it is essential to review what the semantic approach has achieved. The "axiomatization" of QM made largely possible to express the assumptions of the theory in order to discuss its fundamental traits. That is, it was possible to observe, with a large extent of precision, what the quantum *theory* is, and where its theoretical pieces fit – its axioms, mathematical (and metamathematical) tools, logic, and so on. It is essential to stress here, however, that this cannot be the end of the story *if* a realist approach to QM is intended.

something which *talks about* this scenario: a *meta*-physical scheme. Where, then, are the ontological beings in the n-uples presented in Chapter 2? The point is: they are nowhere there. The most interesting point is: they should not be expected to be there. Let this statement be examined in more detail.

Considering QM, the problem stressed by Muller (2011) becomes even more evident: what do interpreters of QM interpret? An obvious answer is "Quantum *theory*". Recall that manners of doing so were defined in Chapter 2 with QM^{bas}. The mathematical tools seem to enable one to precisely observe what QM, in its syntactical and semantic aspects, can be. Call the *lato sensu* interpreter of QM the one who interprets precisely mathematical structures (*i.e.*, QM^{bas}) – this was presented in in Chapter 2.

As an example consider CCCH and MWI: a theorist inclined to CCCH formally interprets the measuring act as collapse, and *ontologically* interprets it as a causal power of human consciousness over the measurement processes. Conversely, a theorist inclined to MWI formally interprets the measuring act as the branching process that *ontologically* leads to physically distinct worlds at every superposition situation. Even though the act of measurement is the crucial point, each interpretation tells a different story concerning what happens throughout the whole experiment, *e.g.*, what are superpositions, whether there is a single experiment, in a single universe, or not.

These ontological claims state something concerning the very existence of processes and entities that describes physical phenomena. However, this – further – interpretative element seems to escape formalization and therefore axiomatization. There are no such matters as consciousness or the many worlds present in the theories' mathematical treatments (such as QM_{col} and QM_{bra} respectively). If not in the syntactic part of the language of the theory, nor the semantic part of the language, these beings seems to be *lost* indeed.

Call, then, an interpretation in *stricto sensu* the attribution of philosophical meaning to mathematical structures. This work suggests, then, that it may be more accurate to introduce the act of ontologically interpreting QM^{bas} in *stricto sensu* as a *meta-meta*theoretical element, which attributes ontological meaning to both the mathematical theory and its (partially interpreted) physical *meta*theory. As stated by Sklar (2001), interpretation seems to add a layer to the theory. As such, the interpretation is mainly considered to be a *non-formal* layer of the theory.[11]

If the goal is to move towards a worldview based on scientific realism, an essential ingredient is missing: a further sense of *interpretation* concerning ontological issues. One metaontological method of extracting the ontology from theories could be a Quinean-like approach of *ontological commitment*.[12] Thus, when looking at the

---

[11] Naturally, it could be formalized under the price of relying on an unformalized *meta-meta*-metalanguage in which its formalization would be done – see Church (1956, §1).

[12] Issues concerning metaontology will not be addressed in this work. Suffice it to say that the ontological commitment *à la* Quine is assumed as a background metaontology.

entities that play some theoretical role in scientific theories, one may argue that these theories are committed to the existence of such entities. Therefore, even though the term "consciousness" does not have any mathematical counterpart in the formalism of QM_{col}, it plays a fundamental theoretical role as the causal agent of $\mathcal{A}_{\mathrm{col}}$[5] It is safe to affirm, then, that QM_{col} is *committed* to the existence of human consciousness, and hence it should be regarded as part of the theory's ontology; the same holds for the multiverses in QM_{bra}.

Is there a legitimate place for ontological and metaphysical discussions in the interpretation of QM? Apparently, there is *not* – at least to what concerns syntactic and semantic structures. If so, the efforts to characterize scientific theories as a class of models – the so-called "semantic view" – or as a formal calculus – the so-called "syntactic view" – are insufficient to provide a complete account for what a scientific theory in fact *is*. Particularly, those approaches fail to cover the theory's interpretational aspects of the theory, responsible for most of its explanatory power regarding its ontological and metaphysical accounts of the world, *i.e.*, the "what the world is like" *modulo* a scientific theory. Instead, perhaps the most reasonable way to address those aspects would be within a meta-level of the discussion, so that metaphysics would lie in a metametalanguage of the theory (the *object language* being the mathematical level and the *metalanguage* being physical level). This may provide a better understanding of where and when notions of metaphysics may be applied to scientific theories. Questions concerning the place of metaphysical and ontological discussions within the interpretation of QM are far from finished. However, its place in the discussion is now clearer than it was before: it lies within the non-formal aspects of the theory.

Perhaps. Nevertheless, there is one view that considers possible to extract at least some fundamental ontological aspect from formalism alone, called "wave function realism". This view is sometimes presented as a natural attitude towards QM (ALBERT, 2013), or through the famous Quine-Putnam argument of indispensability for obtaining the ontology from QM – that is, that ontology can be "read off" directly from the formalism. A scheme of the argument, as proposed by Colyvan (2019) and generalized by Ney (2012, p. 67), is presented as follows.

P_1 We ought to have ontological commitment to the entities that are indispensable to our best scientific theories.

P_2 Entities of kind X are indispensable to QM.

$\therefore$ We ought to have an ontological commitment to entities of kind X.

As representation of the wave function ($|\psi\rangle$) is indispensable to the quantum-mechanical description of quantum systems, one ought to be ontologically committed to the wave function *as an entity* in the theory's ontology. Take the *which-detector* description of the Mach-Zehnder experiment, as shown in Equation (12), as an example. It shows the motion of the wave function $|\psi\rangle$ through time, so the entity "wave function" should be included as an existing entity *modulo* QM.[13] Then, at least *some* part of the ontology is *read off* directly from the theory's formalism, and thus (some) of Muller's lost beings may be found within the mathematical structures of QM.

So that's it, right? Theories gave away their ontology, thus there is the science-based worldview in a naturalistic fashion: *science states what the world is like, and according to QM, the world is such and such.* Not quite so. Theories' ontologies may have been extracted – directly from formalism or otherwise – which is an account of what there is. Nevertheless, what it is like? Is ontology *informative* concerning the metaphysical nature of those entities? Not really.

4.3 LOST METAPHYSICS

Regarding the wave function, Ney states that *even if* one concludes that the wavefunction exists – there is have no *prima facie* reason preventing this statement to be extended to a consciousness-based or world-splitting account of the universe – there is no "[. . .] justification for making factual assertions about what sort of entity this wave function is" (NEY, 2012, p. 68). Therefore, QM (QM_{col}, QM_{bra} or else) does not provide an answer regarding what are, in metaphysical terms, the entities to which it ontologically commits itself.

This might be a drawback for the attempt to look to QM to achieve information what the world is like – a cornerstone of scientific realism. Regarding this matter, Chakravartty wrote:

> One cannot fully appreciate what it might mean to be a realist until one has a clear picture of what one is being invited to be a realist about. (CHAKRAVARTTY, 2007, p. 26).

This claim calls for the need for a metaphysical explanation, the so-called *clear picture* that explains in metaphysical *what those entities are*. This further sense of interpretation is here called the attribution of a "metaphysical profile". It should be evident, however, that obtaining such a clear picture of the metaphysical profile is not so simple: it should be handled, as French (2013) argues, with some degree of epistemic humility (as there is not such a thing as a point of view of nature from a *cosmic exile* to evaluate between rival options in metaphysics). Handling the need for a

---

[13] Whether wave function realism should be regarded as an interpretation of QM, in addition to QM_{col} and QM_{bra} (ALBERT, 2013), or as a general attitude towards the ontology of QM, which is independent of theoretical choices one might make to solve the measurement problem (LEWIS, P., 2004; NEY, 2013) is a matter not discussed here, for the point made by this discussion does not depends on such stances.

metaphysical profile (the “clear picture”) with epistemic humility was called by French (2013, p. 85) the “Chakravartty’s challenge”. According to the challenge, it is not enough to point to some feature of a theory and claim realism about it. In order to achieve a legitimate realism about the contents of a scientific theory, one must specify *what are those contents*, and doing so involves – at least partially – providing a metaphysical characterization of such content.

Suppose, then, that one claims to be a realist about QM_{col}. This means this person believes that QM_{col} makes true statements about the world, *including* its unobservable processes – such as the causal power of consciousness (to which the theory is ontologically committed). However, if no metaphysical profile is offered for consciousness, the alleged realism about the theory is empty.

Here, the *philosophical* aspects of interpreting QM (*e.g.*, ontological in the sense of the existence of a causal consciousness or multiple actual worlds, and metaphysical in the sense of the kind of existence of those entities) are at stake, not a function between mathematical and physical systems. In this sense, these aspects represent separate metaphysical possibilities – distinct proposals about the nature of the physical world. Therefore, this feature of interpreting of QM leads to a worldview, an essentially metaphysical discussion, as it tells *stories* about the world and the kinds of entities which integrate it – the objects which compose its ontology. Again, this metaphysical-ontological sense of interpreting QM is referret to here as interpretation in *stricto sensu*, from which arise the problems of ontological and metaphysical underdetermination, as all the options briefly stated above are available.

The next chapters address the subjects concerning underdetermination. The main concern in this chapter is methodological, *i.e.*, it lies on the question of how ontology and metaphysics comes into the conceptual scheme of QM.

One may be naturally led to the question: how to obtain a metaphysical profile (*e.g.*, Chakravartty’s “clear picture”) for a theory’s ontological entity? Can philosophers simply create metaphysical characterizations that, as French (2011) worries, “float free” from scientific theories themselves? Worrying about the risk of driving metaphysical inquiries which are distant from the empirical results, thus creating the need for justification, led many authors to argue for discontinuation of this maner of conducting analytic metaphysics as a philosophical discipline.[14]

Metaphysics, however, must float free from physics in the context of the metaphysical profile; otherwise, it would be impossible to attribute a metaphysical profile to QM. Furthermore, it would be impossible to claim realism about QM, according to Chakravartty’s challenge. The quest for realism through Chakravartty’s challenge, then, justifies the use of the metaphysical work that is not necessarily scientific informed –

---

[14] See Ladyman and Ross (2007) and references therein.

the so-called *armchair methods*.[15]

In such a project, some authors acknowledge the utility of metaphysics to scientific theories precisely related to filling this metaphysical gap, being, in principle, useful for the (*stricto sensu*) interpretative work. Analytic metaphysics, thus, may be regarded as a "toolbox" (FRENCH; MCKENZIE, 2012) used to interpret scientific theories, or a "spot for pillaging" (FRENCH, 2014, p. v). The last suggestion comes from French's (2014) "Viking Approach" to metaphysics, which justifies the free development of metaphysics based on the scientific usage of metaphysical concepts. According to the Viking Approach, as French (2014, p. 50) argues, "[...] the products of analytic metaphysics can be regarded as available for plundering!".

Chakravartty's challenge is thus addressed by the Viking Approach in the following way: one simply chooses among the available options in the metaphysics' literature in order to *fill* or *dress* the ontological entities in a metaphysical profile.[16] In this sense, metaphysics, as a discipline, presents roughly the same level of independence from empirical science as mathematics, for it provides theories, tools and strategies of investigation and speculation which can be employed in order to interpret scientific theories.[17] An interpretation of a scientific QM, then, not only provides the realist content of the theory (RUETSCHE, 2015) but also, following Chakravartty's challenge, presents the *possibility* of obtaining a realist content.

One question, at least, remains unanswered: when is the challenge completed? Or, at least, when is the challenge *sufficiently* completed in order to fill one's realism about unobservable entities of a given scientific theory? Recall that it is not possible to extract metaphysical profiles from scientific theories *and* it is not possible to be a realist about something without knowing its metaphysical profile. However, "[i]t is *always* possible to ask finer-grained questions [...]" (CHAKRAVARTTY, 2019). Then, when does the metaphysical profile become sufficiently developed in order to justify a realism about it? This is here called the "Meta-Chakravartty's Challenge". By recalling that the *clear picture* challenging demands can only be obtainable within a *floating-free* metaphysics, the Meta-Challenge appears not so shocking, becoming more naturally acceptable. After all, it is indeed always possible to investigate finer-grained metaphysical questions – this consists most of the metaphysical work as well as its prerogative.

French (2018, p. 394) acknowledges this problem, by asking "how much further should the realist go", and "to what extent should our realism be metaphysically informed?" (FRENCH, 2018, p. 395). The problem, then, returns to the matter of epistemic humility. As metaphysical claims cannot be directly given by observation (*e.g.*, no physical theory can tell whether the concept of "mass" is an instantiated *universal* or a

---

[15] See Ladyman and Ross (2007, p. 10).

[16] Chapters 6, 7 and 8 deal with examples of this matter.

[17] A similar argument for the independence of *a priori* metaphysics from empirical sciences and the analogy with pure mathematics, can be found in Morganti and Tahko (2017).

trope), a humble attitude towards metaphysical profiles must be adopted. The amount of humility one should adopt, however, is unclear: if too much, the risk is telling the same story that relevant scientific theories already do (thus not forming a worldview); if too little, then one may have to face underdetermination.

To French (2018, p. 401), the perfect balance lies in the Viking approach, close enough to the "Toolbox" approach: metaphysical literature provides many views, moves and approaches which can be used for articulate a metaphysical profile for relevant features of the believed theory.[18] According to this view, QM_{col} may be assumed to be within a Cartesian-like dualism (CCCH) or a Husserlian-like phenomenology (CRCH).[19] Therefore, Chakravartty's challenge and the Meta-Challenge are completed with the *use* of metaphysical theories, developed by metaphysicians, in a way that allows the realist to employ the tools for articulating questions concerning *how the world is* – *modulo* CCCH or some other interpretation of QM.

This is, clearly, a heuristic move, as one may articulate, by itself, such a clear picture. Then again, French (2018, p. 404) asks: "why reinvent the wheel?" – to what we wholeheartedly agree: it is more fruitful first to examine the available options.[20] French's method of approaching metaphysics within the context of science, thus, is not an anecdote. The Viking and the Toolbox approaches are not just ways of stating, in a dismissive tone, something along the lines of "let us look at many things that metaphysicians have done", but instead poses a literal suggestion. Concerning such suggestion, French states that scientific metaphysics *is*:

> [...] to engage with extant metaphysics, draw on the tools it has already developed, and work with metaphysicians themselves to hone and sharpen them in various ways, so that they can be developed more precisely to help us understand what it is that science is telling us. (FRENCH, 2018, p. 405).

Looking at scientific metaphysics from this angle, it does not seem to be so distant from traditional, armchair metaphysics. One first and somewhat obvious reason for this is: if the Viking approach to metaphysics employs what metaphysicians have already done in the history of philosophy, then much of what is plundered are products of this traditional metaphysics (in which, for example, Plato is still an available source for pillage). A second, perhaps speculative, reason for this conclusion is that the so-called scientific metaphysics do not seemed to produce metaphysical content, thus remaining distant from a methodological attitude *towards* metaphysics – a possible reason as to why it might be more prudent to call it a *metametaphysical* attitude.

This chapter argues for the indispensability of ontological and metaphysical considerations in the development of a worldview based on QM. It was also argued that

---

[18] See also French and McKenzie (2012).

[19] These metaphysical profiles are carefully analyzed in Chapters 6 and 7, respectively.

[20] Chapter 8 parts ways with this suggestion.

French's approach, based on the application of Chakravartty's challenge and the Viking approach to metaphysics, makes more sense if metaphysics is somehow considered to be independent of QM – if it *floats free* from science.

Even if sticking to French's approach, the realist will be bothered with interpretational underdetermination: should one believe the metaphysical profiles of QM_{col} or QM_{col}? Why? Put differently: is there a causal consciousness according to QM? Are there parallel worlds? There are no easy answers. Cushing (1993, p. 269) eloquently states that "[a]ll interpretations of quantum mechanics have price tags attached." The discussion presented here argues that philosophy might have a reasonable opinion in this business. If the currency of this market is philosophical, maybe a metaphysical turn is required: to compare theoretical virtues and explanatory power in order to choose between them. This is, however, as Arenhart (2017, p. 124) states, "[...] what typical metaphysical debates already do". The question of whether there are metametaphysical methods available for objectively evaluate rival metaphysical theories in order to "break" metaphysical underdetermination will be subject of Chapter 5.

Part III

ON METAMETAPHYSICS

5 UNAVAILABLE METAPHYSICAL STORIES

> "*All* interpretations of quantum mechanics have price tags attached. Again, it's a buyer's market."
>
> ---
>
> James T. Cushing
> *Underdetermination, Conventionalism and Realism*

In standard formulations (more specifically, Hilbert-space formulations), QM,[1] is *compatible* with several distinct interpretations (or *theories*, as argued in Chapter 2). Up to this date, no objective criteria based solely on scientific constraints have been established in order to choose an interpretation. Moreover, while those interpretations provide general guidelines concerning the furniture of the world, they generate trouble by being *compatible* with a different set of metaphysical profiles. In other words, distinct metaphysical approaches can be provided to each of the possible furniture or *ontology* provided by the interpretations.

In summary, the situation is as follows: different quantum theories (theoretical underdetermination) populate the world differently (ontological underdetermination), according to the interpretation chosen. Each interpretation, then, might be compatible with a multiplicity of metaphysical profiles, depending on the chosen approach to metaphysics (metaphysical underdetermination). It is far from clear how quantum theories may help cut down the proliferating number of options. This may be seen as part of a reasonably well-known problem called "underdetermination", a worry that concerns the naturalistically-oriented scientific realist, who considers QM to tell a *single* story about the furniture of the actual world.[2]

Notice that the source of the problem is directly related to interpretation. Why do scientific theories need to be interpreted? Concerning QM, the most straightforward answer is *measurement*. Measurement in QM seems to require a process apparently at odds with the theory, having no intuitive or natural place in the world or dynamic processes described by the theory. In essence, this is the so-called *measurement problem*.

Dealing with this problem is a task left to *interpretations*. As Sklar (2010, p. 1124) remarkably states, this is not to be taken as an imperative from philosophers alone:

---

[1] For simplicity, the terminology employed in the previous chapters will be momentarily suppressed, and "QM^{bas}" will be simply referred to as QM, except when the need for explicitly in stating the basic formulation of QM (QM^{bas}) arises.

[2] This discussion does not concern the so-called *instrumentalist* or the *working physicist* and other FAPP approaches to QM ruled by the maxim "shut up and calculate!", for which the effort to interpret QM, in the sense of assigning it a "worldview" is meaningless.

"[. . .] the demand for interpretation [of QM] arises within theoretical science". Scientists who aspire to develop a *scientific image* of the world rely on interpretation – and, consequently, on *ontology and metaphysics*. As a result, they are also subject to the underdetermination problem.

In order to clearly present the problem, take a rough characterization of the word "interpretation" in this context, as given by van Fraassen (1991, pp. 242, 336–337): interpretation of a scientific theory informs us "what the world is like" *modulo* such theory. This characterization seems to lead to a kind of "naturalist" stance to ontology and metaphysics if regarded to be the theoretical view that attributes the task of answering what is there and what the world is like to scince. In this sense, an interpretation of QM (ideally) enables one to "extract" a *scientific image* of the world as if QM were true, thus playing a non-trivial role in a scientifically informed metaphysics. This is really tempting, and it would be a straightforward situation if there existed a single picture of the world *modulo* QM. If it were possible to *extract* an interpretation from the theory somehow, then the metaphysician's job would be completed – the world is just as QM says it is. Were that the case, one would completely agree with Maudlin's naturalist claim:

> Evidence for what exists, at least in the physical world, is provided solely by empirical research. Hence the proper object of most metaphysics is the careful analysis of our best scientific theories (and especially of fundamental physical theories) with the goal of determining what they imply about the constitution of the physical world. (MAUDLIN, 2007, p. 104).

Unfortunately, the situation is not that simple: there are *several scientific images compatible with QM*, as many as there are interpretations of QM. This results from the fact that interpretations operate fundamentally on non-testable statements, discussing unobservable entities and processes. In order to evaluate them properly, it is necessary to inquire about the evaluation of ontological and metaphysical theories. Otherwise, the necessary elements to adhere to a particular scientific image of the world are non-existent, as there are different interpretations positing different entities. The theories, with added interpretations, cannot be simultaneously true in any sense of truth relevant to the realist.

In line with Ruetsche's (2015) claim that the realist content of QM is the realist content of an *interpretation* of QM, discussed in Chapter 3, Sklar also emphasizes that, in QM, the three kinds of underdetermination sketched above imply that:

> Our foundational theories usually exist in a scientific framework in which they are subject to multiple, apparently incompatible, interpretations. And given the interpretation you pick, your view of what the theory is telling us about the basic structure of the world can be radically unlike that of someone who opts for a different interpretation of the theory. (SKLAR, 2010, p. 1123).

Consequently, the scenario is as initially described: QM is an invaluable source of empirical results; however, it falls prey to different forms of underdetermination when it is considered a guide to what there is and how the entities look. Given that the mathematical story told by QM alone is unable to break underdetermination, this chapter suggests adopting the required philosophical spin in the discussion. Leaving naturalistic concerns aside, the inquiry made here is whether philosophy, as a discipline, could be of help to a better understanding of this general framework of metaphysical underdeterminations entailed by the efforts of interpreting QM.

For this purpose, a distinction between metaphysics and ontology is further explored, as well as their interrelationships. From a methodological point of view, this shall provide two kinds of possible manners in which metaphysics may help QM: the possibility to discard some metaphysical views associated with interpretations due to quantum mechanical reasons, or, when that fails, due to metaphysical reasons. (Naturally, it is impossible to break the underdetermination fully, but at least the range of options is *limited*.) This provides a relation between science and metaphysics that does not need to appeal to intuitions, which in some cases may somehow benefit from the epistemic privileges attributed to QM.

The overall structure of the chapter is as follows. Section 2 briefly recall the measurement problem, advancing two interpretations in order to serve as test cases for metaphysical methodology. Section 3 discusses two methodologies that could help settle the question of which interpretation and which metaphysics to choose. Section 4 advances this work's own proposal. As mentioned, this proposal seems to be the one that better uses the resources of the scientific theory to aid theory choice in metaphysics. The final remarks in Section 5.

5.1 THE PROBLEMS IN A NUTSHELL

This section begins with another formulation of the measurement problem. This is the source for the need for interpretations, which span a wide array of possible ontological and metaphysical theories, generating underdetermination.

The measurement problem can be stated in numerous ways. Perhaps the most intuitive (although and rather cruel) way to perceive it is through the thought experiment made famous by Schrödinger in his "Schrödinger's cat" scenario. Consider the following situation. Suppose the following elements are locked in a box: a cat, a venom flask, a hammer and a quantum system. After one hour, the quantum system $|\psi\rangle$ has equal probabilities of dacaying or not, in which case two distinct chains of effects may result:

a) If the quantum system decays, the flask is broken by the hammer, and the cat dies. Its vectorial representation is $|\psi_{\uparrow}\rangle$;

b) If the quantum system *does not* decay, the hammer stands still, the flask remains intact, and the cat remains alive. Its vectorial representation is $|\psi_{\downarrow}\rangle$.

These vectors are presented here with simplifications, since the point of interest is the fact that each possible chain of effects, if actual, excludes the other. After one hour, QM describes the state of affairs involving the cat inside the box as a linear combination of the two possible outcomes for the fate of the cat, being $|\psi_{\uparrow}\rangle$ the case where the cat remains alive and $|\psi_{\downarrow}\rangle$ the case where the cat dies, so that the sum is:

$$\sqrt{\tfrac{1}{2}}\Big(\,|\psi_{\uparrow}\rangle + |\psi_{\downarrow}\rangle\,\Big). \tag{13}$$

This result does not describe a possible measurement outcome, but rather a linear combination of state vectors related to possible measurement outcomes. To find the cat in a determinate state, one must open the box (a metaphor to the act of "performing a measurement"), so the quantum-mechanical description of the cat changes from the vector sum to $|\psi_{\uparrow}\rangle$ or $|\psi_{\downarrow}\rangle$, with equal probability, that is, $|\psi_{\uparrow}|^2 = |\psi_{\downarrow}|^2 = 0,5 = 50\%$. One can naturally wonder about *what exactly happened*, in order to change the description from a vector sum to a single-state description (called an "eigenvector"). As soon as one this kind of inquiry starts, one enters the realm of the interpretation of QM.

The standard textbook approach to the measurement problem is as follows. While undisturbed, quantum systems evolve in time according to the Schrödinger equation, a linear and deterministic equation that implies that, if the eigenvector $|\psi_1\rangle$ evolves to $|\psi_1'\rangle$ and the eigenvector $|\psi_2\rangle$ evolves to $|\psi_2'\rangle$, then $|\psi_1\rangle + |\psi_2\rangle$ evolves to $a\,|\psi_1'\rangle + b\,|\psi_2'\rangle$. As the latter is not an eigenvector, it is posited that when a measurement is done, it collapses to one of its eigenvectors (say, $|\psi_1'\rangle$), in the form of

$$a|\psi_1'\rangle + b|\psi_2'\rangle \longrightarrow |\psi_1'\rangle. \tag{14}$$

Then, the problem becomes assigning meaning to this change in description, which seems to be an unnatural process that is not governed by the Schrödinger equation – again, this is the domain of the *interpreter* of QM.

As we previously stated, there are many distinct possible interpretations to QM, but in order to illustrate the metametaphysical point stressed by this work, only two interpretations are considered:

1. The QM_{col}'s CCCH, presented by Wigner (1983);[3]

---

[3] As argued in Chapter 4, even though literature considers von Neumann (1955) as a proponent of CCCH (see Jammer (1974, p. 480)), it is safer to point Wigner (1983) as CCCH's leading original proponent – see Bueno (2019) for details.

2. The QM_{bra}'s MWI, proposed by DeWitt (1970).[4]

The choice of the interpretations considered in the case study is based on the clear divergence of the ontological theses entailed by them. Whereas CCCH commits to the idea that human consciousness has some kind of privileged reality, thus exerting a causal role in quantum measurement, MWI commits to the idea of actual splitting worlds and to the existence of a plurality of physical worlds, different than the one we live in, all of them equally real.

As a disclaimer, it is worth mentioning that the discussion presented here does *not* engage in the debate regarding whether those are *reliable* options to interpret QM based on theoretical standards, such as whether QM *needs* consciousness as stated in CCCH, or whether the decoherence-based MWI approach to the measurement problem actually provides a solution.[5] This is not the point here. Rather, this chapter's goal is *methodological*: how to evaluate metaphysical theses in the case of metaphysical underdetermination. Considering this goal, the discussion shall proceed *inferentially*: *if* both CCCH and MWI are available options in the efforts of interpreting QM, *then* we proceed with the methodological discussion. Once that point is established, the discussion evolves to a schematic overview of these interpretations of QM.

