Worldly Structures

Where we touch the essence

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Preface

Let me start by introducing myself and my fascination for structural realism. Where most structural realists are realists who turned more and more modest in the light of skeptical arguments, I came from an other direction.

For years I have been a Kantian. An idealist who believed that each of us had his or her own representation of the world. We are unable to know the world-*an-sich* directly. This gives problems when considering knowledge. When having knowledge is a justified true belief, the proposition "snow is white" is true if and only if snow is white. To verify the truth of the proposition from within my representation, would require knowledge from the snow-*an-sich*. But all my access to snow was from within my representation, leaving out the possibility to verify my knowledge.

Truth became coherence, depending on the structure of my set of beliefs. It seemed as if I could choose my own truths, making truth a completely trivial notion. There was no need to value something over anything else, nothing touched the world. Now I had been given the choice and control over my own representation, to choose a preferred reality seemed pointless. Physics became a trick, philosophy became mind training.

Within this view there was one big question. How can it be that we agree on so many things when each of us is entitled to validate his or her own truth. It seemed as if we can agree on things, even things we do not share beliefs on. Knowledge is a social phenomenon. We agree on truths, so there must be something in common between the different views.

While writing a bachelor thesis, something struck me. I was comparing different interpretations of quantum mechanics and I recognized a pattern. This was a pattern I was familiar with, it was the pattern of disjunct elimination. When we have multiple views on reality, each entitled to its own truths, we can perform an analogue of disjunct elimination between the views. Disjunct elimination in logic tells us that

$$(\psi \longrightarrow \chi), (\phi \longrightarrow \chi), (\phi \vee \psi) \ \vdash \chi \tag{1}$$

Whenever we have multiple views each entitled to its own truth, what we can be certain of when we allow each of them their truth is the intersection of those views. [1]

Other bits of argument came knocking at my door. How we communicate and understand each other while having a different representation is solved by this line of reasoning as well. Colour is a good example: it dawned on me early in my life that nothing can tell us that what I define as

[1] At first I was afraid that this would turn me into an empiricist. I have a lot of respect for the empiricist view, but since our representation is ultimately based upon the empirical input received, that it is a part of each and every representation seems more of a truism instead of an exciting hypothesis. So I looked further.

purple is the same colour as what someone else defines as purple. Still we agree on an object that has this colour. We link the object, giving us a stable set of sense stimuli, to the colour in each of our different minds that is labeled "purple". We do not know how our individual perceptive systems alter the incoming sense data, but we can know that the colour defined is a mixture of the two colours "blue" and "red".

So even if we do not agree on what purple *is*, we do agree on how what each of us calls "purple" relates to other colours. We know its position on the colour sphere of Itten, even though our individual sense impressions of the sphere can differ.

Another example has to do with white snow. To validate something about snow, we go and interact with the world. To validate the truth of the proposition "snow melts", we interact with snow. And the object in our representation, "snow", is actually changing in our representation and through changes in our sense impressions. It's becoming all wet. And we agree that by heating snow, it melts. Not being able to know snow-*an-sich*, we can know what corresponds to it and agree to it. The relation of the object "snow" in our representation to "heat", namely "Melts(snow, heat)", agrees with our representation. We can make predictions with it and we cannot divert from some form of truth we as a community agree upon. The relation is not a part of our sensory inputs, however, it is knowledge of the world. But what kind of knowledge?

What we can communicate within the epistemic community is the structure of our sense experiences, everything we perceive is nothing but structure. It is called the *transmissibility argument*.

Each of us has an interpreted structure as a representation and the structures of the world are communicated to us through empirical sense data. To communicate successfully about the world, we have to share a structure in each of our representations similar to the structure of the world. When knowledge is social instead of private, the epistemic community agrees on the structure of the world. Specific subgroups of the community agree on interpretations as well, but when we eliminate those interpretations, we are left with structure, bare structure.

That we can have structural knowledge with a community gives us a hint of something deeper. There is a physical structure in the world. There will always be hardcore realists who naively think our representations mirror the outer world. How naive. That only the structure of our representation touches the structure of the world is quite a humble attitude, and next to that it solves more riddles than it poses.

During my research on structural realism, I discovered the power of automorphisms. Automorphisms are isomorphisms of a structure to itself, preserving the structure. These automorphisms divide the structure up into invariants. It is as if different ways of representing the same structure keep something intact. Needless to say, I recognized the disjunct elimination argumentation pattern in the application of automorphisms to structures. The automorphisms give rise to equivalence classes that we acknowledge in the physical structure. It gives us a natural way to carve up nature, we just carve at the joints.

