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Interpreting Relational Quantum Mechanics:
Everything I Always Wanted to Know About the Relationality of Quantum Mechanics But Was Afraid to Ask, and Still Am

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Introduction

According to Stein (1972, p. 367), “nowadays, relativity is quite tame; but nobody yet understands the quantum theory”. Although Stein’s claim might still be true today, in the past half century extensive work has been done by both physicists and philosophers in order to make sense of the weirdly successful predictions of Quantum Mechanics (QM). The former have developed different *physical interpretations* of the theory that gave an account of the same experimental results, i.e. interpretations of the “bare” mathematical Hilbert Space formalism of the orthodox quantum theory, as defined by Ruetsche (2011) in *Interpreting Quantum Theories*. The latter have consequently provided such interpretations with philosophical analysis - *philosophical interpretations* - that was often expressed in terms of friction between scientific realism and antirealism, with a view to explaining the nature of the properties described by quantum states, the nature of entangled systems, the nature of the measurement process, and ultimately the nature of the theory’s commitments (for example, Jones 1991). Contrary to General Relativity, which suffers no incoherence in its formulation as a physical theory that only an interpretation could resolve (Curiel 2009), QM does stand in need of an interpretation, both physical and philosophical. In this sense, an uninterpreted quantum theory is just a symbolic calculus, with rules governing how the elements of the calculus may be manipulated, but with no indication of the representational significance of its formalism.

Several different physical interpretations of the quantum formalism have been developed after the first formulation of the theory, e.g. *Pilot-Wave*, *Many-Worlds*, *Statistical*, *Relational,* just to name a few. Philosophical investigation, on the other hand, has been set up as an attempt to clarify the fundamental concepts at the core of each interpretation, such as ‘indeterminism’, ‘probability’, ‘observation’, ‘superposition’, ‘measurement’, and the way these concepts correspond to reality. In this sense, a distinction between ontic and epistemic aspects turns out to be essential in order to define the interpretation domain and the metaphysical ‘posture’ that is entailed. For instance, in some cases the probabilities of measurement outcomes are interpreted as a result of intrinsic properties of the observed system, e.g. in Spontaneous Collapse theories (Ghirardi 2018); in other cases they are not, since according to these interpretations quantum theory does not directly deal with intrinsic properties of the world but with the experiences an observer has of the observed system, e.g. QBism (Fuchs et al. 2014). Another aspect that might be considered is the 'descriptive power' of the wave function ψ. ψ-ontic interpretations conceive the quantum state as an intrinsic property of the observed system, e.g. Many-Worlds (Albert & Loewer 1988), whereas ψ-epistemic interpretations view the quantum state as representing knowledge of an underlying objective reality, e.g. in the Statistical interpretation (Ballentine 1970). It is important to notice, however, that the choice about being realist or antirealist with respect to quantum theory in general depends on a philosophical analysis, rather than on the different specifications of the interpretations of QM.

Independently of the privileged interpretation, quantum-mechanical features have a strong philosophical character: indeterminism of the values of quantum properties, systems characterized by a constitutive probability, superposition of states that collapse into a single component. Each of these aspects is closely linked to the role of an observer that seems to be the reflection of a metaphysical antirealism in which the reality of physical systems cannot be identified with what Kant expressed as a *thing in itself*, that is, that noumenal reality independent not only of particular phenomenal knowledge, but from any possible knowledge, as Chevalley (1994) emphasizes. It is evident that the very peculiar structure of quantum theory poses some fundamental questions on its own status that typically belong to general philosophy of science: is there a direct correspondence between formal language and the fundamental constitution of nature? Are we in a position to know that our theories are true? The same peculiar structure brings up also general metaphysical questions concerning the nature of objects, relations and properties, that are normally addressed by metaphysics with reference to scientific practice, which in fact should not be overlooked if scientifically informed metaphysics - or naturalized metaphysics (Ladyman & Ross 2009) - is what we aim for.

However, regardless of the peculiar features of quantum theory, it is worth stressing that theories are neither realist nor antirealist. It is rather one's attitude towards a theory that can be either realist or antirealist. And although this categorical clarification seems to be quite straightforward, it is not uncommon to find in the quantum foundations literature terms like 'realist', 'realistic', 'antirealist' or 'antirealistic' attached to theory themselves, which I think is meaningless, and, according to Maudlin (2019, xii), produces "terrible consequences for discussions in foundations in quantum theories".

For instance, it is often claimed that Bohmian mechanics provides a realist formulation of quantum theory, because – I suppose – in its deterministic formalism particles actually execute defined trajectories, although may be unknowable a priori. This however brings in an extremely high degree of contextuality that hardly goes along with a fully realist view[1]. Similarly, relational quantum mechanics (RQM) is sometimes referred to as a realist interpretation, with particular respect to the way in which it treats quantum relations. However, as we will see, the view of the wave function it provides is rather far from being a realist account, which makes it hard to see how the theory *itself* can be viewed as realist. A fine example is also provided by Maudlin's recent book on quantum theory: "Bell, we are told, ruled out all local *realistic* theories, for example. And that locution strongly suggests that one can avoid non locality and evade Bell's results by saying that *realism* is what ought to be abandoned. But this suggestion is nonsensical. Bell proves that no local theory, full stop, can predict violations of his inequalities" (Maudlin 2019, xiii).

The present work is set against the background that I have just described, namely the philosophical analysis of features and concepts of quantum mechanics that are understood within realist or antirealist frameworks, which, if a form of realism is embraced, may be extended to the metaphysical implications of the theory. In fact, the aim of the thesis is not to directly provide a structuralist

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[1] In the case of the two-slit experiment, if we take into account the velocity vector of the particles sent against the screen, at a fixed starting position there is a substantial modification of the trajectory that depends on the presence (or absence) of a detector-system *beyond* the two slits, on which the initial velocity depends, that is, a *future* context of the experiment.

interpretation of relational quantum mechanics, but, rather, to investigate its conditions of possibility, by tracing the relational foundations and the structural content of RQM, and highlighting any point of contact between the relationality of the interpretation and structuralist epistemologies and ontologies.

The plan for doing so is organized as follows. In the first chapter I will discuss the main concepts that underlie the distinction between scientific realism and antirealism, out of which the contemporary structuralist stance emerges. This and other considerations concerning the notion of observable introduce one of the main background assumptions of the thesis, namely that realist stances take very different shapes depending on the theoretical content they are confronted with, which in turn makes the critical juxtaposition between philosophical claims and selected scientific theories much more fruitful than analysing – or endorse – the former as metaphysical positions alone.

The central chapter is dedicated to the examination of the relationality at the core of RQM. Such a notion will be preliminary clarified from a philosophical standpoint distinguishing between the relationalism of the ontology and the relativism of values. This distinction will turn out to be crucial in the sections that follow. Indeed, the historical analysis carried out in §2.2 will reveal how the same dichotomy of the notion of relationality was already present in the first developments of quantum theory, in particular in Heisenberg's matrix mechanics relationalism, and Bohr's and Hermann's relativism. Remarkably, Rovelli's relational solution to the measurement problem, thoroughly presented in §2.4, relies on precisely the conjunction of an Heisenberg-type relationalism of systems and an Hermann-type relativism of values: variables of quantum systems have a value only within interactions, and such interactions do not assign absolute values to the variables. I conclude the chapter by discussing several objections to RQM, with particular respect to the implications of the 'Wigner's friend' thought experiment, which has gained renewed attention in the recent literature about observer-(in)dependence in quantum mechanics.

This serves as the basis to explore the possibility – and the sense – of a structuralist interpretation of RQM that is undertaken in the final chapter. I will start by introducing the two main formulations of contemporary structuralism, i.e. epistemic and ontic structural realism, and their respective problems. §3.2 will be dedicated to presenting the motivations for an ontological revisionism coming from quantum mechanics, devoting particular attention to the problem of identity and individuation of quantum objects. I will then critically assess the different philosophical interpretations of RQM found in the literature (epistemic structural realism, radical ontic structural realism, relativism and neo-Kantianism), and conclude by proposing a moderate ontic structuralist reading of the interpretation, based on the notion of 'object-relation identity', a correspondence between the notion of 'object' and the notion of 'relation' at the quantum level that establishes a symmetry through which one can be ontologically reduced to the other.

Chapter I

REALISM*(S)*

1. Realism(s)

In this chapter I will introduce the main concepts that underlie the distinction between scientific realism and antirealism, out of which the contemporary structuralist stance emerges. The most common tripartition of a realist attitude, i.e. metaphysical, semantic and epistemic, will be introduced and its relation with two main theories of truth will be discussed. I will present the main arguments in support of and against both views, focusing on the notion of ‘observable’, which essentially represents the blurred boundary between the different ontological commitment towards the content of a theory. The problem of generalizing these arguments to the “scientific practice” as a whole will become particularly clear when discussing Stanford’s (2006) Unconceived Alternatives argument (UA), which will be presented as an emblematic case of generalization of an antirealist stance with no reference to a particular theory. Hopefully, these final remarks will help support one of the main background assumptions of the present thesis, namely that realist stances take very different shapes depending on the theoretical content they are confronted with, which in turn makes the critical juxtaposition between philosophical claims and selected scientific theories much more fruitful than analysing – or endorse – the former as metaphysical positions alone.

1.1 Three Dimensions of Scientific Realism

Chakravartty (2017, p. 1) ironically introduces the debate over scientific realism as follows: “It is perhaps only a slight exaggeration to say that scientific realism is characterized differently by every author who discusses it, and this presents a challenge to anyone hoping to learn what it is”.

In fact, the extensive literature on the topic makes a unitary definition hard to track, without oversimplifying the position of each author. Whether they be pro or against realism, however, much of the arguments share a tendency to extend the range of their claims to general notions such as “scientific practice” or “our best theories”, that often results in a problematic tradeoff between generality and efficacy to adjust to specific individual cases. Having said that, and keeping the problem of generality aside for now, what characterizes scientific realism can be summarized in the following attitudes: (i) confidence in scientific method: as time progresses, the theories that scientists accept are progressively closer to being true; (ii) confidence in contemporary science: the most successful of our current theories are approximately true; (iii) belief that our current scientific ontology - the list of entities that scientist currently accept - is approximately correct. Chakravartty (2017) takes scientific realism as a "positive epistemic attitude" towards the content of (allegedly) well-established scientific theories and models, whereas antirealism as neglecting the even approximate truthfulness of currently available scientific paradigms.

1.1.1 The Semantic, Epistemic & Metaphysical Dimensions

Before going into the details of the specific arguments for and against scientific realism, I shall introduce what seems to be the most common and effective way of framing this notion, decomposing it into three different types of questions (Psillos 1999, Kitcher 2001): (s*emantic)* are theories literal descriptions of the world? Should their (theoretical) terms be understood literally as having truth values, whether true or false? (e*pistemic)* are we in a position to know that our theories are at least approximately true and able to provide knowledge of the world? *(metaphysical)* does the objects of scientific inquiry exist independently of our conception and observation?

In order to grasp the extension of the domain of scientific realism and clearly differentiate it from antirealist alternatives, it is particularly useful to understand its general claim in terms of these three dimensions. Semantically, realism is committed to a literal interpretation of both empirical and theoretical claims formulated within a theory, so as to assign truth values to the statements about scientific entities and facts, whether they be observable or unobservable. In this sense, therefore, scientific statements represent a literal description of nature. On the contrary, antirealist semantic commitments are usually supported by instrumentalist philosophies of science, according to which theoretical claims should be interpreted as valid instruments with the purpose of making sense of and predicting observable phenomena, despite having no literal meaning at all. Epistemically, realism is committed to the idea that theoretical claims (literally interpreted) constitute actual knowledge of the world. In other words, the empirical success of a theory and in particular the successful reference of its theoretical terms represent a sufficient condition to conclude that the theory itself is (approximately) true and able to provide us with actual knowledge of the phenomena that is under investigation (Boyd 1983).

In fact, the possibility for epistemic accesses grounded on the truth of the theory, depends on the theory of truth that is assumed. On the one hand, the realist complementarity of the semantic and epistemic dimensions generally requires some version of the so-called correspondence theory of truth, according to which the truth or falsity of a statement is determined only by how it relates to the world and whether it accurately describes (i.e., corresponds to) that world (Fine 1986). The basic claim of the correspondence theory is that what we believe or say is true if it corresponds to the way things actually are, to actual state of affairs, so that: *x* is true *iff x* corresponds to some thing or fact; *x* is false *iff x* does not correspond to any thing or fact.

On the other hand, skeptical positions towards the epistemic dimension of realism are generally supported by deflationary accounts of truth, according to which asserting that a statement is true accounts for asserting the statement itself. For instance, to say that 'snow is white is true' is equivalent to saying simply that 'snow is white', which is all can be meaningfully said about the truth of 'snow is white'. In this sense truth has no nature beyond what is captured in ordinary claims such as that '*p*' is true just in case *p*, in the form of the so-called equivalence schema: <*p*> is true *iff p.* [1]

The basic idea of deflationary theories is that there is no such property as truth and thus there is no need for, or sense to, a theory of truth distinct from a theory of truth ascription. Epistemically antirealist views based on deflationary theories of truth claim that the truth of a scientific statement is not a sufficient condition

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[1] Angle brackets indicate an appropriate name-forming device, e.g. quotation marks or 'the proposition that …', and occurrences of '*p*' are replaced with sentences to yield instances of the schema.

for knowledge (Devitt 2005). Indeed, even though such sceptical views accept the semantic dimension of realism, they argue that theoretical claims are not epistemically powerful enough to produce actual knowledge of their content.

Metaphysically, realism is committed to the idea that the objects of scientific theories exist independently of our conception and observation. The metaphysical dimension of scientific realism is perhaps the most complex, since it partially relates to metaphysical realism in general, without however being entirely reduced to it. It is important to linger on the fact that metaphysical scientific realism is concerned with the ontological status of the world investigated by the sciences, i.e. the specific aspects of the world to which the theory refers. Therefore, the direct antirealist alternative in this regard is for instance represented by a neo-Kantian conception of the nature of scientific theories, which denies the mind-independence of the world of our (scientific) experience and interaction, despite accepting the mind-independence of the world in itself. The idea underlying this view is that the world sifted through scientific investigation, as distinct from 'the world in itself', depends in some important sense on the ideas the subject brings to scientific practice, e.g. perceptual training and theoretical assumptions.

It can safely be argued that any form of metaphysical antirealism in general negates the possibility for a realist attitude towards the metaphysical dimension of scientific realism. However, it is essential to keep in mind that the range of such negation cannot be extended to the other dimensions of scientific realism - semantic and epistemic. In fact, if the aim of science is not to provide a description of the world in itself whereas to produce true theories, then the semantic and epistemic dimension of scientific realism can be preserved, since in this perspective scientific theories are not ontologically committed to the (mind-independent) existence of the unobservable entities or facts they postulate. This final remark leads me to emphasize the fact that the different dimensions characterizing scientific realism and antirealism are not necessarily expressed in one single coherent view.

1.1.2 Existence & Independence in Metaphysical Realism

In contemporary debate, the problem of metaphysical realism has been structured into a further distinction, between the notion of 'existence' and 'independence'. The metaphysical realist thesis about a particular domain appears to be composed of two sub-theses: (I) there are facts or entities distinctive of that domain;[2] (II) their existence and nature is in some important sense objective and mind-independent. With respect to their existence, it is important to distinguish between facts and entities, for it is possible to be a realist about a certain domain without thinking that there are any particular entities distinctive of that domain. And the existence of the facts in question does not depend on the existence of entities in the same domain; for instance, one might believe that quantum structures and relations are real without committing to the existence of theoretical entities such as electrons, or believe that it is a fact that Bernie Sanders could have won the US elections without believing there is a possible world in which Sanders in fact wins.

A clear distinction between existence and independence is explicitly exposed by Brock & Mares (2007) in the attempt to provide the most effective representation of realism and antirealism and to unify the debate across different domains. However, the same dichotomy can be traced back to the work of some previous authors working in the field, such as Miller (2002, p.1):

> "There are two general aspects of realism, illustrated by looking at realism about the everyday world of macroscopic objects and properties. First, there is a claim about *existence*. Tables, rocks, the moon, and so on, all exist, as do the following facts: the table being square, the rock being made of granite, and the moon being spherical and yellow. The second aspect of realism about the everyday world of macroscopic objects and their properties concerns *independence*. The fact that the moon exist and is spherical is independent of anything anyone happens to say or think about the matter".

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[2] Where *entities* are the referents of the singular terms in a language, and *facts* are aspects of the world represented by whole declarative sentences in a language.

It is evident that metaphysical and scientific realism are concerned with different domains. However, the respective views on reality and science are interconnected and mutually dependent.

On the one hand, metaphysical beliefs concerning the ultimate nature of reality shape the notion of science and influence the interpretation of its results. In fact, a metaphysically realist attitude towards the world (in short, there is such a thing as an external mind-independent world) does not necessarily imply a realist interpretation of scientific theories, but most likely does imply a realist view about their *aim* : to provide a true description of how the world really is, or at least of some features and relations the world really has. This might not be what even the most successful theories do, but is what science should aim for: if there is such a thing as a world in itself, scientific practise should try to capture it. On the contrary, a metaphysically antirealist attitude towards the world (in short, there is no such thing as an external mind-independent world) hardly goes along with the idea of science just described. Within the framework of this metaphysical conception, scientific theories cannot in principle reflect things and facts in themselves, given that things and facts are considered to be always dependent at some level on a subject's mind. Nevertheless, if the aim of science is not to provide true descriptions whereas to produce true theories, in terms of empirical adequacy, then realist views of scientific theories are admitted by antirealist metaphysical conceptions: the aim of science is to give an account and make sense of empirical data, and our best theories do so.

On the other hand, our beliefs about scientific theories affect the metaphysical attitude we hold towards the world in general. While an antirealist view of science accepts both realist and antirealist metaphysical conceptions, a fully realist account of scientific theories entails the belief that there is such a thing as an objective reality, which science is at least partially capturing within its most successful theories.

Taking a realist stance at both metaphysical and scientific levels seems to be the most straightforward attitude, according to which there is an objective mind-independent world that successful theories are able to describe in a literal way, providing the link between epistemic access and ontological commitment. However, this approach might have to face peculiar difficulties when applied to quantum mechanics (QM), which makes realism more problematic to maintain at both levels, given the central role that the observer-system plays in determining the measurement outcomes. The related question is then whether a realist interpretation of quantum mechanics paradoxically implies a form of philosophical antirealism, at the metaphysical level. I shall briefly return to this in the following sections.

1.2 Some Arguments for and against Realism

Let us know turn the attention to the different arguments that shape the debate over the problem of scientific realism.

1.2.1 Putnam's No-Miracles Argument

The main expression of the realist stance is represented by the so-called 'no miracles argument', introduced by Putnam (1975) and later developed into a more explicit abductive form by other realist supporters, such as Smart (1989). What the different specifications of the argument have in common is a combination of 'inferences to the best explanation', which motivate the belief in a particular theory, and 'ontological commitment', which motivates the belief in the existence of a particular entity postulated by the theory we accept. The realist intuition is grounded on a direct correspondence between the success of a theory and its truth. Successful theories are able to provide strong empirical predictions; if their theoretical statements were wrong, their success would be a miracle, which in fact does not seem to represent the best available explanation.

Here is a synthetic formulation of the abductive argument. Scientific theories provide very accurate predictions about observable phenomena and postulate theoretical entities and laws; observable phenomena behave as if the theoretical entities exist and the postulated laws are true. The best available explanation of why observable phenomena show such a behaviour is that postulated theoretical entities actually exist and postulated laws are true. We should believe the best available explanation [abductive premise], therefore, we should believe that the theoretical entities postulated by successful theories exist (and that the laws are correct).

It is precisely the (legitimate) use of abduction that some antirealist contenders wish to undermine (e.g. Fine 1986). The question is how can we justify the use of abduction to ground our scientific beliefs that reliably lead us to accept true theories, given the problem of 'empirical underdetermination of theories by evidence': for every set of observable phenomena, there could be many different theories that can adequately explain the same data. Surely some common examples that are used to present simple cases of underdetermination tend to be really implausible and easily fall back into the problem of miraculous explanations in favor of which is hard to argue (e.g. the accepted explanation for the presence of fossils is the existence of dinosaurs million of years ago, but an evil spirit who placed them to trick us could be postulated instead).

1.2.2 Stanford's Predictive Similarity

The real extent of the problem of empirical underdetermination emerges when considering similar and yet incompatible theoretical claims about the same set of phenomena, and it is along these lines that Stanford (2000) argues against the abductive argument. His claim is framed into two options, that follow the definition of predictive similarity. A theory *T* is predictively similar to a theory *Q* iff *T* makes the same empirical predictions as *Q*; We can either believe that: (1) *T* is approximately true; or (2) *T* is predictively similar to a theory that is approximately true. According to Stanford, the problem lies in the probability of choosing one option over the other. If, in virtue of empirical underdetermination, for any successful theory we can imagine many other predictively similar theories, the majority of which are not approximately true, the probability of choosing an approximately true theory is not favourable at all, and empirical evidence cannot tell us whether we are choosing (1) or (2). Thus, *T*'s approximate truth and *T*'s predictive similarity to an approximately true theory are underdetermined explanations of *T*'s empirical success. In other words, Stanford asks the realist to provide the reason for believing that we have in fact chosen the approximately true theory, rather than a false but empirically successful one. Stanford's argument tries to show that there is no such a reason, and therefore there is no reason for believing that approximate truth is the best explanation for the success of scientific theories.

1.2.3 Laudan's Pessimistic Induction

Other antirealists have focused their attention on the historical record provided by the evolution of scientific inquiry, with particular respect to the process of theory change within the same discipline and their discontinuous character. The 'pessimistic meta-induction' argument (Laudan 1981) also aims at invalidating the realist correspondence between 'success' and 'truth' like Stanford does, but through the path of historical analysis rather than empirical underdetermination and predictive similarity. Laudan points out that a great number of theories that have now been falsified still had some level of empirical success in the past. Unless we arbitrarily confer some privileged status to contemporary science, it is evident that truth cannot be generally inferred from success alone, considering the numerous past successful theories whose truth attribution changed over time. The implicit question is why should think that contemporary theories are essentially different from those of the past: if past successful theories were falsified, the same could happen to current theories.

Here is a schematic reconstruction of the inductive argument. Many past theories were highly empirically successful but not approximately true; then, any given present theory cannot be considered approximately true just in virtue of its high empirical success [inductive premise]. If we cannot infer that a theory is approximately true just because it is highly empirically successful, then without further evidence we should not adopt the approximate truth of a theory as an explanation of its success.

In order to support his antirealist argument, Laudan's mentions 'Fresnel's theory of electromagnetic ether' and 'Greek theory of planetary motion' as paradigmatic examples of historically successful theories that are now known to be false. As we shall see in the next chapter, the first contemporary expression of a structuralist stance emerges precisely in response to the pessimistic induction, while trying to identify some sort of theoretical elements that survive theory-change.

1.3 The Notion of Observable

Some other arguments on the problem of scientific realism particularly concentrate on the notion of 'observable'.

In the early 1980's, two works (van Fraassen 1980; Cartwright 1983) appeared on the scene of general philosophy of science, that characterized the debate around the issue of observables and realism. With the abandonment of the realist stance of authors like Maxwell, Smart, Sellars and Popper, a new form of agnostic (van Fraassen), and causal-phenomenological (Cartwright), empiricism was gradually established.

1.3.1 The Constructive Empiricist Stance

Van Fraassen proposed a new form of antirealism, which he called 'constructive empiricism', useful - among other things - for clarifying the notion of observable. Directly from the title, it was van Fraassen's intention to clearly explain how his conception of science differs from that of general realism. In fact, in his book *The Scientific Image* van Fraassen refers to an expression of Sellars (1963), which placed the scientific image of the world in contrast with its manifest image, namely with the way the world appears in human observation. It is precisely this position that van Fraassen opposes: science postulates non-observable structures (such as atoms or electrons) but its purpose is not to submit a truthful image by searching for constitutive elements. Rather, it strives to "save" this image that we have received and continue to receive from our senses. In short, science has to save the phenomena.