1. CCCH's reasoning is simply put as follows:
    - Assuming QM holds for *all* physical systems, the attachment of a macroscopic measurement would not be enough to generate a measurement outcome, as the linear evolution predicted by the Schrödinger equation must be obeyed;
    - This must be true for all further measuring apparatuses which one could, in principle, attach to the first;
    - Moreover, this should also hold for the experimenter's eye, its optical nerve, and its brain. This this chain, however, must stop somewhere;

---

[4] Some comments on this issue are necessary. Traditionally, Hugh Everett (1957) should be on the list of main proponents of MWI – see Jammer (1974) and Wallace (2012). It is not trivial, however, to place Everett among the proponents of MWI. Although Everett himself mentioned, in a debate with Podolsky, and others, that his theory contains a non-denumerable number of worlds (WERNER, 1962), it is also clear that he distances himself from the idea propagated by DeWitt (1971) that QM_{bra} *dictates* the need for multiverses as real as the one in which this PhD thesis is written. Furthermore, there are "single world" interpretations of QM_{bra}, in which the main claims are based on Everett's writings. In our terms, this consists of another ontology for QM_{bra}, that explicitly differs from many-worlds ontologies (this matter is discussed in Chapter 8). To mention a few of the main references to such an interpretation, see Ben-Dov (1990), Barrett (2011),and Conroy (2012, 2018). Thus, the "many worlds" notation is employed here only with relation to DeWitt's conception, remaining neutral in relation to the historical debate concerning Everett's position on the ontology of many or a single world.

[5] Turns out it does not. See d' Espagnat (1999, §14.5) for a survey on "improper mixtures", an erroneous argument concerning decoherence as a solution of the measurement problem.

  - The proponents' hypothesis is that the *consciousness* of the observer causes the superposition dynamics to collapse in a single-state description, as it is not subject to the laws of QM.

2. The central point of MWI's reasoning is:
   - Accepting the universal validity of the Schrödinger equation, the superposition is taken literally: both terms in Equation (13) are *equally real*;
   - To the MWI, the world branches itself into each possible outcome of a superposition. If a live cat is found in the box as a measurement outcome, then we happen to live in this branch of the world – the dead cat still exists in another branch of the world, where such measurement outcome is simultaneously found;
   - Then, although the collapse is apparently happening (in the sense that the superposition is not actually *seen*), it is not *really* occurring. What happened, in truth, is the branching of the world in two, and those branches do not communicate with each other.

In terms of ontology, the catalogue of what exists, the world can be populated with two distinct kinds of being, according to what is stated by each interpretation.[6] From an ontological point of view, CCCH considers human consciousness to be real. That is, human consciousness is not an epiphenomenon and plays a causal role in the quantum measurement process. However, it says nothing about the existence of multiple worlds. Conversely, MWI defends the world branching as real, and not a merely logical, counterfactual possibility. Therefore, it is causal in the quantum measurement process. Note that it says nothing about consciousness. In this sense, as it was argued in Chapter 4, there is an *ontological underdetermination* in QM. This is literally all that can be *extracted* from CCCH and MWI.

At this point, one may ask: "but does QM *entails* that there are multiple worlds?" or "does QM *entail* that our consciousnesses acts upon matter?" to what the must answer must be: "we do not know." QM does not answer that. In fact, QM cannot be said to entail such facts about interpretations, given that those interpretations are being added to QM in order to make sense of the theory (that is, to tell a story about the physical world that suits its mathematical description). CCCH and MWI cannot simultaneously be true regarding correspondence with the world, and therefore are *competing* interpretations of QM. Since both interpretations of QM differ, and is not possible so far to conduct experiments to distinguish them, QM alone seems to provide

---

[6] There is no clear and definitive metaontological method to *extract* some kind of *catalogue* of the furniture of the world *modulo* an interpretation of QM. However, we assume as a working hypothesis that any such method would agree with this part of the catalogue considering these examples.

no clue as to which of them is to be preferred. This is ontological underdetermination in a nutshell.

The problem, however, still worsen. In terms of metaphysics, each of these two ontologically different *catalogues* can be connected to at least two different metaphysical theses. On the one hand, CCCH is compatible with a dualist metaphysics, as it considers that consciousness and physical processes lie in different ontological domains of reality, thus obeying different dynamic laws (ALBERT, 1992). However, as presented in Chapter 4, that is not the only possible interpretation of the role of consciousness in QM. Recall that, alternatively, London and Bauer (1983) present a *phenomenological* account of CCCH, comprising a different metaphysics within the same ontological commitment with a causal consciousness.[7] Thus, the same ontology of consciousness is compatible with distinct metaphysical dressings of ontological posits. The same holds for the MWI, which seems to require some type of metaphysical realism for possible worlds, that is, the idea that *there are indeed* parallel worlds, physically real, in some sort of modal realism. QM_{bra} can, however, be understood in several metaphysical ways other than the typical modal realist.[8] Again, branching ontology may be metaphysically understood in incompatible ways. This is a familiar worry, called “metaphysical underdetermination”: two empirically equivalent and rival metaphysical theories to interpret QM are presented.

Given that QM is silent about which interpretations, and, consequently, which ontology and metaphysics to adopt, how to proceed? This is clearly a question of theory choice involving not only physics, but also ontology and metaphysics. It is here that such philosophical disciplines step in. Debates on metaontology and metametaphysics addressing the issue of theory choice in ontology and metaphysics could be, perhaps, of some help.

5.2 EVALUATING PHILOSOPHICAL THEORIES

The naturalist stance has been roughly characterized by stating that ontological and metaphysical questions should be settled by science alone. Science was argued to be compatible with distinct ontological *outputs*, which must be further extended to distinct metaphysical theses in order to generate different scientific images of the world. Therefore, a radical naturalistic stance to metaphysics appears to be quite problematic and does nor provide a solution concerning metaphysical underdetermination.[9]

---

[7] See also French (2002) and references therein for details. The interpretation presented by London and Bauer (1983) is discussed in Chapter 7.

[8] Chapter 8 deals with this issue.

[9] It should be noted that this section suppresses the distinction between ontology and metaphysics pointed previously, as the authors engaged in this section do not make such a distinction. This is done without any theoretical loss. It should be mentioned, however, that *ontology* and not metaphysics that is at stake in this section. In the next section we proceed with our distinction.

Therefore, the first metametaphysical question to be answered is the following: *what kind* of features concerning theory choice in metaphysics could, at least in principle, help to thin the number of possible interpretations? There are at least two obvious contenders, which can be defined according to their degree of proximity with the empirical results[10] obtained from QM. An *appeal to science*, from which ontology in a naturalist-fashion can only be extracted from scientific theories, and an *appeal to metaphysics*, according to which empirical results do not need to be considered in order to inquire about the world as a whole. This two contrary, radical stances seem to lead to a dilemma, as French argues:

> [...] either the metaphysics floats free of the physics and requires justification itself; or it is continuous with the physics but then it can't actually break the underdetermination. (FRENCH, 2011, p. 210).

If one is not to stick with QM solely in metaphysical investigations, how far from it can one go? The suggestion proposed by this study provides an initial approximation to answer this question. Before presenting it, however, it is essential to consider two alternative approaches.

Aesthetic values

When dealing with the evaluation of metaphysical theses, it is perhaps convenient to initiate an inquiry by questioning *when* to do so. For instance, if two metaphysical theses are *equivalent* in some sense, perhaps there is no need to choose between them: the debate, in this case, is merely *verbal*, not substantial. To our best knowledge, up to this date, the CCCH and the MWI are *empirically equivalent*[11] in the sense that both lead to the same set of empirical results.[12] Are they, however, *metaphysically* equivalent? In order to attempt to settle this fundamental question, the recent metametaphysical methodology proposed by Benovsky (2016) is considered to the discussion.

Benovsky (2013, 2016, §1, §4) argues for a metaphysical equivalence based on the role of the *primitives* of metaphysical theories at stake: if the primitives of theory $\mathcal{T}$ and the primitives of theory $\mathcal{T}'$ are *the same*, the difference between $\mathcal{T}$ and $\mathcal{T}'$ is not substantial. Such primitives come into play as “problem-solvers”, being individuated according to the theoretical roles played on these theories (*i.e.*, a kind of functional approach to individuation of primitives). In essence, whenever a metaphysician meets a problem, it can be solved by positing primitives and relations between such primitives. Benovsky (2016, p. 66) warns that his functional criterion to individuation of metaphysical theses may be somehow vague, and metaphysicians should carefully

---

[10] See Chakravartty (2013).

[11] See Allori (2015), Peter Lewis (2016), and de Barros and Oas (2017).

[12] That is, both take into account the same models of data – see Suppes (2002).

analyze each case – which is done here for the selected cases of interpreting QM. One of his arguments is that even the so-called *content view* to individuation is reducible to the functional view in the sense that if two primitives differ due to their content, it is so *because* they also do not play the same functional role. Therefore, it makes sense to apply the account of Benovsky (2013, 2016, §4) for metaphysical equivalence to selected cases of interpretation of QM, CCCH and MWI.

As mentioned earlier, interpretations of QM operate on a non-testable level. Moreover, they are mainly engaged in response to the measurement problem. Thus, it seems safe to consider their ontological charge as *primitives*: whereas "consciousness" is a primitive entity of CCCH, parallel worlds are primitive entities of MWI. Clearly, the interpretations may be compatible with a common core ontology involving particles, waves, space, and time, but the uncontroversial portion of the discussion shall be left aside.

Both interpretations utilize primitive notions as *problem-solvers* to the measurement problem, in the sense that *these solutions cannot be analyzed within the framework of the theory*. This matters can be schematized as follows. Consider the answers to this question: "*What happens during a measurement process?*"

CCCH: Postulates the action of an arbitrary observer's subjective consciousness, from a separated ontological domain, that collapses the superposition of states in a single-state description.

MWI: Postulates the world-branching process, in which the two states in superposition literally occur, each in different ontological domains (different parallel, physically real, worlds) that do not interact with each other.

If one were to investigate the functions and details of each ontology, they would appear not to present results. Consider the dualist metaphysical approach to CCCH again: according to it, there is a real consciousness in the world (and there is only one world as far as we can extract our ontology from what the theory tells about the world). Moreover, the process by which this primitive operates has a mathematical counterpart in the theory: the *collapse*. Consciousness *causes* the collapse. On the contrary, consider MWI: according to it, there is *more than one* real world (probably *way more* than one), and consciousness has no privileged role on that, considering that *what there is* is to be determined judging solely from QM.

Additionally, by the process by which MWI's primitives operate, there is also, a mathematical consequence in the formalism: there is no collapse. In the MWI, all terms of a superposition are actual, each in its corresponding world. Therefore, their primitives are distinguished by virtue of the theoretical process by which they operate. The metaphysical differences between CCCH and MWI appear to be, then, more than verbal: there are substantial differences in the primitives they postulate, and so they are not *metaphysically equivalent* in the sense argued by Benovsky (2013, 2016, §1, 4). It is worth emphasizing that, as employed by Benovsky (2013, 2016), the term "metaphysics" here is to be understood as "ontology". That is, the so-called "metaphysical equivalence" is then an "*ontological* equivalence". Ontological underdetermination, then, strikes back (as if it never really left the scene).

So far, the ontological aspects of the selected interpretations of QM have been dealt with. What about the metaphysical profiles *within* CCCH and MWI? Since both CCCH and MWI have, firstly, *ontological* differences, it is to be expected they also have metaphysical differences. Metaphysical underdetermination, then, also strikes back. Could the theory proposed by Benovsky (2013, 2016) help in this matter? Unfortunately, it seems that it cannot. In fact, Benovsky (2016, p. 70) acknowledges this. According to the author, finding objective reasons to choose one theory over another is not an easy goal. As for this positive proposal, he utters: "I do not have a good answer to this question", proceeding to state that this choice must be grounded in aesthetic considerations since metaphysical theories are literally beautiful and could be allegedly chosen over another based on such beauty. The problem in this metametaphysical[13] view is precisely the lack of objectivity regarding theory choice: one could *always* choose a *less beautiful* metaphysical theory over another. It is easy, indeed, to imagine cases where some find more beauty in CCCH than in MWI – and *vice versa*. In fact, Benovsky (2016, p. 123) concedes that such aesthetic move is not objective: "[. . .] the evaluator's taste plays a role from the beginning to the very end of the evaluative process".

Moreover, to objectively (in a strong sense) assess the dispute between metaphysical theses related to scientific theories, something along the lines of a "the whole picture" might be needed, which Benovsky (2016, p. 84) calls the "'widen the net' criterion". Interesting as it may seem, this sort of goal sounds somehow unrealistic, especially when working with metaphysics of scientific theories. All metaphysical inquiry related to scientific theories should be *as provisional as the scientific theories themselves*. Thus it seems to be unnecessary asking metaphysicians to wait for fundamental science achieves a final *theory of everything* (if there may be such thing at all) before beginning their work with a scientifically-informed metaphysics. Instead, the work of the metaphysician, when related to science, is to account for a better understanding of the scientific(s) image(s) of the world that may be compatible with scientific theories.

Furthermore, even if it was possible to reach an agreement over which interpretation and its accompanying metaphysics is the most beautiful, Benovsky's solution is not based on science, in any possible sense of how metaphysics could relate to

---

[13] As remarked by Benovsky (2016, p. 122), the alleged beauty of metaphysical theories is not an *additional* metametaphysical criterion, but rather a *way of seeing* the non-aesthetic metametaphysical features that a metaphysical theory *already has*, such as internal consistency and explanatory power. Nevertheless, this nomenclature is maintained in the discussion since aesthetic values are, in fact, considered in the process of (metaphysical) theory choice. It seems odd, then, that this notion escapes the nomenclature of "metametaphysics".

science. Any interpretation that could somehow have its admissibility lent by a scientific theory, indirect as this seems, would have more credentials than a choice based on beauty. The main problem, then, is that this approach leaves too much to be achieved by the metaphysician, and nothing for science. The choice is entirely based on a first philosophy.

Well, perhaps our expectations are too high to be met. Maybe it would be more advisable to step back and try to focus on the *wrong* alternatives, rather than on the right one, in order to momentary settle the issue. That is where this discussion is heading.

Epistemic risk

In order to better understand metaphysical underdetermination in the interpretation of QM, this work attempts to evaluate metaphysical theories to verify whether there is – objectively – an alternative that fares *worse* than another. The general criterion of *simplicity*, and subsequently, the notion of "epistemic risk" recently proposed by Chakravartty (2017a), analyzes whether these criteria are sufficient. Spoiler alert: they Are not. The explanation to why it is so begins considering simplicity as a metametaphysical criterion to compare rival metaphysical theses.

The argument states that *simpler* alternatives should be preferred. This attitude towards metaphysics and ontology applies the famous Ockham's razor, which seems to be weightless in establishing a metametaphysical criterion to evaluate metaphysical theories. It presents, at best, heuristic value for evaluating *ontological* aspects of theories. As stated by Terence Parsons (1979):

> There is no prima facie reason to suppose that the universe contains a small number of things, or a small number of kinds of things. There is no prima facie reason to believe that a theory that endorses a smaller number of things, or kinds of things, or employs a smaller number of primitives, is simpler or likelier to be true or likely to yield more insight than another. (PARSONS, T., 1979, pp. 660–661).

Briefly, as simplicity is not related to truth, it can hardly be an acceptable objective metametaphysical criteria in the evaluation of rival metaphysical theories. As remarked by Benovsky (2016, p. 87), "the requirement of parsimony and simplicity comes from *us* rather than from the metaphysical reality" (just as beauty). Therefore it seems safe to assume that simplicity is a criterion that should be dropped in this kind of inquiry.[14]

---

[14] The same seems to apply to the *appeal to intuitions*, a metametaphysical criterion that states, roughly, that concerning theory choice, one should stick to the metaphysical theory that somehow better preserves our "intuitions" (which is another manner of saying "save the appearances"). An example is the "phenomenological principle" proposed by Shimony (1997).An extensive account of this matter will not be provided since QM is not intuitive *at all* – and therefore, its corresponding metaphysical theory does not need to be either. Nevertheless, the reader interested in a critical account of this particular metametaphysical criterion should refer to Benovsky (2016, §6).

Chakravartty (2017a, §3.4–3.5) presented the idea that the *epistemic risk* of some metaphysical theories should somehow guide the process of theory choice: roughly, the smaller our ability to assign truth value to a hypothesis, the greater the epistemic risk. Such risk increases when the hypothesis strays from the empirical test and decreases the greater its explanatory power. A closer look at this proposal is needed in order to evaluate whether it could allow the decision between rival metaphysical theses.

As intended, epistemic risk should be applied to *metaphysical propositions* rather than to metaphysical theories. Therefore, considering CCCH, propositions such as, in the case of CCCH, "a causal act of subjective consciousness upon the measurement device[15] is responsible for measurement outcomes" are being evaluated. When one is not in a position to judge whether a metaphysical proposition is true or false, such proposition is epistemically risky (CHAKRAVARTTY, 2017a, p. 84). Again, when dealing with a *non-testable* field, *i.e.*, the *interpretation* of QM, such effort tends to be of high epistemic risk – and Chakravartty's (2017, p. 85) argues that "the less epistemic risk the better". As an alternative measure to epistemic risk, one might appeal to a proposition's *explanatory power*, which basically claims that the higher the explanatory power, the lower is the epistemic risk. Bearing in mind the selected interpretations of QM, these two criteria do not seem to be different, as both explain the measurement problem, albeit in different (incompatible) manners. What they *explain*, really, is the working of QM when a measurement is happening.

Therefore, it seems that even if one takes the notion of *epistemic risk* to be the metametaphysical criterion considered to choose between the ontologies of CCCH and MWI, both interpretations ultimately seem to yield the same measure of epistemic risk. The same is true for their metaphysical profiles. As a result, this criterion is not of help in the search for an objective way to evaluate these interpretations of QM, as the discussion remains stuck with both ontological *and* metaphysical underdetermination. Chakravartty (2017a, p. 215) approaches this stalemate trough *voluntarism*: the notion that "[. . .] relevant beliefs and actions are freely chosen, or voluntary, as opposed to being forced in virtue of reason alone". Again, there is no objective evaluation here, as the decision concerns the one who decides, not the world. Notice, however, that it seems challenging to recommend voluntarism when the very constitution of reality is at stake.

Suppose that the metaphysical theses put forth by CCCH and MWI *indeed* differ in their degree of epistemic risk: assume that it is possible to determine that CCCH, per example, has more epistemic risk than MWI. Would that really help to objectively evaluate them? Again: no. Imagine a *diehard* proponent of CCCH: one may always choose an alternative with higher epistemic risk than another (someone may be willing

---

[15] More precisely, the vector which represents the state of a measurement apparatus *entangled* with the vector which represents the state of a quantum system.

to take the risks!).

Thus, ontological and metaphysical underdetermination remains unbroken. This seems to be a difficult spot, but it deserves one last try.

5.3 AN INTERPLAY BETWEEN TWO PARTIES

Metaphysics over ontology

Here, the distinction between ontology and metaphysics presented in the Introduction, and drawn throughout the previous sections of this chapter is explicitly employed. Such distinction is not standard but is becoming more widespread recently, and so the relation between the two concepts is now less vague than before, even though many authors employ them in confusing ways. Following recent literature, such as Arenhart (2012, 2019), Berto and Plebani (2015) and Tahko (2015), the task of "ontology" is understood here as that of providing a *catalogue* of the furniture of the world (what are the beings), whereas "metaphysics" is, among other things, taken to be the theorizing on a correspondent story about such furniture (whether they have properties or not, how they relate or not to each other, and mainly answers regarding "what are those things that are"). In this sense, "metaphysics" present a broader sense, *i.e.*, "ontology" is considered a branch of metaphysics.

Two senses of the term "ontology" shall be acknowledged. In the first sense, "ontology" is characterized by the investigation of *ontological categories*, which provide the most general ways to approach and classify existent beings, closely related to the so-called "*metaphysical dressing*", following French (2013), or what is here called the "*metaphysical profile*" of entities. In a second sense, "ontology" is characterized by the investigation of the furniture of the world *modulo* some scientific theory according to its ontological commitments. The first sense is said to be ontology in a *traditional* sense, while the second is accepted as a *naturalized* sense.

Perhaps, it would be more appropriate to follow Jacquette (2002) and name them "pure" and "applied" ontology, respectively, but it depends on what naturalized ontology amounts to. To avoid possible misunderstandings grounded on terminological issues, the first sense of "ontology" (*i.e.*, the "traditional" or "pure" sense) shall be called "metaphysical profile".

Initially, the metaphysical profile and applied ontology may be taken as incompatible, as one may reasonably indicate that the former is taken to be universal, prescriptive and independent of contingent empirical findings of any scientific theory (as stated by French (2011), "floating free" from the empirical content), whereas the latter is descriptive and relative to a scientific theory. In fact, there is an ongoing debate between authors who favor that contemporary philosophy should study exclusively the metaphysical profile[16] and those who exclusively favor the applied ontology.[17] The novelty of our proposal[18] lies precisely on an attempted reconciliation between those two parties by establishing a middle ground utilizing a scheme for a "scientific oriented metaphysics".

The first step towards such reconciliation is acknowledging that the applied sense of ontology does not imply that the only existing things are those to which a given scientific theory is committed to, since different theories may present different ontological commitments. In order to exemplify this claim, is has been previously argued that the CCCH and MWI approaches to QM fulfil these requirements. The second step is to understand that the metaphysical profile studies a plurality of possible ways to address these ontologies, meaning it is possible to assign different metaphysical theses to each ontology extracted from the same set of interpretations of QM, per example. Whereas the study concerning the metaphysical profile of entities provides an investigation that accounts for what may possibly exist, applied ontology accounts for the connection between those ontological categories with the ontological commitments which may be presented by the empirical investigation of some specific scientific theory. Thereby, when an ontologist attempts to study the ontology associated with a scientific theory, both senses of "ontology" complementarily employed.

Thus, it is no surprise that the theory alone does not provide an answer concerning what kind of metaphysical profile would be more (or less) adequate to its interpretation's ontology, as such a discussion ought to be conducted not within science, but on a rather different ground, precisely the domain of the metaphysical profile.[19] One option For narrowing the field of possibilities entailed by underdetermination consists of recognizing it is false that anything is valid in applied ontology: one may discover that some kinds of entities are not compatible with a specific scientific theory.

In this context, *the applied sense of ontology could preclude some form of metaphysical profile*. Notice this is almost a paraphrase of Arenhart (2012, p. 354): "[. . .] ontology in the naturalized sense bans some form of ontology in its [traditional] sense". In some sense, the discussion presented here updates Arenhart's (2012) work with substantial terminological distinctions as to better apply it to the discussion concerning metaphysical underdetermination in QM, as well as to the relationship between science and metaphysics in general.

As a classical example of this *negative feature* of applied ontology, the "experimental metaphysics" of Shimony (1984, pp. 35–36) might be recalled, which considers that some experiments (such as the experimental tests of Bell's Inequalities) as "[. . .] a near decisive test of those worldviews which are contrary to that of QM". To Shimony

---

[16] See, for instance Lowe (1998).

[17] For which the work of Ladyman and Ross (2007) can be cited.

[18] Following Arenhart (2012, §2).

[19] Reiterating: when dealing with the *interpretation* of a theory, such as QM, one is also dealing with elements that lie *outside* the structure of the theory itself, as stressed by Bueno (2011, p. 93), even thought this interpretative effort often emerges *within* the scientific community (SKLAR, 2010).

(1984, p. 44), this means “[. . .] the [empirical] evidence has narrowed the [metaphysical] choices”.[20]

One may object that this may be a hasty move and that a *diehard* metaphysician may not be convinced due to the lack of objectivity on theory choice. If this is so, this positive proposal fails as badly as other metametaphysical alternatives that we critically analyzed in previous sections.

At least to what concerns the theoretical and ontological domains, this seems to be the case. It seems there was no advance in establishing a good criterion to objectively choose between CCCH and MWI as competing scientific and ontological theories. However, recall Chakravartty’s challenge: the metaphysical profile gap in our ontology must be filled in order to understand what does being a realist about CCCH or MWI mean. Within the *metaphysical* realm, there seems to be a sort of objectivity at stake in such negative feedback resulting from the interplay between applied ontology and metaphysical profile. Apply, then, the methodology sketched above to the discussion analyzed in the previous sections, to evaluate whether it is possible to provide a way to better understand the matters of underdeterminations in the selected examples when interpreting QM.

Ontology over metaphysics

According to the CCCH approach to QM, consciousness is an entity that inhabits the furniture of the world: CCCH is *ontologically committed* to consciousness – whatever it may be, in terms of a *metaphysical profile*. This is the best conclusion one may withdraw regarding consciousness as per the applied ontology.

The metaphysical profile, then, comes as an *extra layer* that attempts to dress this very entity so-called “consciousness” metaphysically. Traditionally, the metaphysical profile associated to consciousness in CCCH is a form of dualism separating consciousness from matter (WIGNER, 1983). CCCH is, however, *incompatible* with several metaphysical profiles in which consciousness is epiphenomenal and devoid of causal power, such as materialistic accounts of consciousness and physicalist accounts of consciousness. In this sense, the ontology furnished by the interpretation of the theory rules out some metaphysical options for the understanding of the world. Thus, if one desires to stick with CCCH, the *applied* sense of ontology tells us that this particular interpretation of QM is incompatible with the metaphysical profile of epiphenomenalism. It is, however, compatible with the metaphysical dressing of dualism and with phenomenology.

Something similar may be said of the MWI. Once it is posited that there is no collapse, and that all terms present in a superposition are equally real when a measurement comes up, then, we are invited to ontologically understand the resulting theory in which the branching processes of reality arises in the catalogue of the world modulo

---

[20] For an account of several experiments in this field, see Aspect (2002).

MWI. In fact, according to this account, each terms in which a wave function is decomposed, depicting one possible outcome of a measurement, represents an alternative branch of reality. Some will choose to metaphysically dress them as possible worlds, all of them equally real, containing a copy of the whole world and of the measurement apparatus plus a determinate outcome (LEWIS, D., 2004).

But recall that MWI is not the only ontology that can be extracted from QM_{bra}. There are single-worlds ontologies for QM_{bra}, such as Relative state interpretation (RS) (CONROY, 2018) and mind-branching ontologies, such as MMI (LOCKWOOD, 1989). Adhering excluively to worlds in order to illustrate the approach defended by this work regarding the relation between ontology and metaphysics, it is clear that, metaphysically, there seems to be many ways one may understand a plurality of worlds. In essence, one simple accept all of them as equally real, in a form of modal realism, or adopt a fictional approach to possible worlds, where only the actual world is real, or, still, a combinatory approach, where only the actual world is real, and such actual world provides the ingredients with which to assemble the possible worlds.

Our approach suggests that checking the relation of a branching ontology with those distinct metaphysical dresses, what results is that those who do not conceive the many worlds as equally real fail to account for the lack of collapse. Indeed, if only *a single* measurement outcome is real, the theory is simply a collapse theory in disguise. Therefore, accounts such as fictional and the combinatorial approaches to worlds seem to be discarded as incompatible, to say the least, with MWI.[21] The metaphysical possibilities are narrowed down by the choice of ontology (given by the MWI) and the attempts to make sense of the theory (due to the requirements for understanding a measurement through branching without collapse).