Once I got tuned into the structural view, I saw structure everywhere. Mathematics is just a way to express the structure of the world. Music rises from a collection of vibrations that is transmitted to our ears, it is the harmonious (or sometimes dissonant) combinations of vibrations we love. The same with colours, a painting is a collection of harmonious and contrasting colours, expressing the (structure of the) perception of the painter, while an impressionistic painting tries to mimic the structure of our shared representation in a way.

The painting I chose for the cover depicts precisely this *Aha-Erlebnis*. It mimics the world and our access to the underlying structures behind it. The moment when it is possible to find and manipulate the structures beyond the (superficial) empirical world. These are the actual relations between kinds in the world.

I think that there are multiple ways to dissect the world, but if you make similar cuts, you get similar cross-sections. There is some consistency in the way we see the world, even from different perspectives. That is why we can understand each other. This is what I will try to accomplish in this thesis: a system that gives us a form of certainty in a world where nothing seems certain.

And this, my dear reader, is a journey through the basics of structural realism we will take together. We will look for justifications of structural realism, we will look for a fitting metaphysics, one that fits our established views of what the world consists of. And finally we will actually compare different views to see structure we can know to exist in the field of quantum mechanics.

But before we take off, I would firstly like to thank my kind supervisor, F.A. Muller, who, with his remarks guided my writing, both in style as in form. Without him this thesis would not have gotten where it is now. I really enjoyed our meetings both in Utrecht and in Amsterdam, both inside and outside the department. [2]

Secondly I would like to thank Femke Kuiling for a weekly drinking night in which we discussed our theses (among other things), even though we didn't manage to meet weekly[3], discussing this subject matter in a drinking environment helped to clear up my mind.

Thirdly I would like to thank my parents, not only for raising me, but for advising my continual in times of despair. One thing lead to another and now I am finishing my master's. Feels good man.

Last but not least, I would like to thank my beautiful girlfriend Elize Rietberg who supported me and believed in me at times I forgot to. Next to this support we also enjoy a loving relationship of which I am also very grateful.

Amsterdam, July 20th
Vincent Schoutsen

[2] On a side note, I would also like to thank him for wearing yellow glasses, this is a very inspiring style accessory. Note that the style cannot be reduced to the sum of accessories! It's a package deal.

[3] Far from it, but it is the intention that counts.

Chapter 1

Structural Realism

Structural realism is a position in realism that has gained a considerable amount of followers in the last two decades. Being interested in the position, we will investigate its origin and spell out the consequences, after which we will try to apply it to actual science.

The outline of this thesis is as follows:

1. A description of the realism debate and the position of structural realism as most plausible candidate.
2. A metaphysical chapter devoted to what the phrase 'structure of the world' refers to.
3. An example from modern quantum mechanics, looking at how orthodox quantum mechanics and de Broglie-Bohm theory relate structure-wise and can be expressed in our just formulated metaphysics.

In this Chapter we describe Structural Realism and its position in the realism debate. The realism debate has a prominent place in the philosophy of science; it is the debate about the status of our scientific theories: Do our scientific theories tell us what the world is? The two main positions within this field can be classified as the realists and the anti-realists, who respectively affirm or deny the thesis of realism.

The realism debate occurs in many fields of philosophy. We see a similar debate in philosophy of mind, philosophy of language, metaphysics, ethics etc. All of these subdisciplines are looking for a way to connect our way of understanding the world, whether this is done in images, knowledge, language or scientific theories, to the world itself.

This connection between phenomenon and noumenon, if it exists, gives us the possibility to gain knowledge about the world. This is the question that drives this Thesis[1]: if we can have knowledge about the world, what is it that we can know? There are different positions regarding scientific knowledge, and we will try to develop a new type of structural realism. Structural realism is a position that is on the scientific realist side of the realism debate. An essential part of scientific realism is its epistemic claim: *That our best scientific theories are (approximately) true, and by being (approximately) true, they can yield knowledge about the world. This knowledge is of how the world is or will be, observable and unobservable elements alike.*

[1] In the remainder of this Thesis, we will use the word "Thesis" with a capital to denote this Thesis.