In order to support this position, van Fraassen had to argue against numerous and heterogeneous realist positions. First and foremost, van Fraassen recognized their common trait in the idea that science aims to provide us, with its theories, a literally true story of what the world is; and the acceptance of a scientific theory involves the belief that it is true. A realist must support the idea that these stories should be considered literally true in order to eliminate the possibility that science can be true only if it is properly understood, but literally false or meaningless, as conventionalists, instrumentalists and positivists think. Therefore, for a realist each term should have its truly existing referent and every theoretical relation must truly be present in the world.

Van Fraassen counterposes to this philosophical view his antirealism, or rather agnosticism, in which science does not aim for literal truth, but 'empirical adequacy'. Accepting a theory involves the belief that it is empirically adequate or, in other words, that it can save the phenomena, in the sense that it correctly describes what is observable. Science, therefore, states the truth only with respect to what is observable. Concerning the existence of what lies beyond, one must suspend judgment, and be, as van Fraassen declares, "agnostic".

The notion of observable therefore becomes central: for van Fraassen, science does not seek to discover new truths about the unobservable, but only to build models, which are appropriate for the phenomena. Observable entities (or physical quantities) have a remarkable ontological role regarding our attitudes towards scientific theories: our theories are based on the experience of the observable, taking humans as an epistemic community of reference. But a constructive empiricist is not required to take the truth of claims about observables to entail the truth of claims about unobservables; she is only committed to the idea that observed phenomena can exist within the structure described by the theory, without this implying that the unobservable entities of such theoretical structure are also part of the world's structure. Therefore, observability is a fundamental part of the typical epistemic attitude of science. But what is observable?

An observable is a hypothetical entity that can exist or not: a winged horse is a non-existent observable; the number two is an existent non-observable. Similarly, some human acts are observations (for example, an act of perception); others are not (for example, the calculation of the mass of a particle, aware of its trajectory in a known force field). Van Fraassen agrees with Maxwell (1962) on the impossibility of distinguishing an observational language from a theoretical language — even though it has no reflection on the problem of the possible existence of observables — but also supports two arguments against Maxwell's thesis on the vagueness of the notion of observable. The first concerns the inability to unambiguously differentiate what is observable from what is not:

> "A look through a telescope at the moons of Jupiter seems to me a clear case of observation, since astronauts will no doubt be able to see them as well from close up. But the purported observation of micro-particles in a cloud chamber seems to me a clearly different case—if our theory about what happens there is right. The theory says that if a charged particle traverses a chamber filled with saturated vapour, some atoms in the neighborhood of its path are ionized. If this vapour is decompressed, and hence becomes super-saturated, it condenses in droplets on the ions, thus marking the path of the particle. The resulting silver-grey line is similar (physically as well as in appearance) to the vapour trail left in the sky when a jet passes. Suppose I point to such a trail and say: 'Look, there is a jet!'; might you not say: 'I see the vapour trail, but where is the jet?' Then I would answer: 'Look just a bit ahead of the trail . . . there! Do you see it?' Now, in the case of the cloud chamber this response is not possible. So while the particle is detected by means of the cloud chamber, and the detection is based on observation, it is clearly not a case of the particle's being observed." (Ivi, p. 42)

The second argument is directed against Maxwell's theory that if something is non-observable to us, it is not in an absolute sense, because with the best tools available or a different perceptual apparatus we could also observe what we now consider non-observable:

> "I have a mortar and pestle made of copper and weighing about a kilo. Should I call it breakable because a giant could break it? Should I call the Empire State Building portable? Is there no distinction between a portable and a console record player? The human organism is, from the point of view of physics, a certain kind of measuring apparatus. As such it has certain inherent limitations—which will be described in detail in the final physics and biology. It is these limitations to which the 'able' in 'observable' refers—our limitations, qua human beings." (*Ivi*, p. 42-43)

Things that are observable only through the aid of instruments are not considered fully observable by van Fraassen and the invention of new instruments such as microscopes do not offer any new and real observations, for the criteria that determine what an observable is still depend on human physiology. When scientific observation is performed, we use the available tools, but what we actually do is referring to an empirically adequate physical theory, even though we cannot state what we are truly observing. It is clear that in order to consistently address the issue of scientific realism, it is necessary to make the notion of 'observable' less ambiguous as possible, which is connected with that of observation in ways that differ according to the type of realism or antirealism that one would want to accept.

1.3.2 Against van Fraassen's 'Observation'

A first critique of van Fraassen's notion of observation, and microscopic observation in particular, famously came by Hacking (1983), who proposed three arguments mainly concerned with 'manipulative realism' designed to show that agnosticism towards unobservables clashes with actual scientific practice. On the same line, Teller (2001) focuses on the issues raised by the agnostic view about microscopic observation and in particular van Fraassen's analogy with spectroscopes. Instruments of this kind are used to produce phenomena that can be observed without the aid of additional instruments; in fact, the only observation of empirical phenomena occurs when looking at the spectrographs that the spectroscope produces. According to Teller, however, this model does not apply to microscopes specifically, in which the equivalent for 'spectrographs' is missing, since what we directly observe are the microfeatures of the object itself on the microscope slide. In this case, Teller insists, we are not observing an independent image, and in fact to claim that "we perceive the microscopic image rather than the object on the microscope slide would be as wrong as to say that we perceive sense-data rather than physical [macroscopic] objects" (Teller 2001, p.133).

Van Fraassen (2001) takes the opportunity to address Teller's criticisms while updating his stance concerning unobservables and microscopic observation. He distinguishes between instruments as direct extensions of our senses that actually provide access to the otherwise unobservable world, and tools that generate new observable phenomena; microscopes are instruments of this second type, according to van Fraassen. "Microscopes", he writes, "are best understood as devices for producing publicly inspectable images" (van Fraassen 2001, p. 157), which fall within the category of "public hallucinations". In this respect, the distinction between empirical study and postulation of geometrical relation is crucial. In fact, the reflection of a tree in water is also a public hallucination, but in this case the geometrical relations that can be empirically studied occur between three empirical phenomena: the human eye, the reflection of the objet in water, and the observable object that is reflected. The same trichotomy does not apply in the case of the microscope, for only the geometrical relations between the eye and the microscopic image on the VDU are empirically accessible, not those between the eye and the postulated unobservable object. Ultimately, the impossibility of investigating the geometrical relations that occur between empirical and postulated entities is what justifies the agnosticism towards the latter. (*Ivi*, p.160).

Finally, an insightful recent suggestion to modify van Fraassen's constructive empiricism comes from Bacciagaluppi (2019), who proposes a moderate antirealist stance named 'adaptive empiricism'. With the focus on theory choice and the problem of theoretical underdetermination, for which the observable-unobservable distinction plays a major role, he suggests to adapt such a dichotomy to the *evolving* theoretical and experimental context. By doing so, the aim of science itself turns out to be not only to save the phenomena, but also "to determine the phenomena worth saving" (*Ivi*, p. 110), taking the 'theory-ladenness' more seriously and considering that the notion of observation in fact partially depends on what the theory tells us is observable.

1.4 Different Domains, Different Realisms: Physics vs. Biology

Irrespectively of its different specifications, I believe has now become clear that a naive form of realism that interprets scientific theories as being literally true full stop needs to be abandoned, also considering the confutation provided by the history of science. Nevertheless, the realist fundamental intuition, according to which empirical success represents an indicator of science being at least "on the right track", does not in any way entail such a naive conception. On the contrary, it can and must be developed and sophisticated through philosophical analysis and shown to be compatible with (and supported by) historical evidence. In doing so, the demand for generality that many realist and antirealist argument claim needs to be moderated and, more importantly, confronted with the actual content of specific theories in order to test their efficacy in describing the nature of scientific practice.

1.4.1 Realism in Quantum Physics

Let us consider for example the aforementioned tripartition of the notion of scientific realism itself, that is commonly adopted in the literature. The distinction works particularly well when considering quantum mechanics. In such a domain, an unavoidable trade-off between the realist and antirealist account with respect to the semantic, epistemic and metaphysical dimensions of the interpretation of quantum theory emerges. More specifically, keeping such tripartition as the framework of reference, it is impossible to hold an equally coherent view, whether it is realist or antirealist, for all the three dimensions. In this sense the very nature of quantum mechanics (indeterminism of quantum relations, systems characterized by a constitutive probability, superposition of states that collapse into a single component, all closely linked to the decisive role of an observer) produces a unique inversely proportional effect: holding a realist view concerning the semantic and epistemic aspects of the theory ends up generating an antirealist view with respect to the metaphysical one, and vice versa. In other words, if we believe that quantum theory is an effective description of the subatomic world and that it is at least approximately true, then we are forced to doubt such a thing as a mind-independent reality, at least at a microscopic scale.

On the other hand, if we believe that QM has to be understood only as a sound 'instrument' capable of good predictions with no descriptive power, whose theoretical statements have no counterpart in the world, than our realist metaphysical view of reality can be preserved, since we are excluding ontology from the theory domain. These three distinct questions, that are quite useful when asked to answer some of the realist problems within the physics - and quantum physics in particular - tend to loose their grasp when framing the realism debate in different scientific domains, for instance that of biological sciences. I shall elaborate more on this, and briefly digress on the problem of monism and pluralism in evolutionary biology.

1.4.2 Realism in Evolutionary Biology

Despite the lack of attention that this field has received from the philosophers interested in the realism-antirealism debate, some work on the issue (Brandon & Burian 1984, Shanahan 1990) seems to suggest that realist and antirealist views play in fact an important role in biological and philosophical debates on the 'nature' of natural selection. According to Darwinian evolutionary biology, much of the transformation of the biological world has been determined by the process of evolution by natural selection, that is, differential survival and reproduction of adapted forms of life. As far as this statement, there is no disagreement among philosophers and professional scientists (unless we are willing to listen to what creationists say, and we should not).

The disagreement begins with the attempt to provide a correct account of the processes that make up evolution by natural selection. The fundamental question in this sense concerns the way in which natural selection operates, and more precisely, the 'levels of nature' at which natural selection operates. The biological world is in fact hierarchically organized in ecosystems, species, populations, kin-groups, organisms, organs, cells, organelles, down to genes. The challenge essentially consists of understanding at which of these levels natural selection actually operates, which biological entities should be taken to be in competition with one another, and which of them show adaptation. The solutions to this challenge provided by the biological literature are very diverse and at times mutually incompatible (Stanford 2001), that is why the issue just described is still an open one.

The first underlying issue is concerned with the notion of observability of natural selection. Empirical research, representing a predominant component of biological investigation, is grounded on observation, and thus on what is observable. But natural selection can hardly be considered as a directly observable fact; it is rather the result of the conjunction of observational claims and theoretical principles. What can be (directly) observed may be phenotypic variation, competition for resources, likeness of offspring to parents, and differential survival and reproduction. The fact that some variations are selected over others in view of their greater fitness, and that such selection determines a progressive evolution of traits over time, are observational statements. Nevertheless, selection itself is not directly observable, and although the biological process of evolution by natural selection is a fact, not all facts are known by direct non-inferential observation of nature.

The second underling issue is concerned with the individuation of the level(s) of operation of natural selection, which are even less directly observable than natural selection itself. In fact, any number of biological entities involved in a selection process can in principle exhibit variation, but simply observing such variation does not represent a sufficient condition for effectively determining the causal roles in the evolutionary change, that is, which entities are actually responsible for it. For instance, during the interaction of a kin-group with some aspects of its environment, there are other levels of entities indirectly involved, such as the organisms of the group and the genes that compose them. These different kinds of entities are in a causal relationship with one another, which determines the interdependence of their respective properties: the properties of the genes largely determine the properties of the organisms, which in turn partially determine the properties of the group they compose. No unequivocal empirical determination is able to disentangle and distinguish the causal role(s) of each of these levels of entities, that is why theoretical assumptions must play a crucial role in solving this issue.

1.4.3 Hierarchical Monism & Pluralism

Many different theoretical accounts of natural selection have been proposed by biologists and philosophers in order to identify the constitutive units and levels of selection, but none of these accounts have been fully successful in such attempt (Brandon & Burian 1984). The impasse seems to suggest that there might be an erroneous underlying assumption in the formulation of the problem itself, and in fact, there is one specific presupposition that is equally shared by each of the theoretical accounts framing the problem of selection in the above-mentioned form. The common underlying assumption is that for every evolutionary phenomenon explainable in 'selectionist' terms, (in principle) it is always possible to isolate the units and the levels of selection that are causally determinant. In other words, what is presupposed is that the units of selection exist, that these units correspond to specific kinds of biological entities that constitute hierarchical levels, and, ultimately, that any explanation of a selection process needs the individuation and isolation of the single units and levels causally responsible for the process in question. This fundamentally realist presupposition, on which most of the theoretical accounts of natural selection are grounded, is defined by Sterelny and Kitcher (1988) as 'Hierarchical Monism'.

They contrast this view with a form of antirealist 'Pluralism', according to which the causal framework of any selection process can be accurately captured by multiple "maximally adequate representations". The main difference between the two positions is spelled out as follows: "Hierarchical monism differs from [pluralism] in an interesting way: whereas the pluralist insists that, for any process, there are many adequate representations […] the hierarchical monist maintains that for each process there is just one kind of adequate representation, but that processes are diverse in kinds of representations they demand." (*Ibid.*).

If, on the one hand, hierarchical monism requires a "plurality of processes", on the other hand pluralism requires "a plurality of models of the same process" (Ibid.). The key argument in support of their pluralist position is obtained by emphasizing the degree of arbitrariness through which the causal chain of the selection process can be subdivided.

1.5 Stanford's Unconceived Alternatives: a Case-Study

I shall conclude the chapter by presenting a particular antirealist argument as a paradigmatic case of (problematic) generalization of "how scientific practice works". According to Stanford (2006), historical records show that scientific communities have repeatedly failed, based on the available evidence at a given moment, to conceive of plausible alternatives to fundamental theories they did in fact develop. This seems to suggest that scientists are not able to exhaust the space of "likely, plausible, or reasonable candidate theoretical explanations for a given set of phenomena" (Stanford, 2006, p. 29). The main claim is that the problem of unconceived alternatives introduces what Stanford calls a new induction, which should be accorded to theorists rather than theories (Ruhmkorff 2011, Bonilla 2019). This shift is what should keep us cautious in granting truthfulness to present successful theories, for it is very unlikely that current scientists have succeeded in what their predecessors have failed, namely, to evaluate all the plausible alternatives to a given set of phenomena. To put it otherwise, for all available evidence at every given moment in every socio-cultural context there are always unconceived alternatives.

1.5.1 Conceivable vs. Inconceivable Theories

But a question naturally springs to mind: are these alternative theories unconceived because of a contingent failure within the scientific community, due to, say, socio-cultural limitations, to conceive them, or because they are inconceivable, due to theoretical, empirical and methodological limitations? In fact, two very different epistemic positions may underlie two very different classes of unconceived theories: alternatives that we could have conceived - being them conceivable - but failed to conceive at the time in which the previous ones were, and alternatives that we could not have conceived at the time in which the previous ones were - being them inconceivable.

Stanford's historical reconstruction draws a picture in which conceived and accepted theories repeatedly turned out to be the unrecognized, unconceived alternative of an antecedent one, and he generalizes such pattern to possibly every case of theory-change. This inductive generalization is indeed what generates his antirealist stance towards the scientific practice as a whole, rather than specifically selected theories.

But the analysis of the historical record that Stanford provides really only accounts for the alternatives of the first type, namely conceivable theories that we failed to conceive because of our constitutive cognitive limitations as epistemic agents. This is also confirmed by a few quotes from the case studies he offers as an exemplification of the problem of UA. Speaking of preformationists and epigeneticists, Stanford writes: "It is an historical commonplace that without any sophisticated chemistry or grasp of molecular complexity and without the benefit of cell theory, neither group could form any concrete conception of how complex structures could form sequentially in the developing embryo by purely material processes" (Stanford 2006, p. 54). A few pages later, in referring to our efforts to theorize about inheritance and generation, Stanford reveals one of the main assumptions of his argument: "[…] we continued to be plagued by the problem of unconceived alternatives long after we came to embrace substantive evidential, metaphysical, and methodological constraints essentially continuous with those of the present day." (*Ivi*, p. 60). In other words, present theories were proposed as alternatives to past ones long after they were (epistemically, metaphysically and methodologically) conceivable.

1.5.2 The 'Conceivability Condition'

Let's then see what the framework each theory-change example needs to fit in order for Stanford's new inductive argument to be consistent:

- At a time t_1, a theory T_1 is conceived and preferred over a set of other conceived but not equally well confirmed theories.
- At a later time t_2, an empirically inequivalent but equally well confirmed alternative T_2 is conceived and preferred over T_1.

- T_2 was conceivable at t_1, despite remaining unconceived until t_2, that is, the choice between T_1 and the not-yet-imagined T_2 remained underdetermined until t_2.

Now, let's make the 'conceivability condition' explicit:

- T_2 needs to be equally well supported by the evidence that supported T_1 at t_1, and compatible with t_1's background assumptions (or constraints), whether they be epistemic, metaphysical or methodological.

As we shall see, the implications of such a framework are quite radical - and implausible - when generalized and applied to other (well-known) cases of theory-change, for which the conceivability condition clearly does not hold. But is the condition itself a necessary element of the UA argument? Or, in other words, does the argument actually require new theories to be conceivable at the time in which the old ones were conceived and accepted?

Stanford claims the scientific historical record proves that we have repeatedly failed to exhaust the space of equally serious and well confirmed alternatives to current theories, based on the evidence that supported the latter. The acceptance of a later theory at t_2 provides, according to Stanford, the retrospective proof of the inability to conceive of at least one alternative at the time t_1 the earlier theory was conceived, irrespectively of what happened between t_1 and t_2. But what happened between t_1 and t_2 matters.

As Magnus (2006) notices, in a typical example, a theory T_2 is conceived within a period of revolution to try to account for some evidential anomalies the theory T_1 struggles with. During the period of controversy, T_1-supporters try to account for such anomalies within T_1 itself, while others formulate the new theory. At this moment (and only at this moment) there really is a problem of underdetermination between T_1 and T_2, but as further, decisive, evidence is gathered, the problem vanishes and the scientific community prefers T_2 over T_1. If Stanford confined his argument to the underdetemination there clearly is when evidential anomalies arise, then his antirealist argument couldn't be generalized — as he wishes — to present uncontested theories. In other words, in order for him to support the idea that even our best current theories, with no open dispute over anomalies of some sort they fail to cover, are open to the problem of unconceived alternatives, he needs not to consider anomalies and additional evidence as the necessary step for the conceivability condition to be met. Then, the choice between T_1 and T_2 needs to be immediately underdetermined at t_1, precisely when the conceivability condition of T_2 needs to be met (which is what does not seem to be the case for every example of theory-change).

1.5.3 From Newtonian Mechanics to Special Relativity

UA does capture some interesting (and often overlooked) features of theory-change when applied to some specific cases. The main example Stanford provides about the biological phenomena of generation and inheritance accurately instantiates the situation schematized by the UA framework: the failure of the scientific community to conceive of a viable alternative to the theory accepted at the time, despite its conceivability. Within the specific context of theory-change from Darwin's pangenesis theory of inheritance to Mendelian genetics, the historical record shows quite an explicit cognitive-epistemic failure in recognizing the available evidence as undermining the former while supporting the latter, rather than empirical, theoretical, and methodological limitations that prevented the conceivability of the latter. "This case", according to Stanford, "constitutes a particularly interesting source of support for the problem of unconceived alternatives, as it offers an especially clear testament to the inability to even recognize a particular unconceived alternative theoretical explanation for which the data, to modern eyes, seem to cry out. (Stanford 2006, p. 61).

While the peculiar example coming from the biological sciences does seem to properly fit the UA framework, some other much discussed examples within physics definitely do not, despite Stanford's confidence to find some sympathy for his general thesis among physicists and philosophers of physics in particular (*Ivi*, p. 51). This is rather evident when considering the paradigmatic passage from

Newtonian theory of space and time to Einstein's theory of special relativity (STR), to which we shall now turn our attention.

As Stanford states, "in the historical progression from […] Newtonian to contemporary mechanical theories, the evidence available at the time the earlier theory was accepted offered equally strong support to the (then-unimagined) later alternative." (*Ivi*, p. 19). But this is not enough, as shown at the end of the previous section, for UA implicitly requires the conceivability condition of the later theory to be met already at the time when the earlier was conceived and accepted. This would mean that at the time of Newton there were no empirical, theoretical, or methodological constraints that could prevent the scientific community to conceive of STR, but only cognitive-epistemic limitations that did so. In other words, STR was conceivable and, yet, remained unconceived until 1905.

This picture may already seem quite implausible, but further analysis will help stress even more some problematic (and perhaps undesired) consequences of UA, which shares with other realist and antirealist arguments a tendency to extend the reach of its claims to general notions, such as "scientific practice" or "our best theories", often resulting in a problematic tradeoff between generality and efficacy to adjust to specific individual cases. Indeed, in some works on closely related issues, such as DiSalle (1991), Norton (2004) and Cassini & Levinas (2019), it is possible to explicitly trace the (i) *theoretical*, (ii) *empirical* and (iii) *methodological* constraints for STR's conceivability that were inaccessible at the time of Newton and that turned out to be essential to Einstein's fundamental intuition about the relativization of the notion of simultaneity.

(i) *Thomson & Lange's Notions of 'Reference frame' & 'Inertial System'*

The general problem raised by the 17th century discussion about space, time and motion was essentially that of physical invariance in an appropriate geometrical structure, that accounts for the principle of Galilean relativity, i.e. mechanics experiments must have the same results in a system in uniform motion and a system at rest. Newton expressed the fundamental invariant quantity as force by solely acceleration, that is, power to accelerate a body independently of the velocity of the system in which it is measured. But he though such dynamical notion had necessarily to be represented in absolute space, which however could not be mechanically distinguished from any frame of reference that is in uniform motion relative to it. This, in turn, precisely implied the distinction between motion and rest that violates classical relativity (Disalle 1991, p. 139). Newton did understand Galilean relativity, which he incorporated in his *Principia* as Corollary V: "When bodies are enclosed in a given space, their motions among themselves are the same whether the space is at rest, or whether it is moving uniformly straight forward without circular motion" (Newton 1687, p.19). What he was not able to understand was that the dynamically equivalent but empirically indistinguishable relative spaces, whose velocity relative to absolute space could not be known, were in fact equivalent in principle, and the notion of a distinguished absolute space at rest was itself superfluous. According to DiSalle (2020), who poses the question of why Newton or his contemporaries could not recognize the equivalence of such spaces, "it must have been difficult, in the mathematical context of Newton's time, to *conceive* of an equivalence-class structure as the fundamental spatiotemporal framework. It required a level of abstraction that became possible only with the extraordinary development of mathematics, especially of a more abstract view of geometry, that took place in the 19th century (DiSalle 2020, p. 17, italics added).

Thomson's (1884) reassessment of the laws of inertia, that made use of the notions of "reference frame" and "dial-traveler" (a body that is rotating with respect to reference frame), highlighted the fundamental relation between Newton's laws of motion and inertial frames, namely, the existence of (at least) one inertial frame, with respect to which any other is in uniform motion. The point was that literally any inertial frame could be constructed as the "absolute" space in which all the others are uniformly moving, and, therefore, the crucial issue was no longer to identify the frame of reference in which the dynamical laws hold, but, rather, how "laws of motion essentially *determine* a class of reference frames" (DiSalle 2020, p. 23).

Lange (1885), independently of Thomson's work, introduced a new definition of inertial system based on the intuition that all motion is relative: an inertial system is a coordinate system with respect to which three free particles, projected from a single point and moving in non- coplanar directions, move in straight lines and travel mutually proportional distances (DiSalle, 1991). According to the laws of inertia, any fourth free particle will move uniformly with respect to any inertial system; thus, Newton's notion of absolute acceleration (and rotation) can be replaced by that of inertial acceleration (and rotation), relative to an inertial system (and timescale).