It seems that even a Lewisian account of possible worlds would fail in this account, given that the branching must create the worlds, and that the resulting worlds must be copies of each other, with the same measurement apparatus and measurer, differing in nothing but the result of the measurement. This is clearly not the case for the approach advocated by Lewis, of course: although distinct worlds are all equally real, it is not true that the same entity may be seen as populating distinct worlds: an entity exists wholly in only one world. This argument seems to oppose the idea of branching worlds. As so, not any kind of realism about possible worlds will suffice to understand MWI in metaphysical terms.

Put briefly, the negative metametaphysics proposed by this thesis is as follows:

Step I: Applied ontology allows the identification of ontological commitments of an interpretation of a scientific theory, and the metaphysical profiles compatible with such ontological commitments.

---

[21] A detailed account of this issue is presented in Chapter 8.

Step II: Metaphysical profiles for such entities can be sought outside of scientific theories, in metaphysical regions that “float freely from science”.

Step III: Returning to the domain of scientific theories, the existence of any theoretical restrictions to those metaphysical profiles that were considered, at least in principle, compatible with the theory’s ontology, is evaluated. This is the step that can now receive a positive contribution: from the previous steps, the abandonment of some metaphysical theses attached to some scientific theories is established.

5.4 FINAL REMARKS

This chapter expanded the meta-Popperian method initially proposed by Arenhart (2012), originally applying it as a metametaphysical method for theory choice in metaphysics related to scientific theories. Such reconstruction and expansion are labelled as the method of “Unavailable Metaphysical Stories”. The following chapters deal with the application of the method of Unavailable Metaphysical Stories in three different cases, concerning metaphysical underdetermination within different interpretations of QM.

As privileged access to the nature of the world, science should be a guide not only to what there is, but also to how those things are. As discussed, the naturalist has expectations of discovering answers to those questions, somehow inferring them from science. However, at least to what concerns QM, there is much interpretative work to be done if one is to determine an answer to those questions. Furthermore, the interpretations always encompass extra-empirical ingredients, additions which cannot be judged purely on empirical grounds. As was presented in this chapter, distinct interpretations provide general grounds which account for the population of the world.

The problem toughens when it is discovered that distinct interpretations provide information only for ontology, the catalogue of what there is. If one is to understand how those things are, the inquiry is of a higher level, on the metaphysical profile of the posited entities. This investigation cannot be supplied by QM. Once it is noticed that distinct metaphysical profiles are available for each interpretation, metaphysical underdetermination ensues. Naturalism is unable to deal with the situation, and therefore some dose of metaphysics is salutary.

Three metametaphysical methodologies were evaluated in order to verify what help they provided when trying to reduce the alternatives of metaphysical underdetermination. The three approaches in metametaphysics, however, were unable to break *theoretical* and *ontological* underdetermination in matters of interpreting QM. As a result, questions concerning *which interpretation one should adopt* could not be addressed. As previously discussed, Benovsky’s appeal to beauty leads to a form of anti-realism in metaphysics that is not conducive with the project of deriving a metaphysics of science. In fact, very goal of engaging metaphysics engaged with science to attempt to benefit from the success of science in gaining objective knowledge of reality. In this sense, remaining at the level of the inquirer's subjective choice seems to abandon the challenge too early.

Chakravartty's solution seems to provide better grounds for choice. While recommending that epistemic risk should be avoided, adopting theories that are more explanatory and closer to empirical confirmation, the solution seems to put metaphysics on the same path as science. However, that is not enough to break metaphysical underdetermination. In fact, metaphysical dressings are still able to multiply themselves without clear criteria to discriminate them according to their explanatory powers, being equally distant from empirical predictions that could allow the attribution of a truth value. The solution proposed by Chakravartty in this case, voluntarism, is again an appeal to subjectivity. There is nothing to prevent one from choosing the riskier theories, and nothing relating voluntarism with truth.

Perhaps the avoidance of epistemic risk could be wedded to this work's proposal, which consists in investigating whether some metaphysical options could not be ruled out on quantum mechanical grounds. That point was verified: on what concerns the test cases addressed in this chapter, CCCH and MWI, it was concluded that some metaphysical theories are clearly not compatible with QM. This provides more objective grounds for rejecting some options. A careful investigation of the precise articulation between metaphysical theses and the ontologies provided by interpretations of QM may prove useful in order to reduce the number of options To do so in a somewhat objective way, benefiting from features of QM itself and not on subjective preferences, is seen as the most interesting advantage of such an approach.

It is important to mention that the method proposed here has a certain proximity to the thesis called, in the philosophy of mathematics, "deferentialism", according to which philosophical theses that speak against non-philosophical disciplines must be abandoned.[22] Ultimately, part of our method involves looking towards science in order to justify the incompatibility of certain metaphysical profiles with certain scientific theories. However, it is essential to emphasize that this method does not determine which metaphysical theory is *wrong*; that is, it does not advocate the abandonment of certain philosophical theses at all.

The method of Unavailable Metaphysical Stories only provides information concerning the incompatibility of specific metaphysical profiles with certain scientific theories. Since scientific theories are fundamentally provisional, metaphysical profiles compatible with a given theory also inherit the same characteristic of provisionality. As a scientific theory can be abandoned for many reasons, either by scientific or extra-scientific criteria (KUHN, 2012), the metaphysical profiles related to a theory can be

---

[22] For an exposition and critique of deferentialism, see Daly and Liggins (2011).

abandoned as well, unless they are compatible with the scientific theory that succeeds the previous one. This feature approximates our method to Lycan's (2019) thesis, which states that the only permanent contributions in the history of philosophy are negative contributions: a metaphysical theory identified as incompatible with a particular scientific theory will be *permanently* incompatible with it.

6 CASE 1: COLLAPSE AND DUALISM

QM is problematic; as is consciousness. As argued in Chapter 4, some ontological implications of QM_{col} supposes there is a connection between these two factors. Although a number of claims constantly made on behalf of such relation are quite dubious,[1] they have an undeniable pedigree, with sources found on the earliest attempts to understand QM, when von Neumann (1955) proposed an interpretation based on the concept of a non-physical causal agent in quantum measurement process. This suggestion is frequently labeled as CCCH, after Wigner's (1983) suggestion that human consciousness is this non-physical agent. Remarkably, as recently demonstrated by de Barros and Oas (2017), the CCCH has survived as many empirical tests as any other interpretation of QM. Moreover, its specific features (namely, the introduction of a causal consciousness) cannot be independently subjected to an empirical falsification,[2] thus remaining a live option to interpreters of QM.

However, as verified by the poll presented by Schlosshauer, Kofler, and Zeilinger (2013), CCCH is rather unpopular among theorists working in foundational fields of QM. For example, a recent book published by Peter Lewis (2016, §9) does not even consider the possibility of CCCH as a candidate for an interpretation of QM that could offer a reasonable worldview, a position justified by the theory's commitments to dualism. It seems, then, that having the label "dualism" attached is enough for CCCH to be rejected. However, what are the grounds for this rejection?

By rejecting CCCH due to its ties to dualism, what precisely is being rejected, and why? The answer does not seem to be clear. Debates concerning mind and consciousness have always been problematic *per se*, so it should not come as a surprise that the issue becomes more complicated to what regards QM. Difficulties arise, mainly, from the fact that the concept of "dualism" is applied to a wide range of metaphysical options throughout the history of philosophy. As a result, even if CCCH clearly falls within the metaphysics of dualism, it is still far from clear to *which* form of dualism CCCH is committed (*e.g.*, is it dualist regarding substances or properties?).

This chapter addresses the issue of the nature of consciousness involved in CCCH. Given that the central hypothesis of CCCH cannot be independently falseable with empirical testing (DE BARROS; OAS, 2017), this metaphysical approach is useful

---

[1] A simple search of the keywords "quantum consciousness coaching" should be enough to attest this. See also Pessoa Junior (2011), Firmo de Souza Cruz (2011) and S. Livramento Machado and Firmo de Souza Cruz (2016).

[2] Nevertheless, CCCH is not assumed to be *unfalsifiable*, as claimed by de Barros and Oas (2017). The main argument against that is as follows: recall Chapter 4, in which CCCH was argued to be an ontological counterpart of QM_{col}. Recall, still, Chapter 2, in which QM_{col} and QM_{bra} were considered to be different quantum theories, thus aligning the discussion to the claim made by Ćirković (2005), that collapse and no-collapse (hence QM_{col} and QM_{bra}) are *in principle* empirically distinguishable. Thus, future experiments (even if they are not feasible soon), should allow one to know which, if any, of the interpretations remain empirically adequate, and which have been falsified.

for those who favor or are against CCCH. As so, this is the first step towards a more rigorous investigation into the metaphysical basis of CCCH. The discussion begins by arguing that, unlike many other interpretations of QM, CCCH largely *determines* its ontology and, to a lesser degree, the metaphysical profile of its posits. That happens because the CCCH is *incompatible* with several metaphysical profiles available in the philosophical literature on consciousness. Following the Viking Approach (FRENCH, 2014) to metaphysics of science, it is argued that, if one considers the distinct approaches to dualism available in the philosophical literature, it can be noticed that most of them cannot be applied to CCCH. That shifts the focus to some very specific approaches to dualism, turning the evaluation of the theory and its ambitions a more straightforward task. Furthermore, given that dualism shall be metaphysically addressed, it is argued that there seem to be no good metaphysical reasons to discard dualism *simply because* it is a dualist approach. To justify that claim, metametaphysical literature grounds the evaluation of whether dualism could be objectively discarded when confronted with other available metaphysical theories.

This chapter is structured as follows. The first section presents the measurement problem, along with von Neumann's solution. The second section presents a distinction between ontology and metaphysics that allows the extraction of an ontological commitment and the determination of a metaphysical profile related to such commitments. Furthermore, the ontology given by the theory is incompatible with many versions of dualism. The third section approaches literature on metametaphysics to verify how dualism survives some of the typical arguments addressed against it. The fourth section stresses that CCCH is compatible with some rather specific kinds of dualism, so that not every approach to consciousness in QM qualifies as CCCH approach, thus considerably reducing the scope of the discussion concerning the mind, causality, and QM. Section five concludes the discussion.

6.1 COLLAPSE AND CONSCIOUSNESS

CCCH, as numerous other interpretations of QM^{bas}, is essentially a *response* to the measurement problem. As presented in Chapter 2, the measurement problem can be understood as the inconsistency of three basic assumptions of the wave-function representation of quantum states $|\psi\rangle$, basic assumptions of QM^{bas}:

1.A $|\psi\rangle$ is *complete*;

1.B $|\psi\rangle$ evolves *linearly* though time;

1.C Measurements of $|\psi\rangle$ always have determinate outcomes.

An informal proof of the inconsistency of the conjunction of these assumptions can be found in Chapter 2 and in Maudlin (1995, pp. 7–8), and thus will only be briefly commented. Suppose an experimentalist intends to measure the position of a quantum system S by means of a measurement apparatus A. According to 1.A and 1.B, the composite system $S + A$ evolves according to the Schrödinger equation. Then, by linearity, the states of $\hat{A}$ are also in superposition, meaning that the possible A-states corresponding to, for example, different pointer positions, are superposed (hence, no definite single-state outcomes). According to 1.C (and to the phenomenal perceptions made in laboratories and daily life), however, there *are* definite outcomes as a result of measurements. Therefore, at least one of these assumptions must be dropped.

Since the interest of this discussion lies on the CCCH approach, von Neumann's QM_{col} is implicitly assumed (which, as seen in Chapter 5, denies assumption *1.B*). The idea of "measurement" as an outcome of the interaction between a quantum signal (S) and a macroscopic measurement device (A) is, nevertheless, an intuitive. Therefore, with the purpose of preserving this intuitive reasoning, one may suggest the attachment of a second measurement apparatus $\hat{A}'$ to measure the composite system $\hat{S} + \hat{A}$, in order to complete a measurement. One can reasonably consider this apparatus to be the experimentalist's eye, that observes the pointer reading. However, as the second apparatus relates to the first in the same manner the first apparatus relates to the quantum object, linearity yields that this is a new composite system $\hat{S} + \hat{A} + \hat{A}'$.

The problem remains in the sense that such interaction does not provide a solution for the superposition describing the states of the composite system. This is, in fact, the first step of an infinite regress, since one could suggest a *third* measurement apparatus attached to the second, such as the optical nerve. This optical nerve is related to a further measuring apparatus such as the brain, and so the argument goes *ad infinitum*.

This problematic situation is known as "von Neumann's chain".[3] The main issue in von Neumann's measurement theory acknowledged here is that linear descriptions of physical systems lead to an infinite regress: any attempt to reduce the superposition of the joint system involving the introduction of further *physical* measuring apparatuses is doomed since as physical systems, they are to be described as a superposition. If the system is described by unitary dynamic laws, it will *always* be described by a superposition. As Baggott (1992, p. 186) stresses, it is difficult to fault the logic behind CCCH's conclusion: if the measuring device is a physical system, it should be described by QM's equations of motion, as quantum systems are. Moreover, if macroscopic physical measuring devices are composed by quantum systems, they should, at least in principle, behave similarly. Therefore, the superposition of macroscopic measuring devices' states (*e.g.*, different pointer positions) is conceivable, and the interaction with a non-physical agent terminates the superposition's chain.

According to von Neumann (1955, pp. 418–420), the solution to this problem lies

---

[3] Chapter 7 returns to this issue.

in the recognizing that the "*act* of measurement" occurs in the (subjective) perception of the observer, as one's subjective perception is the most reliable source in which superpositions are not experienced. von Neumann (1955, pp. 418–419) calls this feature the "principle of psychophysical parallelism"[4] breaking down the meaurement process into three stages in order to explained (VON NEUMANN, 1955, p. 421). These are the stages I, II, and III, where "I" is the quantum object, that is, the system S being measured; "II" is the measurement apparatus (which could correspond to anything, from the instrument to the image registered in the observer's brain); and "III" is *the observer* – more precisely, it is the observer's *abstract ego*.[5] The result of a measurement on I performed by $II + III$ is the same as the one yielded by a measurement on $I + II$ provided by III. In the first case, the Schrödinger equation applies to I, while in the second case, it applies to $I + II$. That is, in all cases, the linearity of the Schrödinger equation does not apply to III, meaning III is the only part in which a measurement occurs: it is the only part that presents the interaction of the abstract ego, that collapses the chain of superpositions.

This agent is described as being outside the ontological domain of physical systems. As argued by Becker (2004, p. 129), the most relevant feature of the reasoning described above is that "physical processes must be explainable entirely in physical terms, but collapse, which is essential to the dual processes of quantum mechanics, cannot be explained entirely in physical terms". Therefore, the transition between a linear and a non-linear evolution is to be understood as a causal act of the observer's abstract *ego upon* the composite system.

Note that this means the agent that completes a measurement does not obey the same laws of systems describable by quantum states. This is somewhat close to the view of complementarity, especifically as presented by Bohr (1928, 1962).[6] Famously, one of Heisenberg's efforts was to determine the boundaries of the quantum-like domain, a central aspect of von Neumann's theory of measurement. This boundary is known as "Heisenberg's cut", which is placed in the measurement act.[7]

This discussion usually concerns circumstances under which this "act" occurs. According to CCCH and complementarity, the circumstances necessary for the mea-

---

[4] See also Barrett (1999, §2.6). As Heidelberger (2003, pp. 9–10) pointed out, the term "psychophysical parallelism", as used by von Neumann in this context of the interpretation of QM, is marked with several misunderstandings regarding the mind-body problem. This is why we will not use it anymore. For more details, see Heidelberger (2003).

[5] Although the term "consciousness" is absent in the writings of von Neumann (1955, pp. 418–420), there is a standard reading in which he refers to the *consciousness* of the observer when he enunciates the causal feature of the "subjective perception" of the observer. For a historical motivation of this reading, see Jammer (1974, p. 480). We find it more prudent to maintain ourselves agnostic towards such reading.

[6] See also Faye (1991, pp. 128–129), Heisenberg (1983), Jammer (1974, p. 98) and da Costa and Krause (2006).

[7] The German term "*Heisenbergscher Schnitt*" was coined by Pauli (1950); to a historical approach of it in the Copenhaguen spirit, see Landsman (2007) and Howard (2004).

surement to occur are placed *outside* the domain of QM, yet, they present a fundamental *ontological* difference in the following sense. While CCCH considers the measurement act ('III') to be placed upon a *macroscopic* measurement apparatus (hence, a physical system), von Neumann (1955, p. 421) places it outside the domain of *physics* – not only *quantum* physics but *outside physics itself*. As von Neumann (1955, p. 418) states, the so-called intellectual inner life of the observer is "[. . .] extra-observational by its very nature". This suggests a "Cartesian cut", as the cut is placed on a different ontological level rather than within the same (physical) ontological domain of existence.[8]

Another feature of CCCH that should be considered in this discussion: whose abstract ego causes the collapse? This issue is initially by Wigner (1983) in his "Wigner's friend" paradox, a thought experiment in which an intermediate observer (the "friend") observes an experiment and then tells a final observer ("Wigner") about the observed result. In this case, one may consider the following solutions (accepting the debatable thesis that the macroscopic instrument enters in a superposition of pointer states):

W_1 : The friend collapses the composite superposed state – this is, apparently, von Neumann's solution. The second observer, "Wigner", should describe the quantum system, the apparatus, and his friend as a collapsed state. This position is adopted by Wigner (1983, p. 177).

W_2 : The friend and "Wigner" enters in superposed state, as well as any other observer in the chain. This is essentially QM_{bra}.

W_3 : The friend also enters in superposition, so "Wigner" is responsible for the collapse of the apparatus and the friend. This view can be encompassed within the relational interpretation of Rovelli (1996), in which the state of the world is relative to the observer. Therefore, from the friend's perspective, he is the one who causes the collapse, while Wigner assumes that he himself is the one who does it.

W_4 : The last observer in the chain seems to have a privileged status in provoking the overall collapse, while the others are in a superposed state during all the experiment. This solution leads to solipsism, the theory in which there is only one causal consciousness, and there is no consensus about to whom it belongs.

It should be clear that only W_1 is being considered in this discussion. W_2 will not be discussed, as to keep this work self-contained since it stands for a different formulation of QM (*i.e.*, no-collapse). W_3 will also not be discussed since it does not relate to the main subject of this chapter, consciousness. W_4 is briefly covered, since it is a frequently adopted solution by authors who propose an integration between QM and spirituality *via* consciousness – see, for instance, Bass (1971) and Goswami (1989).

---

[8] See Atmanspacher (1994).

As W_4 leads to solipsism, the authors *modify* the hypothesis that states subjective consciousness causes the collapse, but there is only one god-like consciousness that causes it. The problem is W_4 appears to be a straw-man version of Wigner's friend, which does *not* imply solipsism by any means.

Another problem regarding W_4 is the status of "cause". In order to avoid misunderstandings concerning this (already controversial) subject, it is crucial to establih that a statement regarding the "causal power of consciousness" usually means that consciousness causes the collapse (and hence, the measurement), and *not* that consciousness is the cause of physical phenomena (*e.g.*, W_4). In this sense, the notion of *causal power* of consciousness should be understood as the power of causing a change of state from indeterminate to determinate.[9] Nevertheless, it should be clear that the measurement apparatus, although not sufficient to cause the collapse, is a necessary element of the measurement process in the sense that consciousness is *unable* to directly perceive the state of the microscopic quantum-mechanical system without an intermediate apparatus. This is noted by de Barros (2014, §3), who argues that in order to measure some observable of a quantum system, an experimental setup that amplifies the signals of the system of interest in so that they can be perceived by the observer must be produced. Thus, the experimental setup needs to exist, as the state of the quantum system cannot be *produced* by consciousness alone.

6.2 ONTOLOGY AND METAPHYSICS

"Ontology" is here understood as the study of *what there is*. Following Quinean tradition, it is assumed to be possible to study scientific theories in order to extract the ontological commitments, and therefore discover *what there is* in the furniture of the world *modulo* such theories. That provides a sort of *catalogue* of the beings the theory assumes as existing. Applied to CCCH, this approach allows claiming that *consciousness* exists. Whatever it is in metaphysical terms, consciousness is causally efficacious in the quantum measuring process, being introduced in the furniture of the world by CCCH with certain features such as causal power.

The fact that consciousness exists in CCCH's ontology is believed to be pacific. Recall what was discussed in Chapter 4: according to Ruetsche (2015, §3.3), "[w]hat a realist believes when she believes a theory T is an *interpretation* of T, an account of what the worlds possible according to T are like". Therefore, interpretation would provide the content of the theory for the realist. Concerning QM, it is well known that pragmatists do not generally believe that QM needs an interpretation. A theorist inclined to accept CCCH must embrace consciousness and the role ascribed to it by the interpretation. This is, however, as far as the theory leads, in philosophical terms. That is, interpretation

---

[9] For a further discussion, see Shimony (1997).

forces the positing of consciousness; however, the theory alone provides no means to understand *what* such consciousness *is* in metaphysical terms. Thst is a pressing issue. Is consciousness a fundamental property of all beings? Is it an emergent property, or a separate one? As we saw in Chapters 4 and 5, QM is silent about these questions. One simply cannot extract a metaphysical profile from an ontological catalogue accounting for what there is, therefore, if one was to inquire about this, one enters the domain of metaphysics.

As argued in Chapter 4, the idea that a metaphysical profile is needed in order to specify the realistic content of a theory completely was called by French (2014, p.48) the *Chakravartty's challenge*. According to the challenge, point to some feature of a theory ("consciousness with causal powers" for instance) and say "I am realist about that" is not enough to claim realism about such feature. In order to achieve a legitimate realism about, say, consciousness, one must specify what it is, and doing so involves, at least partially, providing a metaphysical characterization of consciousness. This connects ontology to metaphysical profile. Furthermore, providing such profile may be enlightening, if one is to know what CCCH amounts to, providing a better grounding for any kind of attitude towards such interpretation of QM (either accept it, reject it, or whatever else).

As is often the case, the posits of scientific theories may be "metaphysically profiled" in many incompatible ways, giving rise to a kind of metaphysical underdetermination. CCCH is much less liberal with metaphysical profiles allowed to join the theory, and, in this sense, the ontology of a conscience with causal power requires a mind with very specific features.

Dualism and metaphysics

Traditionally, CCCH's consciousness is understood within a *substance-dualist* metaphysical profile.[10] As mentioned above, von Neumann's solution to the measurement problem states that the agent causing the collapse is placed *beyond* the domain of application of QM, which concerns only the *physical* (in the sense of *material*) domain of reality. Therefore, according to this traditional viewpoint, consciousness acts upon the material domain, causing the superposition of states to collapse into a non-superposed state. The quantum system, then, is found to be in a definite state due to such a causal act of the observer's consciousness. This is a metaphysical statement regarding the nature and behavior of this entity that was introduced in CCCH's catalogue of existing beings, and, metaphysically, this is a dualist claim.

However, it is important recognizing that to label CCCH "dualist" does not mean much to the search for the nature of the posited consciousness. There are many forms of dualism, and the CCCH is not compatible with all of them. This section determines,

---

[10] See Albert (1992, p. 83), Stapp (2011, p. 167), and Stöltzner (2001, pp. 58–59).

as much as possible, which dualism(s) may fit CCCH's ontology (so that one may address Chakravartty's challenge). In sequence, a part of the dualist taxonomy presented by Rodrigues (2014, pp. 201–203) will be sketched, making for a more explicit case concerning the situation one is getting involved when adhering to CCCH.

Namely one of its weakest formulations, the fundamental dualism will be defined as *property dualism* (ROBINSON, 2017), holding that *material* properties (*e.g.*, mass, charge, spin, and so on) and *mental* properties (*e.g.*, consciousness, intentionality, and qualia) are not reducible in terms of each other. Moreover, matter and mind are defined as fundamentally being of a different nature. This is dualism at its most basic characterization, from which other types of dualism can be distinguished evaluating how they modify this fundamental thesis.

1. *Substance dualism*: Material and mental properties are different substances, and the bearer of such substances are also of a different nature;
    a) *Strong substance dualism*: The mental stuff is immaterial, and their properties are distinct and exist independently of the material stuff;
    b) *Moderate substance dualism*: The mental stuff is immaterial, and their properties are distinct; their existence depends on the material stuff.

The focus here lies on *substance dualism*, as dictated by CCCH's ontology. Moreover, although the main difference lies between the strong and moderate versions, dualism's taxonomy can be further extended as:

1. *Pure dualism*: Material objects are defined by material properties only;
2. *Compound dualism*: Material objects are defined by material and mental properties;
3. *Non-spatial dualism*: Mental objects are defined by merely temporal properties;
4. *Spatial dualism*: Mental objects have spatial properties; hence dualism is extended through space;
5. *Theistic dualism*: Mental objects and properties are created by God;
6. *Naturalistic dualism*: Mental objects and properties are integrated into the material world;
7. *Interactionist dualism*: Material and mental objects maintain two-way causal relations;
8. *Epiphenomenalism*: Material stuff cause mental stuff, but the opposite is not true;

9. *Pre-established harmony*: There are no causal relations between the material and the mental.

According to this dualist spectrum, Cartesian dualism may be classified as a *strong theistic interactionist non-spatial pure dualism* (RODRIGUES, 2014, p. 203). What about CCCH, however? Which metaphysical taxonomy of dualism should apply to its ontology? As argued in Chapter 4, there are at least two CBI approaches to the measurement problem in QM, but only CCCH's approach to QM requires a consciousness with causal powers. Therefore, the fundamental ontological features of consciousness in CCCH are:

1. *Causality*: Consciousness must be a causal agent in the quantum measuring process;
2. *Transcendence*: The laws of QM that apply to *physical systems* should not apply to consciousness;
3. *Interaction*: There must be an interaction between physical systems and consciousness, as the latter modifies the dynamics of the former.

These three main ontological features of CCCH's consciousness make evident its incompatibility with several metaphysical profiles listed above. As currently formulated, the only metaphysical profiles compatible with CCCH's ontology are strong versions of *naturalistic* and *interactionist* dualism, all others being discarded by some features of the ontology.

Take epiphenomenalism, for instance: it does not admit mental causation, thus being unable to count as an interpretation of CCCH's consciousness. In essence, it is incompatible with the *ontological output* given by the theory. The same holds concerning any moderate version of dualism: if the very existence of a substance, say, mental, is *dependent* of the material, consciousness would not be able to act as a causal agent in the measuring process of QM. Conversely, the opposite would not be compatible either, as the mind *alone* could not create a result of quantum measurement since its causal power is strictly dependent of the experimental setup in which the quantum system lies.