What this knowledge tells us about the world is the next question, after we have established *that* we can know something about the world. Structural realism is a very humble position in that it claims that we can only know the *structure* of the world. What and how this structure is will be defined in the next chapter, Chapter 2.

This Chapter gives a brief overview of different positions in the realism debate. First we discuss realism and anti-realism, concerning the question whether it is possible to know the world at all (Section 1.1). Structural realism is a third position on the realist side of the debate. The different versions of structural realism we discuss in Section 1.2 and as promised in the Preface we end this Chapter with a summary and conclusion (Section 1.3). This chapter is a sketch of the landscape in which our arguments will be presented.

1.1 Characterizations of Realism and Anti-Realism

Realism is the doctrine that says that reality exists independently of our representation of it and that we have access to this reality. Let us quote the characterization Stathis Psillos gives in his *How science tracks truth*[84].

> - The *metaphysical* stance asserts that the world has a definite and mind-independent natural-kind structure.
> - The *semantic* stance takes scientific theories at face-value, seeing them as truth-conditioned descriptions of their intended domain, both observable and unobservable. Hence, they are capable of being true or false. Theoretical assertions are not reducible to claims about the behaviour of observables, nor are they merely instrumental devices for establishing connections between observables. The theoretical terms featuring in theories have putative factual reference. So, if scientific theories are true, the unobservable entities they posit populate the world.
> - The *epistemic* stance regards mature and predictively successful scientific theories as well-confirmed and approximately true of the world. So, the entities posited by them, or, at any rate, entities very similar to those posited, do inhabit the world. (Psillos 1999, p. xvii, [84][2])

Starting with the first thesis[3]; in realism there is necessarily a claim of a mind-independent world. This is THE WORLD, following Putnam's notation in [87]. The metaphysical world has a structure of natural kinds that are related to one and another. The definiteness of THE WORLD is necessary to gain valuable knowledge about THE WORLD, valuable because if THE WORLD's structure does not change, the knowledge stays applicable. What the structure of THE WORLD is like and the role of natural-kinds in this, we shall address in Chapter 2.6.

The semantic thesis secures the connection between the terms in the language referring to THE WORLD. It tells us how we are able to speak of unobservable items such as electrons and that by speaking of electrons we speak about objects in THE WORLD. Our theories make statements about these objects and these statements are true or false. The values of the statements are (mostly) approximate. Exact truth is a more appealing claim, but the examples of approximation are so widespread that there are no realists who would like to claim exact truth[4]. The notion of

[2]My emphasis.

[3]Psillos is very fond of the word stance. The term thesis might be more appropriate, since "stance" has some connotations closer to "attitude".

[4]Remember the farmer who asks the physicist to help him device a solution for the stagnating egg production at his farm. The physicist finds a solution, but says that it will only work for spherical chickens in a vacuum.

approximate truth is problematic, but we prefer to let that issue rest here[5]. The semantic part of realism is the most important part in this Thesis, because this is where we close the gap between THE WORLD and our knowledge of it.

The epistemic thesis claims that our predictively successful scientific theories are indeed approximately true. The knowledge that we have by knowing the theory can therefore be said to be knowledge of THE WORLD. This is called epistemic optimism. The main argument for epistemic optimism, the "no miracle"-argument, will be looked at in Section 1.1.1.2.

The realist argument is called the "no miracle"-argument (**NoMir**), the anti-realist argument is Putnam and Laudan's infamous *pessimistic meta-induction* (**PessMI**). PessMI is connected to Kuhn's historicism, and conventions.

Although the realism debate covers virtually all areas in philosophy, we restrict ourselves to science because it is a well-documented enterprise that has been evolving for centuries. In this thesis we give some examples from the domain of physics, because physics has a very long tradition and is, if anything, a mature science[6]. And because the object of study of physics is assumed to be static[7]; all theories that have been formulated over the past couple of centuries essentially speak about the same object, i.e. THE WORLD, making the theories comparable.

Both camps agree on the physical subject matter being static, but they attach different conclusions to this assumption. The realists claim that there is a form of epistemological convergence; we are getting closer and closer to the actual truth, a description of the world-*an-sich*. The anti-realists, beginning with Laudan, use the same assumption to show we cannot describe THE WORLD, for, over the course of history, our depiction of the external world kept changing. This argument will be spelled out in Subsection 1.1.2.3. Before we will come to the anti-realist's attacks on the realist arguments, the realist's arguments will be spelled out.