Although Lange's and Thomson's direct influence on Einstein, as well as their historical impact in general, is difficult to assess (DiSalle 1991, p. 140), by the beginning of 1900 the notion of inertial system had permeated the debate around mechanical philosophy and was assumed as the foundation for classical mechanics. In fact, as DiSalle (2020) notices, "in writing 'On the Electrodynamics of Moving Bodies' in 1905, Einstein took it to be obvious to his readers that classical mechanics does not require a single privileged frame of reference, but an equivalence- class of frames, all in uniform motion relative to each other, and in any of which 'the equations of mechanics hold good'." (DiSalle 2020, p.34). Surely, then, these works on the problem of reference-systems represent some of those essential theoretical advancements that contributed to make STR conceivable.

(ii) *Fizeau's Experiment on Ether*

In the late 19th century, some important experiments in optical physics were performed to determine the relative motion of the earth and the luminiferous ether – the alleged medium spreading through space that was thought to carry light waves – as well as to evaluate how the speed of light was affected by the motion of material (transparent) media. The notion of light defined as an electromagnetic wave spreading throughout the ether entailed that the frame of rest of the medium itself should have been a distinguishable element of the electrodynamical phenomena. However, the 19th century 'ether-drift' experiments

(Michelson-Morley's in particular) were not able to detect this state of rest (Norton 2004, p. 5), and the (re)interpretation of the results obtained by matter-ether interaction experiments eventually turned out to be crucial[3] in the abandonment of the ether as superfluous. We shall here focus on this latter class of experiments.[4]

Fizeau (1851)'s starting point was that any ether theory needed to properly relate the velocity of light, by taking into account the index of refraction of the medium through which it propagates, to a theoretical explanation in terms of ether-drag.[5] The second point was that no ether theory could yet give an account of light aberration (from a star reaching a telescope on the moving earth), and, therefore, a good explanation of the interaction between ether and matter was missing. Fizeau tried to measure the relative speed of light in water, using a particular interference system that measured the effect of the moving medium on the speed of light itself, by observing interference fringes produced by two rays of light passing through two parallel pipes filled with water flowing in opposite directions.[6]

Fizeau considered three hypotheses, only one of which to be confirmed by his experiment: (*a*) the ether has no interaction with the moving medium, (*b*) it is partially dragged by the moving medium (Fresnel's hypothesis), (*c*) it is fully dragged. He erroneously considered his observations of small fringes displacement to confirm (*b*), by assuming a portion of the ether was fixed to the water molecules, but Fizeau never considered that the effect could be explained without any reference to matter-ether interaction (Patton 2011, p. 215). And, in fact, Lorenz (1895) considered this fourth hypothesis, and proved it to be the right

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[3] A crucial experiment is usually understood as a way to test two or more predictions deduced from two or more rival hypotheses, but needs not to be decisive, namely, to provide the eliminative evidence that supports the acceptance of one hypothesis and the rejection of the others (Patton 2011 p.211 & Cassini & Levinas 2019, p.56).

[4] For a thorough analysis about the influence of the Michelson-Morley's results on Einstein's STR see Holton (1969), Pais (1982), Van Dongen (2009).

[5] Fresnel's ether-drag hypothesis has it that the ether is partly dragged along in the motion of a medium (e.g., water) having a refractive index larger than 1 (Stachel, 2005).

[6] For a detailed presentation of the experiment see Patton (2011) and Cassini & Levinas (2019).

one: the effects obtained by Fizeau, despite being compatible with (*b*), were determined solely by the reflection and refraction of light waves, rather than matter-ether interaction. This fact alone, however, did not prompt the Dutch scientist to abandon 'still ether' as a reference frame. It was only with the successive reinterpretation of Fizeau's experiment under the new conceptual framework of the equality of all inertial systems that its results turned out to be crucial for STR's conceivability.

Establishing the actual historical role the experiment has played on Einstein's formulation of STR is not devoid of controversy, given that Einstein does not firsthand state it in either published or unpublished articles on the topic (Cassini & Levinas 2019, p. 57). But the historical record of Einstein's oral presentations shows some explicit references to the relevance of Fizeau's results. For instance, Norton (2004, p. 25) mentions that Einstein recalled two experiments as having been important in guiding him to special relativity: Fizeau's experiment and the observation of stellar aberration. Here Norton is (most probably) referring to the conversation between Einstein and Robert Shankland, according to whom "when I asked him how he had learned of the Michelson-Morley experiment, he told me that he had become aware of it through the writings of H. A. Lorentz, but only after 1905 had it come to his attention! 'Otherwise', he said, 'I would have mentioned it in my paper'. He continued to say the experimental results which had influenced him most were the observations on stellar aberration and Fizeau's measurements on the speed of light in moving water. 'They were enough', he said" (Shankland 1963, p. 48).[7]

(iii) *Hume and Mach's Empiricist Philosophy*

Tracing those methodological aspects that were fundamental to the development of special relativity is a somewhat fuzzier operation than doing so with respect to the empirical results and the theoretical formalism. Yet, Norton (2004) does a great job in trying to isolate Einstein's methodological debts to the writings of

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[7] For additional references on the influence of Fizeau's results see Einstein (1923) and Moszkowski (1972).

Hume and Mach in particular, in terms of an account of the nature of concepts in general rather than the specific analysis of space and time carried out by the two authors.

The impasse that Einstein was confronted with was essentially that of an (apparent) incompatibility between the relativity principle and the constancy of the speed of light. Any Galilean-covariant theory (a theory of light that incorporates the principle of relativity) must be an emission theory, in which the speed of light is considered on a par with any other velocity of the Newtonian framework,[8] but Maxwell's electrodynamics could not be reconciled with the principle of relativity since it required a constant speed of light. As it is well known, the above- mentioned incompatibility vanished as soon as the notion of absolute simultaneity was abandoned. As Einstein himself clearly pointed out, his intuition came from a reconsideration of certain types of concepts that physical theories include, which, in order for them to represent something physical, must be grounded in experience: "The concept of simultaneity does not exist for the physicist until he has the possibility of discovering whether or not it is fulfilled in an actual case" (Einstein 1917, § 8).

This is precisely what Norton claims as the methodological insight that allowed Einstein to "take the step" towards STR, and whose foundations can be traced back to Hume and Mach's empiricist philosophy. As Norton shows, the demand that concepts must be properly grounded in experience permeates the two author's literature, and, in fact, "much of their philosophical critiques amounts to the purging of a priori elements from concepts that do not meet this demand" (Norton 2004, p. 17). Einstein (1916) makes explicit reference to the valuable method of conceiving concepts as physically meaningful only in so far as they are empirically grounded. But in Mach's writings specifically, it also emerges a radical attitude towards fictional concepts that leads to their complete elimination from any relevant account of the physical world, to which Einstein was reluctant. In his own words, from a 1948 letter to the friend Besso: "I see [Mach's] weakness in

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[8] The velocity of light relative to the emitter must be vectorially added to the velocity of the emitter relative to the observer, in order to determine the value of the observed velocity.

this, that he more or less believed science to consist in a mere "ordering" of empirical "material"; that is to say, he did not recognize the freely constructive element in the formation of concepts" (as quoted in Holton 1968, p. 231).

Hume's *Treatise of Human Nature* is also based on the analysis of certain notions ("ideas") that must be grounded in sense experience ("impressions"), in line with Mach's empiricism. But on the other hand, the Scottish philosopher did not propose to completely eradicate such notions that were not empirically grounded, as in the case of causality, but simply to give an account of their arbitrariness. And, indeed, the reconceptualization of a fictional concept whose arbitrary character is recognized but accommodated within the physical theory in such a way to "preclude unwitting introduction of false presumptions" (*Ivi*, p. 3), is precisely the theoretical step that Einstein took towards the relativization of the notion of simultaneity. It is perhaps for this reason that Einstein firsthand declared Hume's work having "much more influence" than Mach in the formulation of STR (Einstein 1949, as quoted in Norton 2004, p. 2).

A particularly insightful quote from Einstein (1916) shall highlight the interconnection there is between (i), (ii) and (iii), all of which together were necessary for STR's conceivability: "It is not improbable that Mach would have hit upon relativity theory if, in the time that he was of young and fresh spirit, physicists would already have been moved by the question of the meaning of the constancy of the speed of light. In this absence of this stimulation, which follows from Maxwell-Lorentz electrodynamics, even Mach's critical urge did not suffice to arouse a feeling for the necessity of a definition of simultaneity for spatially distant events" (Einstein 1916, p. 157).

In conclusion, if UA's analysis of the scientific historical records takes into account the distinction between conceivable and inconceivable theories, Stanford's argument turns out to be applicable only to those cases in which a certain theory (or set of theories) was conceivable but not conceived. In other words, if the distinction is accepted, the applicability of UA – together with the reach of its antirealist claim – has to be severely restricted.

Chapter II

RELATIONALITY

2. Relationality

This chapter is dedicated to the examination of the relationality at the core of the relational interpretation of quantum mechanics. Such a notion will be preliminary clarified in §2.1 from the perspective of the philosophy of spacetime (and philosophy of sociology for comparative purposes), distinguishing between the relationalism of the ontology and the relativism of values. This distinction will turn out to be crucial for the sections that follow, and for the general purpose of the chapter. In §2.2 I will historically trace some signs of relationality thus distinguished in the early developments of quantum theory, in particular in Heisenberg's matrix mechanics relationalism, Bohr's principle of complementarity, and Hermann's neo-Kantian "splitting of truth", the latter of which represents a remarkably explicit (and underestimated) example of a relativist reading of quantum observations. §2.3 is dedicated to presenting the measurement problem posed by the friction between the two different evolutions prescribed by the standard quantum formalism, out of which the need of an interpretation emerges. Rovelli's relational solution to the problem is thoroughly presented in §2.4. Remarkably, this interpretation relies on precisely the conjunction of an Heisenberg-type relationalism of systems and an Hermann-type relativism of values: variables of quantum systems have a value only within interactions, and such interactions do not assign absolute values to the variables. In the fifth and final section I extensively discuss several objections to RQM, with particular respect to the implications of the 'Wigner's friend' thought experiment, which has gained renewed attention in the recent literature about observer-(in)dependence in quantum mechanics. This, hopefully, will serve as the basis to explore the possibility – and the sense – of a structuralist interpretation of RQM that will be undertaken in the third chapter.

2.1 Relationalism & Relativism

Trying to delimit the semantic domain of the word 'relation', circumscribing the area of its concept within well defined boundaries is extraordinarily difficult, although relations are an everyday part of life that most people take for granted. Philosophers and scientists have always been perturbed about the intrinsic meaning of relations and they have tried to understand it through both theoretical and empirical analysis.

Speaking at the general metaphysical level, the notion of relationality applied to ontological investigation provides an interesting pattern to work with especially when counterposed to its alternative: substantivalism. The contrast between relational and substantivalist ontology is in fact strongly connected to the core of many different research areas (logic and metaphysics of course, but also physics, biology, sociology…), representing a constitutive aspect in particular within the study of space and time, as we shall see in a moment. The metaphysical question imposed by the friction between substantivalist and relational thinking is posed at both ontological and logical level, asking whether substances or relations are more fundamental. The basic claim of a relational approach is simply that the relations between substances are more fundamental than the substances themselves, whereas in substantivalist ontology substances are primary and relations derivative.

There is indeed some vagueness in the literature about relational ontology for the key idea of relation is nearly intangible. The difficulty also lays on the variety of relations, which seems to make the category untraceable. Even focusing on a single field of study the problem of complexity remains, for instance if we assume physical relations to be the simplest to analyze: classic-mechanical collisions, ordinary fields, relativistic thermodynamics and quantum entanglement show such a diversity in relations - and correspondent entities - that a unified physical theory of relation seems to be unachievable, and this philosophical issue becomes more relevant as soon as we take into account multiple areas of research. But even their formal set-theoretic characterization is complex. In a structure $S = \langle O, R \rangle$, each relation $r_1, r_2 \ldots r_n \in R$ is an ordered set of objects $o_1, o_2 \ldots o_n \in O$ between which the relation holds. Relations are n-adic or n-ary (where $n > 1$) because they are exhibited by particulars only in relation to other particulars. A binary relation R is symmetric iff whenever x bears R to y, y bears R to x. R is non-symmetric iff R fails to be symmetric. Asymmetric relations are a case of non-symmetric relations: *R* is asymmetric iff whenever *x* bears *R* to *y* then *y* does not bear *R* to *x*. A unigrade relation *R* is a relation that has a definite degree or adicity: *R* is binary, ternary, or *n*-ary (for some unique *n*). By contrast a relation is multigrade if it fails to be unigrade. And actually it is not even clear if there are such things as multigrade relations.[1]

2.1.1 Relationalism & Relativism in Classical Theories of Space & Time

Let's consider the very classic example of how relationalism has been shaped in opposition to substantivalism in the study of space, time and motion in modern physics. In his famous *Principia*, Newton introduced the notion of absolute space, which exists beyond and outside the relations between objects. Newton considered space as a 3-dimensional container in which God arranged the material universe at the moment of its creation, which implies that space was what it was before there were any material objects.[2] The main reason that prompted Newton to perceive space as an absolute was to distinguish between absolute and relative motion; the latter is the movement that an object has with respect to another, while absolute is the movement of an object with respect to the absolute space itself, understood as a system of universal reference. Leibniz did not agree with the Newtonian absolutist conception; he believed that space did not have any independent nature of the objects, but rather it was precisely defined by the totality of the spatial relations between objects. This relational interpretation implies the impossibility of identifying an absolute reality of space independently of other entities; on the contrary, entities are specially defended only through their relations. Leibniz's theory had a powerful argument. It demonstrated that the idea of absolute space contradicted the sound logic of the Principle of the Identity of Indiscernible. The proof by reduction to the absurd, initially grants the Newtonian assumption, showing the contradiction in a second excerpt: imagine two different universes, each containing the exact same objects. In the first

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[1] MacBride (2005) claims there are, Armstrong (2010) claims there are not.

[2] Newton accepted the principle that everything that exists, exists somewhere – i.e., in absolute space. Thus he viewed absolute space as a necessary consequence of the existence of anything, and of God's existence in particular.

universe each object occupies a particular position in absolute space; in the second universe each object has been transferred to a different position in absolute space. There would be no way to distinguish these two universes. We cannot observe the position of an object in absolute space, as Newton himself admitted; we can only observe the positions of the objects relative to each other, and these remain unchanged since all the objects have been moved to the same extent. Therefore, there is no observation or experiment that could ever reveal whether we live in the first or second universe.

Newton's definition of space as "of its own nature without reference to anything external, always remains homogeneous and immovable", presented in the *Scholium*, are usually (and appropriately) taken to be a defence of substantivalism, even in its more contemporary acceptation: the basic parts of space(time) figure among the complete list of the fundamental objects of the world, in addition to the elementary constituents of material entities. This, however, gives me the chance to introduce some important clarifications that will be useful when extended to more general terms in the following sections. Considerations about the ultimate nature of space were not the starting point of Newton's work, which was not primarily metaphysical but, rather, mechanical, and dynamical in particular. The questions that needed to be addressed concerned in fact motion, and the possibility of a privileged sense of (true) motion in opposition to his main polemical target, namely Descartes' 'change of place', that in the well-know bucket argument was shown to be not a mechanically significant sense of motion. The problem, as mentioned in §1.5, was that of physical invariance in an appropriate geometrical structure that accounts for the principle of Galilean relativity. Newton expressed the fundamental invariant quantity as force by solely acceleration, that is, power to accelerate a body independently of the velocity of the system in which it is measured, and he though such dynamical notion had necessarily to be represented in absolute space, a temporally enduring, rigid, 3-dimensional Euclidean space relative to which true motion occurs.

So, it is appropriate to introduce a distinction here, between interconnected but different uses of the term 'absolute' in these discussions:

(i) *absolute vs. relational*: refers to the question of whether theories about spacetime structure are merely theories about the spatiotemporal relations between physical objects or whether they describe independently existing entities, such as space, time, or spacetime, in which physical objects are contained.

(ii) *absolute vs. relative*: refers to the question of whether the values that characterize the elements of spatiotemporal structure are well-defined independently of any reference frame or well-defined only with respect to some specified reference frame.

2.1.2 Relationalism & Relativism in Special & General Relativity

The introduction of absolute space in response to the dynamical need of understanding motion and providing an interpretation of the concepts of constant motion and acceleration that appeared in Newton's laws, turned out to be posing also a (different) question on the ontological status of such an absolute space. As Hoefer et al. (2021, p. 14-15) pointed out, both types of problems were separately addressed by Leibniz in the influential correspondence with Clark (1715–1716): on the one hand, the problem of dynamically equivalent but empirically indistinguishable relative spaces, whose velocity relative to absolute space could not be known; on the other, the problem of characterizing absolute space as either material or non-material, as either a substance or an attribute.[3]

In fact, a contingent reason to further appreciate the distinction between (i) and (ii) comes directly from a general analysis of Newton's theory of motion itself, that can be seen as a composition of relational ii-type concepts inscribed in i-type absolutism: kinematic and Galilean relativity[4] on the one hand, absolute space on the other. In the specific context of spacetime theories, however, (i) and (ii) do depend on each other, to some extent. The so-called kinematic shift argument, for example, emphasizes that the Galilean covariance of Newtonian mechanics goes

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[3] Leibniz was presumably unaware of the unpublished *De Gravitatione* in which Newton developed these particular ideas more consistently, in what we might call a 'pseudo-substance', more like a substance than property, yet not quite a substance. (Hoefer et al. 2021, p. 14).

[4] Kinematic relativity: motion is motion with respect to something; Galilean relativity: absolute uniform straight line motion is undetectable.

against classical substantivalism, and in general underlines the strong connection between the spatiotemporal symmetries of dynamics and the spacetime ontology that the dynamical theory seems naturally committed to (Maudlin 1993). Nevertheless, it is not so straightforward that theories that deal with relative concepts must necessarily adopt a relational approach. This becomes even more evident when considering relativistic theories of spacetime. More explicitly, the question is whether special and general theory of relativity (STR and GTR respectively) require a relational account of spacetime, considering the relativization of some fundamental physical notions that were thought to be absolute in the classical regime.

Some early neopositivist interpretations (e.g. Reichenbach 1924), understood Einstein's relativistic physics as urging for a relational spacetime, full stop. And this idea have permeated the folk reading of the transition from Newtonian to relativistic mechanics as a clear vindication of Leibnizian mechanics and relationalism in general. But this was shown to be an oversimplification of the problem, e.g. in Sklar (1974) and Craig (2001), and it was pointed out that the reinterpretation of space in terms of spacetime recovered the possibility for a substantivalist account of STR specifically, in light of Minkowski's formalism, in which the problem of the dishomogeneity between spatial rotations and Galilean transformations was overcome by a 4-dimensional reinterpretation of the Lorentz group, of which the two classical ones were a particular case. Such a 4-dimensional geometry, together with a literal interpretation of the mathematical structure of spacetime, provided the basis for Minkowski's substantival stance. So, Craig (2001, p.1) argues, "in Newtonian theory an event's temporal location is absolute, while in STR its temporal location is relative, though its location in spacetime is absolute". Of course STR shall not be seen as directly supporting substantivalism as it was conceived in the classic debate, but still seems to leave some room for a (reformulated) substantivalist approach that does not conflict with the relativity of simultaneity and length contraction. According to Hoefer (1998), this is enough to consider substantivalism at least a plausible ontology for

STR; according to Rynasiewicz (1996) it is not, and more in general, the debate in relativistic context is meaningless.

The debate over GTR and spacetime ontology interestingly exhibits a very similar pattern. The theory also introduces a relativization of classically absolute terms, in particular extending Galilean relativity to accelerated motion (diffeomorphism invariance). Some see the reflexive qualitative content of the theory – quite poetically described by Misner et al. (1970) as “space acts on matter, telling it how to move. In turn, matter reacts back in space, telling it how to curve” – as an expression of the geometro-dynamics that would support a substantival view of a space-container. Many (e.g. Belot 1996, Gaul & Rovelli 2000, Martin-Dussaud 2021), however, believe a substantivalist ontology is in fact prevented by GTR’s diffeomorphism invariance combined with the so-called Leibniz Equivalence, according to which diffeomorphic models must represent the same physical world. By interpreting the 4-dimensional “bare” manifold without the metrical structure as representing physical spacetime, the substantivalist is committed to the idea that any arbitrarily diffeomorphic general-relativistic model,[5] to which different properties are assigned, represents a distinct possible world. This evidently negates Leibniz Equivalence, which in turn makes the theory highly indeterministic, as prescribed by one of the equivalence’s corollary, according to which diffeomorphic models can differ in properties that remain undetermined. This, in short, is the (in)famous Hole Argument[6] (Earman & Norton 1987, Stachel 1989). But this isn’t the *hole* story (pun intended).

In fact, others (e.g. Maudlin 1989, Hoefer 1996, Pooley 2006) believe that with the conceptual aid of modal metaphysics, and in particular some form of ‘antihaecceitism’, one is lead to deny that the relevant haecceitistic differences correspond to distinct physical possibilities, leaving some room for a – rather sophisticated – substantivalist stance. Finally, a few are convinced that, as in the

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[5] Of the type $\mathcal{M}_1 = \langle M, g_{ab}, T_{ab}\rangle$ and the diffeomorphic $\mathcal{M}_2 = \langle M, d^*g_{ab}, d^*T_{ab}\rangle$, where M is the 4-dimensional manifold, g_{ab} the pseudo-Riemannian metric tensor, and T_{ab} the stress-energy tensor.

[6] Einstein’s original formulation of the argument was meant to highlight the supposed problem of indeterminism for any generally covariant theory.

case of STR, the debate over GTR's spacetime ontology has completely lost its grip on the actually relevant question, that Curiel (2015, p. 28) characterizes as "what mathematical structures best represent our experience of spatiotemporal localization?", also skeptically asking what, after all, is lost to our comprehension of the physical world without such a unique, canonical explication provided by either substantival or relational approaches.

Regardless of the side one might take in this articulated debate, the point is to stress the distinction between the relationalism of the theory and the relativism of the elements within the theory, which tend to be not so neatly separated in the literature, perhaps also because of the strong interconnection these notions have in the specific domain of spacetime theories, as it has been pointed out. For example Martin-Dussaud (2021) nicely exposes the "relational trend" that fundamental physical theories have followed, analysing the relativization processes within general relativity and quantum mechanics. But despite the declared intention of "reaching precision about what is meant by relationality, because it is a very general notion, and it is easy to get confused by a misuse of terms" (*Ivi*, p. 1), it seems like he missed the chance of really pointing out the above-mentioned distinction. On the contrary, with not much awareness the author jumps from GTR's general covariance and diffeomorphism invariance, purely dynamical notions, to spacetime relationalism, which, as we have seen, brings with it a metaphysical stance. Similarly, after insightfully looking at the relativization of quantum properties based on contradictory measurements outcomes that Wigner's Friend scenarios make explicit, jumps to relational quantum mechanics without much attention to the interpretational aspect of it, which, again, bear some ontological weight as well.

2.1.3 The Case of Relational Sociology

Perhaps the clear-cut separation of relationalism and relativism appears more vividly once different scientific domains are considered. Take sociology for example. Its latest paradigm-shift consists precisely of the idea that the kind of ontology underlying social phenomena is relational. Especially since Emirbayer's

(1997) Manifesto for a Relational Sociology, relationality has been characterized as the ontological foundation of the social world, primarily constituted by relations among actors rather than by actors themselves. This relational perspective was first sketched out by some of the founding fathers of sociology, such as Karl Marx and Georg Simmel, but since the mid 90s, it has become the predominant approach within the study of social networks and social structures (e.g. Somers 1994, Abbott 1997, White 1997).