In this sense, the discussion reached a position to examine some very specific attempts at determining what consciousness could be (and what it *could not*) according to CCCH. Naturally, this does not solve the problem but presents a clearer situation (even allowing one to formulate the difficulties related to the view clearly). Recall that Chapter 2 argued that interpretations of QM are new quantum theories. Bearing this in mind, notice also that, once CCCH is adopted, even if simply as a working hypothesis, this counts as a quantum *theory*. From this perspective, it is the theory that discards certain metaphysical versions of dualism, providing a sort of epistemic credentials that metaphysics alone would not.[11]

6.3 METAPHYSICS DISCARDING DUALISM?

Even though it is possible to classify what CCCH's consciousness *could be* in metaphysical terms with greater precision, dualism remains a very unpalatable idea for many. Perhaps it could be discarded on other grounds other than empirical? This section addresses the debate from a metametaphysical perspective, searching for an evaluation of metaphysical theories in order to verify whether there are good arguments for excluding at least some forms of dualism compatible with CCCH.

Widen the net

If dualism could not be directly ruled out by physics (DE BARROS; OAS, 2017), it could perhaps be excluded if the scope was to be expanded to other sciences somehow dependent on results given by fundamental physical theories, such as neurosciences. This metametaphysical criterion was recently coined by Benovsky (2016, pp. 82–84) as "widen the net": one should not look at isolated areas, but rather evaluate how a metaphysical theory fits in a broader picture. In this sense, if dualism is compatible with physics but incompatible with everything produced by neuroscientists so far, *widen the net* would be a satisfactory metametaphysical criterion to recommend the abandonment of such metaphysical theory. However, this not seems to be the case. As demonstrated by Arshavsky (2006), there would not be a single result in neurosciences incompatible with dualism (at least so far). In fact, his study shows that much of neuroscientists' vocabulary is essentially dualist. This metametaphysical criterion, then, would not suffice when one is looking for a way to discard dualism.

Causation

If dualism is the only metaphysical profile that can be connected to CCCH's ontology, it could be argued that despite solving the measurement problem, von Neumann's proposal also raises philosophically puzzling problems concerning mind-body causation. In fact, causation is the ground from which traditional challenges to dualism often occur. Therefore, the fact that the best theories about causation are incompatible with dualism poses a problem to the interpreter of QM adhering to CCCH. However, as claimed by Rodrigues (2014, pp. 214–216), most popular theories about causation (such as counterfactual, covering law, probability raising, primitivist and energy flow theories of causation) are compatible with at least interactionist versions of dualism – with which the CCCH is also compatible. Therefore, still according to Rodrigues (2014,

---

[11] See also Arenhart (2012).

p. 84), “[w]hatever truth about causation is, the best theories we have now don’t rule out immaterial minds causing bodily changes”.

Causal closure and naturalism

Consider another objection commonly held against CCCH: the violation of the causal closure of the world. Roughly, the causal closure thesis asserts that every physical event must have a physical cause, and if that is true, it is violated by the attribution of causal power to a non-physical entity.[12] The argument can be written as:

1. Everything happens according to the laws of physics;
2. There is no mental causality in the laws of physics;
∴ There is no mental causality in the world.

Notice that the second premise is based on *naturalism*, the thesis which holds that science is the best guide to metaphysics. If such a premise is correct (and that is debatable), one may add CCCH with mental causality to the laws of QM, hence denying this very step. Therefore, causal closure cannot be used to exclude dualism, once such metaphysical profile is compatible with CCCH.

Uninformativeness

Another common ground of criticisms against dualism is uninformativeness (RODRIGUES, 2014, pp. 203–207). It is often objected that dualism does not adequately characterize, in metaphysical terms, what the mind-stuff *is*. As stated by de Barros (2014, §2), CCCH’s solution seemingly replaces “[. . .] a mystery by another mystery, without adding any explanatory power”. It does not explain consciousness in terms of what it *is*, but in terms of what it *does*. In this sense, CCCH is uninformative and hence should lose its attractiveness to interpreters of QM.

To resist this objection, one might look at *opposite* metaphysical views. Take materialism, for example. Does it answers what matter *is*? Its answer is as functional as the dualist’s. In QM, other approaches to the measurement problem fail to explain what the mechanisms of measurement *are*: what are parallel universes (DEWITT, 1970)? What is the mechanism responsible for physical collapses (GHIRARDI; RIMINI; WEBER, 1986)? The answers, again, Are *functional*. CCCH is not in a worst situation than the alternatives.

Rodrigues (2014, p. 222) argues that dualism raises more questions than answers. However, so does QM to what concerns the measurement problem.[13] Therefore, there seem to be no definitive objections to CCCH and its dualist metaphysics.

---

[12] See Auletta and Wang (2014, p. 263).

[13] Although some would say that there is a fundamental difference: QM gives confirmed practical results.

FINAL REMARKS

Dualism suffers from a curious fate. While it seems a rather natural step in explaining conscious phenomena that will not leave by any empirical means, it is widely regarded as excessively exoteric in order to account for quantum collapse. In fact, there are rarely arguments against it; it simply is taken by many to be a non-starter. To worsen the situation, dualistic understandings of quantum mechanics are responsible for most of the pseudo-scientific literature on quantum mechanics, making it difficult to provide a sensible account of the view, free of prejudices.

This chapter attempted to provide clearing of the ground for further serious work concerning the relation of mind and quantum mechanics on the CCCH. Carefully articulating the view requires the role of consciousness in QM to be interpreted as a causal factor responsible for the collapse. In this sense, the ontology associated with CCCH requires a consciousness with causal powers over matter and a clear distinction between matter and mind. This, in turn, results in a *pricing* the kind of approach to consciousness compatible with CCCH, as well as in a restriction on the scope of available metaphysical theories. That illustrates a collaborative work between science and metaphysics, with science providing for a test ground for metaphysical theories, as explicitly shown in Figure 5.

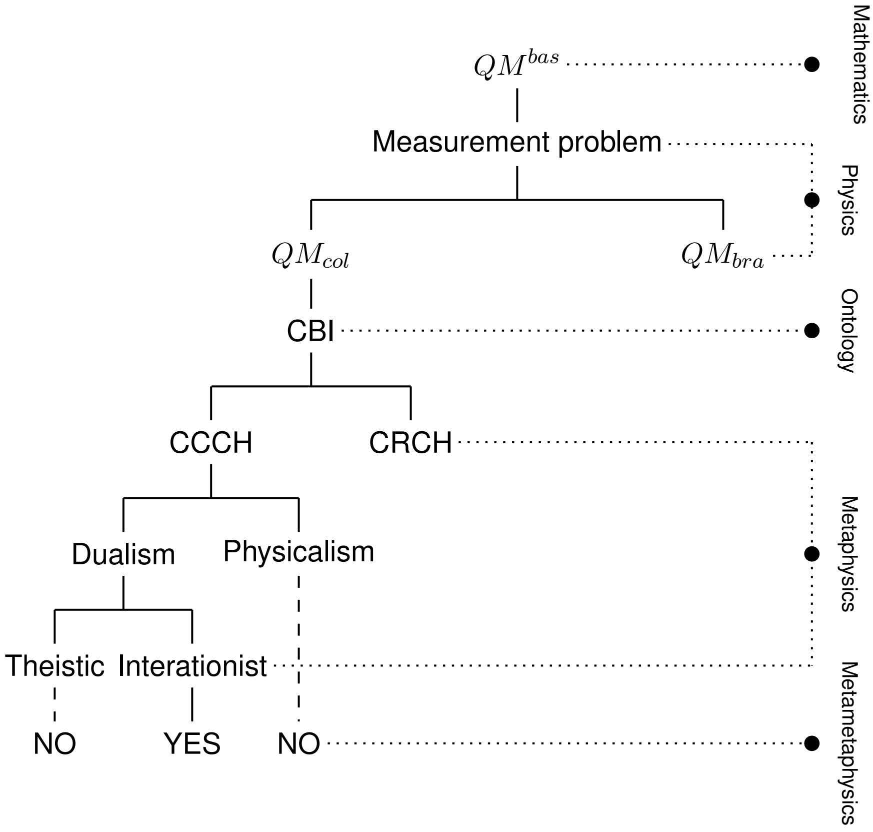

Figure 5 – QM_{col} and CCCH.

Furthermore, this chapter argued that, given that metaphysics plays a crucial role in dressing the posited consciousness with some important features, purely metaphysical arguments are also – at least so far – unable to rule CCCH as implausible. Therefore, CCCH could be better understood if current forms of dualism compatible with it could be articulated more clearly, so that existing metaphysical theories could be employed to clarify the role of consciousness in CCCH somehow. This is a demanding task, left for future works.

7 CASE 2: COLLAPSE AND PHENOMENOLOGY

As presented in Chapter 5, currently, the matters concerning the choice of an interpretation of QM are not strictly objective. Suppose, then, one chooses one of the interpretations presented in Chapter 2 as a working hypothesis. In favor of advancing the discussion, let QM_{col} be the chosen interpretation.

Chapters 4, 5 and 6 argue that the ontological aspect to be extracted from QM_{col} is that consciousness exists; and it is somehow related to the process of collapse. It must, then, somehow exist in the *catalogue* of the world *modulo* QM_{col}. Such ontological aspect of QM_{col}, as presented in Chapter 4, is CBI.

However, even if CBI is chosen as a working hypothesis, how to interpret it in metaphysical terms is still unknown, as different metaphysical profiles can be associated with the concept of "consciousness". For example, as argued in Chapter 6 Chakravartty's Challenge can be met by understanding the ontological commitment to "consciousness" through metaphysical profiles according to which CCCH, such as specific forms of dualism. This chapter analyzes a different possibility: attempting to fulfill Chakravartty's Challenge by attaching CBI's ontology to a metaphysical profile in which consciousness does not *cause* the collapse, but *recognizes it*. This is, in summary, London and Bauer's (1983) proposal of a theory of quantum measurement, labeled CRCH in Chapter 4.

As French (2002) demonstrated, CCCH is the *received view* of CBI. The criticism found in the lteratura concerning CBI, however, also classifies London and Bauer's (1983) CRCH within CCCH's metaphysical scope. This is a common mistake. Despite London and Bauer's efforts indicate a phenomenological view of their quantum measurement theory, literature interpreted it as a natural continuation of CCCH.[1]

With conflations between CCCH and CRCH left aside, the discussion returns to the underdetermination issue. Since CBI is compatible with more than one metaphysical profile (CCCH *and* CRCH), this proposal argues that it is subject to the problem of metaphysical underdetermination, even though they are developed upon the common hypothesis that consciousness has a role in the measurement process. Both metaphysical options are equally compatible with QM_{col}'s CBI, but the metametaphysical method proposed by this thesis, the Unavailable Metaphysical Stories, would be of no help in objectively deciding between CCCH and CRCH. There is, however, still a point to be considered.

Suppose CRCH is selected as a working hypothesis: it is still unknown how it should be interpreted in (*even further*) metaphysical terms. This chapter presents a case study on the metaphysical profiles (or *phenomenological profiles*)[2] of CRCH.

A milestone of the CRCH metaphysical profile is set by French's (2002) paper,

---

[1] See French (2002) for this detailed characterization and references therein.

[2] In this chapter, we use both terms interchangeably.

whose account demonstrates that the CBI proposed by London and Bauer (1983) should be metaphysically understood within a phenomenological framework, and, as such, radically different from CCCH. There seem to be at least two metaphysically incompatible phenomenological profiles to CRCH, the *eidetic* and the *transcendental*. If thas is, indeed, the case, CRCH raises the problem of not determining its metaphysics. This discussion argues that French (2002) combines both approaches. An argument in favor of the eidetic approach is also presented, making use of the Unavailable Metaphysical Stories as presented in Chapter 5.

For that purpose, the chapter is structured as follows. The first section reviews how CBI responds to the measurement problem in QM. The second session analyzes CRCH in more detail, emphasizing the two metaphysical possibilities for its interpretation in metaphysical terms. Lastly, the third session, offers an assessment of phenomenological interpretations of CRCH, evaluating their effectiveness in deciphering the formalism of QM_{col}. The chapter concludes by stating that the eidetic approach is compatible with the formalism of London and Bauer, whereas the transcendental approach is not. Thus, the most viable way to metaphysically interpret the CRCH is, among these choices, through the lens of an eidetic phenomenological metaphysics. Such efforts allowed the understanding of the available options for interpreting QM_{col} in the case of CRCH in (further) metaphysical terms.

7.1 CONSCIOUSNESS AND MEASUREMENT

The framework of quantum measurement proposed by von Neumann (1955) utilizes two distinct dynamical laws of movement, as presented in Chapter 6. As discussed in Chapter 2, the usage of two apparently incompatible dynamic laws, however, originates the measurement problem, briefly defined as their problematic conjunction.[3] Remarkably, von Neumann's approach to the measurement problem is QM_{col}, and its ontological counterpart is CCCH, which, argued in Chapter 6, considers both dynamics ($\mathcal{A}_{\mathrm{col}\ 4}$ and $\mathcal{A}_{\mathrm{col}\ 5}$) to operate within different ontological domains of reality, one material and other mental, thus, replacing the solution of the measurement problem with the solution of the mind-body problem. Similarly, London and Bauer (1983) advance the *rationale* in von Neumann's framework of quantum measurement, stating that the transition from one (linear) dynamics from another (non-linear) – *i.e.*, the *collapse* – can only occur due the interaction with the conscious mind of a human observer.

This ontological aspect of QM_{col} is labeled here as CBI. CCCH became the *received view* about the concept of "consciousness" related to CBI. This discussion states that CBI is not a unitary interpretation of QM, but a basis for a *family* of interpretations (SHIMONY; MALIN, 2006) which is a set of interpretations that share the common

---

[3] Again, this is the reason why QM^{bas} needs to be interpreted.

hypothesis regarding the measuring process. Jammer (1974, §11.2–11.4) labeled the received view as the "subjectivistic interpretations" of QM.

However, in contrast to CCCH, London and Bauer (1983) assumed contrasting assumptions regarding the ontological status of each dynamic law. This fact originates a divergence of metaphysical interpretations *within* the CBI: a *causal* one, due to Wigner (1983) and the received view on CBI, and a *phenomenological*, originated by London and Bauer (1983), in which consciousness does not *cause* the collapse, but *recognizes* in the meaning-attribution process within phenomenological tradition.

The present section briefly outlines CCCH and CRCH approaches to quantum measurement theory, emphasizing their metaphysical differences. As French (2002) argues, the critiques presented by these authors towards CBI only affects he *received view* of CBI – *i.e.*, CCCH. In essence, these critiques *miss the point* when one interprets CRCH through a phenomenological (rather than dualist/subjetivistic) approach. This issue is dealt with in the next sessions.

The measurement problem

It was mentioned that von Neumann's framework considers two different dynamic laws for quantum systems. First let the discussion address the dynamics that account for undisturbed systems, named "process 2", or "process of the second kind". Since the underlying formalism was already sketched in Chapter 2, there is no need to dwell on these topics, so considerations in this regard will be kept brief.

Consider, for simplicity, an observable O to be measured in a Hilbert space $\mathcal{H}$ as a Hermitian operator $\hat{O}$ whose state, before measurement, is $|\psi\rangle = \sum_i^n a_i|\psi_i\rangle$. When left undisturbed, this system's states will evolve deterministically according to the Shrödinger equation (see item 10). Recall that according to QM_{col} the evolution in time of undisturbed quantum systems is ruled by linearity, which implies that if $|\psi_1\rangle$ evolves to $|\psi_1'\rangle$ and $|\psi_2\rangle$ evolves to $|\psi_2'\rangle$, then $a|\psi_1\rangle + b|\psi_2\rangle$ evolves to

$$a|\psi_1'\rangle + b|\psi_2'\rangle. \tag{15}$$

However, recall also that the vector sum in item 2 is *not* a measurement outcome, as it is not an eigenvector of the observable in question. In the same vein, should QM hold true for *all* physical systems, there seem to be no reasons to preclude that any macroscopic measurement apparatus is treatable within QM. Therefore, the situation of a measurement apparatus A interacting with a quantum system S should be describable by linearity, meaning the macroscopic measurement apparatus is describable by a Hilbert subspace $\mathcal{H}_A$, and its interaction with a quantum system is described by a $\mathcal{H}$ factorized into "system" and "apparatus" subsystems with Hilbert spaces $\mathcal{H}_S$ and $\mathcal{H}_A$ respectively, so that: $\mathcal{H} = \mathcal{H}_S \otimes \mathcal{H}_A$.

If this is the case, it is hard to understand how a measurement apparatus plays a causal role in the measurement process. That is, it is difficult to grasp how it produces, alone, a single-term measurement outcome since its states $|\varphi\rangle$ will become entangled[4] with the states of the operator $\hat{S}$ in the interaction, so that the formalism describing the composite system $\hat{S}+\hat{A}$ in a given $t_{x>0}$ is as follows:

$$|\psi\rangle = \sum_{i}^{n} a_i \Big(|\psi_i\rangle \otimes |\varphi_i\rangle \Big) \tag{16}$$

This is the most relevant issue for the present discussion concerning von Neumann's measurement theory: it is committed to an infinite regression of measurement apparatuses. That is, any attempt to reduce the superposition of this composite system by utilizing further measurement apparatuses results in further superpositions. Consider the case of adding the image registered in an observer's eye being represented by $|\varphi_i'\rangle$, its optical nerve being represented by $|\varphi_i''\rangle$, its brain by $|\varphi_i'''\rangle$, and so on infinitely. The case will then be described by:

$$\sum_{i=1}^{n} a_i \Big(|\psi_i\rangle \otimes |\varphi_i\rangle \otimes |\varphi_i'\rangle \otimes |\varphi_i''\rangle \otimes \cdots \otimes |\varphi_i^{n}\rangle \Big) \tag{17}$$

No eigenvector of the observable (which characterizes the very idea of measurement) is obtained in this process. This is, as labeled by d' Espagnat (1999, p. 169), "*von Neumann's chain*". Due to that effect, the number of measurement apparatus one might introduce as an attempt to reduce the superposition of the composite system is unimportant, as if the system is described by unitary dynamic laws, it will *always* be described by a superposition (even though, awkwardly, a superpositon is never actually seen).

Due to von Neumann's (1955) framework, a *new dynamic law* is introduced via a postulate to deal with measurement outcomes. The *collapse postulate* ($\mathcal{A}_{\text{col 5}}$) is introduced to reduce the infinite superposition of measurement apparatus stated above. This is precisely what "process 1" (or "process of the first kind") does: it collapses the deterministic evolution of the composite system into a new state which is one of the states contained in the superposition:

$$\sum_{i}^{n} a_i \Big(|\psi_i\rangle \otimes |\varphi_i\rangle \Big) \longrightarrow \Big(|\psi_\lambda\rangle \otimes |\varphi_\lambda\rangle \Big)_{\lambda \in i} \tag{18}$$

---

[4] Even though von Neumann did not mention the term "entanglement" (since the term was coined by Schrödinger in 1935, and von Neumann's seminal book dates from 1932), it is clearly an entanglement situation as both subsystems $\mathcal{H}_S$ and $\mathcal{H}_A$, and not simply the values of observables within the same system are *correlated*.

As we mentioned earlier, the attempts to reconcile these two dynamics is one way to obtain the “measurement problem”.

The phenomenological response

Examine, now, London and Bauer’s (1983, pp. 251–252) account of the process of quantum measurement, which further develops the rationale presented by von Neumann (1955) by defining “measurement” as an act with epistemic charge: “[a] measurement is achieved only when the position of the pointer has been observed. It is precisely this increase of knowledge, acquired by observation [...]”. The referred “knowledge” would be responsible for the choice of one among several other possible states within a superposition, as presented in Equation (16).

Then, the composite system $\hat{S} + \hat{A}$ should then be treated with the addition of the consciousness of the observer C in a Hilbert space $\mathcal{H}_C$ as a self-adjoint operator $\hat{C}$. Let $\{|\chi_n\rangle\}$ be the eigenvectors of its observables, which possible values (*e.g.*, a definite state of mind at a time t) are given by the sum of all possible states of $|\chi\rangle$. The state of this new composite system $\hat{S} + \hat{A} + \hat{C}$, represented by the vector $|\psi\rangle$, is described in a subspace $\mathcal{H}_S \otimes \mathcal{H}_A \otimes \mathcal{H}_C$ as follows.

$$|\psi\rangle = \sum_{i}^{n} a_i \Big(|\psi_i\rangle \otimes |\varphi_i\rangle \otimes |\chi_i\rangle \Big) \longrightarrow \Big(|\psi_\lambda\rangle \otimes |\varphi_\lambda\rangle \otimes |\chi_\lambda\rangle \Big)_{\lambda \in i} \tag{19}$$

As acknowledged by London and Bauer (1983, p. 251), from an *objective* point of view, the addition of C to the composite system does not seem to solve the problem in comparison with von Neumann’s chain, as expressed in Equation (16). The state of the system’s objective components remains indeterminate. The subjective component, however, by presenting a so-called “faculty of introspection” (that is, a subjectivity that distinguishes the *kind* of states of $\hat{C}$ from the objective states of $\hat{S}$ and $\hat{A}$), has the ability to recognize its own states at any time in virtue of some kind of “immanent knowledge”. This “knowledge” enables the creation of the system’s own objectivity, thus breaking the chain of superpositions by simply stating “I am in the state $|\chi_\lambda\rangle$” or “I perceive the pointer in $|\varphi_\lambda\rangle$” or even “$\hat{S} = |\psi_\lambda\rangle$”. Therefore, the transition depicted in Equation (18) occurs due to a property of C that is not shared by the other – objective – parts of the system, *e.g.*, subjectivity.

This feature presents a *significant difference* between the metaphysics associated with CCCH and London and Bauer’s CRCH use of the notion of “consciousness” in the role of quantum measurement. The former is compatible with some kind of *dualist* metaphysical profile, which places the role of the observer outside the domain of physics, suggesting that it needs to be a different substance, other than the material, in a substance-dualist fashion. The latter is compatible with a different kind of metaphysical profile, where mental and material systems occur and interact *in the same ontological level* (see Shimony (1963)). As a formal counterpart, in London and Bauer's formalism treats the consciousness of the observer is treated as another Hilbert space $\mathcal{H}$ that interacts with the "objective" parts.

The ontology of CBI is shared by both CCCH and CRCH: consciousness appears as an item of the catalogue of the world *modulo* QM_{col}. Notice, however, that the metaphysical profiles that we can be connected to this ontology are different for CCCH and CRCH. London and Bauer's CRCH dictates, through the formalism, that consciousness, the macroscopic measurement apparatus, *and* the microscopic quantum system must be in the same level of existence. Applying our Unavailable Metaphysical Stories, it follows that CRCH *precludes* a dualist metaphysical profile in order to interpret its concept of consciousness. Similarly, as argued in Chapter 6, von Neumann's theory of quantum measurement precludes a phenomenological metaphysical profile, since CCCH dictates that the existence of a non-physical causal agent must be ontologically separated from the measurement apparatus and the quantum system, in a distinct realm of existence.

It should be mentioned that it was London and Bauer (1983, p. 259) themselves who acknowledged the phenomenological compatibility of their interpretation, specifically the one regarding Husserl – a point also stressed by London's biographer, Gavroglu (2005). Advancing the debate, French (2002) argues that the concepts involved in London and Bauer's proposal suggest that these should be understood in terms of the metaphysical profile given by Husserl's phenomenological project.

Let us press this point again. If London and Bauer's CRCH is to be understood within a (general) phenomenological profile, then consciousness should not be regarded as the *cause* of the collapse, but rather as a *relational act* between the objective parts and the so-called "immanent knowledge", which can undoubtedly separate itself from the superposition and continuously track its own.

Phenomenologically interpreted as a relational act, consciousness would, through collapse, set a *new objectivity* by stating specific properties of the whole composite system. Consciousness, then, would act in *recognizing* the collapse rather than *causing* it. Hence, CRCH.

In this sense, concerning the phenomenological profile, the objectivity is not given *a priori*, neither resides in some subjectivity that is separated from the whole process of measurement. Instead, objectivity is *constituted* by a creative act of observation in which the observer separates itself from the observed object. According to this approach, a superposition such as Equation (19) correctly describes the situation *externally*. However, only consciousness that would be able to describe it *internally* through the separation of its "I" from the composite system, becoming able to choose one component of the superposition among many others, as described by the formalism of QM.[5] It is worth mentioning that this act constitutes a new objectivity. Due to this fact, further reference to the internal aspects in judging it can be avoided.

7.2 PHENOMENOLOGICAL UNDERDETERMINATION

Phenomenology, as it is known, is a philosophical investigation demarcated by the so-called "method of phenomenological reduction", which is divided into two main groups: one concerning intentional objects called "eidetic reduction", and other, more radical position, concerning ego or pure consciousness, called "transcendental reduction". If French's (2002) account is to be considered, the two distinct metaphysical profiles for CRCH are conflated. This work argues in favor of this distinction, which rises a problem: CRCH, then, seems to be metaphysically underdetermined by both methods of phenomenological reduction. By applying the method of Unavailable Metaphysical Stories, we claim that only one of these phenomenological profiles remains an available option to attach a metaphysical profile to CRCH. These issues are dealt with hereafter.

Two methods of phenomenological reduction

According to Husserl (1964, pp. 18–19), phenomenology is a descriptive science concerning phenomena.[6] The primary function of phenomenology is to explain how phenomena are constituted and how are they possible. Phenomenology does not concern the discovery or passive receipt of information about the world; instead, it is about constituting meaning to it. In this sense, phenomenology does not inquire about *after* or *before* the phenomena. Likewise, it is not a matter of interacting with a passive and hidden world that hopes to be discovered, as it is sometimes presupposed in dualism. Unlike the dualist profile, phenomenology considers subject and object to be poles of the same process of meaningfulness. In the phenomenological profile, then, there is no real difference between observer and observed. In this sense, a measurement outcome is not to be considered previously available, waiting to be discovered by a neutral observer. There are several phenomenological profiles with a singular feature common to all: there is no external (transcendent) reality, and there is no internal reality (immanent); the reality is what appears for us at any given moment (HUSSERL, 1964, §6). All that can be reached is the actual phenomenon in each observation.

These ideas do not differ highly from the dualist view concerning measurement. In the phenomenological profile, however, there is no ontological difference between

---

[5] As such, CRCH avoids the standard criticisms directed CCCH, such as the paradox of Wigner's friend, as presented in Chapter 6 – see also Wigner (1983), Shimony (1963) and Jammer (1974). This is so since in the CRCH there is no such thing as *a mental process acting as causal agent in the reduction of superpositions* in CRCH.

[6] See also Husserl (1982, §65–66).

observer and observed: there is simply observation in order to obtain meaning. So dualism turns out to be an incompatible metaphysical profile for CRCH's consciousness. Differently from dualism, the phenomenological profile allows the existence of a metaphysical explanation of London and Bauer's measurement process, without the need of indicating different ontological levels for each term in Equation (19). So, the formalism for quantum measurement in Equation (19), as presented by London and Bauer (1983), seems to require an interpretation within a phenomenological metaphysical framework instead of a dualist one. As previously stated, this was demonstrated by French (2002). However, where the author identifies a unique option within this general phenomenological profile, this work argues that there are at least two options while agreeing with his main point: until now, the phenomenological profile seems to be the better option to interpret London and Bauer's account for quantum measurement in metaphysical terms.