It is not possible to give a full description of all the discussions and issues playing in the realism debate. The discussion is too broad to explain in an overview Chapter of a master thesis. We will therefore go over the argumentation and highlight those arguments that motivate our choices in later chapters.

1.1.1 The problems and arguments of Realism

An important part of scientific realism is that it is possible to gain knowledge about the unobservable parts of the world. Observability is an anthropocentric notion and its definition has recently been given by Muller [80].

The classical anti-realist wants to deny the possibility of knowledge about the unobservable parts, and therefore needs the distinction between the observable and unobservable entities to have epistemic significance. This distinction is without epistemic significance for the realist. The realist says that the observability of objects do not influence the way we gain knowledge about the object in question.

A possible attitude towards realism about unobservable objects is given by Hacking.

[5] For those interested, the work of Kuipers focuses on approximate truth, e.g. [64].

[6] The maturity of sciences used to be a prerequisite for realism, but maturity demands evade the problem; after every scientific revolution we can claim that the former theory was still immature, making it an ad hoc rescue attempt.

[7] Not to say that THE WORLD lacks dynamics, on the contrary, it is always in motion, but to claim that the form of these dynamics somehow obeys a fundamental set of laws. This is how THE WORLD is perceived as static and physics has as job to find the laws, which are the static elements of THE WORLD.

1.1.1.1 Entity Realism

The classical scientific realist, such as Putnam in 1975 [86] and [87], takes realism to consist in what we have dubbed the *semantic stance.*

> (*a*) our best scientific theories are (approximately) true and (*b*), the terms in those theories genuinely refer.

There are some partial realisms that have evolved from this stance, denying some claims of full scientific realism and only defending one. The most prominent example is *entity realism.* Hacking's slogan is "If you can spray them, they are real!", referring to an experimentalist who (allegedly!) sprays electrons on a Niobium ball to decrease the charge [49].

Entity realists deny the truth of theories altogether, they only claim that our terms refer to existing entities. This is their way to claim consistency over scientific revolutions; even though the theoretical content was different before the theory change, the scientists did refer to the same object. How we know that there is an entity in THE WORLD corresponding to the terminology in the theories used is because we can manipulate the entities. There is one question that comes to mind here, which is why entity realism is an unlikely candidate, and that is *why* do we believe we manipulate the entities? **This is justified by the belief in the *theories* that tell us we manipulate the entities.**

This is the point where entity realism collapses on itself. Hacking's entity realism implicitly assumes the truth of the *theories* explaining what our experiments do in terms of entities. We cannot explain the entities without referring to the truth of the theories. Hacking infers the truth of our best theories to explain the behaviour of the entities. This form of argumentation is called *inference to the best explanation* and it is the main intuition behind realism, let's spell it out.

1.1.1.2 The "No Miracles"-argument

The "No Miracle"-argument is the argument that the realist's explanation of the success of science is the only explanation that does not leave the empirical and technological success of science miraculous. The realist explanation of the success of science says that science is successful because the theories in science are (approximately) true. By invoking the semantic stance, the claim that terms in our theories refer to objects in the world, we can explain *why* our theories work so well, because they are true.

We take the success of science as one of our true premises. This is not without reason, science is such a fascinating subject because it is able to make successful predictions. We can calculate how to fly to the moon and actually do it. With the press of a button, we can capture the appearance of a beautiful scene in a digital format while simultaneously capturing the precise position of the scene with the help of satellites orbiting our planet. The amount of knowledge needed to create this magic button is mindboggling.

Practical applications can be found by trial and error, but a theoretical prediction is something else. Einstein's famous prediction of the bending starlight visible during an eclipse makes us believe that we not only have empirical success, but that this knowledge (e.g. curved space-time) is (approximately) true. According to the realists, Einstein's empirically adequate prediction was made on the basis of the theory of general relativity. The only explanation of the success of this theory that does not allow for miracles is the (approximate) truth of this theory. Somehow, somewhere the terms latched onto the actual objects in THE WORLD.

There is an unspoken intuition that constructive explanations, or causo-mechanical explanations, are the only valid explanations. There is no consensus on this topic, there are different accounts of explanations around. A causo-mechanical narrative of the inner workings of a phenomena, when true, does constitute a valid explanation of the phenomenon. Let us grant this intuition for now.

Van Fraassen tries to take the ontologically least committing explanation. In his constructive empiricism we should only believe in the empirical adequacy of a theory. The truth of theories, notably about unobservables, cannot be attained.