In order to describe the sociological concept of relationality, it would be useful to evoke the philosophical focus on 'action' proposed by Dewey and Bentley (1949). They distinguished between three different kinds of action: self-action, inter-action and trans-action. Entities in self-action "act in their own power" apart from all the others; entities in inter-action are "balanced […] in causal interconnection" between each others; in trans-actions instead, "systems of description and naming are employed to deal with aspects and phases of action, without final attribution to 'elements' or other presumptively detachable or independent 'entities', 'essence' or 'realities', and without isolation of presumptively detachable 'relations' from such detachable 'elements'" (*Ivi*, p. 108). According to Emirbayer (1997, p. 287), self-action and inter-action correspond to the substantivalist sociological perspective, whereas trans-action instantiates the relational approach in sociology, where entities are not conceived as something ontologically independent of, or logically antecedent to, the relations they establish. On the contrary, substances acquire their ontological status within their relations. Generally speaking, the transactional view has been the main path followed by contemporary sociology, reflecting the logic behind social network analysis, which conveys the following idea: a social network *is* "relations among actors".

Notice that such a relational approach does not (need to) rely on the relativization of the values of the elements its theories deal with. And, in fact, it does not: in social network analysis, for example, networks dynamics, centrality measures, networks flows and interactions rates are regularly described by absolute values, within a relational sociological approach.

2.1.4 Final Remarks

It is useful at this point to broaden the distinction between (i) and (ii) that was given in the restricted context of spacetime theories, so as to provide a more general framework to refer to when discussing the relationality of quantum mechanics and RQM in particular:

(i*) *substantival vs. relational*: different metaphysical stances that describe the nature of an object-relations structure, ascribing ontological priority to either objects or relations.
(ii*) *absolute vs. relative*: different characterization of the values of the properties of whatever entity or fact the theory is describing, as either well-defined irrespectively of other entities or facts or well-defined only with respect to other entities or facts.

Metaphysical considerations come into play in (i*), and for this reason are naturally and inevitably intertwined with the problem of realism. Relational views have often been associated quite directly to antirealist metaphysics,[7] as in the case of Leibniz, whose works are characterized by a robust rejection of any notion of space as a real thing rather than an ideal, purely mental entity, and simply denying the mind-independent reality of space (Hoefer et al. 2021). But structuralist approaches, and in particular their ontic formulations introduced in contemporary philosophical debate, most notably by the work of James Ladyman and Steven French, have provided an interesting framework to recover a form of realism within relational approaches. This and other aspects of structural realism will be discussed in greater detail in the third dedicated chapter. For now, it is worth mentioning that there is no necessary correspondence between structural realism and relational accounts. With respect to spacetime, for instance, Pooley (2006) believes that while generally covariant theories may well support a relational view of spacetime, they definitely do not support or suggest structural realism and its

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[7] In particular its independence sub-thesis (II) discussed in chapter I.

interpretation of the metaphysics of spacetime points.[8] Nevertheless, if any correspondence can be established, it would have to be between relational rather than substantivalist approaches, as we shall see.

In the sections that follow, the notion of relationality in quantum mechanics will be explored, keeping the relational-relative distinction as a framework of reference that will be particularly useful when discussing RQM. This interpretation, in fact, represents quite a unique merge of relationality of systems and relativization of values that Rovelli incorporates in his response to the major interpretational difficulty raised by the quantum formalism, i.e. the measurement problem, and its exemplification in a 'Wigner's friend' scenario. The conjunction of the two notions was already implicit in Rovelli's (1996) first sketch of the interpretation and became explicit in many later works (e.g. Rovelli 2016, Rovelli & Laudisa 2019, Rovelli 2021, Rovelli & Di Biagio 2021): (a) variables of quantum systems have a value only within interactions; (b) such interactions do not assign absolute values to the variables.

This operation, together with the analysis of the relational aspects of the early developments of quantum theory, will serve as the basis to explore the possibility – and the sense – of an ontic structuralist interpretation of RQM that will be undertaken in the third chapter, in opposition to other three main interpretational lines: epistemic or information structural realism, relativism and neo-kantianism.

2.2 Relationality in (early) Quantum Mechanics

Before undertaking an analysis of RQM's relationality, it will be profitable to historically trace some signs of this notion in the early formulations of the theory.

2.2.1 Discreteness & Indeterminism in Matrix Mechanics

Let's start by introducing some of the general features of QM in opposition to classical physics: the irreducibly discrete character of the values of some variables, and the irreducibly probabilistic character of their predictions. In classical mechanics energy was thought as a continuous physical quantity forming a

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[8] There is no general consensus on this. For example Dorato (2000) claims the opposite.

continuous spectrum. However, the curves resulting from the measurements (few long waves, few short waves, a peak in an intermediate area that depends on the temperature, quick drop towards zero in the area of short waves) were in complete contradiction with the theoretical results obtained by the application of Maxwell's equations and the laws of thermodynamics, which predicted a distribution of wavelengths concentrated on the blue-violet, and an intensity tending to infinity in the most extreme ultraviolet areas. Planck's attempt to resolve the so-called "ultraviolet catastrophe" of the spectrum of a black body in 1900 represents the first step towards a 'quantization' of energy, and the related fundamental physical quantities. He empirically derived an equation that was able to give an account of experimental data, proportionally relating energy and the frequency of its associated electromagnetic wave through a constant: $E = hf$.

Planck constant,[9] often expressed in its reduced form $\hbar = h/2\pi$, ended up representing the discreteness at the core of quantum theory, laying at the very basis of its fundamental equations describing the mechanics of atomic physical systems. In more technical terms, it imposes a minimal limit to the volume of the region that the values of variable properties can have in phase-space. In the formal description of the state of a physical system, systems are defined by a set of variables, such as position and momentum, and a phase-space in which the possible values of the variables are inscribed. In classical mechanics it is always possible to determine a point in phase-space for every variable, that is, each possible value corresponds to a unique point in the phase-space, whose region R can be taken to be arbitrarily small. In QM, instead, the volume of the phase-space region is limited by the dimension of the Planck constant according to the relation $V(R) \geq h$, which, in turn, limits the values that each variable of a system can take.

Planck constant also fixes the maximal limit of the accuracy in predicting the values of the variables from certain initial conditions. This fact is famously grounded in Heisenberg's (1925) "breakthrough" paper, formalized in Born &

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[9] Sometimes referred to as Planck-Einstein constant, given its use within the description of the photoelectric effect. Einstein realized that the energy of light itself was not transferred continuously, but in quanta, i.e. photons, whose size corresponded to Planck's energy "packets".

Jordan (1925), and further developed in Heisenberg's (1927) introduction of the uncertainty principle. Bohr's atomic model was still based on Rutherford's planetary structure and was not able to give an account of the spectrum of most complex elements (actually, it only worked well with Hydrogen). Heisenberg realized that knowing the trajectory of the electron around the nucleus was not necessary for an exhaustive account of atomic radiation, and that classical description of motion on sharply defined orbits needed to be replaced by only the relevant observable quantities expressed by the Fourier-transform[10] components of motion., i.e. intensity and frequency of the emitted light during the quantum jumps. This non-classical description of motion implied the impossibility of answering classical questions concerning the exact position and momentum of a particle in a trajectory; that a certain value was possible and occurred with a certain probability were the only relevant aspects. His equation was based on an unusual relation between amplitudes and intensity of the oscillation, which implied that arithmetical commutation law wasn't always valid. Heisenberg's original paper neither used nor mentioned matrices directly, but Born soon recognized them as being the mathematical tool at the core of his approach. Classical dynamical quantities were redefined within the quantum context through a new algebra of physics,[11] in which the commutative property of multiplication does not hold for position and momentum operators, respectively q and p, so that $qp \neq pq$.[12] With respect to position for example, q_1, q_2, $q_3 \ldots q_n$ in the matrix represented all the possible values that the electron could take in each possible jump.

But there was more: not only were the electron's trajectories unnecessary for the computation of the related spectrum, they were also impossible to calculate. Indeed, the young scientist realized that a measurement on a variable of a particle would have affected the precision in the measurement on the related non-

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[10] A mathematical transformation that decomposes functions depending on space or time into functions depending on spatial or temporal frequency.

[11] It was not really knew, in fact, but it had been only applied to abstract numerical systems.

[12] The relation refers to a matrix of values of q and p (not to a single value of q and p), so qp and pq represent matrix multiplications of the two matrices, whose result is a third matrix.

commuting variable. In other words, there is a minimum amount of momentum disturbance caused by any position measurement, and vice versa. The uncertainty paper is based on this idea: non-commutativity implies that the two values cannot be simultaneously sharply measured, and the uncertainty on the measurement of q and p tends to a minimum that, again, is fixed by $\hbar$, so that: $\Delta q \Delta p \geq \hbar/2$.

It should be noticed that the probabilistic character of quantum predictions was already implicit in the non-commutativity of variables, whose difference is fixed by $\hbar$, that was formalized by Born & Jordan (1925) in the canonical commutation relation: $[q, p] = \hbar i$. In more technical terms, for a pair of operators Q and P, a commutator is defined as $[Q, P] = QP - PQ$, which gives a measure of the extent to which a certain binary operation fails to be commutative. In matrix mechanics, the size of non-commutativity of conjugate quantities is represented by Planck constant, so, contrary to classical mechanics, their values can never be sharply determined in phase-space, that is why the prediction of their values is always probabilistic.

2.2.2 Heisenberg's Relationalism

The merge of discreetness of values and probability of their predictions already posed an early form of interpretational question, even independently of the wave mechanics formulation of the theory, namely, how (and when) variables actually take one of the determinate (discrete) possible values probabilistically predicted. It is perhaps possible to identify a form of relationalism in Heisenberg's reply to such a question, that is implicit in the algebraic approach to quantum theory.

Rovelli (2018), glimpses some reference to the relational character of QM in the abstract of Heisenberg's 1925 paper, which reads: "The aim of this work is to set the basis for a theory of quantum mechanics based exclusively on relations between quantities that are in principle observable." Then Rovelli adds: "Only relations between variables, not new entities" (*Ivi*, p.2). Although this specific reference may be a bit of a stretch, Heisenberg's approach is in fact based on an exclusive focus on observable physical quantities, whose values are well defined only under the appropriate measurement conditions. Values evolve in time, and quantum jumps represent the updates of these values upon measurement, so given the results obtained within a first system-observer interaction, the possible results of a second system-observer interaction are statistically computed. In this perspective, only physical quantities evolve in time, not quantum states, and what happens outside of an interaction is none of the theory's business, so to say: "the matrix mechanical picture assumed that systems were always in stationary states, and randomly performed quantum jumps between them." (Bacciagaluppi 2021, p. 4). So, as opposed to the wave formulation, in which – as we shall see in the next section – the quantum state provides a complete description of an individual system that evolves in time, in the algebraic approach a quantum state merely represents the information about antecedent measurements which gets updated only through a subsequent measurement interaction. In other words, operators incorporate a dependency on time, but the state-vectors are time-independent (Peres, 1984).

The interaction-dependent character of value acquisition of stationary-state systems does seem to point towards a form of relationalism in matrix mechanics, in the sense expressed by (i*) in § 2.1. Nevertheless, Heisenberg was never really explicit about it, and, as Jaeger (2009, ch.3) notes, his views about quantum theory in general, and quantum state in particular, oscillated over the years from positivism and empiricism, to a form of realism without ever attributing any form of relationalism to his interpretation of quantum theory. And neither was he ever fully convinced about the whole matrix mechanical picture that provided no description of the state itself, as he clearly stated in the Solvay joint report with Born (Bacciagaluppi 2021, p. 5).

2.2.3 Bohr's Complementarity

Bohr was also never explicit about a possible relational reading of quantum theory, but some elements of his analysis of the contextual character of quantum phenomena seem to point in the direction of a relativisation of quantum observations. What he was explicit about is the impossibility of sharply separating the behavior of quantum systems from the measuring system that creates the context in which the measured objects behaves. So different experimental contexts determine different pictures of which no single privileged one can give a full account of physical reality. This was essentially the idea at the core of the principle of complementarity, first presented at the International Physics Congress held in Como in 1927, and published one year later: the quantum realm manifests itself in the form of different and yet complementary pictures, all of which together are needed for a complete account of the phenomenon under investigation, and to provide a generalization of the way classical physical phenomena are commonly described. He saw in the essential discreetness of atomic processes fixed by Planck constant (what he called "the quantum postulate") the origin of the observer-dependent values of the properties of a system that did not allow an unambiguous definition of its state – as opposed to classical mechanics – irrespectively of the experimental context. In Bohr's words: "The quantum postulate implies that any observation of atomic phenomena will involve an interaction with the agency of observation not to be neglected. Accordingly, an independent reality in the ordinary physical sense can neither be ascribed to phenomena nor to the agencies of observation" (Bohr 1928, p. 580). Perhaps misleadingly (Rovelli 2018, p. 2), Bohr had also taken Heisenberg's uncertainty relations to be another expression of quantum complementarity in terms of the so called wave-particle duality: depending on the measurement setup, either wave-like or particle-like behaviour emerge as one of the two complementary aspects of the nature of quantum phenomena which cannot be simultaneously observed independently of the experimental context (Baggott 2011, p. 97).

A shifted – or perhaps enriched – understanding of complementarity was also a central notion in Bohr's (1935) reply to EPR paradox (Einstein Podolsky & Rosen 1935), an argument formulated against the completeness of quantum theory, through the inviolability of locality,[13] and grounded on a classical reality criterion that lead to emphasize the problem of the "spooky action at a distance"

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[13] Locality is the key aspect of EPR argumentative structure, and completeness just its means: the principle of locality is inviolable; if QM is complete, it violates the principle of locality; therefore QM must be incomplete.

between two non-directly-interacting entangled particles. Bohr's response, in which "spookiness" was not taken to be a real problem and the argument itself was not taken to be a real paradox, was to some extent unexpected and focused on a thorough account of quantum measurement in light of complementarity: in Bohr's view, EPR relied on a classical (non-contextual) notion of measurement that was supposed to be sufficient to directly determine the elements of reality in terms of real physical properties; but in his response, he emphasizes how the reference to the particular experimental procedure essentially shapes the meaning of physical reality itself. In other words, the complementarity of different measurement contexts cannot be ignored, for a statement concerning one particular setup of the experimental apparatus cannot be unambiguously combined with a statement deduced by means of the other.

This applies to quantum mechanical measurements in general, whether they be of two spatially separated entangled particles, as in EPR case, or of a single particle passing through a slit, as in Bohr's reply. Bacciagaluppi (2015) has extensively discussed the connection between the two cases, and made a powerful point about their equivalence in terms of the extended notion of complementarity that comes into play when referring to the two-stage structure of experimental procedures. Within such a structure, it is essential to isolate the first interaction between the primary system and an auxiliary system, that is when mechanical disturbance occurs, from a successive measurement on the auxiliary system, which implies no further interaction with the primary system. Crucially, the role of 'auxiliary system' can be played by both the entangled distant particle of EPR's example and the diaphragm in the single particle example. The different character of the predictions that emerges from the free choice of the measurement to be performed on the auxiliary system represents, on the one hand, the irreducible difference between classical and quantum experimental contexts, and on the other, the symmetry between EPR's and Bohr's scenarios: "depending on the free choice of the observer, one is able to reconstruct only one or another aspect of the original interaction between system of interest and auxiliary system, leading to different kinds of predictions on the system" (*Ivi*, p.16). This is true of any quantum measurement, and false of every classical one.

Thus, it is only within the interaction between the physical system and the correlated measuring system that property ascription becomes meaningful, and the values of each measured property are well-defined. Within this view, the variables of a system can take contextual values with respect to a particular type of observer. In fact, Bohr's reference to the fact that ordinary measuring apparatus are macroscopic may lead to the misleading conclusion that the apparatus themselves are not subject to quantum mechanical descriptions. For instance, Rovelli (2021, p. 12) argues that "[Bohr] expressed this contextual character in the "observer-measurement" language. This language requires that special systems (the observer, the classical world, macroscopic objects...) escape the quantum limitations". This very statement, however, is also context-dependent. It is rather clear (e.g in Bohr 1949) that these macroscopic systems are to be treated quantum mechanically, indeed, within the specific experimental context in which predictions *about them* are made, so, if they become themselves the primary system to be measured. In this regard Dieks (2009, p. 772) suggests that Bohr's reference to the macroscopic nature of a measuring device is simply aimed at making contact with experience and ordinary language, by referring to situations in which the concepts of classical physics, like position and momentum, are applicable.

According to Jammer (1974), Bohr's account of quantum theory, and measurement specifically, introduced a form of "epistemic relationism" that needs to be understood under a broader instrumentalist stance: theories predict observable measurement outcomes but do not (necessarily) describe physical reality. It is argued that Bohr's view is relational because of the necessary reference to specified physical arrangements, each of which denotes a different perspective. And it is instrumentalist, because "although a perspective may be occupied by an observer, it also exists without such an occupancy." (*Ivi*, p. 201).

2.2.4 Hermann's Relativism

I shall return on the relationship between relationalism and realism in a few pages, but it is worth spending the rest of the current section discussing some relevant aspects of the philosophy of Grete Hermann, who, contrary to both Heisenberg and Bohr, was rather explicit about the relative character of quantum observations. The work of this multifaceted and creative thinker, that ranged from philosophy and foundations of physics to ethics and politics, is to be placed in the context of a marked neo-Kantian natural philosophy (the 2017 book on Hermann edited by Crull and Bacciagaluppi collects a number of insightful contributions that emphasize this). This mid-nineteenth century movement tried to recover the original aim of Kantian philosophy, conceived as an investigation of human cognition and its conditions of possibilities and justification that provides an epistemological foundation for scientific knowledge, without falling into either transcendental idealism or full-fledge positivist materialism (Cuffaro 2021). This general stance has been at the core of Hermann's work throughout her philosophical development, and emerges quite clearly in her philosophy of physics. In particular, the 1935 essay on a natural-philosophical foundation of quantum mechanics represents a turning point in her intellectual enterprise, which, on the one hand, stands in contiguity with the neo-Kantian tradition, but on the other, marks her original disruptive approach.

A first aim of the essay is indeed to recover a fundamental classical concept on which our knowledge is grounded that needs to be reconceptualized in light of quantum theory, i.e. causality; but a second and perhaps more subtle aim is to investigate at what cost this can be done. Crull (2017) sharply points out that this second aim hides the most fundamental aspect not only of the paper itself, but also of the more general framework of Hermann's natural philosophy, represented precisely by the irreducible context-dependence of observation.

The "splitting of truth", according to Hermann, is the cost of preserving causality from quantum indeterminism. The guiding principle of her analysis is neither to abandon causality completely as a superfluous notion for predicting measurement outcomes due to the uncertainty relations, nor to maintain it as an absolute concept. In a sort of middle ground, the explicatory applicability of causality needs to be relativized, that is, a retrospective – and yet classical – causal account of a measurement is possible, but only within the specific observational context in which it was produced. For instance in Heisenberg's γ-ray thought experiment, on which Hermann starts her analysis, the choice between image and focal plane determines whether we are able to measure position or momentum of the electron after colliding with a photon. This applies to any measurement of quantum systems, whose causal history can be meaningfully reconstructed only within the selected experimental context that registered a certain value for a certain property. This, in turn, prevents ("cuts off") the experimenter from ascribing a complete causal history to the system with respect to its other non-commuting variables.

Thus, while it is true that in QM we can no longer completely determine a physical system in space and time by mathematical and dynamical (Kantian a priori) principles, "the classical description is compatible with the quantum mechanical one insofar as its quantities remain undetermined to such a degree that the indeterminacy relations are fulfilled" (Hermann 2017, p. 244). There is indeed a precarious connection between such a perspectival account of physical descriptions and objectivity, which fundamentally depends on the characterization of this latter notion. If by 'objective' we mean 'absolute', then no, the possibility of such a description of physical reality is ultimately prevented by quantum mechanics; but if by 'objective' we simply mean 'non-subjective', then yes, such a description of physical systems is allowed by quantum mechanics, as long as it is formulated within a particular experimental context. Hermann (2017, p. 260) explicitly writes about the relative nature of quantum mechanics: "Control of the arising disturbance does not fail because the formalism is still defective with respect to the explanation of this disturbance and thus in need of completion, but because the explanations it provides – which are complete and therefore not liable to emendation – are valid, as are all quantum mechanical statements, only relative to a certain observational context. […] The explanations for the disturbance provide a foothold for predictions only to one who has performed this observation, and thus finds himself in this observational context."

In other words, within the perspective of a well-defined experimental context that is set up to measure a certain variable, there is no missing information that can prevent us from ascribing a complete (retrospective) causal history to the system, in such a way that having a particular value for a certain property can be characterized as the cause of the measuring apparatus indicating that particular value. This is a contextual fact, and yet, an objectively testable fact.

As we shall see, this perspectival account of (objective) value ascription is a constitutive element of relational quantum mechanics, even though Rovelli has never firsthand recognized Hermann's relativism as precursor for his interpretation. In fact, Hermann's *Spaltung der Wahrheit* seems to be more radical and fundamental than Bohr's epistemic view, and for this reason, more hospitable for the relationality of RQM, whose central tenets turn out to be very much in line with what Hermann takes to be the most important lesson from quantum mechanics: "the splitting of truth goes deeper than philosophy and natural science had previously assumed. It penetrates into the physical knowledge of nature itself; instead of merely delimiting its scope against other possibilities for grasping reality, it separates various *equally legitimate* representations within the physical description that cannot be unified into a single picture of nature." (Hermann 2017, p. 277, emphasis added). In full neo-Kantian spirit, epistemological constraints do not eradicate ontological considerations completely. They certainly represent the limits of our cognitive access to "things in themselves", but this does not imply that all talk of things in themselves should be thought of as empty and without significance (Cuffaro 2021, p. 8). In fact, quantum mechanics can be seen as providing the (missing) link between the limitations that were previously though to pertain to human cognition exclusively to some constitutive limitations of the physical world itself.

Bohr's view, on the other hand, exhibits a much more marked epistemic character, especially concerning the notion of objectivity, as it is reflected by the "linguistic turn" that has been pointed out by de Ronde (2015), in which physics is understood as being fundamentally grounded in language. The ontological questions concerning quantum phenomena had to be "suspended", because what the mathematical formalism was really about became the "unspeakable". In a somewhat positivist spirit, the alleged objectivity of quantum observations is guaranteed by linguistic reference to classical phenomena and experimental devices: "On the lines of objective description, I use the word phenomenon to refer only to observations obtained under circumstances whose description includes an account of the whole experimental arrangement.[...] The experimental conditions can be varied in many ways, but the point is that in each case we must be able to communicate to others what we have done and what we have learned, and that therefore the functioning of the measuring instruments must be described within the framework of classical physical ideas." (as quoted in Wheeler & Zurek 1983). So, in Bohr's framework, correspondence principle[14] and intersubjective agreement play the major role in bridging the gap between classical and quantum concepts while saving objectivity, rather than the relative character of quantum observation, as in Hermann's view.

A final remark that I wish to make concerns the surprising affinity between Hermann's middle-ground approach towards causality, and the influence of Hume's empiricism on Einstein's conceptual step towards special relativity, that has been discussed in chapter I. Recall what has been pointed out about the Humean empiricist stance: in the *Treatise*, Hume did not intend to completely eradicate concepts that were not empirically grounded, but to give an account of their arbitrariness, that is, to reconceptualize the fictional concept whose arbitrary character is recognized but accommodated within the physical theory in such a way to preclude unwitting introduction of false presumptions. This is precisely the theoretical step that Einstein took towards the relativization of the notion of simultaneity. Similarly, Hermann is not willing to completely abandon the fundamental classical notion of causality that no longer finds an unambiguous and intuitive application in the quantum domain, but rather restricts its criteria of application to the chosen contexts of measurement. In both examples, the

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[14] See Crull (2017) for a detailed analysis of Hermann's Kantian reading of the principle.

classical notion in question is still considered to be indispensable to our understanding of the physical world, but needs to be relativized in accordance to the empirical and theoretical restrictions that each non-classical theory prescribes. In both cases, a relativization of values in the sense expressed by (ii*) of § 2.1 is implied.

But it is now time to introduce another essential piece of the quantum formalism, that has so far remained in the background of these discussions concerning the problem of measurement.

2.3 Interpreting the Measurement Problem

Let’s begin by sketching out the main features of the wave formulation, whose introduction and development contributed to posing the actual problem of an interpretation of the quantum formalism, and of measurement more specifically.