However, we disagree with his view about how Husserlian phenomenology works in this explanation. Here is the reason: there are two main metaphysically distinct paths *within* the phenomenological profile. The first is the *eidetic reduction*, which deals with intentional objects and the domains where such objects are disposed. The second one is the *transcendental reduction*, which deals with the transcendental ego, where there is no interest in intentional acts and objects. This is precisely where metaphysical underdetermination fits: between the eidetic and the transcendental reduction within CRCH's phenomenological profile.

The eidetic reduction is a method by which one moves from the consciousness of individual and concrete objects to the domain of pure essences, thus achieving an intuition of the essence of a thing, *i.e.*, of what it is in its invariable and essential structure, apart from all that is contingent to it. These essences are the principle or necessary structure of the thing. As a science of essences, phenomenology finds this reduction necessary for its methodology. Apparently, in London and Bauer's case, the eidetic method arise as the best philosophical interpretation in order to understand its philosophical approach to the quantum measurement process.

Conversely, the transcendental approach in phenomenology *considers only pure consciousness*, and eidetic reduction is seen as an intermediary method. The use of the transcendental approach to interpreting London and Bauer's proposal is unreasonable, as it does not concern object and subjects, such elements which were previously presupposed, and are now dismissed in the transcendental reduction.

According to London and Bauer's proposal, the quantum object (*i.e.*, the intentional object) is considered to be an intentional correlate of the subject, which is not the point when working with the transcendental reduction. Unlike French's (2002) approach, which considers the transcendental method, the position defended here takes London and Bauer's (1983) approach to be compatible with the eidetic reduction but not with the transcendental reduction.

When French (2002) assumes the complete Husserlian project (both eidetic *and* transcendental) as a background for London and Bauer's proposal, we believe that he makes a mistake. Inevitably the Husserlian project reaches far beyond London and Bauer's conceptual needs. In most cases, Husserl does not deal directly with intentional objects directly, which is a key characteristic of London and Bauer's formalism. In particular, the transcendental reduction presupposed by French (2002) is useless in London and Bauer's case, since, according to the transcendental profile of CRCH, talking about intentional objects (as the quantum system and the measuring apparatus) carries no meaning whatsoever.

A dangerous conflation

French's (2002) paper was seminal for the debate between the dualist and the phenomenological profiles. However, we argue that there is a misconception in his final position about how to interprets London and Bauer's proposal, as he conflates both the eidetic and the transcendental reduction within Husserl's whole phenomenological project. This becomes clear when the author interprets London and Bauer's formalism as including different stages of Husserl's philosophy, including eidetic and transcendental reduction:

> Such an account is useful in the present context since it enables us to situate London's dissertation, for example, in the Husserlian first stage, whereas, as we shall see, the considerations of consciousness and objectivity that we find in the monograph with Bauer span the second and third stages. (FRENCH, 2002, p. 484).

Apparently, French is correct when utilizing eidetic reduction in order to interpret CRCH, referencing to the ego-object structure as in the following passage:

> Note, first of all, that at the beginning of this characterization, the observer is not set outside of the domain of quantum mechanics. She too is represented by a wave function within the superposition. But she, as an "I" or ego, possessing this characteristic faculty of introspection, has "immanent knowledge" – that is, absolute and indubitable knowledge – of her own state by virtue of which she can, on the one hand (namely that of the ego), separate herself from the superposition and, on the other (namely that of the object in question), create or set up [...] a "new objectivity". This separation should not be thought of in terms of consciousness "causing", in whatever sense, the wave function to collapse, but rather in Husserlian terms, as that of a mutual separation of both an Ego-pole and an object-pole through a characteristic act of reflection. (FRENCH, 2002, p. 484).

It is difficult to understand how London and Bauer's proposal connect to the last stages of Husserl's philosophy. As previously argued, this connection is not possible because as it is not compatible with the scheme object-apparatus-subject presupposed in London and Bauer's formalism. However, French employs the concept of *pure consciousness* (or *pure ego*), which is a concept of the *transcendental* phenomenological reduction, utilizing all of Husserl's philosophy, as it is possible to observe in the following passage:

> Hence, the perception of something immanent is indubitable, in the sense that there can be no failure of reference. This is not so for something transcendent, of course. This then leads to a further difference between the physical and mental, that bears on the apparent retention of the pure ego: the positing of things in the world is always a contingent positing, but the positing of my "pure ego", as – crucially – the subject of mental acts, is necessary and absolute [. . .]. (FRENCH, 2002, p. 480).

Although French (2002) stated that the phenomenological profile is the best way to understand London and Bauer's formalism in metaphysical terms, he eventually commits himself to a much broader philosophical position, making use of the eidetic and the transcendental reduction in order to explain how London and Bauer's proposal works. In CRCH, as shown by Equation (19), the quantum object, the measurement apparatus *and* the observer are included in the same mathematical level. However, in some sense, the observer has a privileged status in the measurement process (*i.e.*, the observer is capable of reducing superpositions and stopping the chain effect).

Therefore, how can the observer to be on the same mathematical level, but on a different ontological level? For the CCCH, this is not a real problem: it is just the way it is! However, for the CRCH, it is possible that the observer and the observed can be in the same ontological level, since, according to phenomenology, when there are an observation and an observer, they are always *codependents*. It is possible to argue that there is no observer without something which is observed, and there is no observed without an observer. If there is some object of our actual knowledge it is present for us in some kind of relation. For instance, when looking at the Sun, there is the intentional act of seeing something, and there is the intentional object which is presented in each relation. Seeing, perceiving, thinking about an object is always a new way to perceive such an object, but the object cannot possibly be a source of meaning without being part of that relation.

This is why London and Bauer (1983) chose the phenomenology as a metaphysical profile to explain their formalism and their ontology. Let us focus in this point. In phenomenology, the "same" object can be part of different kinds of relations. A change in the relation implies a new meaning for this object. Therefore, one can observe a mountain and perceive something beautiful or sad, or have an impression about the past or future; one can hate or love that place. The object itself is the same in all instances, but the kind of meaning (or *information*) is always different in each of them.

The same applies to the process of measurement in QM: it is possible to obtain different kinds of information in each measurement – the type of observation simply needs to be modified. The object is the same, but the information provided by it is always different.

However, when French (2002) accepts the whole phenomenological project, including transcendental reduction, a problematic conflation between two distinct methods of phenomenological reduction – which, as argued in previous discussions, is very problematic in the specific case of interpreting CRCH. The next section demonstrates how the phenomenological profile for CRCH can be better understood through the eidetic reduction.

7.3 NEGATIVE METAMETAPHYSICS

The goal is to reduce the number of options which form (a state of) metaphysical underdetermination concerning both the *eidetic* and the *transcendental* phenomenological profiles to CRCH. This problem is engaged here in a further analysis of the formalism presented by London and Bauer (1983, pp. 251–252).

There are in fact historical reasons to believe that London and Bauer (1983) considered *only* the eidetic approach, specifically if one considers the philosophical roots of London. Jammer (1974, pp. 482–483) stated that London became deeply interested in philosophy in the 1920's, having earned his PhD degree for a thesis in philosophy studying phenomenology under a Husserl's follower, Pfänder. The main point among the historical reasons to support this thesis' argument is precisely London's relation with Pfänder. Like many others disciples, Pfänder was a controversial follower of Husserl's ideas, defending that only the eidetic approach was a viable path in phenomenology as the investigations about the ego were some kind of idealist turn inside the Husserlian project. Moreover, still as stated by Jammer (1974, pp. 482–483), Pfänder and London were also influenced by Lipps, who was also was very critical concerning the idealist turn in phenomenology. Gavroglu (2005, p. 179), however, states that at the time of the discussions between London and Pfänder took place, Pfänder (2009) had already published his critique on philosophical psychologism, such as that proposed by Lipps.

Nevertheless, Pfänder (2009) endorses the eidetic phenomenological profile. Therefore, it is improbable that London, who, according to Jammer (1974, p. 483) and Gavroglu (2005), primarily wrote the philosophy part of their monograph, could possibly endorse a transcendental reduction within the phenomenological profile. London could be referring to a specific kind of phenomenological profile, namely the eidetic one. However, from London and Bauer's monograph, only the phenomenological insight can be defined, albeit not specifically. Thus, this thesis cannot be ground solely in this historical argument.

The next subsection, then, justifies the position adopted here by comparing both phenomenological profiles and identifying which is more compatible with the formalism presented by London and Bauer (1983). In some sense, even if London and Bauer stated that their position was the one exposed by French (2002), the defense of an eidetic approach presented in this thesis is much more coherent with their formalism, precisely with relation to Equation (19).

A *coup de grâce* through the formalism

There is a natural relationship between the transcendental ego and other intentional structures. There is no point, however, in resorting to transcendental reduction in order to interpret the formalism of quantum measurement put forth by London and Bauer (1983), as such method of phenomenological reduction cannot make any clarification over their formalism. This becomes clearer when considering that London and Bauer presuppose at least three instances in its formalism: the object, the apparatus and the consciousness of observer. This assumption matches the eidetic reduction perfectly, which examines the intentional structures that enable the formation of phenomena. Eidetic reduction examines the intentional acts and their intentional correlates (intentional objects). In contrast, the transcendental reduction casts those structures aside, by a demand of the method itself. For this reason, CRCH's formalism becomes meaningless to the transcendental reduction.

The whole endeavor conducted by London and Bauer (1983) had two main objectives. First, to explain when a measurement is made without falling into the *reductio ad infinitum* of von Neumann's chain, as in Equation (17). Second, to explain how consciousness operates in the measurement process without committing oneself with to the problems of dualism. There is indeed no metaphysical underdetermination problem in this case, for the transcendental phenomenological reduction is not really compatible with the formalism presented by London and Bauer (1983). Take, for instance, London and Bauer's description for a quantum superposition, as in Equation (19). Then, rewrite it utilizing the concepts of the eidetic phenomenological profile to CRCH, as presented by Equation (20):

$$\sum_{i=1}^{n} a_i \Big(\underbrace{|\psi_i\rangle \otimes |\varphi_i\rangle}_{\text{intentional objects}} \otimes \overbrace{|\chi_i\rangle}^{\text{intentional act}} \Big) \tag{20}$$

This notation aligns well with the eidetic approach as it considers intentional objects and intentional acts. Consciousness ($|\chi_i\rangle$) as an *intentional act* states its own the contents as well as the content of the intentional objects. Notice that this distinction between intentional acts and intentional objects *only* makes sense in the eidetic phenomenological reduction. Conversely, in the transcendental phenomenological reduction, such division would not be possible. Thus, the transcendental approach to

London and Bauer's CRCH does not seem to be possible. If that is the case, as argued in the previous section, French's (2002) conflation of the eidetic and transcendental phenomenological reduction is indeed misleading due to the concepts involved in the *transcendental* reduction.

Schematically, this thesis' criticism towards the transcendental approach to the phenomenological CRCH is as follows:

- The transcendental reduction does not concern an intentional act and its correlates; it concerns the reduction of the natural ego in order to describe the pure ego. The pure ego, or absolute consciousness, is empty. As Husserl states:

  > As pure Ego it does not harbor any hidden inner richness; it is absolutely simple and it lies there absolutely clear. All richness lies in the cogito and in the mode of the function which can be adequately grasped therein. (HUSSERL, 1989, §24).

- As such, the transcendental reduction does not consider mathematical constructions, since such constructions are taken to be simply abstractions over pre-scientific experiences of the world. Different from other stages of Husserl's philosophy, in the transcendental reduction there is no interest in ideal objects, such as mathematical objects like those presupposed by London and Bauer;
- The transcendental reduction is a radical position inside the Husserlian phenomenological project, which is considered, even for his most known followers, as impracticable.[7] Without a reference to a more concrete conceptual apparatus, several philosophers discredit a productive use for the transcendental reduction, which is directed for the investigations about the pure ego;
- The transcendental approach does not deal with mathematical constructions as London and Bauer's formalism. Conversely, the eidetic approach considers such constructions in the object-subject schema by labelling mathematical objects as intentional objects. Therefore, between these two (apparently) available phenomenological profiles to CRCH, the eidetic phenomenological profiles, the eidetic profile is the *only* viable option to interpret London and Bauer's formalism.

This occurs since the thesis regarding the transcendental ego represents a return to idealism (HUSSERL, 1970, §65–67), giving special attention to the pure ego, an instance without reference to intentional structures as intentional acts and objects. When French (2002) employs such a radical instance of Husserl's phenomenology, he

---

[7] As an example, Heidegger (1996, p. 210, §219) was one of the leading opponents of Husserl's late work on the transcendental reduction, emphasizing that "[t]he idea of a 'pure ego' and a 'consciousness in general' are so far from including the a priori character of a 'real' subjectivity [. . .]".

eventually abandons the explicit correlation between London and Bauer's formalism and the intentional structures presupposed by the eidetic reduction. Thus, it seems that eidetic reduction is the only compatible metaphysical profile to interpret CRCH, as the transcendental reduction does not deal with quantum objects, and quantum objects *do appear* in London and Bauer's formalism, as shown in Equation (19).

Therefore, the transcendental reduction is not a phenomenological profile that is compatible with the author's interpretation of QM. There is no obvious way in which the formalism in Equation (20) can be understood in a transcendental phenomenological profile to CRCH: thus, it was never really an option to interpret it as *ipso facto*. Hence, *if* the CRCH poses a meaningful option to interpret QM_{col} metaphysically (as it apparently does) since until now the only way to understand it further in metaphysical terms is through the *eidetic* phenomenological profile, thereore there is one less metaphysical option in this case.

7.4 FINAL REMARKS

The matters of interpreting QM is far from obvious, and also far from concluded in the sense of a settlement of a unitary, single scientific image of the world *modulo* QM. Nevertheless, with the application of Unavailable Metaphysical Stories, it was argued that philosophy might indeed help to understand the available options for interpreting QM, in the sense that it could offer criteria for "discarding" some alternatives for the interpretation of QM.

This chapter presented a distinction between two alternatives metaphysical profiles for CRCH and offered motivations for the rejection of one of them, as it does not conform to the formalism of CRCH. Thus, it was evidenced that:

- Dualism is an incompatible metaphysical profile to interpret CRCH;
- Phenomenology is an incompatible metaphysical profile to interpret CCCH;
- Transcendental reduction is an incompatible metaphysical profile to interpret the phenomenological profile to CRCH.

Therefore, eidetic reduction remains as the only available option so far, as explicated by Figure 6.

This chapter concludes the inquiry concerning QM_{col}. Therefore, as sketched in Chapter 5, the discussion shall evolve to the analysis of QM_{bra}.

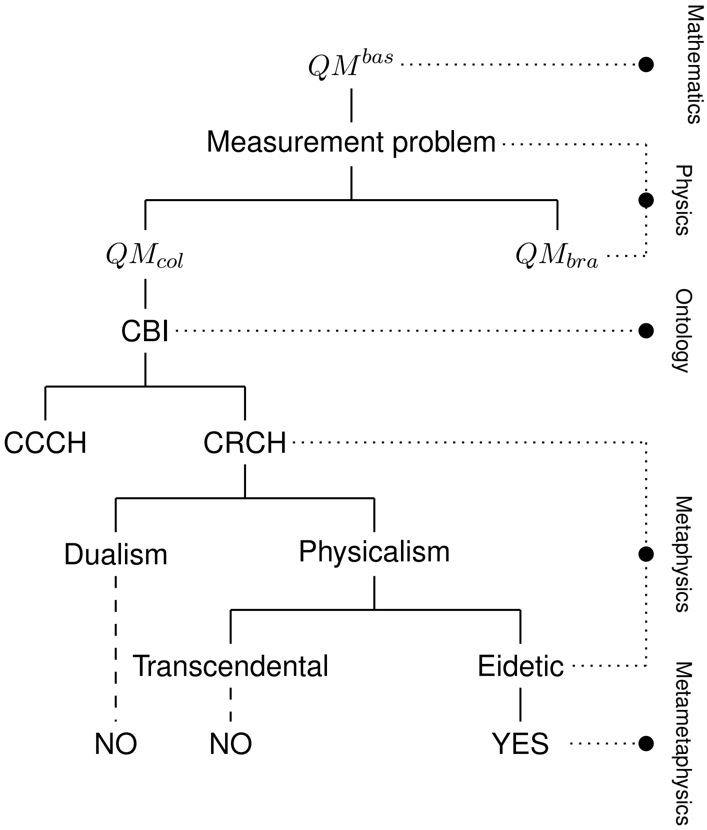

Figure 6 – QM_{col} and CRCH.

8 CASE 3: MANY WORLDS

> "Never put forward a philosophical theory that you yourself cannot believe in your least philosophical and most commonsensical moments."
>
> DAVID K. LEWIS
> *On the Plurality of Worlds*

Almost every chapter of this thesis begins by stating the obvious: quantum mechanics works. And, yes. It does. It seems there is a natural attitude towards such empirical success that suffices our naturalist and realist expectations. However, why doesn't QM provide an explanation of how the world is? The short answer for it is underdetermination. That is, there are many available accounts of "what the world is like" that shows compatibility with QM.

Let us recall the lessons learned so far. As stated in Chapter 2, there is no such thing as a unitary view that can be called "QM". Chapter 5 argued many ontologies can be read off the many available quantum theories, and that several metaphysical profiles can be connected to them, allowing for an explanation of *what are* those things that ontology states that there are. One way to do it is to employ French's Viking approach to metaphysics: searching in the history of philosophy for what sort of metaphysical profiles philosophers developed, and choose some of the theories to attach to scientific theories' ontologies, since, as argued in Chapter 4, a scientific-realist stance for QM must inform its metaphysical profiles; otherwise the realism lacks content.

According to the discussion developed in Chapter 5, the decisions concerning theory choice in physics and ontology are not strictly objective. Therefore, one can follow the voluntarism put forth by Chakravartty (2017a, p. 215) and pick a theory *to the customer's choice*. The work developed in this thesis closely examines the ontological constraints of the theories to assess which metaphysical profiles cannot be bound to different theories, by applying the Unavailable Metaphysical Stories in a metametaphysical evaluation.

So, until now, the discussion engaged underdetermination. There was always *more than one* option for understanding quantum phenomena, both theoretically, ontologically and metaphysically. A remarkable point concerning QM_{col} was that *all these three levels* of description presented available options.

This chapter analyzes the ontological outcomes of QM_{bra} found in Chapter 4 and applies the methodology presented in Chapter 5 in order to (i) attest whether some metaphysical profile can be found (in the Viking's way) and (ii) evaluate the available options to narrow metaphysical options. Therefore, from this point onward, the discussion addresses one of QM_{bra}'s ontological counterparts, which is MWI. Narrowing the number of options is important for numerous reasons, the most important one, perhaps, allowing for the proper handling of humility.[1]

So far, there seemed to be many options. We will see, in this chapter, that the whole thing seems to be going in another direction: perhaps there are no metaphysical profiles available to interpret the entities postulated by scientific theories. This chapter deals exclusively with MWI, but in the end, we will see that the argument can be generalized to other interpretations of QM.

The absence of metaphysical profiles is a major obstacle to meeting Chakravartty's Challenge. Such a problem is here called "null-determination", presenting difficulties for both realistic and naturalistic expectations.

Let us see why.

8.1 NATURALISTS' EXPECTATIONS

The naturalist project must be considered if the expectation of extracting a world view from QM_{bra} is nurtured. As Wallace (2012, pp. 3–4) nicely states, naturalism is "[. . .] the thesis that we have no better guide to metaphysics than the successful practice of science".

One part of the project consists of criticizing so-called "traditional" metaphysics. Ladyman and Ross (2007, p. vii) open their famous book by criticizing contemporary analytic metaphysics, considering it a failure "[. . .] to qualify as part of the enlightened pursuit of objective truth, and should be discontinued". The propositional part of the project is represented by the efforts to naturalize metaphysics (or to establish a scientific metaphysics), in which metaphysical questions are answered by science,[2] or at least in a scientifically respectable manner.

Therefore, the naturalist expectation is to *extract* metaphysics from science somehow. To naturalists like Ladyman and Ross (2007, p. 65), metaphysics should be "[. . .] a unified world-view derived from the details of scientific research". In this way, the naturalist's claim aligns with the scientific-realist stances, as argued in Chapter 3. French (2014, p. 48) even characterizes such a thesis in the form of a *recipe*: "[. . .] we choose our best theories; we read off the relevant features of those theories; and then we assert that an appropriate relationship holds between those features and the world".

The attractiveness of these conceptions lies in the compatibility with the intuition that scientific theories are true because they refer to the world in which we live (and not a purely theoretical construct). However, as argued in Chapter 3, such scientific-realist's expectation may be too high to what concerns fundamental physics, since QM underdetermines its own interpretation.

---

[1] See French (2013).

[2] See Guay and Pradeu (2017, §2).

But what about the naturalist's expectations? They are, also, too high, being torn apart by QM, partly due to a common conflation between "ontology" and "metaphysics". Therefore, there are arguments such as Maudlin's (2007, p. 104), for example, stating that "[m]etaphysics is ontology". As defined in the Introduction, and throughout Chapters 4, 5, 6 and 7, ontology is concerned with issues of existence, so a catalog that lists entities in the world is part of ontology. Chapters 4 and 5 have demonstrated that ontology can be extracted from theories, in a sense that it is possible to "read off" its elements based on ontological commitments criteria. Ontology, then, might be *naturalized*. The problem lies within the number of *ontologies* available in the case of QM (as many as there are interpretations of QM), so ontological underdetermination is at sight: the necessary elements to choose *which one* of such ontologies are true descriptions of this world are not available. This may frustrate some scientific-realist expectations; however, it does not frustrate the naturalist's expectations: it i possible to extract ontologies from interpretations of QM.

What completely frustrates the naturalist's expectations is to extract *metaphysics* from interpretations of QM. As argued in the previous chapters, the metaphysical profile is not given by scientific theories. Rather, metaphysical theories can be found in the philosophical literature and linked to the ontologies of the theory as metaphysical profiles. This is the Viking Approach to metaphysics in the form of a tweet.

Metaphysics starts where ontology ends. Given the posits of an ontological theory (the entities comprising the catalogue of reality according to such a theory), one may further inquire about their status. These questions are of a broader, metaphysical nature. Answering these questions leads to fulfilling a kind of "metaphysical profile" for the posits. For instance, if properties are accepted as part of the ontological catalog, one may ask whether properties are universals or tropes, or if tropes and universals are needed to characterize properties correctly. This aligns with the Viking Approach to metaphysics of science, as proposed by French (2013, 2014). These terms shall guide the discussion further developed here. In this sense, metaphysics is an *extra layer* to the theory's interpretation – a non-trivial layer, since the lack of a metaphysical profile would render the realist content of an interpretation empty.

Two related levels of interpretational underdetermination must be cast aside to allow the discussion to proceed: the theoretical underdetermination (regarding, for example, QM_{col} *versus* QM_{bra}), and the *naturalized* ontological underdetermination (concerning, for example, CBI *versus* MWI, or, still, RS *versus* MWI). Now, following the Viking's strategy, the efforts proceed to search for metaphysical profiles that could accommodate MWI's ontology. To that purpose, a review ofhow MWI addresses the measurement problem is presented.

8.2 MANY WORLDS

Why many worlds? As is well known, MWI is one (among many others) solution to the measurement problem. Recall Schrödinger's cat scenario: an idealized closed box containing a cat, a flask of poison, a hammer, a radioactive material (an α particle), and a Geiger counter. The α particle presents the property of having a 50% chance of decaying or not. If it decays, the Geiger counter detects the α particle's decay and the hammer is activated, breaking the flask of poison, which kills the cat. If the α particle does not decay, then none of this happens, and the cat remains alive. At the end of one hour, *something* happens to the α particle, with both cases presented above being possible subsequent chains of events following the state of the α particle.

Assume that $|\psi\rangle$ is a quantum-mechanical description. Following the notation presented by Auletta and Wang (2014, p. 290), the whole system $|\psi\rangle$, composed by the radioactive particle R, the hammer and the flask H, and the cat C, may be described by the following superposition state:

$$|\psi\rangle_{RHC} = a|d\rangle|a\rangle|D\rangle + b|d'\rangle|a'\rangle|A\rangle, \tag{21}$$

where:

- a and b are probability *amplitudes*;
- $|d\rangle$ represents the α particle *decaying*;
- $|d'\rangle$ represents the α particle *not decaying*;
- $|a\rangle$ represents the active hammer;
- $|a'\rangle$ represents the inactive hammer;
- $|D\rangle$ represents the dead cat;
- $|A\rangle$ represents the living cat;

In a simpler notation, the component $|d\rangle|a\rangle|D\rangle$ can be represented by $|\psi_1\rangle$, and the component $|d'\rangle|a'\rangle|A\rangle$ by $|\psi_2\rangle$. Thus, $|\psi_1\rangle$ is the description for the scenario in which the particle's decay occurs and $|\psi_2\rangle$ represents the scenario in which it doesn't. *One* of these two scenarios will take place after one hour, which is described by $|\psi'\rangle$. The temporal evolution of $|\psi\rangle$ to $|\psi'\rangle$ is represented by the Schrödinger equation, which implies that the state of affairs of the box and its contents, after one hour, is

$$|\psi'\rangle = a|\psi_1\rangle + b|\psi_2\rangle. \tag{22}$$

According to the MWI, a branching process happens whenever a quantum system enters a superposed state. The cat is then found in a specific state in virtue of living in the branching of the world in which it occurs. In MWI, the Equation (22) has universal validity; thus, all the terms of the equation are equally real:

- The dead cat, with the poison flask broken, as a result of the falling atom, represented by $|\psi_1\rangle$;
- The living cat, with the poison flask intact, since the atom did not decay, represented by $|\psi_2\rangle$.

The terms are not real in the same world, but in different worlds that originate in the superposition described by Equation (22).

Before proceeding, is it important to take a step back and remember something that was said in Chapter 5. Does the branching process in any way *imply* the existence of many worlds? No.

To understand why, the distinction between RS and MWI is indispensable. Both interpretations use the same formalism to describe the vectors and physical observables mathematically: the Born Rule for probabilities and the Schrödinger Equation for temporal evolution. The responses to the two interpretations are also (formally) in line with the solution to the measurement problem: no collapse. Here's where RS and MWI start to disagree: while MWI says the measurement problem is solved because *physical systems* somehow branch into distinguishable states, RS would say that what branches into different states is the *states of physical systems*.

This is noteworthy because, although MWI's mathematics is practically the same as that of RS, its difference in terms of ontology is enormous. By multiplying physical systems into branches, MWI multiplies entire physical worlds - hence "*many* worlds". On the other hand, RS, when multiplying vectors, multiplies only vectors, that is, mathematical entities in a mathematical space. Therefore, in terms of a naturalized ontology, the following result can be obtained:

RS $\longrightarrow$ One world;

MWI $\longrightarrow$ Many worlds.