But Van Fraassen's constructive empiricism gives no valid (causo-mechanical) explanation of our scientific success. To give an explanation of why our theories are successful, Van Fraassen turns to Darwinian evolution theory. In his 'Concerning Scientific Realism', an excerpt from *The Scientific Image*, he states that

> In just the same way, I claim that the success of current scientific theories is no miracle. It is not even surprising to the scientific (Darwinian) mind. For any scientific theory is born into a life of fierce competition, a jungle red in tooth and claw. Only the successful theories survive –the ones which *in fact* latch on to actual regularities in nature[8]. (Van Fraassen 1998, p. 1084, [99])

In this quote Van Fraassen claims that the acceptance of a theory is a Darwinian process. This is no matter of discussion; of course we will always choose the empirically best fitting theory. The miracle is not that our current theory is successful as compared to others that are less successful, the miracle is that the theory *is successful at all.* In the last sentence quoted above, he mentions that the theory has *in fact* latched on to the actual regulations in nature. This is a form of realism, the question remains what kind of regularity Van Fraassen is talking about. This last sentence shows the power of the "no miracle"-argument: even a prominent anti-realist has to equate the success of science with factual latching on to actual regularities in the world. What these regularities might be and how the latching works, we investigate in subsection 1.2 and the remaining chapters.

A claim often made by realists is that we infer the best explanation to be (approximately) true. This is an abductive argument in which we infer the truth of the explanation, in this case the theory which explains the phenomena best. It is possible that all of our explanations are bad, but that our best one is inferred to be true. It is an intuitionally appealing argument, but it only gains its strength when we couple it to the "no miracles"-argument.

Before moving to a description of the anti-realist position, we want to emphasize this argument. It is the main argument for any realist position, including structural realism.

> <u>NoMir</u>: We need a connection between the theory and THE WORLD in order to explain the empirical and technological success of science, otherwise this success would be a miracle.

What NoMir provides us with are essentially the implicit assumptions that are the basis of all induction on successful science [107]. It is why we believe that bridges will not collapse under our weight. It explains us why we can apply science: precisely because there *is* something in the theory that has latched onto THE WORLD.

[8] His emphasis.

1.1.2 Anti-Realism, its many faces and attacks

Anti-realists deny the realist's claim that our theories tell us about the world. There are various reasons to reject realism. This leaves us with a multitude of anti-realist theses, they all have different ways of explaining the success of science.

Let's focus on the main idea of anti-realism, that we cannot have knowledge about THE WORLD. There are multiple definitions of THE WORLD and different approaches of why we cannot have knowledge. Let us list some famous anti-realist theses. It is not our goal to give an in depth description of the different positions, but to find out what all anti-realists share.

Idealism The Kantian idealism says that it is not possible to have any knowledge about the world-*an-sich*, all we know is shaped and molded by our cognitive apparatus, the *anschauung*-forms, i.e. space and time. This is how the world appears to us, the world-*für-mich*. The idealists hold a strong form of anti-realism, they focus mainly on the mind, and though they believe in the existence of the world-*an-sich*, we can only talk about our representation of it in the world-*für-uns*.

Logical Positivism Logical positivism started with the members of the *Wiener Kreis*. Their main idea is that we should eliminate every metaphysical statement from science and that we should found all knowledge on experience. All that is left is a set of observation sentences that is connected with theoretical terms through logic. Theoretical terms can always be reduced to observation sentences.

Operationalism Operationalism states that every concept is connected with a set of operations. We are able to know the operations and it is possible to reduce all non-operationalist terms to operationalist terms. This is closely related to the logical positivism.

Instrumentalism Instrumentalism sees the theoretical parts of a theory as mere theoretical instruments that can be used to produce empirical outcomes, they are devoid of any epistemic significance.

Constructive Empiricism Van Fraassen's constructive empiricism is by far the most sophisticated of the anti-realist positions. Constructive empiricism is about empirical adequacy, i.e. aims at the truth of what a theory says about observables. Claims about unobservables are taken literally, but belief in the statements is not necessary. That we use terminology of unobservables literally means that statements about unobservables are capable of a truth value. By taking the statements literally, constructive empiricism does adhere to Psillos' second principle, the semantic stance. This is in contrast with logical positivism, operationalism and instrumentalism, they take the unobservable terms to mean something else, namely a set of either observations or operations.