In general terms, the state of a physical system is the most exhaustive mathematical representation of the variable (or contingent) properties[15] of the system that the theory admits. Being a representation of variable properties, the state of a system is (generally) time-dependent; so, given a certain state at a certain time, the theory provides a way for computing the state at later (or previous) times. In classical mechanics, the state of a particle at time t is represented by (x_t, v_t), where x_t is the position of the particle and v_t its velocity. Given the (known) state at the time t_0 (x_{t_0}, v_{t_0}), the state at the time t_0+dt is given by $x_{t_0+dt} =$ $= x_{t_0}+dx$, and $v_{t_0+dt} = v_{t_0}+dv$. By iterating this process one gets the state (x_t, v_t) at every t, and the evolution is deterministic.

2.3.1 The Notion of State in the Standard Formalism

In quantum mechanics, and in its Dirac–von Neumann formulation specifically, states have a much more complex structure. They are specified by the wave-function, a complex function $\psi_t(x)$ of the position variable of the system which belongs to a function space $\mathcal{L}^2(\mathbb{R})^3$, i.e. a Hilbert space.[16] The most important

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[15] As opposed to invariant state-independent properties, such as the mass.

[16] An abstract complex vector space.

property of this space is linearity: if $\psi'(x)$, $\psi''(x) \in \mathcal{L}^2(\mathbb{R})^3$, also $c'\psi'(x)$, $c''\psi''(x) \in \mathcal{L}^2(\mathbb{R})^3$, where c' and c'' are complex numbers. In particular, if $\psi(x) \in \mathcal{L}^2(\mathbb{R})^3$, then $c\,\psi(x) \in \mathcal{L}^2(\mathbb{R})^3$. Also, each element of $\mathcal{L}^2(\mathbb{R})^3$ is taken to be a possible state of the system, so if $\psi'(x)$, and $\psi''(x)$ are states of the system, then $c'\psi'(x)+c''\psi''(x)$ is also a possible state; this is the formal expression of the superposition principle, when adequately extended to more general systems. The wave-function can be also expressed in the synthetic notation $|\psi\rangle$, Dirac's "kets". Its temporal evolution is computed as follows: given the wave-function $|\psi_{t0}\rangle$ at time t_0, the wave-function at time t_0+dt is given by $|\psi_{t0+dt}\rangle = |\psi_{t0}\rangle+|d\psi\rangle$, where $|d\psi\rangle = - i/\hbar\ \hat{H}|\psi_{t0}\rangle dt$ (Schrödinger's eq). $\hat{H}$ is an Hamiltonian linear operator that unitarily acts on $|\psi_{t0}\rangle$ and produces another element $\hat{H}\,|\psi_{t0}\rangle$ of $\mathcal{L}^2(\mathbb{R})^3$, encoding every information (i.e. mass, forces) of the system's dynamics, corresponding to its total energy. By iterating this process one gets $|\psi_t\rangle$ at every t, and the evolution is, again, deterministic (and the condition of normalization[17] is preserved). The evolution is also linear, namely, if $|\psi'_t\rangle$ and $|\psi''_t\rangle$ are possible temporal evolutions, then $c'|\psi'_t\rangle+c''|\psi''_t\rangle$ is also a possible evolution. It shall be noticed that in classical mechanics the elements that constitute the state of the systems always have a direct physical meaning. This is no longer true of the wave-function and the quantum state, so an interpretation is needed.

Rovelli (2021, p. 2) points out that a (misleading) interpretational step was to understand the quantum state as representing "the actual stuff described by quantum mechanics, endowing it with ontological weight". When Schrödinger first introduced his wave formulation, the aim was to reconceptualize quantum phenomena in a more familiar way by describing the electron as an actual wave propagating in space, and the solution $\psi_t(x)$ of his equation, encoding all the relevant information of the particle, was supposed to avoid the problem of probability emerging from the matrix formalism. In fact, Schrödinger's (1926) basis for assigning ontological weight to the wave-function, a view that we would

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[17] There is no one to one correspondence between wave-functions and states: to each state correspond a family of wave-functions of the type $c\psi(x)$, where $\psi(x)$ is fixed and c an arbitrary complex number; vice versa, to each family of the type $c\psi(x)$ correspond a possible state. So fixing c through the normalization condition is convenient: $\int_{\mathbb{R}^3} dx\,|\psi_t(x)|^2 = 1$.

now refer to as 'ψ-ontic', was the claim that QM is a theory of waves in physical space. Bacciagaluppi (2021, p. 4) further specifies that "Schrödinger was able to interpret quantization of energy in terms of the discreteness of eigenoscillations, and hoped to derive other quantum phenomena as arising from his continuous and deterministic wave equation".

But major conceptual problems arise when such a view of the wave function is confronted with Born's statistical interpretation[18] of its solutions, in which $|\psi_t(x)|^2$ represents the probability of finding the electron in point x at time t. Here is a standard example. Suppose that at a time t a measurement is performed to check whether a particle is contained in a certain volume of space V in $\mathbb{R}^3$. In general, both "*in*" and "*out*" are possible outcomes, and each probability is given by $P(in) = \int_V d^3x\,|\psi_t(x)|^2$; $P(out) = \int_{\mathbb{R}^3-V} d^3x\,|\psi_t(x)|^2$. Note that, taking into account the normalization condition, $0 \leq P(in) \leq 1$, $0 \leq P(out) \leq 1$, and $P(in)+P(out)=1$. Such statements concerning the probabilities for measurement outcomes are standardly taken to represent the link between the quantum state and the physical property of the system. The problem is that in general the measurement process has some (sort of) effect on the system. In this case, whether the outcome is "*in*" or "*out*", the post-measurement wave-function is essentially different from the pre-measurement one. The modification of the state of the system as a consequence of a measurement is referred to as reduction (or collapse) and it is a stochastic process: the theory specifies only the probabilities for the two outcomes and the resulting evolution of the state – a radically different evolution from Schrödinger's deterministic one.

2.3.2 Two Incompatible Contexts

Two different contexts are thus defined: (1) the deterministic, unitary and linear evolution prescribed by the Schrödinger equation, where the wave-function can be considered as a mathematical structure that essentially describes the transition probabilities between all possible measurement outcomes for each observable

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[18] Bacciagaluppi (2021) shows that the first statistical reading of the wave-function introduced by Born does not correspond to the full-fledge statistical interpretation that was later developed by von Neumann.

property of the system; and (2) a measurement context, in which performing a measurement of some observable P on a system S in a certain state $|\psi\rangle$, has the effect of reducing the system to a certain eigenstate corresponding to the eigenvalue that is observed, and the process that reduces the system to one specific eigenstate is irreducibly probabilistic (and governed by Borns' rule). This can be understood as the original state of the system being projected along a certain "direction" in the vector space. More specifically, the observables are represented by self-adjoint operators so that given a property P, a system S takes one of N mutually exclusive eigenvalue p_i ($i = 1 \ldots N$) for the property P *iff* S is in an eigenstate of P that corresponds to p_i (eigenvalue-eigenstate link). Here is how Mermin (2003) summarizes the problematic relation between the two different contexts: the post-measurement state $|p\rangle$ contains no trace of the information present in the pre-measurement state $|\psi\rangle$, besides revealing that the amplitude $a_p \neq 0$, where $|a_p|^2$ represents a probability density.

Le Bellac (2006) points out that whether or not state vectors are taken to describe the physical reality of an individual quantum system, it has no effect on the practical application of quantum mechanics. But if we are interested in providing with a precise characterization both the notion and the role of measurement and try to understand under what circumstances and onto what basis the wave-function of the system is reduced to a precise value, then we get into unavoidable interpretational questions. The problem is essentially represented by the clash between the two different contexts mentioned above: context (1) would seem to entail that variable properties should never have definite values, and yet, each time a specific property is measured, definite values are obtained in (2). In other words, there is a gap between the linear evolution that predicts interference effects between different possible values and the empirical fact that variables exhibit definite values. The gap is only methodologically filled by the Born rule, which is not part of the physical model and, therefore, does not really help making the notion of measurement less mysterious.

The standard textbook answer that is commonly associated to the Copenhagen interpretation states that certain interactions to which physical systems are exposed – generally corresponding to measurement processes – determine the transition from a wave-function representing the system to another, and therefore from a certain physical state to another, in a way that is not described by Schrödinger's equation. This view is based on the following schematic assumption: there are special situations that can be identified as measurements, in which special rules are applied, and where the measuring device is a special physical systems whose presence identifies in some way the measurement. Evidently, no principled way of precisely characterizing the measurement itself is provided.

2.3.3 Measurement Problem(s) & Possible Solutions

It is perhaps helpful to distinguish between two different levels, and two related questions, that compose the measurement problem (as in Bub & Pitowsky 2010). A first question is immediately raised by the probabilistic character of quantum predictions, and, as it has been pointed out, it can be posed independently of the wave formulation of the theory. The problem consists in explaining why one specific outcome, instead of its other alternatives, is obtained in a certain experiment. But a second reading helps seeing how the question is really about the problem of completeness, rather than measurement itself. In fact, if the probability of quantum predictions is taken to be fundamental and, therefore, irreducible, then the impossibility of knowing why one particular outcome is obtained upon a particular measurement is also fundamental and irreducible. In other words, if the completeness of quantum theory is accepted, which essentially entails that there are no additional variables that can allow a particular outcome to be predicted with certainty, then this first measurement problem should be simply understood as a direct consequence of there being no hidden causes that determine which outcome is obtained.

A second level of the problem is sarcastically summarized by Bell (1990, p. 34): "What exactly qualifies some physical systems to play the role of 'measurer'? Was the wave function of the world waiting to jump for thousands of millions of years until a single-celled living creature appeared? Or did it have to wait a little longer, for some better qualified system…with a PhD?". In other words, what does make a measurement a measurement? This was already considered a problem by Heisenberg and Bohr when discussing the problem of the "cut" between the measurement apparatus and the measured quantum system[19] (which had nothing to do with the cut between microscopic and macroscopic worlds, contrary to what is sometimes claimed). In the next section, the implications of moving this cut from isolated systems to compound 'system-observer' systems will be explored within the relational framework of RQM.

But let's go back to the original problem raised by the friction between contexts (1) and (2). Once a measurement is appropriately modelled within the theory as some relevant interaction between the measured system and the measuring device that leads to their entanglement, it seems impossible to derive the probabilisitic non-linear reduction of the measured system from the deterministic linear evolution of the (pre-measurement) entangled system+device. Maudlin (1995) reframes this problem into the conflictual composition of three statements, all of which cannot be simultaneously accepted:

(A) The wave-function is a complete description of the state of a system
(B) The wave-function evolves according to a linear dynamic (Schrödinger eq.)
(C) All measurements have determinate outcomes

Endorsing (A), for any property the system can be conceived as a superposition of states; endorsing (B), a superposition of states must evolve into another superposition of states, thus, no reduction happens. If (A) and (B) are accepted, and the state of the measuring device is coupled with the system being measured and described as a composite wave-function, then also the system+device must be in a superposition of states, which is in conflict with (C). Negating either (A) or (B) implies providing the theory with additional structure, and some interpretations go in this direction.

A De Broglie-Bohm-type interpretation, for instance, rejects (A) by positing punctual particles in addition to the wave-function. It offers a fully deterministic

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[19] See for example Heelan (1975) and Camilleri & Schlosshauer (2015).

picture, in which every particle is attributed a position and the dynamics is given by the Schrödinger evolution plus definite guiding equations that describe how the particle's positions move under the influence of the wave-function. The linearity of the wave equation is maintained, and so complementary variables need to be added to express the "non-waviness" of the world on the macroscopic scale (Bell 1990, p. 40). The essential conditions for any deterministic completion of quantum theory by hidden variables can be summarized in the following points: once the state of a physical system is fixed, every physical quantity must have a precise value; the way in which the state is prepared must lead to a dispersion of the hidden variables so that at each instant the probability associated with the values of every quantity coincides with the results obtained by quantum laws. If such conditions were taken together, with no additional constraints, they would describe a local non-contextual hidden variables theory. And of course there are no such theories.

In fact, while the second point necessarily implies instantaneous actions at a distance between systems, i.e. non-locality, as prescribed by Bell's theorem, the first requires contextuality, as imposed by the Kochen-Specker theorem. If a certain value is objectively possessed by a physical quantity, then such value must correspond to the one obtained when carrying out the measurement. Any attempt to complete the theory in the perspective of an objective description of physical reality cannot but accept such a request. But one of Kochen & Specker (1967)'s implications is that every hidden-variable theory inevitably brings with it a certain degree of contextuality. This notion comes into play with any theory that aims to assign objectively possessed values to all the physical quantities of a system. Let's consider a physical quantity P and let λ indicate the hidden variables that determine the state of the system, with $p(\lambda)$ representing the value that P assumes in the state in question; contextuality emerges if the truth of the statement "P assumes the value $p(\lambda)$" does not only depend on the variables but on the entire physical context of measurement. The necessary condition for considering the probability of quantum measurements in an epistemic sense rather than ontological, allowing a deterministic completion of quantum mechanics, is to admit the contextual nature of the measured physical quantities.

Another possibility is to reject (B), which is what collapse theories do. A first formulation was proposed by von Neumann, who postulated random physical projections of the wave-function, i.e. collapses, determined by the act of (conscious) observation. After the measurement, the state of the system is instantaneously reduced to one of the eigenstates of the measured variable, which leaves the system in a state that can be interpreted on the basis of the eigenstate-eigenvalue link: an operator $\hat{O}$ has a well-defined value for a quantum a system S in state $|\psi\rangle$ *iff* $|\psi\rangle$ is an eigenstate of $\hat{O}$. A less 'anthropocentric' formulation is offered by GRW interpretation, which introduces spontaneous discrete collapses of the fave function. The predictions provided by this collapse theory are different from those of standard quantum mechanics, but the parameters that define the collapses are consistent with the empirical confirmations of quantum theory. The central tenet of this interpretation (to which some would refer to as a theory in its own right), consists of eliminating observers from the scheme and view the state reduction as a process that occurs as a consequence of the basic laws of nature. This is obtained by adding to the Schrödinger equation a stochastic term which describes the state reduction occurring in the system. So in the spontaneous-collapse model, a system standardly evolves according to the Schrödinger equation at all times except when a collapse happens, or, as Bell (1987) puts it, when a "hit" occurs at a space-time point.

Finally, some other solutions interestingly reject (C), that is, the fact that empirical outcomes are determinate. This is the case for the many-world-type interpretations, according to which the wave-function, realistically interpreted and extended to the entire universe, evolves at each measurement into relatively independent branches on which each observer happens to be located and from which each measurement is seen as having determinate outcomes. This peculiar view negates the reality of the state reduction and assumes that all possible alternate histories and futures are real and constitute a real 'world'. The relational approach to quantum theory, specifically in Rovelli's contemporary formulation, also rejects (C), but, as we shall see in the upcoming section, such a shared premise leads to completely different conclusions.

2.4 Relational Quantum Mechanics

Relational quantum mechanics, as proposed in Rovelli (1996) and further developed in Rovelli (1998, 2005, 2016, 2018, 2021a) offers an interpretation that is crucially based on the conjunction between Heisenberg's (i*)-type relationalism and Hermann's (ii*)-type relativism: (a) variables of quantum systems have a value only within interactions; (b) such interactions assign relative values to the variables. The first assumption is what defines the "sparseness" of quantum values, events, facts, or whatever ontology is taken to represent a quantum interaction between different systems.

2.4.1 Heisenberg-type Relationalism & Hermann-type Relativism

In this sparse ontology picture, only physical quantities evolve in time, not quantum states, and, as in Heisenberg's early formulation of the theory, a quantum state merely represents the information about antecedent measurements which gets updated only through a subsequent measurement interaction. Thus, the only relevant ontology is represented by the values of the observable variables of a physical system upon the interaction with another system: "what evolves with time are the operators, whose expectation values code the time-dependent probabilities that can be computed on the basis of the past quantum events" (Rovelli & Smerlak 2007, p. 431).

The second (interconnected) assumption relativizes such values to the specific interaction between the measured system and any other physical system that counts as an observer. In this sense the values of a quantum system at an interaction are considered observer-dependent. As Rovelli writes: "Quantum mechanics is a theory about the physical description of physical systems relative to other systems, and this is a complete description of the world" (Rovelli 1996). Quantum events, and thus the values of the properties of a physical system, are relational, that is, they do not express properties of the system alone, but rather refer to the relation between one system and another, which can be defined as 'observer' in a generic physical sense, without the classical-macroscopic Copenhagen connotation. It is important to highlight that in RQM quantum systems and observers thus conceived are taken to be equivalent – in fact the observer system may well be a quantum system itself – and are therefore interchangeable in the symmetrical relation of attributing some value to some property. So a quantum event is defined by the value that a variable of a system takes at an interaction with another system, only with respect to which the value is actualized.

Within such a relational account, it becomes meaningless to say that a certain variable P of the system S has the value p; it is instead meaningful to say that the variable P of the system S takes the value p relatively to a second system O. So quantum theory essentially specifies the spectrum of the possible values p_i that the variable P of a system S can take, and allows to compute the probabilities for these values relative to a second system as a function of other values q_i, but the transition amplitudes of a value p given q have physical meaning only relative to the same second system. This means that there is no absolute sense in which an outcome is measured, that is, no absolute sense in which a quantum event occurs.

This very idea of value relativization, coupled with the interaction-dependent character of value acquisition, lies at the core of RQM's solution to the measurement problem. Indeed, the incompatibility between the unitary evolution of context (1), which describes the transition probabilities between all possible measurement outcomes, and the state reduction postulated by context (2), which projects the system to a certain eigenstate corresponding to the eigenvalue that is observed (and updates the probabilities accordingly), is overcome by considering that the two contexts refer to different systems. Thus, both contexts can still be simultaneously meaningful as long as their relative use is made explicit. Context (1) applies to a system S in isolation, before it interacts with any other system O, which in fact predicts interference effect between the possible values of its variable by unitary evolution. Once they interact, context (2) is used to update the state of S with respect to O, but not with respect to any third system T, which is in fact not prevented from still using context (1) to update the state of the now entangled systems $S \cup O$. (1) and (2) refer to different systems: “with respect to Schrödinger’s cat the poison is definitely out or not, but this has no bearing on the possibility of an external observer to observe quantum interference effects between the two alternatives” (Rovelli 2021b, p. 2).

This statement is consistent only if (a) and (b) are taken together. On the one hand, the Heisenberg-inspired ontology interprets the measurement outcomes, e.g. p and q, as the only elements of reality and makes them compatible with the (pre-interaction) superposition quantum states, to which no ontological weight is assigned: “the phrase ‘Schrodinger’s cat is in a quantum superposition’ means only that we cannot use either the cat being dead or the cat being alive as inputs for transition amplitudes” (Rovelli 2021a, p. 5). On the other hand, the values of such measurement outcomes are taken to be context-dependent rather than absolute, so that a well-defined event in a certain context is not necessarily a well-defined event in another. The relativism of value ascription, which in RQM’s terminology becomes event occurrence or fact realization, is remarkably in line with Hermann’s understanding of complementarity, in light of which a statement concerning one particular context cannot be unambiguously combined with a statement deduced by means of the other.

2.4.2 The ‘Third Person’ Problem

The key implication of the relational interpretation is the following: in quantum mechanics different observers may give different accounts of the same sequence of events (Rovelli 1998); such accounts are relational, and yet, equally correct. This idea is, again, in line with Hermann’s insight concerning the complementary ‘splitting of truth’, which “instead of merely delimiting its scope against other possibilities for grasping reality, it separates various equally legitimate representations within the physical description that cannot be unified into a single picture of nature.” (Hermann 2017, p. 277). This idea is also entailed by the so-called ‘third person problem’ of a Wigner’s friend scenario, which in fact seems to represent a real problem only outside of a relational account of quantum events.

Consider for example a system S being in a state in which p and q are the only two possible values that one of its variables can assume, and $|p\rangle$ and $|q\rangle$ represent the related eigenstates. A generic wave function ψ of S at time t_1 can then be defined as $a|p\rangle+b|q\rangle$, where $|a|^2+|b|^2 = 1$. If an observer O interacts with S at time t_2 and measures p, then the state of S – relative to O – would evolve into $|p\rangle$. Now consider the composite quantum system $S\cup O$ from the perspective of a third system T and assume they have not yet interacted at time t_2. According to T no "collapse", or rather collapse-like event, has happened and the composite system is still in a superposition, since its state is still governed by the linear evolution of the wave function prescribed by Schrödinger eq. Therefore the description provided by T of the set of events is at t_1: $(a|p\rangle+b|q\rangle) \otimes |O_{ready}\rangle$, whereas at t_2 it is: $a|p\rangle \otimes |Op\rangle+b|q\rangle \otimes |Oq\rangle$, where $|O_{ready}\rangle$ is the state of O before the measurement on S, $|Op\rangle$ the state of O recording p and $|Oq\rangle$ the state of O recording q.

So, two different and apparently incompatible evolutions refer to the same sequence of events from t_1 to t_2:

(D_1) $a|p\rangle+b|q\rangle \Rightarrow |p\rangle$

(D_2) $(a|p\rangle+b|q\rangle) \otimes |O_{ready}\rangle \Rightarrow a|p\rangle \otimes |Op\rangle+b|q\rangle \otimes |Oq\rangle$

In fact, the descriptions at t_2 seem to be contradictory: the "collapse" has and has not happened; the variable has and has not assumed the value p. But notice that these two evolutions refer to different observers, and, in particular, T has not performed any measurement on $S\cup O$ within the time frame of the event; the only information carried by T is about the correlation between S and O, but it will not have access to the outcome of the interaction between the two until a measurement is directly performed on $S\cup O$ at t_3. When this happens, quantum mechanics predicts that if T performs a measurement on S and finds $|p\rangle$, it will necessarily – and consistently – find $|Op\rangle$ on O, and, alternatively, if T performs a measurement on S and finds $|q\rangle$, it will necessarily - and consistently - find $|Oq\rangle$ on O. So in T's perspective, there is no disagreement between the description of S provided by T itself and O, even though relative to O the value might be a different one. This particular feature of RQM is what has generated the most controversy, and the corresponding objections will be discussed in the following section.

2.4.3 A Comparison with Everettian Relative States

A final remark concerns the interpretation of the wave function. As it has been pointed out, RQM interprets the measurement outcomes, e.g. p and q, as the actual elements of reality, whereas the quantum state as a mathematical tool to which no ontological weight is assigned. The wave-function is seen as a predictive (relational) device that refers to two systems and encodes the history of the 'actualizations' of the quantum events represented by the value of a variable of one system interacting with another. It can then be used to predict possible values of a certain property of one system with respect to the other. In this perspective, ψ represents the information that one system acquires about the other system with which it interacts. But speaking of wave function, it may be worth stressing some crucial features that differentiate the relational view from that of a Many Worlds, or more generally, Everett-like interpretation, which are often associated in the literature given their recourse to relativism. This notion, however, is of two different kinds in the two respective accounts of quantum theory: system-system and system-branch relativism: while in Rovelli's account the value of variables is always relative to a second system, in Everettian approaches variables of physical systems take value with respect to branches of the universal wave-function. In this second case, in fact, Schrödinger's deterministic and linear evolution is realistically interpreted and taken to be the only one. Such a unitary evolution preserves superposition and entangled states, but makes them unaccessible for local observers. It is the co-existence of multiple branches (or words) that determines the relativism of a single one; each observer happens to be in a separate branch from which each measurement is seen as having determinate outcomes. As it has been said, RQM allows for real physical interactions between systems, characterized by determined - and yet relational - outcomes, of which the quantum state is merely a predictive device. In Everettian approaches the universal quantum state represents instead the core ontology.