To recap what was said in Chapter 4, this distinction (which is common, but also not standard) is used in this chapter.[3] To name the names, Everett (1957) would be better characterized in the interpretive panorama of RS, and DeWitt (1971) in that of MWI. As stated earlier, the focus of this chapter is exclusively on MWI.

According to the MWI, the notion of "world" is defined by our own experience, corresponding to the perspective of classical physics that there are no observable

---

[3] See (BEN-DOV, 1990) and (BARRETT, 2011).

superpositions in a single world. For example, the state of the cat is always perceived as well defined, and the other worlds are never perceived.

For someone with naturalistic inclinations, MWI provides the catalog of reality that contains parallel worlds. As a scientific theory, MWI provides the branching process, stating that the world branches out in each superposition situation, and thus "multiple worlds" can be included in the ontology as an item in the universe's catalogue. Thus, ontology, that deals with what exists, can be naturalized: it (or part of it) can *indeed* be extracted from MWI. This catalog, however, does not provide enough elements for one to infer what are multiple worlds, in metaphysical terms (the so-called "metaphysical profile" of the worlds).

Let us, then, in the Viking style, assess whether we can find a metaphysical profile suited to a branched reality, with many worlds, as required by the MWI ontology. There are two main candidates: a fictionalist treatment of worlds and modal realism about such worlds. Let's start with the last one.

The Viking's pillage

Theories of possible worlds, as proposed in modal metaphysics, seem to be obvious alternatives to metaphysically profile MWI's worlds, since the MWI's account of worlds shares many characteristics with the possible worlds typically employed to study modality.

The many worlds of MWI can be employed to explain alternative conceptions of how the world could have been (maintaining the laws of QM). For example, consider Schrödinger's cat: there is a *possible* result in which the cat stays alive; similarly, there is a *possible* result in which the cat is found dead.

MWI and theories of possible worlds consider that a world describes a state of things that could occur, it is counterfactual description of reality under certain conditions. Moreover, possible worlds in logic are taken as *maximal situations*, *i.e.*, any distinct proposition p is either true or false in a given situation. In this sense, maximal situations are incompatible. Also, those situations are typically thought of as consistent, so that the same proposition cannot be simultaneously true and false in the same world.[4] Likewise, MWI takes a measurement of a state such as the one described by the Schrödinger cat's scenario to induce two incompatible situations (one in which the cat is dead, one in which the cat is alive). Therefore, two distinct worlds are required to account for the measurement outcome.

The comparison between the notion of many worlds in logic and QM can be expanded: roughly, logic employs the notion of the world to explain modalities, while MWI does so in order to explain the measurement. In both cases, informally speaking of worlds seems to help this discussion. However, in no case is the metaphysical meaning

---

[4] See Lowe (2002, pp. 81–82).

of the world clear, seen that a clear meaning of such worlds is given by the metaphysical layer.

In order to provide a more accurate account of worlds and modality, the Lewisian account of modal realism may offer the metaphysical profile needed to worlds of MWI. According to the theory, the plurality of worlds is taken literally.

> I believe that there are possible worlds other than the one we happen to inhabit [. . .] I emphatically do not identify possible worlds with respectable linguistic entities; I take them to be respectable entities in their own right. When I profess realism about possible worlds, I mean to be taken literally. Possible worlds are what they are, and not some other thing. If asked what sort of thing they are, I cannot give the sort of reply my questioner probably expects: that is, a proposal to reduce possible worlds to something else. (LEWIS, D., 1973, p. 84).

Genuine modal realism, however, is not the only available metaphysical option to profile MWI's ontology, *i.e.*, worlds. Some authors claim that the idea of many worlds is only a convenient metaphor for understanding measurement. According to this vision, MWI does not ask for a reality of many worlds.[5] The many worlds would be a convenient fiction that does not need to be taken literally. Thus, in principle, it also seems legitimate to attribute a fictional metaphysical profile to the entities postulated by MWI, in which the many worlds are merely fictional, and only the present world is real.

Thomasson (2014, pp. 177–178) argues that, according to the fictionalist view the discourse of parallel worlds should be interpreted as merely fictional (metaphorical, figurative, etc.). Therefore, there is no connection with existence: there is no need, then, of committing to the existence of MWI's parallel worlds for the discourse to be acceptable.

8.3 METAMETAPHYSICS

Thus, there seem to be at least two metaphysical options available to understand the worlds of MWI. Apparently, there is a metaphysical underdetermination for MWI, and no metametaphysical approach available seems to help an objective decision between metaphysical profiles.

At this point of the discussion, it is relevant to review the two metametaphysical accounts for theory choice presented in Chapter 5: According to Benovsky (2016), aesthetic values would be sufficient to decide on a metaphysical profile; Conversely, Chakravartty (2017a) argues that metaphysics could be voluntarily adopted. However, both decisions are knowingly subjective solutions (that is, are criteria imposed by *us* and not by the world).

---

[5] See Skyrms (1976).

Unavailable metaphysical stories once again

Here the negative metametaphysical method, as presented in Chapter 5 is applied. Let, then, MWI's ontology be closely conideredin order to asses which metaphysical profiles sketched above pass the test of metaphysical compatibility with MWI's ontological constrains.

This is what DeWitt, MWI's main propagator, says about the reality of the worlds.

> Our universe must be viewed as constantly splitting into a stupendous number of branches, all resulting from the measurement-like interaction between its myriads of components. Because there exists neither a mechanism within the framework of the formalism nor, by definition, an entity outside of the universe that can designate which branch of the grand superposition is the "real" world, all branches must be regarded as equally real. (DEWITT, 1971, p. 178).

Therefore, the worlds must be real *and* created in events of superposition, since it is assumed ($\mathcal{A}_1, \mathcal{A}_2$) that $|\psi\rangle$ describes how reality evolves. The following discussion presents how metaphysical profiles cope with these ontological constraints, beginning with the Lewisian modal-realist account of many worlds.

According to the Lewisian modal realism, there is an infinity of worlds as real as our world. However, Lewis's conception argues that there are *many more worlds* than in MWI. Whereas in the MWI, the worlds are proliferated in situations of *superposition*, the Lewisian theory states that there exists a world where, for example, Schrödinger's cat studies quantum physics! This incompatibility was already eidenced by Papineau.

> [...] the extra "branches" that Everett adds to reality all lie within the actual world that evolves from the actual initial conditions in line with the actual laws of physics – these branches by no means include all possibilities. (PAPINEAU, 2004, p. 153).

That is, ontology is not inflated only with the counterfactuals of superposition cases, but with all possible counterfactuals: the multiplicity of Lewisian-like worlds encompasses *all possibilities*.[6]

Another difficult point in assigning a Lewisian metaphysical profile to the many worlds of MWI is that in the former, worlds exists *independently* (*i.e.*, "have always been there"). Conversely, MWI imposes constraints for worlds created *from* the branching, which happens only in superposition situations. Therefore, the histories of the many worlds are accessible from and dependent on the branching process.

---

[6] It has been argued it also encompasses *impossibilities* – see Mortari (2010).

Finally, Mortari (2000, pp. 43-44) notes at least four major differences between the worlds of MWI (which the author calls “multiverses”) and Lewis’ logical space, among which the first relates to the argument constructed so far:

> [MWI’s] multiverse is *real*; that is, every universe which is part of it really, actually exists. Reality is just bigger than we thought, whereas for Lewis the inhabitants of other worlds, though existent, do not *actually* exist. [. . .] I guess Lewis would agree and say that, besides and beyond our own multiverse, there are other possible ones, which exist, but are not real. (MORTARI, 2000, p. 44).

Lewisian modal realism is, therefore, a metaphysical profile incompatible with MWI due to restrictions imposed by MWI itself, in what concerns the reality of many worlds. Thus, it is not a metaphysical profile available to understand what the many worlds of MWI are.

The application of the method to the fictionalist alternative is even simpler. According to the fictionalist approach, the present world is ontologically privileged. If a living cat is found, the ramification of the world in which the cat is found dead is merely imaginative, fictional, deprived of the same *status* of reality of this world in which you read this PhD thesis.

For this reason, a fictional metaphysics does not conform to MWI constraints (*e.g.*, that all the worlds must be equally real), and therefore does not offer a metaphysical profile for the many worlds of MWI.[7]

8.4 METAPHYSICAL NULL-DETERMINATION

It seems the application of the method of Unavailable Metaphysical Stories results in a situation similar to that of the beginning of this discussion: deprived of a metaphysical profile available for the MWI, as current metaphysical layers fail for MWI. We do not find metaphysical places to plunder, in the Viking way.

This characteristic is here called “metaphysical emptiness”. Like metaphysical underdetermination, this situation also poses a problem for scientific realism, as the absence of a metaphysical profile renders the realist content of the theory empty. This problem is here labeled “null-determination”. It is essential to emphasize that this is a problem exclusive to the Viking approach explored in the Chapter 4, which aspires to “loot” the metaphysics produced by *a priori* methods (the so-called “traditional metaphysics”) for interpretive purposes. In place of underdetermination, the adherent of the

---

[7] According to the Meinongian approach, the present world is also ontologically privileged. If a living cat is found, the branch of the world in which the cat is found dead is considered non-existent (there is, but does not exist), therefore deprived of the same reality status world. Thus, a Meinongian metaphysics also is unable to understand what the many worlds of MWI are, for the same reasons as the fictionalist approach is so.

Viking Approach to metaphysics faces, according to the terminology adopted here, a null-determination regarding the (un)available metaphysical options to qualify the nature of the many worlds of MWI.

Here, the realists about worlds in quantum mechanics seems to be in the same situation as the realists about objects in quantum mechanics. There is simply no way to determine a metaphysical profile concerning the individuality of such objects endorsed by quantum theory.[8] Ladyman presents the issue as follows:

> We need to recognize the failure of our best theories to determine even the most fundamental ontological characteristic of the purported entities they feature. It is an ersatz form of realism that recommends belief in the existence of entities that have such ambiguous metaphysical status. What is required is a shift to a different ontological basis altogether, one for which questions of individuality simply do not arise. (LADYMAN, 1998, pp. 419–420).

Realism is, apparently empty of content, unless one can provide for a metaphysical profile for its posits.[9] If those endorsing the MWI should follow Ladyman's suggestion and change the ontological basis, this is an issue that shall be briefly discussed in what follows.

One less interpretation

As there are several other quantum theories (in the sense of answers to the problem of measurement) which empirical success is hitherto indistinguishable from that obtained by MWI, perhaps it would be the case to favor other quantum theories (or QM interpretations) which have metaphysical possibilities at their disposal. This is one way to follow Ladyman's suggestion that we should change the ontological basis.

This alternative seriously interprets the idea that metaphysics, as a philosophical discipline, could actively contribute actively to the development of science, being a criterion for the choice of theories[10] (which, up to this date, does not exist in the case of QM).

Quantum metaphysics

As there are no available metaphysical possibilities, considering the Viking approach, perhaps it would be advisable to develop a metaphysical profile for the many worlds of MWI that obeys the theory's constraints and characteristics.

---

[8] In fact, the term "metaphysical underdetermination" originally arose in this context. See French and Krause (2006).

[9] This issue was discussed in more detail in Chapter 4 under the label of "Chakravartty's Challenge".

[10] As mentioned earlier in Chapter 2, the notion of "theory choice" also involves the choice of an interpretation – which, in this particular case, is QM_{bra}.

This alternative seriously accepts the idea that QM requires a radical revision of the traditional metaphysical concepts available. In order to illustrate the problem, consider the possibility that MWI is *compatible* with a metaphysical profile, such as Lewis' genuine modal realism. Does *compatibility* stands for *applicability*? That is, does the fact that a metaphysical theory is compatible with the theoretical and ontological constrains of a scientific theory imply that such metaphysical theory is applicable in metaphysically profiling the scientific theory's entities? Does the fact that a metaphysical profile was not dismissed as incompatible to a scientific theory mean that it fits perfectly into the puzzle?

Well, it does not seem to be the case. Recall French's (2018) worry regarding reinventing the wheel: it is undisputed that it brings no benefits. However, the mere fact of grasping an already existing metaphysical theory for interpreting entities of current science is not assumed as being enough to complete the task. The first argument states that compatibility does not imply applicability: one might be able to find that a metaphysical profile is not *incompatible* with a scientific theory. Criteria for the *compatible* ones, however, were never mentioned!

The second, more straightforward argument stresses that metaphysical theories frequently do not enrich themselves with current science, and as so, they are not able to interpret current science. They simply do not fit.

If a metaphysical profile is not being informed by MWI to its development, the plundering of *a priori* metaphysics, Viking's style, does not seem to help in fulfilling Chakravartty's Challenge for the MWI. Some adjustments in the metaphysical theory should be done. In this case, metaphysics must be *tailored* to physics, so stakes in quantum metaphysics seem to be high. French scratched the surface of this development by stating the following:

> If we want to speculate in a philosophically light-hearted manner then what's the harm in letting our imaginations run wild?! However, if we're engaged in serious naturalistic metaphysics, as I take it we are here, then our modal reflections must be appropriately tailored to what we've learned about the world. (FRENCH, 2019, p. 28).

Recall that according to MWI, the branching process is required to be real, so it may seem a natural attitude for the Viking to look directly at modal realism for metaphysical plundering. At first glance, the Lewisian genuine modal realism would suffice for a compatible metaphysical profile: MWI's branching worlds are, metaphysically, Lewisian worlds. There is, however, evidence of incompatibility between MWI's ontological catalog and the metaphysics of Lewis' worlds (MORTARI, 2000; PAPINEAU, 2004). First, there are many more Lewisian worlds than MWI requires: according to the former, conceivability implies reality, while to the latter, it does not. Instead, MWI takes the worlds to be made of possible measurement outcomes. Another reason for incompatibility is the *creation* of worlds in MWI's branching process, which has no parallel within Lewisian modal metaphysics.

This does not com as a surprise. Lewis' metaphysics was not being informed by QM; therefore, it is to be expected that none of these metaphysical theories is compatible with QM. Lewis is not what Guay and Pradeu (2017) would call a "scientific metaphysician". MWI's ontological restrictions clearly call for a metaphysical profile in which the postulated worlds are real. Therefore, a genuine modal realism provides the guidelines by which one can originally develop such a metaphysical profile. Here, it is accepted that this job is recently being done by Wilson (2013), with his "Everettian Modal Realism", considered a tailor-made version of Lewisian modal realism that fits MWI's metaphysical gap.

Such reasoning might be extended to other interpretations of QM. Consider Wigner's CCCH. It states that consciousness *causes* a modification in the dynamics of quantum systems, so it constrains the available metaphysical profiles for that entity. Whatever it may be in metaphysical terms, ontology requires consciousness to be real, with causal powers. It has been said that it is *incompatible* with some metaphysical profiles, such as physicalism, and *compatible* with others, such as specific kinds of dualism (ARROYO; ARENHART, 2019a). Take a traditional exponent of dualism, for instance. It is not by chance that the first surname that pops up in one's mind is Descartes.

Cartesian dualism indeed *seems to be* compatible with CCCH's ontology. Quantum systems are *res extensa*, and consciousness is *res cogitans*. Fair well. But Cartesian metaphysics also depends on a third substance, *res divina*, which turns out to be god. But where is such god-substance in CCCH? Precisely: nowhere. Descartes was not being informed by CCCH to develop his metaphysical theory, and this is why plundering Cartesian dualism, Viking's style, does not seem to help to fulfill Chakravartty's Challenge for the CCCH. In the particular case of the CCCH, a tailor-made metaphysics was constructed by Stapp (2006), who developed a quantum-mechanical version of interactive dualism.

This should be one of the attributions of philosophers of science willing to study scientific metaphysics: to develop metaphysical concepts for scientific theories they intend to interpret in order to look search in scientific theory and history of philosophy sources from where to derive informative aspects for the development of scientific metaphysics. The price of asking for a metaphysical profile for ontologies extracted from science is losing the possibility of a scientific level of epistemic justification for a metaphysical theory, the point which started the discussion regarding "scientific metaphysics" in the first place. The gain – if it can be considered so – is a relative autonomy of metaphysics as a philosophical discipline.

However, the price to pay for such autonomy, as argued in chapter 4, is that metaphysical underdetermination is taken for granted. Thus, while the Viking approaches generate a metaphysical null-determination, Taylor-made approach generates metaphysical underdetermination.

8.5 FINAL REMARKS

This chapter present a negative approach to metaphysics' relations with science, applying the metametaphysical method developed in Chapter 5. As a result, MWI was found to be incompatible with the metaphysics known hitherto in philosophical literature. Figure 7 elucidates this conclusion.

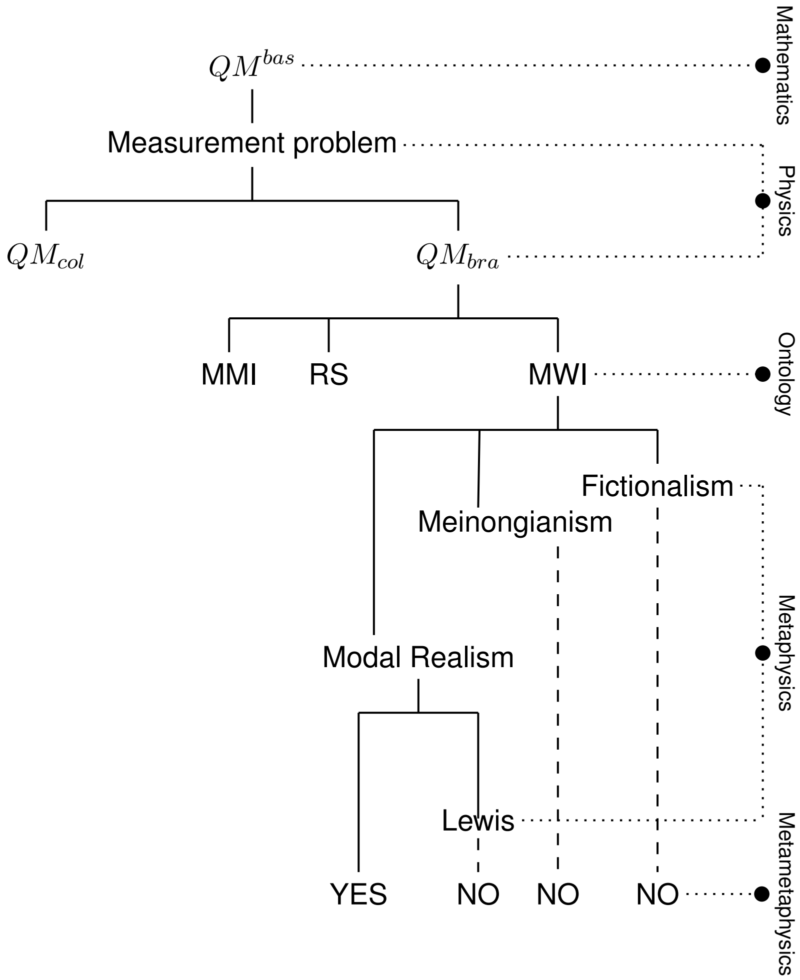

Figure 7 – QM_{bra} and MWI.

Therefore, our method is suggested to be a step closer to metametaphysical methodologies that focus on the choice of theories. It may be, as seems to be the case with MWI, that there are no alternatives from which we could decide.

CONCLUSION: ON PHILOSOPHY, DRAGONS AND TAILORS

> "But I don't want to go among
> mad people," Alice remarked.
> "Oh, you can't help that," said
> the Cat: "we're all mad here."
>
> LEWIS CARROLL
> *Alice's Adventures in Wonderland*

The following report exposes the main results of this research. Let's face it: the present state of affairs of the foundations and interpretation of QM is undeniable messy, being adequately described as pure fragmentation. The first point to be made is: there is a basic mathematical formalism that says nothing about physics. The basic formalism of QM^{bas} tells a mathematical story. QM, however, is quantum *physics*; thus one might want to add some physics to mathematics. When this is done, a foundational problem arises (the measurement problem). In order to have a physical story, an interpretation where the measurement problem is addressed must be added. This fragmentation begins to solve this problem and continues to grow indefinitely.

Some would stop here. "So what? Just pick one! Flip a coin, if you wish", some would say. There is no problem with that. The price to pay for digging deeper into the rabbit-hole is to deepen fragmentation. Empiricists, for example, would reject this step: they are satisfied with QM's operational role in society. After all, as this thesis has repeatedly stated as if it were a mantra, *QM works* FAPP. If there is pain, however, there must also be a gain. In this case, the gain is the possibility to discuss the world in which we live. Each interpretation adds a further ingredient to the world: a causal role for consciousness, in the case of CCCH; a branching reality in the case of the MWI. This is ontology, *naturalized*, right there! Underdetermination? Unquestionably. Nevertheless, some would gladly embrace it, driven by the motto that *science should talk about the world*

However, do these interpretations discuss the world? Chakravartty's Challenge argues that they don't – *yet*. To do so, one should advance further, dressing the ontology with metaphysics. While not everyone would accept that step peacefully, an assessment of the pros and cons can be made. Is the goal to talk about the world? If so, this step should be taken. For science to talk about the world, it is necessary to respond to the Chakravartty Challenge, and to answer it, it is necessary to adopt a metaphysical profile. At this point, you are already inside the rabbit hole.

Ontological catalogues may be understood metaphysically in rather contrasting terms. However, it is possible to determine that some metaphysical approaches do not make sense according to the underlying scientific theory. As this thesis remarked, materialistic approaches and their proposed interpretations to CCCH's consciousness are disregarded due to quantum mechanical considerations. They fail to provide the ingredients for a collapse to occur. As far as MWI is concerned, a metaphysical understanding of worlds that does not attribute ontological dignity to all worlds will fail to explain the measurement problem. The failure of those metaphysical profile is objectively granted as long as QM is the underlying theory, as the interpretations of QM are not compatible with any kind of metaphysical profile.

To what concerns CCCH, the very possibility of metaphysically dressing consciousness with epiphenomenalism is precluded, since consciousness (whatever it may be in terms of a metaphysical profile) must be causal, and therefore, *real*. However, is it epistemically justifiable to plunder, Viking's style, every single dualist metaphysics in the history of philosophy, even if those who developed them were not directly addressing QM when developing their metaphysical theories?

The short answer is "no" and the long answer is presented in a few paragraphs below. For now, it suffices to insist on the previous step: decisions between dualism and phenomenology seem to be safe from the narrowing of metaphysical choices. Regarding MWI, some metaphysical possibilities are discarded due to constraints of the interpretation itself, according to which all branchings must be equally real; therefore, there seem to be some precluded metaphysical profiles such as fictionalism. A treatment of possible worlds *à la* David Lewis (2004) seems to be also discarded when considering our metametaphysical method, as one must account for the *creation* of parallel worlds in the act of branching, and thus the worlds cannot exist independently *before* the branching process.

This work was able to restrain the metaphysical profiles *inside* each interpretation of QM, within its own ontological commitments, *i.e.*, the metaphysical alternatives *within* CCCH, CRCH, and those *within* MWI. It was not possible, however, to compare interpretations directly, such as CCCH *versus* MWI.

This conclusion, however, can be questioned by a somewhat bad argument, which considers metaphysical null-determination as a sufficient reason for abandoning an interpretation of QM. Let us look briefly at what this argument is about, and why it is weak. Consider for a moment the "Viking" approach to metaphysics, as promoted by French (2014). Roughly, it states that the scientific-informed metaphysician merely chooses a metaphysical theory available in literature in order to metaphysically dress the entities of scientific theories. It seems that the Vikings return empty-handed from their metaphysical pillage, as it was demonstrated here, that there are no available options to interpret QM in metaphysical ways.

For a realist-oriented philosopher, this situation may be just as bad as metaphysical underdetermination. With underdetermination, there are *many* options to interpret a theory, so one is not in a position to say what the world is like *modulo* such theory. In the present case, there *no* options to interpret the theory, which makes one unable to determine what the world is like. This situation is called here a metaphysical "null-determination". In other words, unlike metaphysical underdetermination, where there was *plenty* of options and no criteria to choose among them, metaphysical null-determination poses just the opposite problem: there are no metaphysical options to be chosen.

Through the application of the metametaphysical method presented by this thesis, MWI is found to incur in metaphysical emptiness. There are no known metaphysical profiles which seem to be compatible with its theoretical and ontological restrains, at least according to the Viking approach.

It can be argued that the absence of metaphysical profiles available for MWI is sufficient for such an interpretation to be discarded from the list of possible interpretations for QM. The problem is that null-determination is an expected consequence of the Viking approach, which can be generalized to other interpretations of QM. Thus, we do not consider the argument that null-determination implies abandoning interpretations of QM to be good. What null-determination seems to disadvantage is the Viking approach itself!

Fortunately, there is another alternative. This thesis suggests that metaphysical emptiness could be resolved by a sort of "tailor-made" metaphysics which fully considers QM's features and constrains. Therefore, unless one is developed, in the sense of "fabricating" a metaphysical profile, as stressed by d' Espagnat (2006), QM is *metaphysically empty* – and this is crucial – *for the Viking only*. This result takes seriously the idea that QM forces us to a *radical* review in our metaphysical theses.

Let us take a pause for meditation. Much of what was discussed until now is summed up in Figure 8. This figure is labeled after Cabello's (2017) "map of madness" since that's what it is: a map of the rabbit-hole. We are lost in this maze of fragmentation, but at least we do have a map! There are cases in which the answer is simply unknown, as is the case in "???" – which we didn't had time to investigate.

Notice that the metaphysical level is framed in the evaluation of metaphysical profiles, pictured as "YES" and "NO". NO depict the *dead ends*. For example, there is *no way* to metaphysically profile CCCH's consciousness with an *eliminativist* metaphysics concerning the mind. Similarly, to pursue a *non-realist* account of MWI's worlds is a dead end. These are, therefore, the no-go paths. Notice, also, that there are metaphysical profiles named after philosophers: these are the *Viking-only* dead ends.

If there are no metaphysical profiles *available* to plunder, so what about to sowing and harvesting? This might sound excessively radical – after all, there is the worry of reinventing the wheel. A different idea might be proposed: tailoring the metaphysics to the physics.