In each of these examples there is a different approach to the unobservable items. None of the approaches allows existence of the unobservable entities, most of the approaches try to give the unobservable entities a theoretical status or try to reduce them to observation statements. This leads us to a great problem for the anti-realists; to claim that we do not have epistemic access to unobservable entities means that need a definition for unobservability.

1.1.2.1 The Observable-Theoretical Dichotomy

The logical positivists made the first distinction between observable and theoretical terms. Every term that referred to something unobservable was coined a theoretical term. Observability is often defined anthropocentric: everything we humans can observe unaided is observable. Unobservable objects are denoted with theoretical terms. This includes objects observed through a microscope, which gives us an image of what we observe. The image must be dissected with the help of a theory, in order to give meaning to the different parts of the image. Plant cells under a microscope are denoted by theoretical terms.

Maxwell has written an influential article in 1962 that does away with the observable/unobservable distinction [76]. He claims that if the plant cells seen through a microscope are not observable objects, the objects seen through a window are not observable either. There is no place where we can put the border between observable and unobservable. We nevertheless want to call a tree observable, even though we look at it through the window.

When Heisenberg told Einstein that his new quantum theory only speaks about observable phenomena, Einstein proclaimed:

> "Denn ist es ja in Wirklichkeit genau umgekehrt. Erst die Theorie entscheidet darüber, was man beobachten kann."(Einstein in Heisenberg 1969, p.80, [51])

A theory decides what is observable. Every observation is theory-laden insofar as the theory explains the observation: the theory states what we see, e.g. the plant cells under a microscope. The theory-ladenness of observable terms comes back in the next subsection on underdetermination of theories by observation and the historical argument of PessMI.

Van Fraassen defines observable as follows:

> X is observable if there are circumstances which are such that, if X is present to us under those circumstances, then we observe it. (van Fraassen in [100], p. 16)

Another problem with observability defined anthropocentric is that anything being spatially separated of all of mankind is not observable. Even though when someone would stand next to it, it would be observable. In van Fraassen's definition observability is connected to the possibility of the presence of humans that can observe the object under consideration. It now is a modal definition, giving it new problems to deal with.

A way out of this modality was in 2005 by Muller [80]. We should not define observability as the *possibility* that an object is being observed, but as our *ability*. In a similar manner the size of a door is necessarily based on human sizes, but a description of a doorsize of 2,20 meters high and 1 meter wide does not mention that ordinary people can walk through the door (most of us can). Muller's definition is grounded in the theory of light, by giving the exact size an object X must have when it is lighted and when a member of the epistemic community is present, this person would see X.

$$\mathrm{Obs}(X, \mathcal{E}, \mathbf{L})\mathrm{Iff} \qquad \forall p \in \mathcal{E}, \exists \mathcal{M} \in \mathbf{L} : \mathrm{true}(\mathcal{M}, \mathrm{Front}(p, X) \wedge \mathrm{Sees}(p, X)) \tag{1.1}$$

This definition reads that X is observable for an epistemic community $\mathcal{E}$, relative to a theory of light $\mathbf{L}$, if and only if, for any person p from the epistemic community $\mathcal{E}$, there exists a model

$\mathcal{M}$ of **L** such that $\mathcal{M}$ makes it true that the eyes of p are positioned 20 cm in front of X (Front (p, X)) such that p sees X.

Let us accept Muller's definition for the remainder of this Thesis. We can point at any element in the observable realm and say: "Do you see that?". Even though we can have different understanding of the objects under consideration, we can agree on the observable part of the world.

1.1.2.2 Underdetermination and Conventionalism

Underdetermination of theory by the empirical facts comes in many forms and is closely connected to conventionalism. There are two versions of underdetermination that should not be confused.

One is the *underdetermination of a theory by the empirical facts* (ThUnderD). This claims that for any set of empirical data, there are multiple ontologically different theories that comply with the data. A huge amount of curves fits a set of points. The data itself cannot tell us which theory is governing the process behind the phenomenon. Because any theory goes beyond the empirical data itself, differences in the unobservable part are easily imaginable. In the Subsection on empirical equivalence, Subsection 1.2.3, we will go into ways of overcoming this form of underdetermination by finding out which parts of the theory are structurally operational.