2.4.4 Relational Quantum Mechanics & Decoherence

In summary, RQM endorses the standard formalism based on the Schrödinger equation,[20] to which no nonlinear corrections are added, as well as the basic principles of quantum theory, i.e. eigenvalue-eigenstate link, projection postulate and Born's rule; moreover, it accepts the irreducible probabilistic character of quantum predictions, so no further (hidden-variables-based) ontology is added to deterministically complete the theory. The interpretational step it takes consists of coupling the relationality of systems with the relativism of the values of their variables, and attempts to (dis)solve the measurement problem by introducing an ontology of sparse relative facts, whose realization does not need a 'special' interaction that represents the measurement in the Copenhagen sense. In fact, within the relational account of value ascription, any interaction can represent a Copenhagen-measurement, but only for the systems between which the relation is established. This solution requires to renounce to the 'value definiteness' assumption that non-local completions of quantum theory maintain, namely, that all observables defined for a quantum system have definite values at all times; this move, on the one hand, represents the condition of possibility for the interpretation itself, and on the other, is generally allowed by QM and compatible with Kochen-Specker theorem.

But if QM is taken to be a complete and fundamental theory, whose predicted values are interpreted as irreducibly relational, that is, well-defined only with respect to the systems among which the interaction occurs, how can the macroscopic world be described non-relationally, that is, without relativizing the values of the classical variables to the measuring system involved in the interaction? This, after all, represents the measurement (sub)problem for RQM.

The emergence of (approximately) non-relative variables through which we can consistently describe classical physical systems is explained through the role of

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[20] Even though it would be conceptually closer to Heisenberg's matrix-mechanical formulation.

decoherence, the spontaneous interactions that lead to the suppression of interference, that consequently allows to maintain relationality as a fundamental aspect of reality. Following some preliminary work by Zurek (1982, 2006), Rovelli & DiBiagio (2021) and, indirectly, Zukowski & Markiewicz (2021) show that the observer-dependent character of physical variables can be ignored in the approximation of interference suppression once enough decoherence intervenes, that is, when the large number of microscopic degrees of freedom of the environment become inaccessible and, therefore, incontrollable. In this sense, then, the absoluteness of the classical world is really just an approximation: we neglect the interference effect that *we* cannot access due to the number of degrees of freedom that *we* cannot control (emphasis will soon be clarified).

Following Bohr (1958), according to whom "the unambiguous account of proper quantum phenomena must, in principle, include a description of all relevant features of experimental arrangement", the decoherence approach can be seen as a composition of two steps within quantum measurement processes: an (in principle) reversible pre-measurement, followed by irreversible decoherence. Say the measured system S is in a state $|\psi\rangle_S = \sum_i a_i|\psi_i\rangle_S$, where $|\psi_i\rangle$ are eigenstates of the measured observable. A correlation entangles S with the pointer observable P of the measuring system ε, in a state $|P_i\rangle_\varepsilon$. So $\sum_i a_i|\psi_i\rangle_S|P_{ready}\rangle_\varepsilon$ unitarily evolves into $\sum_i a_i|\psi_i\rangle_S|P_i\rangle_\varepsilon$. The measuring devise ε is a macroscopic system, which therefore has its own uncontrollable environments characterized by a countless number of degrees of freedom and related micro-states, whose evolution is impossible to describe. Then, as Zurek (2006) shows, irreversible decoherence intervenes once these environments unitarily interact with the pointer variable, so that the system-pointer state turns into a classical mixture of states $|\psi_i\rangle_S|P_i\rangle_\varepsilon$, whose respective probabilities are given by $|a|^2$. Thus, there is a sense in which, in presence of enough decoherence, context (1) and (2) tend to coincide.

But the problem of deciding whether or not context (1)'s time evolution provides a complete description of the composite system is not solved by simply introducing decoherence per se, and as Bacciagaluppi (2020, p. 13) points out, an interpretation that either modifies (1) or at least makes sense of it is still needed.

Interestingly, RQM includes decoherence itself among the relational phenomena that make up measurement interactions. Indeed, the variables $|\psi_i\rangle_S$ of the measured system that decohere are determined by the physical interactions between S and $\mathcal{E}$, which represent a fact only with respect to the two systems involved, but not for another system. A third system T, with grater measuring capacities, may in fact interact differently with the compound system $S \cup \mathcal{E}$, and still detect interference effects (Rovelli & DiBiagio 2021).

This line of reasoning may represent an attractive way out of the impasse that characterizes the standard, and in particular Bohr's, understating of complementarity in light of decoherence. On the one hand, any meaningful description of physical reality requires, according to Bohr, the use of classical concepts, whose absolute validity simply brakes down at the quantum level. Their applicability is restricted by quantum phenomena to perspectival (in fact, complementary) descriptions of physical reality, but "according to Bohr, classical concepts are autonomous from, and indeed conceptually prior to, quantum theory" (Bacciagaluppi 2020, p. 30). On the other hand, decoherence seems to represent precisely the mechanism through which classical phenomena can be seen as emerging from the fundamental quantum level. Now, the relational approach allows for the possibility of endorsing the perspectival context-dependent descriptions prescribed by Bohr's complementarity, and, ultimately, by the fundamental limitations of the uncertainty relations, without however ascribing any fundamental status to the classical domain, which in turn does not conflict with the role of decoherence, relationally understood. In other words, RQM offers a way of preserving the fundamentality of the quantum domain that gives rise to the classical world through decoherence, while recognizing the irreducibly relational context-dependent character of such a fundamental domain. But further investigation would need to be carried out to expand on this last point.

Nevertheless, the most problematic aspect of the relational approach to quantum theory seems to be represented by the interpretation of the Wigner's friend situation that leads to the much discussed 'different observers – different descriptions' picture. The corresponding question is essentially the following: is the consequence of a Wigner's friend scenario, namely, that there are no absolute facts, a paradox or a physical possibility?

2.5 Criticalities

The foundational literature gravitating around the problem of the interpretation of quantum mechanics can be quite intricate, especially when is read outside of a particular framework of preference. Once the basic quantum principles and the relevant no-go theorems are taken into account and accommodated within the interpretational setup, it would seem natural to assume that wether or not a particular interpretation is embraced depends on some meta-assumptions that characterize one's metaphysical priorities and general philosophical stance. Also, it would seem natural to think that if the measurement problem is indeed a problem, there cannot be a straightforward solution that does not have to face some sort of drawback, if the answer is to be formulated within quantum theory itself. Nonetheless, the debate tends to take a very different form, e.g. of the type: "we prove false Rovelli's claim that RQM provides a satisfactory, realistic, non-solipsistic description of the world. Moreover, his reply serves us to further exhibit the serious problems of the RQM proposal, as well as the failures of its author to understanding the basic conceptual difficulties of quantum theory" (Muciño et al. 2021b, p.1). Claims of this kind are actually not rare, that is, it is not rare to find assessments of rival interpretations that are not based on a critical analysis of the meta-assumptions on which they are grounded, but rather on an attempt to show that they are simply "false" or incompatible with quantum theory itself.

2.5.1 A (not so) Fruitful Debate

If this were actually the case, this type of critiques would not be problematic of course, in fact, it would be necessary for a fruitful foundational discussion. But sometimes what is claimed to show the incompatibility of some interpretation with quantum theory turns out to show instead its incompatibility with the meta-assumptions on which the privileged interpretation is grounded and that ultimately depend on what is taken to be the relevant aspects of the theory worth "saving" from the measurement problem. And this is of course a whole different story than pointing at actual inconsistencies within a specific interpretation, as in the case of, say, an obviously inconsistent non-contextual hidden variable theory. In other words, one should first verify whether the rival interpretation under examination is equivalent to quantum formalisms and predictions, regardless of possible modifications, and compatible with the conditions fixed by the related no-go theorems, such as Bell, Kochen-Specker and Pusey-Barrett-Rudolph for example. Then, even if it is, there is certainly still room for a debate, which needs however to be shifted to the level of the meta-assumptions on which the interpretations are grounded and evaluate them on the basis of theoretical convenience, ontological parsimony, or whatever other criteria (outside of QM) is considered.

This is not to say that there are no principled ways of choosing one interpretation over another. If one's choice to save determinism is well motivated, for instance on the basis of the conviction that probabilities in physics are ultimately epistemic, she may well "go Bohmian", and that would be a reasonable move. But, quite evidently, one should not classify the interpretations that do not take the same interpretational step as inconsistent. Say an interpretation I_1 is endorsed because of its compatibility with quantum mechanics coupled with the adequacy to some preferred meta-assumption, e.g. that the quantum state represents a real thing. Indeed, I_1 is 'ψ-ontic'. A rival interpretation I_2 is also compatible with quantum mechanics but adequate to some meta-assumptions that are incompatible with I_1's, e.g. the quantum state is nothing more than a mathematical predictive device. In fact, I_2 is 'ψ-epistemic'. I_2 is then labeled by I_1-supporters as an inconsistent interpretation because it fails to be ψ-ontic. This obviously does not make any sense.

But surprisingly, a less trivial but equally problematic argument is given by Muciño et al. (2021a) in assessing RQM. In particular, among the problems the authors see in the relational proposal there is the failure in providing a "realistic description of the world". Regardless of the general perplexity expressed in the introduction of the present thesis about referring to an interpretation as 'realist' per se, the question is on which grounds the realism of an interpretation can be ascribed. If the only aspect of the theory about which one could be realist or not were the wave-function, then being *ψ*-ontic would coincide with being realist. And in fact, irrespectively of the underlying metaphysics, realism about QM is mostly understood in the literature in terms of realism about *ψ*, so for example Many Worlds, Bohmian, Modal and Spontaneous Collapse interpretations are usually thought as providing a realistic description of quantum phenomena, whereas Qbism, Healey's Pragmatism, the Statistical interpretation and RQM are taken to be on the antirealist spectrum (see e.g. Cabello 2016). But why such an exclusive focus on the wave-function? Why being realist about quantum systems, events, values or any other element of the formalism rather than the quantum state does not count as realism?

Muciño et al. (2021a) do not pose these questions in arguing that RQM fails to be realist, but it is quite evident that they argue so on the basis of a *ψ*-ontic Spontaneous Collapse framework of reference, which is taken to be *the* framework on the basis of which realism should be ascribed. Their approach to quantum theory is crucially based on the introduction of a special mechanism (which represents the measurement in the Copenhagen context) through which the physical collapse of the objective and universal evolution of the wave-function can be explained. So, even more crucially, they claim that RQM fails to provide a realistic description of quantum phenomena essentially because it does not provide a precise way of realistically making sense of the brake-down of the objective unitary evolution of the wave-function. But the fact that RQM does not ascribe any special role to any process that explains "how and in which basis will the collapse occur" (*Ivi*, p. 6) is simply not a problem because within the relational framework there is really nothing objective happening outside the interaction between two systems, that is, there is nothing that physically collapses when something "special" happens. As Rovelli puts it in his reply, "the formulation of the problem of QM according to [Muciño et al.] is predicated on the basis of assumptions that are explicitly rejected in RQM" (Rovelli 2021b, p. 2).

On the other hand, it is sometimes improperly claimed that the privileged interpretation is somewhat more naturally suggested by a particular no-go theorem. But the proofs given by these theorems are, by definition, aimed at simply restricting the physical possibilities of certain situations given certain premises; in other words, they indicate where "not to go", rather than suggesting where "to go". Nevertheless, Rovelli (2018, p. 4) for example argues that one of the main assumptions of the relational interpretation, namely that all variables do not have definite values at all times, is *confirmed* by the Kochen-Specker theorem: "the predictions of quantum mechanics are incompatible with all variables having simultaneously a determined value. A number of mathematical results, such as the Kochen-Specker theorem, confirm that if all variables could have a value simultaneously, the predictions of quantum mechanics would be violated". And a few pages later claims that RQM, contrary to other interpretations, "assumes seriously the Kochen-Specker theorem: variables take value only at interactions" (*Ivi*, p. 6).

But this is (at best) a peculiar way of interpreting the constraints the theorem requires any theory to satisfy, for Kochen & Specker (1967) only establish a contradiction between the predictions of quantum mechanics and these three conditions taken together: (*c1*) all variables of a quantum system have definite values at all times; (*c2*) a variable has a definite value independently of any measurement context, i.e. independently of how it is measured; (*c3*) there is a one to one correspondence between variables of a quantum system and projection operators on the system's Hilbert space. Thus, the only strong limitation set by the theorem is that the acceptance of QM implies rejecting either *c1*, *c2* or *c3*. This means that any interpretation that is willing to give up for example the 'non-contextuality' condition is equally legitimated by the theorem as those which are willing to give up (in fact, are based on giving up) the 'value definiteness' condition. Indeed, choosing which condition shall be more naturally abandoned is an interpretational step, and by no means directly implied by the theorem itself. So

Rovelli's claims are justified only under some additional meta-assumptions on which his interpretation is based, which are themselves incompatible with those of a contextual (as defined in § 2.3) hidden-variable theory that accepts c_2 and rejects c_1.

It is quite comprehensible that each tries to "feather one's own nest" to some extent, but analyzing each argument outside of a particular framework of preference allows to further appreciate the complexity, the uniqueness and perhaps the beauty of the interpretational problem posed by the formalism of the theory that is ultimately framed in terms of an unavoidable tradeoff between mutually incompatible assumptions, whose respective rejection always come at a (philosophical) cost.

2.5.2 A (more) Fruitful Debate: Wigner's Friend & Observer-(In)Dependence

A second and more serious class of objections is specifically concerned with the Wigner's friend paradox, as formulated in § 2.4, whose interpretation has received renewed attention and become a divisive topic in the recent literature. The original argument formulated by (the actual) Wigner (1967) was aimed at exposing the problem of deciding when a collapse happens, that is, when the linearity of the description brakes down. In fact, at the end of the mental experiment the state of the quantum system has collapsed to a definite value with respect to Wigner's friend, but not to Wigner, who is instead still linearly describing the composite system from outside the lab. Assuming that a system can be described by one (absolute) state only, one must then determine which is the correct description. (Actual) Wigner ascribed to the friend's conscious act of measurement the role of making the state of the system collapse, and considered consciousness itself as the necessary condition to make sense of quantum mechanical laws. But this reading of the paradox has been considered largely unsatisfactory because of the mind-dependent characterization of measurement processes.

The issue at stake in the contemporary debate is whether the different descriptions provided by Wigner and his friend of the same set of events should (or at least can) be interpreted relationally, that is, in terms of non-absolute facts, a move that would allow to reconcile the apparently contradictory descriptions provided by the two different observers. And it is easy to see how this possibility is strictly connected with the possibility of a general relational interpretation of QM. The landscape is rather controversial: on the one hand, Laudisa (2019), Castellani (2021) and Pienaar (2021) argue against this possibility; on the other, Brukner (2018), Dieks (2019), Bong et al. (2020) and, indirectly, Frauchiger & Renner (2018) argue in favour of it. I shall discuss the first paper in greater detail, since no direct or indirect reply to the specific argument is found in the literature.

2.5.3 Laudisa against Observer-Dependence

Laudisa (2019) proposes to reinterpret the Wigner's friend scenario so as to avoid the conclusion embraced by RQM concerning the different observations of the same event made by different observers, claiming that Wigner himself "interprets [it] *not* as a sign of any fundamental relationality in the quantum-mechanical description but rather of the need to account for where exactly the linearity of QM is supposed to stop holding" (Laudisa 2019, p. 221). The argument is not aimed at showing that an interpretation of the paradox in terms of relative facts is erroneous per se, but, rather, that it is unnecessary. In fact, it is argued, once a fundamental disambiguation of the measurement process provided by the different observers is made, the alleged difference between the two apparently incompatible descriptions vanishes, and so the motivation for the relativization. The misinterpretation of the conclusion of the paradox made by Rovelli, and in fact by any other who sees the two description as essentially different, seems to be caused by not taking into account the correlation between the friend and the system.

I shall recap the argument as formulated in § 2.4 for reference: a system O (Wigner's friend) is ready to measure a system S that at t_1 is in the superposed state $a|p\rangle+b|q\rangle$. O measures S at t_2 and finds p, so applies the collapse postulate and updates the state of S to $|p\rangle$. In the same timeframe, a third system T (Wigner) has no direct access to the two systems but knows about their correlation, so he linearly describes the time evolution of the measurement as $(a|p\rangle+b|q\rangle) \otimes |O_{ready}\rangle$

at t_1 and $a|p\rangle \otimes |Op\rangle + b|q\rangle \otimes |Oq\rangle$ at t_2. The time evolution of the same sequence of events from t_1 to t_2 is described differently by O and T respectively:

(D_1) $a|p\rangle + b|q\rangle \Rightarrow |p\rangle$;
(D_2) $(a|p\rangle + b|q\rangle) \otimes |O_{ready}\rangle \Rightarrow a|p\rangle \otimes |Op\rangle + b|q\rangle \otimes |Oq\rangle$.

In the relational approach the two descriptions are accepted as essentially different, but their contradiction is overcome by relativizing them: D_1 refers to S, while D_2 refers to $S \cup O$, so O appropriately applies context (2) to describe the state of S, and T appropriately applies context (1) to describe the state of $S \cup O$. According to Laudisa, however, this reconstruction of the argument is misleading, because it "appears to overlook the correlation between S and O that according to quantum mechanics is assumed to take place *before* the collapse" (*Ivi*, p. 222), and suggests that if one takes into account the description of the measurement from the perspective of O, that is, the description of $S \cup O$ with respect to O itself, D_1 would become:

(D_1*) $(a|p\rangle + b|q\rangle) \otimes |O_{ready}\rangle \Rightarrow a|p\rangle \otimes |Op\rangle + b|q\rangle \otimes |Oq\rangle$ [adapted notation].

So, he argues, D_1* is not a different sequence with respect to D_2, but "simply the same sequence under the (standard) assumption that the correlation between O and S is taken explicitly into due account" (*Ibid.*).

I see two major problems with this argument. Firstly, the modified interpretation of the experiment, according to which O does not exclusively describe S but the composite system $S \cup O$, does not make sense within the relational approach. In RQM the relational quantum state of a system is always described with respect to another system, so one and the same system cannot be both the measuring system and the (sub)system being measured. In fact, the very possibility of O describing $S \cup O$ through a D_1*-type evolution is prevented in RQM essentially because O cannot have information about itself, an idea grounded on the proof of impossibility for a complete self-measurement given by

Breuer (1995), and made explicit in the first formulation of the interpretation: "The unitary evolution does not break down for mysterious physical quantum jumps, or due to unknown effects, but simply because *O* is not giving a full dynamical description of the interaction. *O* cannot have a full description of the interaction of *S* with himself (*O*), because his information is correlation, and there is no meaning in being correlated with oneself" (Rovelli 1996, p. 1666). Hence, the compatibility of D_1 and D_2 via the reformulation of the former as $D_1{}^*$ is prevented by RQM's own assumptions.

But secondly, and more importantly, even outside of a relational framework the reconcilability of D_1 and D_2 seems to be unachievable; in fact, it seems that D_1 can never be reformulated as a $D_1{}^*$ evolution irrespectively of the privileged interpretation, that is, even under the "standard assumptions" endorsed by the author. Recall that D_2 represents how *T* describes the evolution of $S \cup O$ from a simple correlation at t_1 to an actual measurement interaction at t_2. This means that the description of the joint system at t_2 refers to a measurement that has already been performed by *O* on *S* (but whose outcome is inaccessible to *T*). In turn, the reformulation of D_1 given by *O* needs to provide a complete account of the sequence of events from t_1 to t_2, namely, also of the fact that the state of *S* has collapsed with respect to *O* itself, and not only of the correlation between *S* and *O* *before* the collapse. Therefore, a D_2-equivalent time evolution would not be $D_1{}^*$, which only gives a partial and intermediate account of the sequence, but:

$$(D_1{}^{**})\ (a|p\rangle+b|q\rangle)\otimes|O_{ready}\rangle \Rightarrow a|p\rangle\otimes|Op\rangle+b|q\rangle\otimes|Oq\rangle \Rightarrow |p\rangle\otimes|Op\rangle.$$

It is evident that $D_1{}^{**} \neq D_2$. Indeed, at time t_2, that is, *after* the measurement, the state of $S \cup O$ is updated to $|p\rangle\otimes|Op\rangle$ by *O*, and to $a|p\rangle\otimes|Op\rangle+b|q\rangle\otimes|Oq\rangle$ by *T*. The "new" friend isn't a much better friend for Wigner, then. In fact, he is possibly even worse: while the "old" friend gave a different description of a different system (*S*), the new friend gives a different description of the same systems as Wigner ($S \cup O$), which leads to an even greater contradiction. In conclusion, even assuming that O can standardly describe $S \cup O$, the two descriptions of the exact same sequence of events would still be different.

2.5.4 Castellani against Observer-Dependence

Let us now review the rest of the literature mentioned above, in order to expose the complexity of the debate. According to Castellani (2021), not only is the reading of the Wigner's friend paradox in terms of relative facts unnecessary, it is also wrong. The argument is framed so as to show that the thought experiment does not support observer-dependent quantum states. The difference between the two descriptions given by O and T that respectively involve a collapse and a unitary evolution is seen as unproblematic since they refer to two different systems, namely S and $S \cup O$ respectively [adapted notation]. But even if O's and T's description of the same system S are compared, so the argument reads, the difference (indirectly) vanishes. The description of S given by T at t_2 is derived through the reduced density operator $\rho^{(S)}$ defined by tracing[21] on the subsystem O, so that, according to T, S is in a mixed state, i.e. a statistical ensemble of pure states, $|p\rangle$ and $|q\rangle$ with probability $|a|^2$ and $|b|^2$. The author points out that such a description is essentially different from the superposed pure state $a|p\rangle+b|q\rangle$ of S that O sees before the measurement at t_1, but it is taken to be essentially equivalent to the description given by O after the measurement at t_2, when S is described as a pure state $|p\rangle$ or $|q\rangle$ with probability $|a|^2$ and $|b|^2$. Castellani acknowledges that the two descriptions do not coincide because O knows the result of its measurement, whereas T does not, but further argues that this difference is inessential because it is "due to lack of information, not to quantum mechanical effects", and for this reason "it does not motivate a relational interpretation of quantum states" (*Ivi*, p. 5). In other words, mixed state are considered to be epistemic.

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[21] The trace of a square matrix is the sum of its complex eigenvalues, and it is invariant with respect to a change of basis. This characterization can be used to define the trace of a linear operator in general. In the example, $\rho^{(S)} = Tr_O(\rho^{(S+O)}) = |a|^2|p\rangle\langle p| + |b|^2|q\rangle\langle q|$, from $\rho^{(S+O)} =$ $= (a|p\rangle \otimes |Op\rangle+b|q\rangle \otimes |Oq\rangle)\ (a^*\langle p| \otimes \langle Op|+b^*\langle q| \otimes \langle Oq|)$.

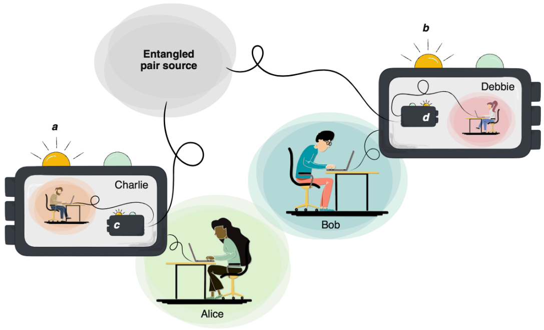
However, one may argue that such a difference in describing the same system, namely, the difference between pure and mixed states that O and T respectively use to describe S, is, on the contrary, quite essential. The problem of interpreting the mixed state of S as representing (classical) ignorance about the real pure state the system is in lies in the fact that if S were actually in one of the two pure states $|p\rangle$ or $|q\rangle$, than $S \cup O$ would also have to be in one of the two pure states $|p\rangle|Op\rangle$ or $|q\rangle|Oq\rangle$, and, therefore, in a mixed state rather than a superposed one. In fact, this is what Dieks (2019) claims in his paper about a perspectivalist view of no-collapse interpretations. Discussing the measurement problem as specifically expressed by a Wigner's friend scenario, he argues that O is justified in ascribing to S either $|p\rangle$ or $|q\rangle$ after the measurement, but T can only derive an (improper) mixture as a state for S, and "well-known arguments forbid us to think that this mixture represents our ignorance about the actually realized eigenstate (indeed, if S's state actually was one of the p or q eigenstates, it would follow that the total system $S \cup O$ had to be an ignorance mixture as well, which conflicts with the premise – supported both theoretically and empirically – that the total state is a superposition)" (*Ivi*, p. 7, adapted notation). The solution proposed by Dieks to makes sense of the two irreducibly different descriptions is indeed to ascribe more than one state to the *same* physical system: with respect to T, $S \cup O$ is correctly described by an entangled pure state so that T should ascribe a mixed state to S obtained by partial tracing. But with respect to O, S is definite-valued, and in fact described by a pure state that reflects such a definiteness. The author concludes: "this line of thought leads to the idea of assigning relational or perspectival states, i.e. states of a physical system A from the perspective of a physical system B" (*Ibid.*).