While the negative points indicate the *no-go* paths for the tailor-metaphysician

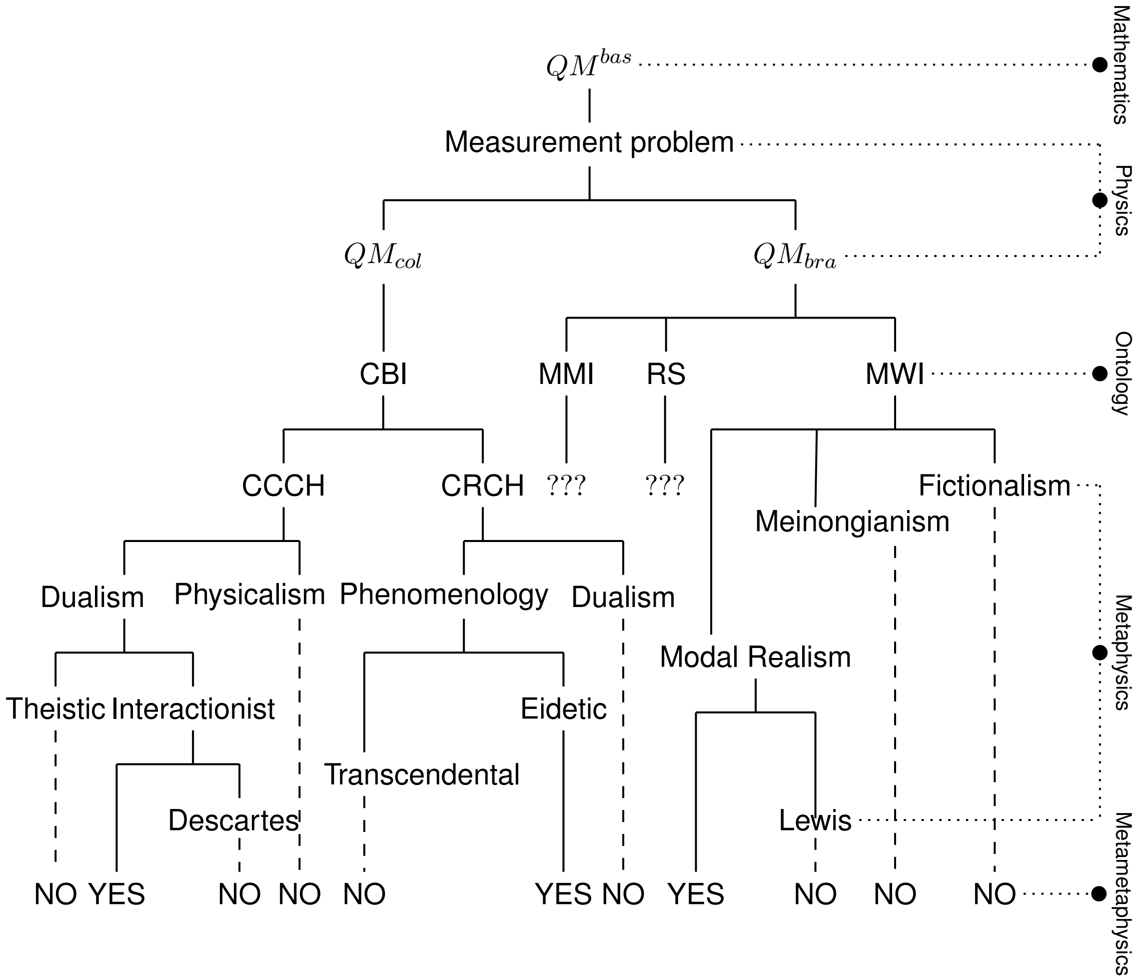

Figure 8 – A map of madness

to pursue in its tailoring job, the points labeled as "YES" are the *ok-go* paths. These pave the way for new studies in the field of contemporary analytic metaphysics: the development of a metaphysical profile tailor-made for MWI's ontology. This option is left to future works.

Nevertheless, the metametaphysical method should proposed in this thesis is suggested to be adopted as a *first* metametaphysical inquiry concerning theory choice, as there may be *no* metaphysical choices to make.

At this point, it is relevant to present some final remarks concerning scientific realism. Interpretational underdetermination is, apparently, winning the dispute against scientific realism concerning fundamental physics (particularly QM), which implies that:

- *Theoretical underdetermination could not be broken.* Up to this date, only experiments can in principle choose between QM_{col} and QM_{bra}. Such experiments, although in principle executable, are not forthcoming in the foreseeable future.
- *Ontological underdetermination could not be broken.* The current tools in ontology and meta-ontology to evaluate among ontological theories are non-objective, thus

concerning us and not Nature, meaning that one may voluntarily choose between QM_{col} and QM_{bra}, even though one is not rationally forced to adopt any possibility. It's up to the customer's choice.

Thus, paraphrasing Sklar (2010), *I would love to be realist about QM, if only I knew what realism was*. In this sense, even fine-grained conceptions of scientific realism, such as OSR, do not seem to be sufficiently justified when faced with the problem of interpretational underdetermination in QM.

Consider this claim more carefully, however. Most commonsensical beliefs are not *sufficiently justified*. After more than two millennia of philosophical discussions, we still do not "sufficiently" respond to philosophical skepticism concerning the external world: Are we dreaming? Is our brain in a vat? Are we experiencing external reality at all? We do not have *sufficient reasons* for believing in that – at least according to the skepticism, we don't. Suppose we do not have such justification. If those standards are failed to be met concerning something as basic as the external reality, why insist that scientists must meet these requirements to believe in unobservable processes of QM?

At the end of the day, the question concerning scientific realism seems to be a problem for philosophers of science, specifically for scientific metaphysicians. As a metaphysician, I am on the side of doubt. Underdetermination compels me to do that. I cannot objectively choose between QM_{col}, QM_{bra} or else. I am personally realistic with uncontroversial entities offered by QM – if there are any. However, scientists should not be forced to do this. They may take a voluntary leap of faith. The scientist is pragmatically justified to adopt a realist stance even to what concerns the most controversial parts of the interpretation of QM, because this is part of scientific development.

However speculative it may be, I would like to conclude by offering another possibility to this scenario, in which one is not forced to make such difficult choices. In a well-known passage concerning the metaphysical status of superposition (recall QM^{bas}'s $\mathcal{P}_4$), Schrödinger (1983, p. 157) states that "[t]here is a difference between a shaky out-of-focus photograph and a snapshot of clouds and fog banks". Krause and Arenhart interpreted this passage as follows:

> It seems that [Schrödinger] is suggesting that the superposed state acts as a snapshot of clouds, really a situation involving vagueness of some sort. It is not that the cat, when in the superposed state, is blurred by the cloud, but she *is* the cloud. (KRAUSE; ARENHART, 2016a, p. 52).

They refer to Schrödinger's cat paradox, arguing that superposition is *something* clouded by itself, not a pure epistemological indeterminacy of states. Similarly, after the discussion presented in this thesis, I would like to conclude this work with the following reflection: it is possible, just as the electron and the cat in the above examples, that the smoky dragon's body is not blurred by a smoky cloud. What if the dragon *is* really made of smoke? What if, contrarily to what d' Espagnat (2006) argues, the so-called "quantum reality" is not covered by a veil, but *is itself, in fact, smoky*? To quote John Bell (2004, p. 214): "Would that not be very, very interesting?" I do think so.

To think of the dragon as a smoky being can be a useful metaphor I wish to discuss only in passing, but it also can be tricky to frame me as a "no-solution" naysayer. It is not necessarily so. To embrace the smokiness can also mean to embrace the need for the development of genuinely new concepts in metaphysics that suits QM. Quoting Maudlin (2019):

> Why think that Aristotle, or any other philosopher or scientist who never considered quantum theory, had developed the right conceptual categories for characterizing everything physically real? The quantum state is a novel feature of reality on any view, and there is nothing wrong with allowing it a novel category: *quantum state*. This is, of course, not an informative thing to say, but it does free us from the misguided desire to liken the quantum state to anything we are already familiar with. (MAUDLIN, 2019, p. 89).

The new concepts of a tailor-made metaphysics for such "new category", which the development is demanded by QM, are not, in many ways, grounded in QM. Hence the smoky smoke. So, how about developing clothes that fit dragons?

REFERENCES

ACHINSTEIN, Peter. **Concepts of Science: A Philosophical Analysis**. Baltimore: Johns Hopkins University Press, 1968.

ALBERT, David Z. **Quantum mechanics and experience**. Cambridge: Harvard University Press, 1992.

ALBERT, David Z. Wave Function Realism. In: NEY, Alyssa; ALBERT, David Z. (Eds.). **The wave function: Essays on the metaphysics of quantum mechanics**. Oxford: Oxford University Press, 2013. P. 52–57.

ALLORI, Valia. **How to Make Sense of Quantum Mechanics (and More): Fundamental Physical Theories and Primitive Ontology**. Pittsburgh: University of Pittsburgh, 2015. Available in: `http://philsci-archive.pitt.edu/11652/`.

ARENHART, Jonas R. Becker. Bridging the Gap Between Science and Metaphysics, with a Little Help from Quantum Mechanics. In: **Proceedings of the 3rd Filomena Workshop**. Ed. by João Daniel Dantas, Evelyn Erickson and Sanderson Molick. Natal: PPGFIL UFRN, 2019. P. 9–33.

ARENHART, Jonas R. Becker. Does weak discernibility determine metaphysics? **THEORIA. An International Journal for Theory, History and Foundations of Science**, v. 32, n. 1, p. 109–125, 2017.

ARENHART, Jonas R. Becker. Ontological frameworks for scientific theories. **Foundations of science**, Springer, v. 17, n. 4, p. 339–356, 2012.

ARENHART, Jonas R. Becker; BUENO, Otávio. Structural realism and the nature of structure. **European Journal for Philosophy of Science**, v. 5, n. 1, p. 111–139, 2015.

ARISTOTLE. **Metaphysics**. Indianapolis: Hackett Publishing Company, 2016. (The New Hackett Aristotle). Translated, with Introduction and Notes, by C. D. C. Reeve.

ARROYO, Raoni Wohnrath; ARENHART, Jonas R. Becker. Between physics and metaphysics: A discussion of the status of mind in quantum mechanics. In: DE BARROS, José Acácio; MONTEMAYOR, Carlos (Eds.). **Quanta and Mind: Essays on the Connection between Quantum Mechanics and the Consciousness**. Switzerland: Springer International Publishing, 2019. (Synthese Library). chap. 3, p. 31–42.

ARROYO, Raoni Wohnrath; ARENHART, Jonas R. Becker. Floating free from physics? The metaphysics of quantum mechanics. In: 11TH Principia International Symposium: The Quest for Knowledge. Florianópolis: NEL - Federal University of Santa Catarina (UFSC), 2019. (Book of abstracts), p. 198–199.

ARROYO, Raoni Wohnrath; ARENHART, Jonas R. Becker. Mecânica quântica, muitos mundos e fição. I Colóquio Imagem e Imaginação. Florianópolis, 2017.

ARROYO, Raoni Wohnrath; ARENHART, Jonas R. Becker. On physics, metaphysics, and metametaphysics. In: IV International Workshop on Quantum Mechanics and Quantum Information. Florianópolis: Federal University of Santa Catarina (UFSC), 2017. (Book of abstracts), p. 4–4.

ARROYO, Raoni Wohnrath; FLAUSINO, Joanne Simon. Da Lógica à Física: Interpretando a Mecânica Quântica. In: III Colóquio de Pesquisa em Filosofia da UFSC. Florianópolis: Universidade Federal de Santa Catarina (UFSC), 2019. (Livro de Resumos).

ARROYO, Raoni Wohnrath; GRACHER, Kherian. Building Quantum Theories. In: VI International Workshop on Quantum Mechanics and Quantum Information: Identity and Individuality. Florianópolis: Federal University of Santa Catarina (UFSC), 2019. (Book of abstracts), p. 8–9.

ARROYO, Raoni Wohnrath; NUNES FILHO, Lauro de Matos. On Quantum Mechanics, Phenomenology, and Metaphysical Underdetermination. **Principia: An international journal of epistemology**, Florianópolis, v. 22, n. 2, p. 321–337, 2018. ISSN 1808-1711.

ARSHAVSKY, Yuri I. “Scientific roots” of dualism in neuroscience. **Progress in neurobiology**, Elsevier, v. 79, n. 4, p. 190–204, 2006.

ASPECT, Alain. Bell’s theorem: The naive view of an experimentalist. In: BERTLMANN, Reinhold; ZEILINGER, Anton (Eds.). **Quantum (un)speakables: From Bell to quantum information**. Berlin: Springer, 2002. P. 119–153.

ATMANSPACHER, Harald. Complexity, Meaning and the Cartesian Cut. **Journal of Consciousness Studies**, Imprint Academic, v. 1, n. 2, p. 168–181, 1994.

AULETTA, Gennaro; WANG, Shang-Yung. **Quantum mechanics for thinkers**. Singapore: Pan Stanford Publishing, 2014.

AUYANG, Sunny Y. **How is Quantum Field Theory Possible?** Oxford: Oxford University Press, 1995.

BAGGOTT, Jim. **The meaning of quantum theory: A guide for students of chemistry and physics**. New York: Oxford University Press, 1992.

BARRETT, Jeffrey A. Everett’s pure wave mechanics and the notion of worlds. **European Journal for Philosophy of Science**, v. 1, n. 2, p. 277–302, 2011.

BARRETT, Jeffrey A. **The Quantum Mechanics of Minds and Worlds**. Oxford: Oxford University Press, 1999.

BASS, Ludvik. The mind of Wigner's friend. **Hermathena**, p. 52–68, 1971.

BECKER, Lon. That von Neumann Did Not Believe in a Physical Collapse. **The British Journal for the Philosophy of Science**, v. 55, p. 121–135, 2004.

BELL, John Stewart. **Speakable and unspeakable in quantum mechanics: Collected papers on quantum philosophy**. Cambridge: Cambridge university press, 2004.

BEN-DOV, Yoav. Everett's theory and the 'many-worlds' interpretation. **American Journal of Physics**, v. 58, p. 829–832, 1990.

BENOVSKY, Jiri. **Meta-metaphysics: On metaphysical equivalence, primitiveness, and theory choice**. Switzerland: Springer, 2016. v. 374. (Synthese Library).

BENOVSKY, Jiri. Primitiveness, Metaontology, and Explanatory Power. **Dialogue: Canadian Philosophical Review/Revue canadienne de philosophie**, Cambridge University Press, Cambridge, v. 52, n. 2, p. 341–358, 2013.

BERTO, Francesco; PLEBANI, Matteo. **Ontology and metaontology: A contemporary guide**. London: Bloomsbury Publishing, 2015.

BIRKHOFF, Garrett; VON NEUMANN, John. The logic of quantum mechanics. **Annals of mathematics**, p. 823–843, 1936.

BOHM, David. A suggested interpretation of the quantum theory in terms of 'hidden' variables, I. **Physical Review**, APS, v. 85, n. 2, p. 166, 1952.

BOHM, David; HILEY, Basil J. **The Undivided Universe: An Ontological Interpretation of Quantum Theory**. London: Routledge, 2006.

BOHR, Niels. Atomic theory and the description of Nature. **American Journal of Physics**, American Association of Physics Teachers, v. 30, n. 9, p. 658–660, 1962.

BOHR, Niels. The Quantum Postulate and the Recent Development of Atomic Theory. **Nature**, v. 121, p. 580–590, 1928.

BRADING, Katherine; SKILES, Alexander. Underdetermination as a Path to Structural Realism. In: LANDRY, Elaine M.; RICKLES, Dean P. (Eds.). **Structural Realism: Structure, Object, and Causality**. Dordrecht: Springer, 2012. v. 77. (The Western Ontario Series in Philosophy of Science). chap. 5, p. 99–116.

BUENO, Otávio. Is There a Place for Consciousness in Quantum Mechanics? In: DE BARROS, José Acácio; MONTEMAYOR, Carlos (Eds.). **Quanta and Mind: Essays on the Connection between Quantum Mechanics and the Consciousness**. Switzerland: Springer International Publishing, 2019. (Synthese Library). chap. 11, p. 129–139.

BUENO, Otávio. Structural empiricism, again. In: BUKOLICH, Peter; BUKOLICH, Alisa (Eds.). **Scientific structuralism**. Netherlands: Springer, 2011. (Boston Studies in the Philosophy of Science). P. 81–103.

BUENO, Otávio; KRAUSE, Décio. Scientific theories, models, and the semantic approach. **Principia**, Universidade Federal de Santa Catarina, Núcleo de Epistemologia e Lógica, v. 11, n. 2, p. 187–201, 2007.

CABELLO, Adán. Interpretations of Quantum Theory: A Map of Madness. In: LOMBARDI, Olimpia et al. (Eds.). **What is quantum information?** Cambridge: Cambridge University Press, 2017. chap. 7, p. 138–143.

CARNAP, Rudolf. **Introduction to symbolic logic and its applications**. New York: Dover, 1958.

CHAKRAVARTTY, Anjan. **A metaphysics for scientific realism: Knowing the unobservable**. Cambridge: Cambridge University Press, 2007.

CHAKRAVARTTY, Anjan. On the Prospects of Naturalized Metaphysics. In: ROSS, Don; LADYMAN, James; KINCAID, Harold (Eds.). **Scientific Metaphysics**. Oxford: Oxford University Press, 2013. chap. 2, p. 27–50.

CHAKRAVARTTY, Anjan. Physics, metaphysics, disposition, and symmetries – À la French. **Studies in Hisory and Philosophy of Science**, Elsevier, v. 74, p. 10–15, 2019.

CHAKRAVARTTY, Anjan. **Scientific ontology: Integrating naturalized metaphysics and voluntarist epistemology**. New York: Oxford University Press, 2017.

CHAKRAVARTTY, Anjan. Scientific Realism. In: ZALTA, Edward N. (Ed.). **The Stanford Encyclopedia of Philosophy**. Summer 2017. Stanford: Metaphysics Research Lab, Stanford University, 2017.

CHANG, Chen Chung; KEISLER, H Jerome. **Model theory**. Amsterdam: Elsevier, 1990. v. 3.

CHURCH, Alonzo. **Introduction to mathematical logic**. Princeton: Princeton University Press, 1956.

ĆIRKOVIĆ, Milan M. Physics versus Semantics: A Puzzling Case of the Missing Quantum Theory. **Foundations of Physics**, Springer, v. 35, n. 5, p. 817–838, 2005.

COLYVAN, Mark. Indispensability Arguments in the Philosophy of Mathematics. In: ZALTA, Edward N. (Ed.). **The Stanford Encyclopedia of Philosophy**. Spring 2019. Stanford: Metaphysics Research Lab, Stanford University, 2019.

CONROY, Christina. Everettian actualism. **Studies in History and Philosophy of Science Part B: Studies in History and Philosophy of Modern Physics**, v. 63, p. 24–33, 2018.

CONROY, Christina. The relative facts interpretation and Everett's note added in proof. **Studies in History and Philosophy of Modern Physics**, v. 43, p. 112–120, 2012.

CONTESSA, Gabriele. Scientific models, partial structures and the new received view of theories. **Studies in History and Philosophy of Science**, v. 2, n. 37, p. 370–377, 2006.

CRAVER, Carl F. Structures of scientific theories. In: MACHAMER, Peter; SILBERTSTEIN, Michael (Eds.). **The Blackwell Guide to the Philosophy of Science**. Oxford: John Wiley & Sons, 2008. P. 55–79.

CUSHING, James T. Underdetermination, Conventionalism and Realism: The Copenhagen vs. the Bohm Interpretation of Quantum Mechanics. In: **Correspondence, Invariance and Heuristics: Essays in Honour of Heinz Post**. Ed. by Steven French and Harmke Kamminga. Dordrecht: Springer Netherlands, 1993. P. 261–278.

D' ESPAGNAT, Bernard. **Conceptual Foundations of Quantum Mechanics**. Massachusetts: Perseus Books, 1999.

D' ESPAGNAT, Bernard. **On physics and philosophy**. Princeton: Princeton University Press, 2006.

DA COSTA, Newton C. A. **Notas de Aula: Lógica e Fundamentos da Ciência**. Florianópolis: NEL – Núcleo de Epistemologia e Lógica, UFSC, 2019. v. 2. (Série NEL-Lógica). Décio Krause (org.)

DA COSTA, Newton C. A.; CHUAQUI, Rolando. On Suppes' set theoretical predicates. **Erkenntnis**, Springer, v. 29, n. 1, p. 95–112, 1988.

DA COSTA, Newton C. A.; FRENCH, Steven. Models, theories, and structures: Thirty years on. **Philosophy of Science**, University of Chicago Press, Chicago, v. 67, s116–s127, 2000.

DA COSTA, Newton; KRAUSE, Décio. The Logic of Complementarity. In: VAN BENTHEM, Johan; HEIZMANN, Gehrard; REBUSCHI, Manuel (Eds.). **The Age of Alternative Logics: Assessing Philosophy of Logic and Mathematics Today**. Amsterdam: Springer, 2006. P. 103–120.

DALLA CHIARA, Maria L. Logical Foundations of Quantum Mechanics. In: **Modern Logic – A Survey: Historical, Philosophical and Mathematical Aspects of Modern Logic and its Applications**. Ed. by Evandro Agazzi. Dordrecht: Springer Netherlands, 1981. P. 331–351.

DALLA CHIARA, Maria L. Logical Self Reference, Set Theoretical Paradoxes and the Measurement Problem in Quantum Mechanics. **Journal of Philosophical Logic**, Springer, v. 6, n. 1, p. 331–347, 1977.

DALLA CHIARA, Maria L.; DI FRANCIA, Toraldo G. Formal analysis of physical theories. In: **Problems in the Foundations of Physics**. Ed. by Toraldo G di Francia. Amsterdam: Worldcat, 1979. P. 134–201.

DALLA CHIARA, Maria L.; DI FRANCIA, Toraldo G. Individuals, Kinds and Names in Physics. In: CORSI, G.; DALLA CHIARA, M. L.; GHIRARDI, G. C. (Eds.). **Bridging the Gap: Philosophy, Mathematics, and Physics – Lectures on the Foundations of Science**. Netherlands: Springer, 1993. v. 140. (Boston Studies in the Philosophy of Science). P. 261–283.

DALY, Chris; LIGGINS, David. Deferentialism. **Philosophical Studies**, Springer, Netherlands, v. 156, n. 3, p. 321–337, 2011.

DE BARROS, José Acácio. On Quantum Mechanics and the Mind. To appear in the Proceedings of the Foundations of the Mind Conference. Berkeley, 2014. Available in: `http://userwww.sfsu.edu/barros/publications/publications/files/deBarros2014a.pdf`.

DE BARROS, José Acácio; HOLIK, Federico; KRAUSE, Décio. Contextuality and Indistinguishability. **Entropy**, Multidisciplinary Digital Publishing Institute, v. 19, n. 9, p. 435–456, 2017.

DE BARROS, José Acácio; OAS, Gary. Can We Falsify the Consciousness-Causes-Collapse Hypothesis in Quantum Mechanics? **Foundations of Physics**, Springer, v. 47, n. 10, p. 1294–1308, 2017.

DE RONDE, C.; MASSRI, C. A new objective definition of quantum entanglement as potential coding of intensive and effective relations. **Synthese**, 2019.

DE RONDE, Christian. Quantum Superpositions and the Representation of Physical Reality Beyond Measurement Outcomes and Mathematical Structures. **Foundations of Science**, v. 23, n. 4, p. 621–648, 2018.

DEWITT, Bryce S. Quantum mechanics and reality. **Physics today**, v. 23, n. 9, p. 30–35, 1970.

DEWITT, Bryce S. The many universes interpretation of quantum mechanics. **Proceedings of the International School of Physics 'Enrico Fermi'**, p. 211–262, 1971.

ENDERTON, Herbert B. Second-order and Higher-order Logic. In: ZALTA, Edward N. (Ed.). **The Stanford Encyclopedia of Philosophy**. Fall 2015. Stanford: Metaphysics Research Lab, Stanford University, 2015.

ESFELD, Michael. Individuality and the Account of Nonlocality: The Case for the Particle Ontology in Quantum Physics. In: LOMBARDI, O. et al. (Eds.). **Quantum Worlds: Perspectives on the Ontology of Quantum Mechanics**. Cambridge: Cambridge University Press, 2019. P. 222–244.

ESFELD, Michael. Ontic structural realism and the interpretation of quantum mechanics. **European Journal for Philosophy of Science**, v. 3, n. 1, p. 19–32, 2012.

EVERETT, Hugh. 'Relative state' formulation of quantum mechanics. **Reviews of modern physics**, APS, v. 29, n. 3, p. 454–462, 1957.

FAYE, Jan. **Niels Bohr: His heritage and legacy – An anti-realist view of quantum mechanics**. Netherlands: Springer, 1991.

FEYNMAN, Richard. **The Character of Physical Law**. Cambridge: MIT Press, 1965.

FINE, Arthur. **The Shaky Game: Einstein, Realism and the Quantum Theory**. Chicago: University of Chicago Press, 1986.

FIRMO DE SOUZA CRUZ, Frederico de. Mecânica Quântica e a cultura em dois momentos. In: FREIRE JUNIOR, Olival; PESSOA JUNIOR, Osvaldo F.; BROMBERG, Joan Lisa (Eds.). **Teoria quântica: estudos históricos e implicações culturais**. São Paulo: Livraria da Física, 2011. P. 303–320.

FRENCH, Steven. A phenomenological solution to the measurement problem? Husserl and the foundations of quantum mechanics. **Studies in History and Philosophy of Science Part B: Studies in History and Philosophy of Modern Physics**, v. 33, n. 3, p. 467–491, 2002.

FRENCH, Steven. Defending eliminative structuralism and a whole lot more (or less). **Studies in History and Philosophy of Science Part A**, Elsevier, v. 74, p. 22–29, 2019.

FRENCH, Steven. Handling Humility. In: GALPARSORO, José Ignacio; CORDERO, Alberto (Eds.). **Reflections on Naturalism**. Plantijnstraat: Springer: SensePublishers, 2013. P. 85–104.

FRENCH, Steven. Metaphysical underdetermination: Why worry? **Synthese**, Springer, Switzerland, v. 180, n. 2, p. 205–221, 2011.

FRENCH, Steven. Realism and Metaphysics. In: **The Routledge Handbook of Scientific Realism**. Ed. by Juha Saatsi. New York: Routledge, 2018. P. 394–406.

FRENCH, Steven. **The structure of the world: Metaphysics and representation**. Oxford: Oxford University Press, 2014.

FRENCH, Steven; KRAUSE, Décio. **Identity in physics: A historical, philosophical, and formal analysis**. Oxford: Oxford University Press, 2006.

FRENCH, Steven; MCKENZIE, Kerry. Thinking outside the toolbox: Towards a more productive engagement between metaphysics and philosophy of physics. **European journal of analytic philosophy**, University of Rijeka, Rijeka, v. 8, n. 1, p. 42–59, 2012.

FRIEDBERG, R.; HOHENBERG, P. C. What is Quantum Mechanics? A Minimal Formulation. **Foundations of Physics**, v. 48, n. 3, p. 295–332, 2018.

FRIEDERICH, Simon. **Interpreting Quantum Theory: A Therapeutic Approach**. New York: Palgrave Macmillan, 2014.

FRIGG, Roman. Models and fiction. **Synthese**, Springer, Switzerland, v. 172, n. 2, p. 251–268, 2010.

FRIGG, Roman; HARTMANN, Stephan. Models in Science. In: ZALTA, Edward N. (Ed.). **The Stanford Encyclopedia of Philosophy**. Spring 2017. Stanford: Metaphysics Research Lab, Stanford University, 2017.