Let us give the definition of this form of underdetermination

> ThUD For any theory T and any body of observation O there exists another theory $T*$, such that T and $T*$ are empirically equivalent, but ontologically different. (as formulated by Lyre, 2008, p.235 [74])

Underdetermination of the theories by the empirical facts can be motivated by *holistic underdetermination*(HUnD) as explicated in what is now often referred to as the Duhem-Quine thesis. Duhem's holism motivates an interpretation of the underdetermination claim, while Quine's expansion relates to Hilbert's conventionalism. Conventionalism makes every statement about THE WORLD theory-dependent and therefore open to criticism.

The Duhem-Quine thesis is the hypothesis that says that we cannot test nor refute one scientific hypothesis, because bulks of scientific hypotheses are somehow linked together. In this respect, Duhem talks only about physical theories, while Quine talks about all possible knowledge, including language.

Duhem begins by stating why physics has problems confirming an hypothesis [23]. The instruments a physicist uses (thermometer, voltmeter, any kind of meter) work on the assumption of a physical theory. If we want to show the falsity of an hypothesis, we derive from the hypothesis a possible observable fact (using a theory), construct an experimental set-up (using an instrument and a physical theory to explain the workings and the connection of the instrument to the phenomenon) and put the hypothesis to the test. If the test is done and the outcome is incongruent with the predicted observable fact, we can infer an inconsistency somewhere in the process. We cannot state with certainty that the hypothesis is wrong, we have to dismiss a complete branch of physical theories.

This becomes obvious when we see the logical form of the process:

$$T_{\text{INSTRUMENT}} \wedge T_{\text{HYPOTHESIS}} \wedge T_{\text{SET-UP}} \wedge O_{\text{EMPIRICAL RESULT}} \rightarrow \perp \tag{1.2}$$

The different T's stand for the theories needed for the workings of the instrument, the construction of the hypothesis and the measurement set-up. The O stands for the observation of the empirical results. Each of these theories can be analyzed as a conjuncture of statements. We can analyse $T_{\text{SET-UP}}$ as a conjunction of statements about different parts of the measurement set up, all governed by different theories. When we would write it all down we have a huge conjunction of statements from different parts of physics, equal to equation 1.2. $\perp$ is the consequent.

To make a conjunction false, only one of its conjuncts needs to be false. It is not possible to test one of the parts, because to test a statement, we need at least a theory about the working of our hypothesis, the experimental set-up and the instrument at hand. The falsity can be in any of these parts and in any of their subparts, making it difficult to find. As a result, there are multiple theories that can be related to the same set of empirical data.

Duhem concludes from this that we can only test bulks of statements. Quine takes it to a different level. He applies Duhem's holistic claims to the whole of knowledge. Quine denies that we can reduce one statement to experience (what the logical positivists have tried for many years). He says that we have to evaluate statements to the whole of science. The meaning of a word is defined by its position in a man-made network of beliefs. According to Quine, we can adapt any empiricist statement by making adjustments elsewhere in our system of beliefs, e.g. change the meaning of our words.

It follows that no statement can ever be reckoned true in isolation. We have to consider wholes of theoretic reasoning. We can hold any theoretical view and always make it agree with the empirical facts by adjusting our total view of the world. This is where HUnD motivates ThUD; we can always create a different theory by changing one conjunct in the conjunction that represents a theory. Even when we see theories as different from conjunctions the example is intuitively instructive.

This is closely connected to conventionalism as expressed by Poincaré and Hilbert at the end of the 19^{th} century. Poincaré stated in 1898 that the application of any geometrical system is only founded upon the conventions that we assume to hold in the world. Hilbert, when he axiomatized Euclidean geometry in 1899, made this point even more explicit. In a correspondence with Frege, he says:

> Wenn ich unter meinen Punkten irgendwelche Systeme von Dingen, z.B. das System: Liebe, Gesetz, Schornsteinfeger ..., denke und dann meine sämtlichen Axiome als Beziehungen zwischen diesen Dingen annehme, so gelten meine Sätze, z.B. der Pythagoras, auch von diesen Dingen. (Hilbert and Frege 1980, p. 13, [43])

When the laws of geometry can hold for anything that we take them to hold for, they are not a part of reality. They become a part of our conventions of dividing reality up into different parts. Of course the laws of geometry are not necessarily about the world, but the application of the laws of geometry *is*. This is an ace up the sleave of the anti-realist, who can claim that the way the world comes to us is a mere accidental way of viewing the world, depending upon the conventions we take for granted.

> Conventionalism: Our claims about reality depend on the conventions of the framework in which we make them.