2.5.5 Three No-Go Theorems for Observer-Independence

The general idea of avoiding any sort of relativization of quantum states without encountering contradictory descriptions arising from the Wigner's friend scenario has been recently challenged by some arguments given in the form of no-go theorems against observer-independent facts in quantum mechanics. Proofs as those given by Frauchiger & Renner (2018) are essentially based on extended versions of the Wigner's friend thought experiment with multilevel 'nested' measurements. These arguments generally depend on a number of plausible assumptions that, if taken together, lead to contradictory results, i.e to the inconsistency of QM. Frauchiger & Renner (2018) in particular is not directly concerned with the problem of observer-dependent or independent facts; it is aimed at investigating whether quantum theory can in principle have universal validity, that is, whether it is possible to use QM to model complex systems that include agents who are themselves using the theory, without violating the following assumptions: (*quantum mechanics*) the rules of quantum theory apply to all agents; (*consistency*) different agents using the same theory must arrive at the same conclusions; (*single-world*) measurement outcomes are unique. On the basis of the contradictory results of their extended Wigner's paradox, they conclude that the first two assumptions are incompatible with the single world assumption.

But Brukner (2019) explicitly derives a no-go theorem for observer-independent facts, reformulating the argument given by Frauchiger & Renner (2018). In particular, their consistency assumption, that was given in the form "if *T* applying QM concludes that *O* has found that the measured variable of *S* is *p* at time *t*, then *T* can conclude that the variable of *S* is *p* at time *t*", is shown to have the same implications as the assumption that observational statements of different observers can be compared in a single (observer-independent) theoretical framework. His Bell-type theorem proves that there can be no theory in which *T*'s and *O*'s facts can jointly be considered as local objective properties. The observer-independence of quantum states is among the assumptions used to derive the contradiction, that is, assuming that the outcomes of the measurements are absolute leads to a contradiction with other three assumptions (locality, freedom of choice and universality of quantum theory). This, according to the author, indicates that in quantum theory we can only define facts relative to an observation and an observer; once this is taken into account, the inconsistency is overcome: "the fact that the friend and Wigner have different accounts of the friend's measurement process [...] needs not give rise to any inconsistency in practicing quantum theory, since the two descriptions belong to two different observers, who remain separated in making predictions for their respective systems" (Brukner 2019, p. 4). In fact, Waaijer & Neerven (2021) analyze Frauchiger-Renner paradox from the point of view of RQM, and show how the inconsistency can be avoided if one renounce to the consistency assumption mentioned above, that is, if one rejects promoting a certainty of one agent's knowledge to the certainty of another, which in fact coincides with one of the main assumptions of the relational interpretation.

Moreover, a corroboration of Brukner's (2019) result comes from Bong et al. (2020), who have theoretically proven and experimentally demonstrated that a set of plausible assumptions, together with the assumption that an observed event is absolute, contradicts quantum mechanical predictions and experimental data, further restricting the possibility of maintaining an observer-independent notion of measurement outcomes. The extend Wigner's friend scenario is set as follows: Charlie and Debbie are separated in two isolated labs and perform a measurement on a particle from an entangled pair, and get outcome *c* and *d*. Alice and Bob are the "super-observers" outside each lab and perform space-like separated measurements obtaining *a* and *b* respectively, and they can either enter the lab and check Charlie's and Debbie's outcomes, or perform an interferometric measurement on Charlie's and Debbie's labs. The authors show that the conjunction of three assumptions – *no-superdeterminism* (the free choices of measurements are independent of the rest of the experiment, so the measurement context can be uncorrelated with other relevant variables), *locality* (the measurement choice in the distant lab does not influence the probabilities of a space-like separated event), and *absoluteness of observed events* (outcomes are not relative to anything or anyone) leads to a contradiction with the quantum mechanical predictions. In particular, from this set of assumptions they derive the



associated inequalities, called "local friendliness", that are predicted to be violated by QM, and are shown to be in fact violated by the quantum correlations of their proof-of-principle experiment with a pair of photons.[22] Therefore, the universality of the theory entails that one of the assumptions must go.

Brukner (2020, p. 1173) points out that this work "puts the strongest constraints so far on the possibility that observed facts are absolute, rather than relative to observations or observers", but being it a (strong) no-go theorem, it does not directly support the rejection of one or another assumption; indeed, pilot-wave interpretations, for example, avoid inconsistencies by violating locality while preserving the 'absoluteness of observed events' assumption. What this and other similar works do is to show that the the relational interpretation of quantum events is a legitimate possibility.

2.5.6 Final Remarks

Of course there is further disagreement. Pienaar (2021) argues against RQM, shaping his objections in the form of five no-go theorems that are supposed to show how some of the major assumptions that make up the relational interpretation (*rqm1* – any system can be an observer; *rqm2* – no hidden variables; *rqm3* – relations are intrinsic; *rqm4* – comparisons are relative to one observer; *rqm5* – any physical correlation is a measurement; *rqm6* – shared facts) clash with one another. The critique exceeds the analysis of the Wigner's friend experiment, and is more generally aimed at showing that either the universality and completeness of quantum theory or the fundamentality of the actualization of quantum events is to be abandoned.

DiBiagio & Rovelli (2021) however reply that the alleged inconsistencies arises because of a misinterpreted notion of quantum state that improperly characterizes *rqm5* in particular. In Pienaar (2021, p. 4) this assumption is defined as follows: "suppose an observer measures a pair of systems and thereby assigns them a joint state which exhibits perfect correlations between some physical

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[22] Where each photon's polarization corresponds to the systems measured by Charlie and Debbie and the photon paths represent Charlie and Debbie themselves.

variables. Then the two systems have measured each other (entered into a measurement interaction) relative to the observer, and the physical variables play the roles of the 'pointer variable' and 'measured variable' of the systems". Pienaar takes the state as primitive and assumes that once the state is known one can deduce which events happen in a composite system. This is proved not to hold in RQM. But DiBiagio & Rovelli (2021, p.) point out that in RQM is the opposite: "events are primitive, and their occurrence is partially reflected in the state of the composite system relative to a third system. But only partially. Events cannot be read out of the state". Once this is taken into account, *rqm5** is reformulated as: "an interaction between two systems results in a correlation within the interactions between these two systems and a third one. With respect to a third system *T*, the interaction between the two systems *S* and *O* is described by a unitary evolution that potentially entangles the quantum states of *S* and *F*". So , they argue, while *rqm5* is incompatible with *rqm3*, *rqm5** is not.

As anticipated, the debate is rather articulated. Castellani (2021, p. 6) in a final note acknowledges that some of the above-mentioned works, such as Frauchiger & Renner (2018), Brukner (2018) and Bong et al. (2020) have been set up to probe the issue of observer-independent facts in quantum mechanics, but further claims: "extreme care is necessary to uncover all assumptions made in real or Gedanken experiments. [...] It is therefore not clear to us that these experiments could directly support observer dependence of quantum states or events". I definitely agree, but I would also like to extend the second part of the quote and add that, at the time being, it is also not clear to me how the opposite arguments directly support observer independence of quantum states or events.

I would like to conclude by discussing some open points that are more relevant from a philosophical standpoint. As mentioned in § 2.4, one major objection is concerned with what is some times referred to as "lack of invariants". Let us go back to the example of the two observers performing some measurement on a system. As has been said, when *T* performs a measurement on *S* at a later time and finds $|p\rangle$, it will necessarily - and consistently - find $|Op\rangle$ on *O*, and vice versa. But there is a further element of complexity: there is no constraint that prevents T from measuring $|q\rangle$ and $|Oq\rangle$ instead, regardless of S being $|p\rangle$ according to O. This peculiar feature of RQM may seem to entail a form of perspectivalism (or solipsism) in which there are no perspective-independent events. Nevertheless, in view of the (intrinsic) relationality of quantum processes that is assumed in this interpretation, this does not seem to represent a conclusive argument for the incoherence of RQM. In the interaction between S and O, the measurement on S is an O-dependent process; similarly, in the interaction between $S \cup O$ and T, the measurement on $S \cup O$ is a T-dependent process. It is precisely in this sense that there is no inconsistency in providing two different accounts: they refer to different interactions, and in this view there does not seem to be any metaphysical necessity that should be forcing the identity of the descriptions.

Another possible problem may be due to the transition from the claim 'there are no properties which correspond to a definite value before the interaction with a system-observer', to the conclusion 'physical quantities represented by such undefined properties do not exist', which may come from a (too) tight link between having properties with definite values and existing. In other words, the corresponding question would be: what's outside the interaction? This question poses the foundation for an analysis of the ontology of RQM from a metaphysical standpoint, and possible answers will be explored in the next chapter.

Chapter III

ONTOLOGY

3. Ontology

In this chapter I will carry out an analysis of the metaphysical implications of the relational interpretation of quantum mechanics, and discuss possible ontologies of RQM. I will start by introducing the two main formulations of contemporary structuralism, i.e. epistemic and ontic structural realism, and their respective problems, which will serve as a basis for the sections that follow. §3.2 will be dedicated to presenting the motivations for an ontic structuralist stance coming from quantum mechanics, devoting particular attention to the problem of identity and individuation of quantum objects. In §3.3 I will critically assess the different philosophical interpretations of RQM found in the literature (epistemic structural realism, radical ontic structural realism, relativism and neo-Kantianism), and will conclude the chapter by proposing a moderate ontic structuralist reading of the interpretation, based on the notion of 'object-relation identity'.

3.1 Structuralism(s)

Structural realism was introduced in contemporary debate by Worrall (1989) as an effective compromise between realism and antirealism, overcoming the challenge of the pessimistic meta-induction by restricting realism to the structural or mathematical content of the theories, such as the relations between entities rather than entities themselves. The claim that the theory's structure, over and above its empirical content, describes the world, entails that what is reflected by our scientific theories are not the intrinsic properties of its objects but the relations among them. SR represents a philosophical conception that challenges the relevance of (theoretical) objects in a theory, as well as the dominance of entity-realism within the landscape of philosophy of science. Worrall's view emphasizes structures as primary over objects in terms of epistemic access, but remains agnostic with respect to both on the ontological level; for this reason it is called Epistemic Structural Realism (ESR). This view is specifically concerned with the problem of theory change in history of science, and individuates some continuity of structure between predecessor and successor theories.

3.1.1 Epistemic Structural Realism

Psillos (2001) refers to Worrall's structuralist approach as the "downward path" to SR, that starts by weakening the standard form of scientific realism and leads to Direct ESR: we can have full knowledge (both structural and non-structural) of the observable aspects of the world addressed by the theory, but only structural knowledge of the unobservable ones. Indirect ESR on the other hand takes its main argument from Russell's theory of perception and claims that we can have full-fledged knowledge of only our sense-data (percepts), but only structural knowledge of the external world *tout court*, regardless of its observability. This view postulates some empiricists epistemological principles that inevitably lead to exclusively structural knowledge of the external world - "upward path". As Russell (1912, p.17) puts it: "although the relations of physical objects have all sorts of knowable properties, derived from their correspondence with the relations of sense-data, the physical objects themselves remain unknown in their intrinsic nature". Russell (1927, p. 270) then concludes that "the only legitimate attitude about the physical world seems to be one of complete agnosticism as regards all but its mathematical properties."

Regardless of the privileged formulation of ESR, the following formal notion of structures shall be introduced:[1] a structure S is composed of a set D of objects forming the domain of the structure and an indexed set R of relations on D; this can be expressed as an n-tuple, i.e. an ordered list of elements: $S = \langle D, R \rangle$; each relation $r_1, r_2 \ldots r_n \in R$ is an ordered set of objects $o_1, o_2 \ldots o_n \in D$ between which the relation holds, e.g. $r_1 = \langle o_1, o_2 \rangle$; the cardinality of S is defined as the cardinality of its domain D.

It is worth pointing out that in this formal notation, relations are extensionally characterized, without any reference to their intension, or material content, that is why the structures in which they are contained can be referred to as abstract. This formal definition often leads to endorse an approach to structures based on the so called Ramsey sentence (Worrall & Zahar 2001), a logical instrument to eliminate the theoretical terms of a theory by replacing predicates by variables and

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[1] Similar definitions can be found in Demopoulos & Friedman (1985) and Ketland (2004)

existentially quantifying over them. In a Ramsey sentence (RS) there are some objects and relations that are logically characterized so as to satisfy some implicit definitions in a higher-order description that eventually bridges the theoretical content with the empirical-observational consequences of the theory. However, this formal method to grasp the structural content of a theory as previously defined is not free of issues. Specifically, any Ramsey sentence approach will have to face the so called Newman problem, originally raised against Russell's structuralist stance, and reanalyzed in recent years within a RS framework by Demopoulos & Friedman (1985, p 630): "if a theory T is consistent, and if all its purely observational consequences are true, then the truth of the corresponding Ramsey sentence T_R follows as a theorem of second-order logic". The basic idea is that adopting the extensional character of relations of a certain domain of objects, structure is not sufficient to univocally identify any relations in the world. Assuming that the world is composed of a set of objects W with structure S_w and some relations V, any collection of objects can be viewed as having the structure S_w in case there is the right number of them and the related structure is empirically adequate. In formal terms: let $S = \langle (D_o, D_u), (R_o, R_m, R_u) \rangle$ be the structure of a theory T, and $S_w = \langle (W_o, W_u), (V_o, V_m, V_u) \rangle$ the structure of the target domain of T; then T_R is true *iff* $| D_u | = | W_u | \wedge \langle D_o, R_o \rangle = \langle W_o, V_o \rangle$ (the subscripts indexes *o*, *m* and *u* stands respectively for observable, mixed and unobservable).

ESR, however, is not the only possible structuralist position. Ontic Structural Realism (OSR) pushes structuralism at a metaphysical level, emphasizing structure once again, but denying the ontological status of entities. Synthetically, according to ESR all we know is the structure of the relations between entities and not the entities themselves, while according to OSR there are no entities and structure is all there is; in fact, we can only know the structure of the world because the world is nothing but structure. Ladyman (1998) argues that the epistemic form of structuralism does not really help overcoming the issues raised by realism in general, especially considering the problem of ontological discontinuity that is left untouched by simply adopting Ramsification, and suggests to interpret structural realism as metaphysically rather than epistemically revisionary.

3.1.2 Ontic Structural Realism

The ontic formulation of structuralism essentially conceives structure as being metaphysically primitive and ontologically self-sufficient, inverting the order of dependence between structures and objects. There are of course different versions of this metaphysically slippery view, but if we take its statement literally, we will end up with a radical version of OSR according to which everything that exists is a structure. However, without any reformulation of the notion of either structures or extensional relations provided earlier, it is rather hard to hold such a position, given that structure thus defined consists of an ordered list of objects and relations that are in turn defined as ordered lists of such objects. We shall return to this point later on, but another way to go is to take the subset R of relations as being ontologically fundamental instead of the superset S of structure, and commit to the idea that relations are metaphysically subsistent without there being anything between which they hold. In other words, relations do not need relata in order for them to exist, as claimed by French & Ladyman (2003), and objects can therefore be removed from the ontological level as redundant entities. This "eliminativist" version of OSR has nevertheless to face the general problem of justifying the existence of relations without relata, as for example Chakravartty (2003) and Morganti (2004) point out.

One major response that has been displayed is to think of the world not as a single-level structure with no entities among which relations can hold, but a multi-level structure where at each level there are some entity-like relata that play the role of ordinary objects but are in fact structures themselves, and this is the case all the way down to the fundamental level, if any (Ladyman & Ross 2009).

Van Fraassen (2006) further claims that in the ontic account of structural realism the distinction between the abstract mathematical structure and the concrete physical structure collapses, or, in other words, that such a difference cannot be explained in purely structuralist terms. OSR in fact implies that what seems to be the structure of something with unknown qualitative features is actually all there is. But if this is the case, he argues, the difference between structure and non-structure vanishes: "from the point of view of one who adopts this position, any difference between it and 'ordinary' scientific realism also disappears. It seems then that, once adopted, it is not be called structuralism at all! For if there is no non-structure, there is no structure either" (*Ivi*, pp. 292-293). More recently, French (2014) has argued that mathematical and physical structures can and must be kept separated. Of course any mathematical formulation requires some domain of quantification, and in order to (set-theoretically) represent structures the semantic reference to its elements is necessary, but nevertheless "one should resist the implication that is usually made from description to ontology" (*Ivi*, p. 206). According to French, it is important to distinguish between ontic eliminativism and the semantics of the sentences that seem to refer to individual objects: while electrons do not exist, 'electron exist' is true. This is because what makes the sentence true are not electrons as real individual objects, but electrons as represented by the underlying structures of the related theory.

Whether or not these replies are fully satisfactory, structuralism is widely adopted to capture some of the epistemological and metaphysical consequences of quantum mechanics, and, to some extent, relational quantum mechanics, as we shall see.

3.2 Structuralism & Quantum Mechanics

Entity-realism plays a crucial role in the conception of classical physics, but in quantum mechanics the notion of entity itself becomes more controversial. That is why some attempts were developed in the direction of a structuralist analysis of QM, both epistemic and ontic. Worrall recognized the implications of the epistemic structuralist approach for quantum mechanics in his seminal paper, emphasizing how the theory "seems to have latched onto the real structure of the universe", and how such a structure "is (probably) something like quantum-mechanical" (Worrall 1989, p. 123). So the epistemic formulation of scientific realism allows one to assign ontological weight to the relations into which the unobservable particles enter, maintaining an agnostic view with respect to such particles. The structural content of the theory is what we can be realist about, and what was and will be preserved throughout theory change, but given the uncertainty at the level of our tentative ontological description of the quantum world, we should be agnostic about what exists beyond those structures.

Notice that the shift from epistemic to metaphysical revisionism suggested by ontic structuralism would be unwarranted if its motivation came from the necessity of solving the problem of scientific realism, which is an essentially epistemic problem. Indeed, deriving metaphysical considerations from the epistemic ones concerning the content of scientific theories would make what we can know from science coincide with what there is in the world, which, in a way, would amount to taking a heavily realist step that a structuralist would not want to take. In other words, there would be no reason to think that the epistemic access to the structure of the world exhaustively reflects the ontology of the world itself, if no additional motivation is adduced other than escaping pessimistic inductive arguments.

3.2.1 The Elimination of Objects

The strong justification for the metaphysical revisionism in fact comes precisely from quantum mechanics. Many supporters of ontic structuralism (e.g. French 1989, Bain 2004, Esfeld 2004, Stachel 2006) claim that the contemporary notions of matter clash with the standard metaphysics of individual, properties and relations. Specifically, the problem of identity and individuality of fundamental particles, as well as quantum entanglement, represent the major concerns for an object-oriented ontology, that ontic structural realists propose to replace with a relational one. This very idea is clearly stated by Stein (1989, p. 57-59): "our science comes closest to comprehending 'the real', not in its account of 'substances' and their kinds, but in its account of the 'Forms' which phenomena 'imitate'. […] If one examines carefully how phenomena are 'represented' by the quantum theory, then interpretation in terms of 'entities' and 'attributes' can be seen to be highly dubious".

It seems, in fact, that quantum particles cannot be regarded as individual objects in the classical sense, such that they can be both distinguished and individuated according to the difference in their properties. Particles of the same kind, such as electrons, may not have determinate spatiotemporal trajectories and therefore enter into states to which correspond indistinguishable physical features. This is often taken to be the basis of quantum statistics. As thoroughly discussed by French & Rickles (2003), major issues arise with the permutation symmetry of quantum particles, and the so-called Indistinguishability Postulate, according to which if a particle permutation is applied to any state for a set of particles, no observation allows to distinguish the resulting permuted state from the original unpermuted one. Considering that the state allows to compute the probability of measurements outcomes, what the Indistinguishability Postulate actually represents is that a particle permutation does not lead to any difference in the probabilities for measurement outcomes.

But the problem of indistinguishability also emerges from the state of entangled quantum systems, which ascribes the same intrinsic and relational properties to each of the particles involved. For instance, the singlet state ascribes to two electrons the relation of having opposite spin in any given direction, without attributing a definite spin to either of them; if also the same (spatial) wave-function is ascribed to the same two particles, the Principle of the Identity of Indiscernibles (PII) would be violated. So, according to French & Redhead (1988), either quantum particles are non-individuals, or their individuation cannot rely on the standard bundle (property-based) approach but on some kind of empirically transcendent haecceity or primitive 'thisness'.

Saunders (2003) tries to rehabilitate PII in quantum mechanics through the notion of 'weak discernibility' of objects that share all their properties (both monadic and relational) but stand in irreflexive relations to one another. French & Krause (2006) point out, however, that the underdetermination of metaphysics by the physics, which arises from the fact that quantum mechanics is compatible with particles being considered both individual and non-individual objects, shall be overcome by completely discarding the metaphysics of objects on which the underdetermination depends. What cannot and should not be discarded are only the features that physicists and object-oriented metaphysicians generally attribute to the behaviour of 'particles', whether individual or non-individual, which the structural realist (and French in particular) reconceptualizes as the more fundamental structure of the symmetry captured by the relevant group. In fact, also the fundamental physical state-independent properties, such as mass and total spin, can be reconceptualized in structural terms. This is an important point, since if only concrete state-dependent properties of quantum systems were reconceived in terms of physical relations, then the state-independent ones could be still thought as fundamental intrinsic properties, and this would be a problem for eliminativism. The main eliminativist solution is to analyze fundamental state-independent properties in terms of symmetry relations, so as to define mass and spin as the invariants of the relevant symmetry group.[2] In other words, the notion of object can be entirely reconceptualized in terms of the fundamental symmetries described by group theory on which the properties of a particle-like behaviour depends; so, for instance, an electron – as an entity of a certain mass, charge and spin – can be represented by that aspect of the structure of the world described by the Galilei group. This and other issues concerning the notion of physical object in light of quantum theory, including the problem of identity over time, countability and absolute discernibility, are insightfully introduced in Castellani (1998b), and have been more recently discussed by French (2014).

3.2.2 The Moderate Formulation of Ontic Structuralism

Esfeld & Lam (2008, 2009, 2010) propose a 'moderate' version of OSR in the context of the metaphysical analysis of quantum mechanics. According to this non-eliminativist stance, quantum objects do exist, but their individuation depends on the structures constituting the world, so, QM is taken to suggest a metaphysics of relations, in which the fundamental physical properties consist in certain relations instead of being intrinsic properties. Moderate OSR does not entirely

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[2] i.e. the eigenvalues of the Casmir operators of the Galilei group in non-relativistic QM, the Poincaré group in relativistic QM.

eradicate objects from the picture: quantum object are considered to be individuals, which however do not have any intrinsic properties, that is, featureless substrata that only instantiate the relations of a structure.

This view shares with more radical formulations of ontic structuralism the idea that the fundamental physical objects – whether they be quantum particles or spacetime points, depending on theory in question – are the relata of concrete relations of a physical structure, independently of which they do not have any identity. But while radical OSR calls for the elimination of such objects *tout court*, the moderate formulation maintains objects in the ontology under the constraint of a *symmetrical* metaphysical dependence with respect to the structure they are part of, that is, their identity and, more in general their existence fully depend on the relations in which they stand. Interestingly, Esfeld & Lam (2010) suggest that the distinction between objects and relations should be conceived as merely conceptual rather than ontological: relations are modes, that is, the (only) concrete particular ways in which objects are. Thus, objects do exist, but their very existence is relational; in other words, physical structures are formed by object whose characterization fundamentally consists in being related in a certain way, and nothing else.