GAVROGLU, Kostas. **Fritz London: A scientific biography**. Cambridge: Cambridge University Press, 2005.

GHIRARDI, Gian Carlo; RIMINI, Alberto; WEBER, Tullio. Unified dynamics for microscopic and macroscopic systems. **Physical Review D**, APS, v. 34, n. 2, p. 470, 1986.

GIBBINS, Peter. **Particles and Paradoxes: The limits of quantum logic**. Cambridge: Cambridge University Press, 1987.

GOSWAMI, Amit. The Idealistic Interpretation of Quantum Mechanics. **Physics Essays**, v. 2, p. 385, 1989.

GUAY, Alexandre; PRADEU, Thomas. Right out of the box: How to situate metaphysics of science in relation to other metaphysical approaches. **Synthese**, Springer, Switzerland, p. 1–20, 2017.

GUDDER, Stanley P. A Survey of Axiomatic Quantum Mechanics. In: HOOKER, Cliff (Ed.). **The Logico-Algebraic Approach to Quantum Mechanics – Volume II: Contemporary Consolidation**. Netherlands: Springer, 1979. P. 323–363.

HALVORSON, Hans. Scientific Theories. In: HUMPHREYS, Paul (Ed.). **The Oxford Handbook of Philosophy of Science**. Oxford: Oxford University Press, 2016. chap. 27.

HALVORSON, Hans. The semantic view, if plausible, is syntactic. **Philosophy of Science**, University of Chicago Press, Chicago, v. 80, n. 3, p. 475–478, 2013.

HALVORSON, Hans. What scientific theories could not be. **Philosophy of Science**, University of Chicago Press, Chicago, v. 79, n. 2, p. 183–206, 2012.

HASKELL, B CURRY. Foundations of mathematical logic. **McCraw-Hill book company, inc. New-York-San Francisco-Toronto-London**, 1963.

HEIDEGGER, Martin. **Being and time: A translation of Sein und Zeit**. New York: SUNY press, 1996.

HEIDELBERGER, Michael. The mind-body problem in the origin of logical empiricism: Herbert Feigl and psychophysical parallelism. In: PARRINI, Paolo; SALMON, Wesley C.; SALMON, Merrilee H. (Eds.). **Logical Empiricism: Historical and Contemporary Perspectives**. Pittsburgh: University of Pittsburgh Press, 2003. chap. 11, p. 233–262.

HEISENBERG, Werner. On The Physical Content Of Quantum Theoretical Kinematics And Mechanics. In: WHEELER, John; ZUREK, Wojciech (Eds.). **Quantum Theory and Measurement**. Princeton: Princeton University Press, 1983. P. 62–84.

HENKIN, Leon. Completeness in the theory of types. **The Journal of Symbolic Logic**, Cambridge Univ Press, v. 15, n. 02, p. 81–91, 1950.

HODGES, Wilfrid. **Model theory**. Cambridge: Cambridge University Press, 1993. v. 42. (Encyclopedia of Mathematics and its Applications).

HOFWEBER, Thomas. Carnap's Big Idea. In: **Ontology after Carnap**. Ed. by Stephan Blatti and Sandra Lapointe. Oxford: Oxford University Press, 2016. P. 13–30.

HOWARD, Don. Who invented the 'Copenhagen Interpretation'? A study in mythology. **Philosophy of Science**, The University of Chicago Press, Chicago, v. 71, n. 5, p. 669–682, 2004.

HUSSERL, Edmund. **Ideas Pertaining to a Pure Phenomenology and to a Phenomenological Philosophy – First Book: General Introduction to a Pure Phenomenology**. Dordrecht: Kluwer Academic Publishers, 1982.

HUSSERL, Edmund. **Ideas Pertaining to a Pure Phenomenology and to a Phenomenological Philosophy – Second Book: Studies in the Phenomenology of Constitution**. Dordrecht: Kluwer Academic Publishers, 1989.

HUSSERL, Edmund. **The crisis of European sciences and transcendental phenomenology: An introduction to phenomenological philosophy**. Evanston: Northwestern University Press, 1970.

HUSSERL, Edmund. **The Idea of Phenomenology**. Trans. by Alston W. and Nakhnikian G. Nijhoff: The Hague, 1964. v. 8.

JACQUETTE, Dale. **Ontology**. Montreal: McGill – Queens University Press, 2002.

JAMMER, Max. **The Philosophy Of Quantum Mechanics: The Interpretations Of Quantum Mechanics In Historical Perspective**. New York: Wiley and Sons, 1974.

JI, Yang et al. An electronic Mach-Zehnder interferometer. **Nature**, Nature Publishing Group, v. 422, n. 6930, p. 415–418, 2003.

KRAUSE, Décio. **Álgebra Linear com um Pouco de Mecânica Quântica**. 1. ed. Florianópolis: NEL/UFSC, 2016. (Rumos da Epistemologia, 15).

KRAUSE, Décio; ARENHART, Jonas R. Becker. A Logical Account of Quantum Superpositions. In: AERTS, Diederik et al. (Eds.). **Probing the Meaning of Quantum Mechanics: Superpositions, Dynamics, Semantics and Identity**. Singapore: World Scientific, 2016. (Quantum Mechanics and Quantum Information: Physical, Philosophical and Logical Approaches). chap. 2, p. 44–59.

KRAUSE, Décio; ARENHART, Jonas R. Becker. **The Logical Foundations of Scientific Theories: Languages, Structures, and Models**. Abingdon: Routledge, 2016.

KRAUSE, Décio; ARENHART, Jonas R. Becker; MORAES, Fernando T. F. Axiomatization and models of scientific theories. **Foundations of Science**, Springer, v. 16, n. 4, p. 363–382, 2011.

KUHN, T. S. **The structure of scientific revolutions**. University of Chicago press: Chicago, 2012.

LADYMAN, James. Structural Realism. In: ZALTA, Edward N. (Ed.). **The Stanford Encyclopedia of Philosophy**. Winter 2016. Stanford: Metaphysics Research Lab, Stanford University, 2016.

LADYMAN, James. What is structural realism? **Studies in History and Philosophy of Science**, v. 29, n. 3, p. 409–424, 1998.

LADYMAN, James; ROSS, Don. **Every Thing Must Go: Metaphysics Naturalized**. Oxford: Oxford University Press, 2007.

LANDSMAN, Nicolaas P. Between classical and quantum. **Handbook of the Philosophy of Science**, v. 2, p. 417–553, 2007.

LEWIS, David. **Counterfactuals**. Cambridge: Harvard University Press, 1973.

LEWIS, David. How many lives has Schrödinger's cat? **Australasian Journal of Philosophy**, Taylor & Francis Group, v. 82, n. 1, p. 3–22, 2004.

LEWIS, Peter. Life in Configuration Space. **The British Journal for the Philosophy of Science**, v. 55, n. 4, p. 713–729, Dec. 2004.

LEWIS, Peter. **Quantum Ontology: A Guide to the Metaphysics of Quantum Mechanics**. New York: Oxford University Press, 2016.

LOCKWOOD, Michael. **Mind, brain and the quantum: The compound 'I'**. New Jersey: Basil Blackwell, 1989.

LONDON, Fritz; BAUER, Edmond. The theory of observation in quantum mechanics. In: WHEELER, John; ZUREK, Wojciech (Eds.). **Quantum Theory and Measurement**. Trans. by John Wheeler and Wojciec Zurek. Princeton: Princeton University Press, 1983. P. 217–259.

LOWE, E. Jonathan. **A survey of metaphysics**. Oxford: Oxford University Press, 2002.

LOWE, E. Jonathan. **The possibility of metaphysics: Substance, identity, and time**. Oxford: Clarendon Press, 1998.

LUTZ, Sebastian. On a straw man in the philosophy of science: A defense of the Received View. **HOPOS: The Journal of the International Society for the History of Philosophy of Science**, University of Chicago Press, Chicago, v. 2, n. 1, p. 77–120, 2012.

LUTZ, Sebastian. What Was the Syntax-Semantics Debate in the Philosophy of Science About? **Philosophy and Phenomenological Research**, Wiley Online Library, 2015.

LYCAN, William G. Permanent Contributions in Philosophy. **Metaphilosophy**, John Wiley & Sons, Oxford, v. 50, n. 3, p. 199–211, 2019.

MAUDLIN, Tim. **Philosophy of physics: Quantum theory**. Princeton: Princeton University PRess, 2019. (Princeton Foundations of Contemporary Philosophy).

MAUDLIN, Tim. **The metaphysics within physics**. Oxford: Oxford University Press on Demand, 2007.

MAUDLIN, Tim. Three measurement problems. **Topoi**, v. 14, n. 1, p. 7–15, 1995.

MERMIN, N. David. Could Feynman have said this? **Physics Today**, v. 57, n. 5, p. 10, 2004.

MILLER, Warner A.; WHEELER, John A. Delayed-Choice Experiments and Bohr's Elementary Quantum Phenomenon. In: **Foundations of Quantum Mechanics in the Light of New Technology: Selected Papers from the Proceedings of the First through Fourth International Symposia on Foundations of Quantum Mechanics**. Ed. by Susumu Kamefuchi and Nihon Butsuri Gakkai. Tokyo: WorldCat, 1983. P. 140–151. (Advanced Series in Applied Physics: Volume 4).

MORGANTI, Matteo; TAHKO, Tuomas E. Moderately naturalistic metaphysics. **Synthese**, Switzerland, v. 194, n. 7, p. 2557–2580, July 2017.

MORTARI, Cezar A. Against Modal Realism. In: A. DUTRA, Luiz Henrique de; MORTARI, Cezar A. (Eds.). **Princípios: Seu Papel na Filosofia e nas Ciências**. Florianópolis: UFSC - NEL, 2000. v. 3. (Rumos da Epistemologia). P. 31–46.

MORTARI, Cezar A. Um realismo modal genuíno impossibilista? **Intuitio**, Porto Alegre, v. 3, n. 2, p. 3–15, 2010.

MULLER, FA. Reflections on the revolution at Stanford. **Synthese**, Springer, Switzerland, v. 183, n. 1, p. 87–114, 2011.

NEY, Alyssa. Introduction. In: NEY, Alyssa; ALBERT, David Z. (Eds.). **The wave function: Essays on the metaphysics of quantum mechanics**. Oxford: Oxford University Press, 2013. P. 1–51.

NEY, Alyssa. Neo-positivist metaphysics. **Philosophical studies**, Springer, v. 160, n. 1, p. 53–78, 2012.

PAPINEAU, David. David Lewis and Schrödinger's cat. **Australasian Journal of Philosophy**, Taylor & Francis Group, v. 82, n. 1, p. 153–169, 2004.

PARSONS, Charles. Informal axiomatization, formalization and the concept of truth. **Synthese**, Springer, Switzerland, v. 27, n. 1, p. 27–47, 1974.

PARSONS, Terence. The methodology of nonexistence. **The journal of philosophy**, v. 76, n. 11, p. 649–662, 1979.

PAULI, Wolfgang. Die philosophische Bedeutung der Idee der Komplementarität. **Experientia**, Springer, v. 6, n. 2, p. 72–75, 1950.

PESSOA JUNIOR, Osvaldo F. Can the Decoherence Approach Help to Solve the Measurement Problem? **Synthese**, v. 113, n. 3, p. 323–346, 1997.

PESSOA JUNIOR, Osvaldo F. **Conceitos De Física Quântica, Volume I**. São Paulo: Livraria da Física, 2003.

PESSOA JUNIOR, Osvaldo F. O fenômeno cultural do misticismo quântico. In: FREIRE JUNIOR, Olival; PESSOA JUNIOR, Osvaldo F.; BROMBERG, Joan Lisa (Eds.). **Teoria quântica: estudos históricos e implicações culturais**. São Paulo: Livraria da Física, 2011. P. 281–302.

PFÄNDER, Alexander. **Logic**. Heusentamm: Ontos Verlag, 2009. Translated from the third and unaltered edition by Donald Ferrari.

PUTNAM, Hilary. **Mind, Language and Reality: Philosophical Papers**. Cambridge: Cambridge University Press, 1975.

PUTNAM, Hilary. The meaning of ‘meaning’. **Minnesota studies in the philosophy of science**, v. 7, p. 131–193, 1974.

PUTNAM, Hilary. What theories are not. **Studies in Logic and the Foundations of Mathematics**, Elsevier, v. 44, p. 240–251, 1966.

REDHEAD, Michael. **Incompleteness, Nonlocality, And Realism: A Prolegomenon To The Philosophy Of Quantum Mechanics**. Oxford: Clarendon Press, 1987.

ROBINSON, Howard. Dualism. In: ZALTA, Edward N. (Ed.). **The Stanford Encyclopedia of Philosophy**. Fall 2017. Stanford: Metaphysics Research Lab, Stanford University, 2017.

RODRIGUES, José Gusmão. There are no good objections to substance dualism. **Philosophy**, Cambridge University Press, Cambridge, v. 89, n. 2, p. 199–222, 2014.

ROVELLI, Carlo. Relational quantum mechanics. **International Journal of Theoretical Physics**, Springer, v. 35, n. 8, p. 1637–1678, 1996.

RUETSCHE, Laura. Getting Real About Quantum Mechanics. In: **The Routledge Handbook of Scientific Realism**. Ed. by Juha Saatsi. New York: Routledge, 2018. P. 291–303.

RUETSCHE, Laura. The Shaky Game+ 25, or: On locavoracity. **Synthese**, Springer, Switzerland, v. 192, n. 11, p. 3425–3442, 2015.

S. LIVRAMENTO MACHADO, Sandro da; FIRMO DE SOUZA CRUZ, Frederico de. A Teoria Quântica e a Apropriação do Conhecimento Científico: O uso da História e Filosofia da Ciência pelos Misticismos. In: VÁSQUEZ, Maria Fernanda; CAPONI, Sandra; SILVA, Márcia Regina Barros da (Eds.). **Anais do 15 Seminário Nacional de História da Ciência e da Tecnologia: Volume III**. Rio de Janeiro: Sociedade Brasileira de História da Ciência, 2016. P. 321–337.

SCHLOSSHAUER, M.; KOFLER, J.; ZEILINGER, A. A snapshot of foundational attitudes toward quantum mechanics. **Studies in History and Philosophy of Modern Physics**, v. 44, p. 222–230, 2013.

SCHRÖDINGER, Erwin. The Present Situation in Quantum Mechanics. In: WHEELER, John; ZUREK, Wojciech (Eds.). **Quantum Theory and Measurement**. Princeton: Princeton University Press, 1983. P. 152–167.

SHAPIRO, Stewart; KOURI KISSEL, Teresa. Classical Logic. In: ZALTA, Edward N. (Ed.). **The Stanford Encyclopedia of Philosophy**. Spring 2018. Stanford: Metaphysics Research Lab, Stanford University, 2018.

SHIMONY, Abner. Contextual hidden variables theories and Bell's inequalities. **The British Journal for the Philosophy of Science**, v. 35, n. 1, p. 25–45, 1984.

SHIMONY, Abner. On mentality, quantum mechanics and the actualization of potentialities. In: PENROSE, Roger et al. (Eds.). **The Large, the Small and the Human Mind**. Cambridge: Cambridge University Press, 1997. chap. 4, p. 144–160.

SHIMONY, Abner. Role of the observer in quantum theory. **American Journal of Physics**, American Association of Physics Teachers, v. 31, n. 10, p. 755–773, 1963.

SHIMONY, Abner; MALIN, Shimon. Dialogue Abner Shimony–Shimon Malin. **Quantum Information Processing**, Springer, v. 5, n. 4, p. 261–276, 2006.

SKLAR, Lawrence. I'd Love to Be a Naturalist—if Only I Knew What Naturalism Was. **Philosophy of Science**, University of Chicago Press, Chicago, v. 77, n. 5, p. 1121–1137, 2010.

SKLAR, Lawrence. Interpreting theories: The case of statistical mechanics. In: CLARK, Peter; HAWLEY, Katherine (Eds.). **Philosophy of science today**. Oxford: Oxford University Press, 2003. P. 276–284.

SKLAR, Lawrence. Naturalism and the Interpretation of Theories. **Proceedings and Addresses of the American Philosophical Association**, v. 75, n. 2, p. 43–58, 2001.

SKØLEM, Thoralf. Logico-combinatorial investigations in the satisfiability or provability of mathematical propositions: a simplified proof of a theorem by L. Löwenheim and generalizations of the theorem. **From Frege to Gödel. A Source Book in Mathematical Logic**, v. 1931, p. 252–263, 1879.

SKYRMS, Brian. Possible worlds, physics and metaphysics. **Philosophical Studies**, Springer, Switzerland, v. 30, n. 5, p. 323–332, 1976.

STAPP, Henry P. **Mindful universe: Quantum mechanics and the participating observer**. Berlin: Springer, 2011.

STAPP, Henry P. Quantum Interactive Dualism: An alternative to materialism. **Zygon: Journal of Religion and Science**, John Wiley & Sons, v. 41, n. 3, p. 599–616, 2006.

STÖLTZNER, Michael. Opportunistic axiomatics – von Neumann on the methodology of mathematical physics. In: RÉDEI, Miklós; STÖLTZNER, Michael (Eds.). **John von Neumann and the foundations of quantum physics**. Netherlands: Springer, 2001. P. 35–62.

STYER, Daniel F. et al. Nine formulations of quantum mechanics. **American Journal of Physics**, v. 70, n. 3, p. 288–297, 2002.

SUPPE, Frederick. **The semantic conception of theories and scientific realism**. Illinois: University of Illinois Press, 1989.

SUPPE, Frederick. **The structure of scientific theories**. Illinois: University of Illinois Press, 1977.

SUPPE, Frederick. Understanding scientific theories: An assessment of developments, 1969-1998. **Philosophy of Science**, University of Chicago Press, Chicago, v. 67, s102–s115, 2000.

SUPPES, Patrick. **Representation and invariance of scientific structures**. Stanford: CSLI publications, 2002.

SUPPES, Patrick. What is a scientific theory? In: MORGENBESSER, S. (Ed.). **Philosophy of Science Today**. New York: Basic Books, 1967. P. 55–67.

TAHKO, Tuomas E. **An introduction to metametaphysics**. Cambridge: Cambridge University Press, 2015.

TAKHTADZHIAN, Leon Armenovich. **Quantum Mechanics for Mathematicians**. Stony Brook: Stony Brook University, 2008.

TARSKI, Alfred. The concept of truth in formalized languages. **Logic, semantics, metamathematics**, Oxford, v. 2, p. 152–278, 1956.

THOMASSON, Amie L. **Ontology Made Easy**. Oxford: Oxford University Press, 2014.

VAN FRAASSEN, Bas C. **Laws And Symmetry**. Oxford: Oxford University Press, 1989. (Clarendon paperbacks).

VAN FRAASSEN, Bas C. **Quantum mechanics: An Empiricist View**. Oxford: Oxford University Press, 1991.

VAN FRAASSEN, Bas C. **The scientific image**. Oxford: Oxford University Press, 1980.

VON NEUMANN, John. **Mathematical Foundations of Quantum Mechanics**. Trans. by Robert Beyer. Princeton: Princeton University Press, 1955.

WALLACE, David. **The emergent multiverse: Quantum theory according to the Everett interpretation**. Oxford: Oxford University Press, 2012.

WERNER, Frederick. **Transcript of Conference on the Foundations of Quantum Mechanics, Xavier University Cincinnati, 1-October-1962, with Everett's remarks**. California: University of California, Irvine Libraries, 1962. Available in: `http://hdl.handle.net/10575/1299`.

WHEELER, John Archibald. How Come the Quantum? **Annals of the New York Academy of Sciences**, v. 480, n. 1, p. 304–316, 1986.

WIGHTMAN, Arthur S. Hilbert's sixth problem: Mathematical treatment of the axioms of physics. In: BROWDER, Felix E. (Ed.). **Mathematical Developments Arising From Hilbert Problems, Part 1**. Rhode Island: American Mathematical Society, 1976. v. XXVIII. (Proceedings of Symposia in Pure Mathematics). P. 241–268.

WIGNER, Eugene. Remarks On The Mind-Body Question. In: WHEELER, John; ZUREK, Wojciech (Eds.). **Quantum Theory and Measurement**. Princeton: Princeton University Press, 1983. P. 168–181.

WILSON, Alastair. Objective probability in Everettian quantum mechanics. **British Journal for the Philosophy of Science**, Oxford Univerity Press, Oxford, v. 64, n. 4, p. 709–737, 2013.

WINELAND, David J. Nobel Lecture: Superposition, Entanglement, and Raising Schrödinger's Cat. **Reviews of Modern Physics**, APS, v. 85, n. 3, p. 1103, 2013.

WITTGENSTEIN, Ludwig. **Philosophical investigations**. Oxford: Blackwell Publishing, 1953. Translated by G. E. M. Anscombe.

WORRALL, John. Miracles and models: Why reports of the death of structural realism may be exaggerated. **Royal Institute of Philosophy Supplement**, Cambridge University Press, Cambridge, v. 61, p. 125–154, 2007.

ZAHAR, Elie G. Ramseyfication and structural realism. **Theoria. Revista de Teoría, Historia y Fundamentos de la Ciencia**, v. 19, n. 1, p. 5–30, 2004.

Appendix

APPENDIX A – BOHMIAN MECHANICS

Chapter 2 sketched two interpretations of QM^{bas}: QM_{col} and QM_{bra}. Bohmian mechanics not included in the discussion, as only two options were needed in order to reach the main point throughout this thesis: underdetermination. To argue for the generality of our scheme, the theoretical aspects of pilot-wave theories, which encompasses Bohmian mechanics (here called QM_{pil}), is presented here. QM_{pil} fits the general schema developed in this thesis' picture, as shown in Figure 9.

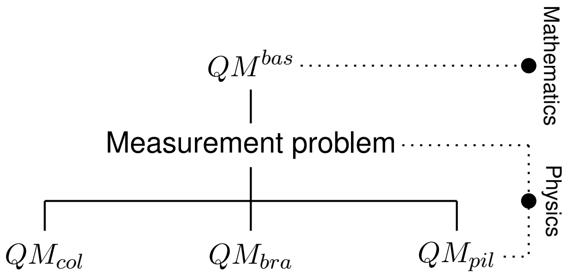

Figure 9 – QM_{pil} in the big picture.

Recall that QM^{bas}'s $\mathcal{P}_5$ is the generalization of the notion of measurement. In pilot-wave theories, the theoretical mechanisms through which this process occurs is a recognition of a preexisting value (BOHM, 1952).

Pilot-wave interpretations (BOHM, 1952), (BOHM; HILEY, 2006) rejects assumption 1.A[1] according to the General Principle $\mathcal{P}_1$, and instantiates the General Principle $\mathcal{P}_4$ in the axiom of dynamics with hidden variables in the differential equations of motion, thus originating the pilot-wave quantum theory QM_{pil}.

A.1 PILOT-WAVE QUANTUM THEORY

Bohm's (BOHM, 1952) pilot-wave solution to the measurement problem is presented as follows. It modifies (or *interprets*) QM^{bas}'s structure, instantiating some of its General Principles in what are called specific axioms of *pilot-wave quantum theories* by denying assumption 1.A. Therefore, a pilot-wave quantum theory QM_{pil} is a n-uple:

$$\mathrm{QM}_{pil} = \langle \mathfrak{F}, \mathcal{A}_{\mathrm{pil}}, \mathcal{R} \rangle \tag{23}$$

where:

1. $\mathfrak{F}$ is the language of QM_{pil}, similar to QM^{bas}'s language, with the introduction of the quantum potential Q in $\mathfrak{F}$;

---

[1] This assumption states that the state vector $|\psi\rangle$ gives a *complete description* of S.

2. $\mathcal{A}_{\text{pil}}$ are the specific axioms of QM_{pil} (*i.e.* the instance of the set $\mathcal{P}$ of QM_{pil}). The list of $\mathcal{A}_{pil}$ is:

$\mathcal{A}_{\text{pil 1}}$ [*Configuration space*]: The same as $\mathcal{P}_1$, except for the following remarks: $a)$ Quantum systems are described in a $3N$-dimensional configuration space $\mathcal{Q}$ (not to be confused with the quantum potential Q above), not in a Hilbert space $\mathcal{H}$, where N corresponds to the number of particles in the system; the standard $|\psi\rangle$ wave-function/quantum-mechanical description is not complete, but is supplemented with extra parameters (see $\mathcal{A}_{\text{pil 4}}$ below).

$\mathcal{A}_{\text{pil 2}}$ [*Quantization Algorithm*]: The same as $\mathcal{P}_2$.

$\mathcal{A}_{\text{pil 3}}$ [*Statistical Algorithm*]: The same as $\mathcal{P}_3$.

$\mathcal{A}_{\text{pil 4}}$ [*Hidden-Variable Dynamics*]: The same as $\mathcal{P}_4$, except for the following remarks. The usual Schrödinger equation (see equation (10) in $\mathcal{A}_{\text{col 4}}$) is *supplemented* with additional terms and *hidden variables* that transform its *probabilistic* nature in a *deterministic* equation of motion (BOHM, 1952). This additional term Q is called “quantum potential”

$$Q = \frac{\hbar^2}{2m}\frac{\nabla^2 R}{R}, \tag{24}$$

which supplements the differential equations of motion with additional parameters. In order to do so, the Schrödinger equation is written in function of the *potential* operator V – instead of the Hamiltonian operator H, to yield the total energy of the system, as in equation (10), as:

$$i\hbar\frac{\partial|\psi\rangle}{\partial t} = \left(-\frac{\hbar}{2m}\nabla^2 + V\right)|\psi\rangle, \tag{25}$$

where $|\psi\rangle$ is also re-written in its polar form, decomposed between its amplitude and its phase (BOHM, 1952). It is noteworthy that $|\psi\rangle$ is an abbreviation of $|\psi(\bar{\mathbf{x}}, t)\rangle$, where $\bar{\mathbf{x}}$ stands for spatial coordinates (x, y, z); these are *position coordinates*, taken to be essentially *unknown*. These are the so-called *hidden* variables, thus denying assumption 1.A. If this is so, the real part of the Schrödinger equation can be rewritten in a *modified Hamilton-Jacobi* equation (also known as its “quantum version” (BOHM; HILEY, 2006)) as follows:

$$\frac{\partial S}{\partial t} = -\left[\frac{|\nabla S|^2}{2m} + V + \frac{\hbar^2}{2m}\frac{\nabla^2 R}{R}\right] \tag{26}$$

Equation (26) is commonly referred to as the “guiding equation” of motion.

$\mathcal{A}_{\text{pil } 5}$ [*Measurement*]: The same as $\mathcal{P}_5$. A position measurement, for example, simply yields the *hidden* states that were guided by (26) in a purely deterministic (albeit statistical via Born rule) manner.

3. $\mathcal{R}$ are the rules of inference of QM_{pil}, which are similar to those stated in QM^{bas}.