In a somewhat Spinozan spirit, the authors understand relations as the instantiations on which object depend, but, crucially, at the ontological level such a dependence is symmetrical, so that objects do not have any existence other than their (relational) modes of existence, and viceversa, their modes of existence do not have any existence independently of the objects. This particular middle-ground approach, in which objects and relations are ontologically equivalent (i.e. objects are relations), has the virtue of providing a structuralist framework that is able to escape, or at least weaken, the relations-without-relata objection that more radical approaches hardly overcome; additional possible virtues of such a metaphysical framework applied to quantum mechanics will be investigated in the final section of the chapter, when discussing the relational interpretation specifically.

Esfeld & Lam (2009) take numerical distinction as the primary motivation for avoiding a radical object-free ontology, and at the same time avoiding intrinsic properties as the basis for identity conditions. This notion does not represent a primitive thisness, since it does not confer an identity in time that is empirically inaccessible; it simply the expression the fact that there is a number of objects greater than one, that in the case of quantum entanglement, is a finite natural number. Taking numerical distinction as primitive seems in fact to be directly motivated by quantum entanglement, in which the plurality of the entangled objects cannot be distinguished on the basis on any intrinsic property they have or relations in which they stand. More specifically, when two quantum systems are entangled, their respective state-dependent properties are indeterminate, in fact, it is the total state of the joint system that determines the properties of the subsystems in terms of correlations between such properties. Claiming that there are intrinsic and therefore local property underlying these corrections, the authors claim (*Ivi*, p.7), would conflict with Bell's theorem, besides being metaphysically unnecessary, considering the characterization of the properties of each entangled system given in the form of correlations between them. They then conclude: "the state is such that it permits and calls for an internal differentiation in the form of correlations and thus correlata – although the correlata are nothing but that what stands in the correlations. We thus get correlations and correlata as internal differentiation of the world, these two being on the same ontological footing" (*Ibid.*).

The last general point I wish to make is that, irrespectively of whether the radical eliminativist or moderate formulation is privileged, ontic structural realism is a general metaphysical framework that does not by it self provide a concrete way of interpreting quantum mechanics, or put it differently, does not provide on its own an ontology for QM. Such a framework needs in fact to be complemented by an additional interpretation of the theory under consideration, for ontic structuralism does not answer the question concerning how the fundamental structures it poses are concretely realized. OSR only tell us that a physical structure is a network of physical relations whose realization does not need underlying objects having an intrinsic identity; but claiming that “structure is all there is” does not indicate how the structure in question is realized.

Esfeld (2013) emphasizes that, in the case of quantum mechanics, entanglement turns out to be the key structural element of the the theory that represents the correlations between the properties of the objects, rather than their individual intrinsic properties. And that this structural element is fundamental: the way in which the state of the joint system determines the properties of the subsystems in the form of certain correlations confirms the (moderate) structuralist claim of a mutual ontological dependence between objects and relations. But the structures that entanglement relations form are very different depending on the privileged interpretation of the theory: “Infinitely many branches of the universe with correlated values of properties in each branch (“relative states”), density of stuff or mass in four-dimensional space-time (smeared-out values), point-like flashes sparsely distributed in space-time and particles with definite trajectories in space-time are radically different proposals for an ontology of QM, although all these ontologies can be regarded as being committed to certain structures, namely structures of entanglement” (*Ivi*, p. 10). Deciding whether Many Worlds, De Broglie-Bohm or GRW fit better or support more directly the structuralist framework is a matter of (philosophical) interpretation of the (physical) interpretation. In fact, some have suggested that RQM is the best candidate for supporting structural realism.

3.3 Interpreting the Relational Interpretation

Some structural realist approaches have been used to analyze specifically the relational interpretation of quantum mechanics, given its clear focus on the relational aspect of the theory.

3.3.1 RQM & Information Structuralism

In “Rovelli’s World”, van Fraassen (2010) understands the interpretation within the framework of Informational Structural Realism, as a reformulation of QM in terms of information theory, claiming that RQM describes *only* the information that systems have about each other. According to van Fraassen, RQM represents a consistent and complete interpretation of the quantum mechanical world, but this comes at the cost of renouncing to a full realist stance: we must give up the idea of absolute observer-independent quantum states, as well as observer-independent values of physical quantities.

But he also seeks to trace what higher-order aspects of the world are absolute (in terms of being objectively known), despite the relationality at the chore of the interpretation, which is seen as as providing a framework for guiding and constraining information acquisition. For example, every system is characterized by a set of questions that can be asked about the family of observables that pertain to it, and this set is absolute. More precisely, there is a maximal number of non-redundant sequence of questions and answers through which maximal information about a system is extracted, and the number of these questions is an absolute fact. Furthermore, the observer-system that has been in a measurement interaction with another system is provided with a record of the questions that were asked and the outcomes that were obtained, and this is also an absolute fact. In particular, the author notices that the information about the state of a system relative to another system is not itself relative, and proposes an additional postulate that provides a weak correlation between the accounts of the same system given by different observers – expressed in terms of orhogonality of relative states – so as to avoid possible inconsistencies and ensure a (transcendental) coherence between the different views.

There is no omniscient privileged "view from nowhere" which has primary access to the 'real' state of the measured system, as it is pointed out in the relational analysis of the Wigner's friend example. But according to van Fraassen, there is a non-relative transcendental knowledge about quantum mechanics in terms of a set of principles that constraint the general form information can take. In general, he understands the relational interpretation as providing a transcendental approach on the basis of which the basic form of information that one system can have about another is described, that is, states relative to a given system are assigned on the basis of the information available to that system: "So we have here a *transcendental* point of view. Rovelli offers us this knowledge of the general form, the conditions of possibility. We must take very seriously the fact that as he sees it, quantum mechanics is not a theory about physical states, but about ('about'?) information. The principles he sees at the basis of quantum mechanics are principles constraining the general form that such information can take, not to be assimilated to classical evolution-of-physical-states laws". (*Ivi*, p. 397).

Information-based approaches to quantum theory can be traced back to Groenewold (1946), for example, who already characterized the states in terms of observer-obtained information, and more recently other interpretations of QM, such as Qbism, have endorsed a marked information-theoretic view. However Rovelli himself has criticized them as pushing towards an excessive instrumentalist stance based on the emphasis on the language of information, that brings with it some ambiguity between its epistemological acception and the notion of information as concrete physical correlation (Rovelli 2021b, p. 5).

More generally, given the exclusive focus on information processing, Van Fraassen's analysis makes RQM compatible with epistemic structural realism, and therefore leaves room for some degree of agnosticism with respect to the ontological configuration of quantum systems in terms of definite intrinsic properties, which however the relational view does not seem to concede. In other words, within an exclusively informational account, the relational character of quantum systems simply represents the form of their interaction with an observer, but not (necessarily) their identity, while in RQM the absence of intrinsic properties is taken as a primitive notion. As Rovelli & Laudisa (2019, p.22) point out, "the lack of observer-independence is not inability of providing an account of the structure of matter, because there are no intrinsic properties that can be assigned to systems independently of their interactions. […] Here, what is abandoned is the presupposition that quantum systems have a non-relational, intrinsic nature."

3.3.2 RQM & Radical Ontic Structuralism

A different structuralist approach is proposed by Candiotto (2017), in which RQM is seen as an instantiation of the metaphysics of radical ontic structuralism, since "it provides good reasons for the argument from the primacy of relation" (*Ivi*, p. 537). Candiotto is particularly interested in emphasizing the ontological status of relations, and argues for the reality of quantum interactions as depicted in the relational interpretation. But not only are relations ontological subsistent, they are also fundamental, as opposed to relata. In fact, she claims, RQM calls for the elimination of objects altogether, which makes it compatible with the radical formulations of OSR, in which objects are taken to be redundant and, therefore, eliminable entities.

She is certainly right, I believe, in trying to recover some degree of realism within RQM directed towards the fundamental (cor)relations emphasized in the interpretation, which is indeed not a theory about agents, beliefs, (conscious) observers or experiences, but rather about relational yet real systems interacting via discrete relative quantum events. However, besides attributing metaphysical priority to quantum relations over objects, she still treats these two categories 'dualistically', as two distinct notions, similarly to those general formulations of OSR that face the difficulties mentioned in §3.1, e.g. how to deal with relations without relata, or how to conceive of a metaphysically consistent structure without objects that however maintains objects as one of its constituents. In fact, by simply inverting the order of dependence between entities and relations without a reformulation of the notion of neither of them, some crucial questions remain unanswered, for instance concerning how the fundamental structures are concretely instantiated or realized, and how pure relational structure can 'play the role' of the subjects of the state-dependent properties ascribed during measurement interactions and, more importantly, the state-independent properties that are non-relational and non-relative even within the relational interpretation. In other words, this radical ontic structuralist approach to RQM does not provide a way to reconceptualize and incorporate physical systems in the ontology of relations that it poses. More generically, I think, something metaphysically deeper of RQM's fundamental features is overlooked by endorsing a radical ontic structuralist framework. Indeed both structuralist approaches to RQM just discussed propose a view based on either epistemic or ontological supremacy of quantum relations over the entities which the theory deals with; however, maintaining ontological priority at the core of the quest does not allow to look at the problem of the connection between objects and relations under a different light, which I think is instead suggested by the relational interpretation of QM, namely the collapse of the distinction between what should count as object and what as relation. I shall return on this point in the concluding subsection.

3.3.3 Non-Structuralist Interpretations of RQM: Relativism & Neo-Kantianism

Other attempts to philosophically 'interpret the interpretation' have also considered non-structuralist approaches. Ruyant (2017) proposes an essentially instrumentalist reading of RQM that is based on a full relativist account not only of the values of the variables, but also of the events in which such values are obtained. The idea at the core of the argument is that in order to avoid the tension between possible incompatible descriptions by different observers, the very existence of quantum events is to be considered relative to an observer. In fact, a radical relativism is, according to Ruyant, the only way for avoiding the discomfort arising from mutually incompatible descriptions concerning the same events, on the one hand, and an ontology of events, on the other. Ultimately, he claims, the theory does not deal with real events but with the knowledge (naturalized) observers have about the events they are part of. Thus, while in a relational view of the ontology of the theory external events are real relations between two objects, just as the events an observer is part of are real relations between it and a second system, in the relativist stance proposed by the author "external events are relations between two objects, but they merely exist relative to the observer that infers them from its measurements" (*Ivi*, p. 6).

This reading of the interpretation is aimed at reinforcing its internal coherence and general consistency, but the philosophical price it pays is not appropriate, not in the sense that it is too high, rather, it is simply the wrong price to pay, I believe.

This and other instrumentalist or information-based approaches to RQM, in fact, ‘save’ the interpretation by discarding its basic ontological-naturalistic commitments. For instance Bitbol (2007) understands the interpretation within a neo-Kantian framework, in which functional rather than ontological relations are seen as being at the core of the theory. He proposes to replace physical properties with functional references for information exchange, and actually criticises Rovelli for maintaining an ontological commitment towards (relative) quantum events. Therefore, he suggests, the idea that quantum mechanics provides any description of (the structure of) the microscopic world should be given up in favor of a theory of knowledge that coherently constrains information-gathering processes.

But these approaches miss the essence of RQM’s relationality – extensively discussed in chapter II – that is, the conjunction of the relationalism of systems and the relativity of the values of their properties. The relationalism at the ontological level is as essential as the relativism at the level of value ascription. What this means is that events exists (occur) only at interaction, but once an interaction is established, the existence of the event is absolute, i.e. not relative to the systems involved. Only the values of the properties measured during the interaction are (and will always be) relative to the systems involved, but not the very existence of the event itself. In other words, any third system (T, in the Wigner’s friend example) will always agree about the existence of an event in which two systems (S and O) interact. The values each system exhibits ($|p\rangle$ and $|Op\rangle$, or $|q\rangle$ and $|Oq\rangle$) strictly depend on a direct measurement on either of them performed by the third system, but their correlation exist irrespectively. Notice that in the much-discussed example, when – at the time t_2 – T has only interacted with the joint system $S \cup O$ but O has already measured S, an event occurred for both O and T, but produced a well-defined value only according to the former. In a slogan: values are relive, existence is relational. In fact, this is not only an interpretational step, it is an empirically determinable fact. As Rovelli & Di Biagio (2021, p. 10) point out, “the interaction between S and O have an influence on the facts relative to T. Indeed after an interaction, S and O are entangled relative to T, meaning that in interacting with the two systems, T will find the two correlated”.

[adapted notion]. Thus, if an external observer does not directly perform a measurement on one of the subsystems, the properties of the two remain undetermined since their values actualize only with respect to the systems involved in the interaction, but the existence of the event itself is non-relative. Indeed, the fact that O obtains a definite outcome for its measurement on S does not prevent T to detect interference effects between O and S. Actually, expecting interference effects is precisely the meaning of describing a system as being in a superposition of states, given the interpretation of quantum states adopted by RQM. Rovelli and Di Biagio then conclude: "in this sense, relative facts correspond to real events, they have universal empirical consequences" (*Ibid.*).

3.3.4 Object-Relation Identity

Ruyant (2017, p. 7) claims that Rovelli explicitly rejects relationalism, since according to RQM "there cannot be absolute facts". But I believe this is a mistake, which represents another unwitting example of the surprisingly common confusion between the relationalism of the ontology and the relativism of the values, to which much attention was dedicated throughout the previous chapter. RQM provides an *ontology* of *relative* facts. The non-absoluteness Ruyant refers to only regards the value of the variable properties of the systems, which are indeed observer-dependent, but this by no means implies the rejection of relationalism.

In my view, what the relational interpretation calls for is neither to renounce to realism *tout court*, nor to eliminate objects altogether, but to adopt a structuralist metaphysics where relations and objects (relationally reformulated) are onto-logically equivalent. Correlations are surely fundamental, and outside of any interaction there are only quantum correlations given by the algebraic relations that determine the possible values of the property that a potential or 'not-yet' system can take. But these relations are concretely instantiated at a physical interaction, (the condition of possibility for information exchange) between two systems, i.e. the relata of concrete relations of a physical structure independent of which, however, they do not have any identity. So, the outcomes of a quantum measurement of the form 'the observable P has taken the value p_i' express the value of the relation itself that is actualized at an interaction, but also depend on there being systems that interact and acquire well-defined properties during such an interaction. This symmetrical metaphysical dependence between systems and the structure they are part of is essentially what the moderate formulation of OSR suggests: the identity and, more in general, the existence of objects fully depend on the relations in which they stand.

As I have argued elsewhere (Buonocore 2022), by fully embracing RQM's relational ontology of relative facts, in which the only properties that define a quantum object are intrinsically relational, *object-relation identity* may be the metaphysical insight suggested by the interpretation: a correspondence between the notion of 'object' and the notion of 'relation' at the quantum level that establishes a symmetry through which one can be reduced to the other. Therefore, objects may be conceived as fundamentally relational, and this makes the question about the ontological priority meaningless, as moderate ontic structuralists suggest by claiming that the object-relations dichotomy is merely conceptual rather than ontological. Evidently, these (somewhat Humean) objects must be redefined as a simple collection of relational properties, without any substance bearing them.[3] Indeed, objects do not have an intrinsic identity even when their variable properties are described by a well-defined value, for such a value is always observer-dependent, according to the relational interpretation of QM. To put it differently, definite-valued systems are not always there for everyone; what it is always there is the correlation between them, as the relational reading of a Wigner's friend scenario clearly exemplifies.

If a classical object-oriented ontology were endorsed, in which objects exist and they only exist with definite intrinsic properties, then according to RQM also the existence of a system (other than the values of its properties) would be relative to the system according to which it has definite-valued properties. But this 'intermittent' existence, so to say, would be very problematic to accept from a physical standpoint, and to support, from a metaphysical one, if some degree of

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[3] Oldofredi (2021) argues for a mereological bundle-theoretic reading of RQM that is compatible with – and possibly complementary to – what I am here proposing.

realism is maintained.[4] But an ontology of relations overcomes – or at least attenuates – this problem, for relations always exist; once a correlation is established between two systems, its existence is absolute in the sense that any possible external observer would agree that they are correlated, and in fact would describe them as a correlation of superposition terms. What is relative is the value of such correlation, so that a relation goes from being abstract and indeterminate to being concrete and definite-valued, filled by the real physical interaction that determines the (relative) value. Objects ontologically coincide with the definite-valued instantiations of relations, but there is really only one entity that populates the (theory's) ontology.

From the general point of view of structuralism, moderate OSR provides an inclusive definition of relations that is able to encode the notion of (relational) objects without requiring a classic domain of objects, and considering entities as nodes in a relational structure. On the other hand, the ontology of structures prescribed by radical OSR seems to be unsustainable without a radical modification of our most fundamental metaphysical understanding of structures as being composed of objects and relations, and the relational interpretation of quantum mechanics seems precisely to suggest an ontology based on object-relation identity that requires such modification.

Within the perspective here proposed, the distinction between epistemic and ontic structural realism in the context of quantum mechanics becomes rather blurred, since what is excluded from either epistemic or ontological domain - (objects) tends to coincide with what is included (relations). Moreover, given the relational interpretation of objects, this view seems also to allow for a possibility of retrieving a form of entity-realism within the structural realist framework. But by no means I wish to convey the idea that either object-relation identity specifically or ontic structural realism more generally provide *the* framework for understanding natural phenomena, reflecting some universal metaphysical truths.

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[4] Notice that Calosi & Mariani (2020) offer an interesting pattern to work with when it comes to a minimal realist interpretation of non-interacting quantum systems, which they base on Metaphysical Indeterminacy, but they do not enter into the details of the relational vs. object-based ontology debate.

In other words, I do not think that the mutually beneficial interaction between moderate ontic structuralism and the relational interpretation of quantum mechanics provides the basis for extending (inductively) its metaphysical consequences to other fields of investigations. In fact, extending the structuralist framework to other domains (e.g. biological sciences, as French (2011)'s attempts) brings with it the same problem of generalization that typically affects overreaching realist or antirealist arguments, as in the case of Stanford's new induction that has been discussed in the first chapter.

Conclusions

The present work has been set against the general background of a philosophical analysis of features and concepts of quantum mechanics to be understood within realist or antirealist frameworks. The main aim of the thesis has been to investigate the conditions of possibility for a structuralist interpretation of relational quantum mechanics, by historically tracing its relational foundations, evaluating its structural content, and highlighting any point of contact and friction between the dichotomous relationality of the interpretation and the different epistemological and ontological alternative attempts found in the literature.

Before getting into the details of the analysis of quantum mechanics, its relational interpretation and structural realism, I have tried to motivate in the first chapter the mutual beneficial interaction between general philosophical frameworks and the specific content of individual scientific theories. On the one hand, the shape taken by the debate on realism and antirealism changes radically depending on the scientific domain under consideration, and the comparison between the three dimensions of realism in quantum theory and hierarchical monism and pluralism in evolutionary biology exemplifies this idea rather clearly. On the other hand, the case-study on Stanford's New Induction makes a powerful point against the common tendency of extending the range of applicability of one own's arguments to general notions such as "scientific practice" or "our best theories", that often results in a problematic tradeoff between generality and efficacy to adjust to specific individual cases. Hopefully, these introductory consideration have assisted in supporting one of the main background assumptions of the thesis, namely that realist stances take very different forms depending on the theoretical content they are confronted with, which in turn makes the critical juxtaposition between philosophical claims and selected scientific theories much more fruitful than analysing – or endorse – the former as metaphysical positions alone.

The central chapter has been dedicated to the examination of the relationality at the core of RQM. Such a notion was preliminary clarified from the perspective of the philosophy of spacetime (and philosophy of sociology for comparative purposes), distinguishing between the relationalism of the ontology and the relativism of values. Regardless of the side one might take in the articulated debate on spacetime ontology, the point was to stress the distinction between the relationalism of the theory and the relativism of the elements within the theory, which tend to be not so neatly separated in the literature, perhaps also because of the strong interconnection these notions have in the specific domain of spacetime physics. But the case of sociology shows that it is not so straightforward that theories that adopt a relational approach must necessarily deal with relative concepts.

This distinction, which was originally designed as a simple conceptual clarification, turned out to be (surprisingly) relevant for the rest of the chapter. Indeed, the historical analysis carried out in the following section revealed how the same dichotomy of the notion of relationality was already present in the first developments of quantum theory, in particular in Heisenberg's matrix mechanics relationalism, and Bohr's and Hermann's relativism. Heisenberg's approach is in fact based on an exclusive focus on observable physical quantities, whose values are obtained only under the appropriate measurement conditions; in this perspective, only physical quantities evolve in time, not quantum states. While the interaction-dependent character of value acquisition of stationary-state systems does seem to point towards a form of relationalism in matrix mechanics, Bohr's account tends towards an instrumentalism about quantum systems. His analysis of the contextual character of quantum phenomena implicitly points in the direction of a relativisation of quantum observations, but it is only with the (often neglected) work of Grete Hermann that the relative character of quantum observations becomes explicit. Her neo-Kantian "splitting of truth" separates various equally legitimate representations within a physical description that cannot be unified into a single picture of nature.

Remarkably, Rovelli's relational solution to the measurement problem relies on precisely the conjunction of an Heisenberg-type relationalism of systems and an Hermann-type relativism of values: variables of quantum systems have a value only within interactions, and such interactions do not assign absolute values to the variables. On the one hand, the Heisenberg-inspired ontology interprets the measurement outcomes as the only elements of reality and makes them compatible with the (pre-interaction) superposition quantum states, to which no ontological weight is assigned. On the other hand, the values of such measurement outcomes are taken to be context-dependent rather than absolute, so that a well-defined event in a certain context is not necessarily a well-defined event in another. The relativism of value ascription, which in RQM's terminology becomes event occurrence or fact realization, is noticeably in line with Hermann's understanding of complementarity, in light of which a statement concerning one particular context cannot be unambiguously combined with a statement deduced by means of the other. The conjunction of these aspects of relationality provides the ground for the relational interpretation of the Wigner's friend experiment, which I have exemplified with the use of standard formalism in the dedicated section. After some general reflections about virtuous and less virtuous ways of debating over the problem of the interpretation of quantum theory, I conclude the chapter by discussing (and replying to) several objections to RQM, with particular respect to the implications of the so-called third person problem. Despite some disagreement concerning the observer-(in)dependence of quantum states, the recent literature seems to show that the relational interpretation of quantum events is at least a legitimate possibility.

The thorough analysis of the notion of relationality in quantum mechanics served as the basis to explore the possibility of a structuralist interpretation of RQM that was undertaken in the final chapter. I have critically assessed the different (philosophical) interpretations of the (physical) interpretation found in the literature (epistemic structural realism, radical ontic structural realism, relativism and neo-Kantianism), and argued that they all fail to provide a satisfactory framework for the peculiar character of RQM's relationality. If, on the one hand, the radical ontic structuralist attempt does not provide a way to reconceptualize and incorporate physical systems in the ontology of relations, relativist or information-based approaches 'save' the interpretation by discarding its basic ontological-naturalistic commitments. Such approaches, in fact, miss the essence of RQM's relationality, that is, the conjunction of the relationalism of systems and the relativity of the values of their properties. The relationalism at the ontological level is as essential as the relativism at the level of value ascription: what this means is that events exists (occur) only at interaction, but once an interaction is established, the existence of the event is absolute, i.e. not relative to the systems involved. Within the relational account, QM must be conceived as a theory about *relational* yet *real* systems interacting via discrete *relative* quantum events, not about agents, beliefs, or knowledge. Thus, I have concluded the dissertation by proposing a moderate ontic structuralist reading of the interpretation, based on the notion of 'object-relation identity', a correspondence between the notion of 'object' and the notion of 'relation' at the quantum level that establishes a symmetry through which one can be ontologically reduced to the other. Such a notion is fully compatible with moderate ontic structural realism, which provides an inclusive definition of relations that is able to encode the notion of (relational) objects without requiring a classic domain of objects, and considering entities as nodes in a relational structure.

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