In the case of Hilbert's love, law and chimney sweeper, whether we can apply our axioms to phenomena always goes with the designation of theoretical terms to objects in the world. The moment we start *using* our theories, we need an interpretation of our theoretical structures. We make a model of our theory, assigning interpretations to the terms in the theory. We can choose such a radical interpretation as Hilbert proposes, we are free to choose whatever we please. In physics we are limited by restrictions of the world. The application of a mathematical formalism is bound by the relations working in the observable world, as well as the ones doing their work in the unobservable parts.

It is good to keep in mind that there is a social aspect to our framework, we are bound by conventions. But no matter how we choose our conventions, might this be possible, we still have to respect the empirical data. Therefore most systems cannot be chosen, they do not fit into our language as we know it or do not accommodate our empirical facts. We will claim that there is a structure in THE WORLD that needs to be respected as well.

1.1.2.3 Incommensurability and Pessimistic Meta-Induction

Holistic underdetermination is related to Kuhn and Feyerabend's incommensurability [63][40]. Kuhn's book places scientific revolutions and the theory choice related to it in a historical perspective. Kuhn defines a scientific revolution as a paradigm shift. A paradigm gives a science amongst others hidden assumptions to function: it states what it is that we see. The paradigm is the complete theoretical framework used to order phenomena we observe. During a scientific revolution a paradigm shift occurs. Often an anomaly in the old paradigm leads to the formation of a new paradigm.

A successful new paradigm leads to new predictions. This is not possible if the paradigms are logically compatible, because if they are compatible, the new predictions are also compatible with the old paradigm. The former paradigm can therefore never be completely reduced to a special case of the newer. And because the meaning of the terms varies with the whole of the theory, we are never able to compare two theories. The different paradigms give a different characterization of how the world is and realists often state that the world can only have one of these views, therefore the scientific community has to choose.

Paradigm choice cannot be settled by logic and experiment, precisely because any of the two theories under investigation can only be viewed as separate wholes. To use logic and experimentation, we already need an overarching paradigm to give meaning to the experimental results of the two clashing paradigms.

In Quine's view any element is given meaning by its function within the complete system of beliefs. Kuhnian paradigms are similar to Quinean systems of beliefs, though not that strict. Within a paradigm it is possible to make progress, to evolve towards a complete world view as stated by that particular paradigm. In Quinean holism, a different system of beliefs is composed of different parts, because the parts are determined by the whole.

This is similar in Feyerabend's view of science. Feyerabend claims that different theories are never comparable, because we can only interpret results using the terminology of a theory (p.922-949 in [**?**]). We should, to be good empiricists, pursue all different possible pathways that describe the world. We cannot compare the theories in observable qualities, but we can compare the theories in usefulness and the possibility to give us some form of understanding.

The incommensurability that Feyerabend preaches is so radical that it does not fit into our daily experience with theories. When Copernicus and Ptolemy are speaking about the sun, they refer to the same object, it just serves a different function in each of their paradigms. When we take our earlier definition of observable, observing is not as theory-laden as Feyerabend wants it to be. According to Feyerabend the observable predictions of different theories are not comparable because we observe different outcomes: a Copernican sun is not a Ptolemaic sun, one is orbited around while the other is orbiting. Though the shift in meaning of the word sun might be apparent, the referent of both terms is the same, i.e. the sun. Because we have agreed upon what we can observe (see Section 1.1.2.1) we *are* able to talk about these objects.

Our definition of observability gives us a realm of which we can speak unambiguously. The theoretical description of the object can indeed be different, the extension of both the theoretical terms can be confirmed by two speakers, e.g. by simply pointing at the sun.

For unobservable items, however, the reference invariance is problematic: we cannot just point at an electron. Here is a problem in meaning shifts that gives the progress of science a radically different character. It is as if we throw away most of our knowledge of the unobservable world every time we change our paradigm. Because the term has a different meaning and we cannot verify through observation that we refer to the same object, the terms cannot be compared[9]. The two theories are incommensurable and objects that functioned in the old theory are not available in the new theory. This is the fertile ground that feeds one of the most important arguments for anti-realism: the pessimistic meta-induction.

Pessimistic meta-induction is an anti-realist argument the present form of which was put forward by Larry Laudan in 1981 [68] and Hilary Putnam in 1978 [87]. It states that science does not converge tot one true ideal, precisely because the history of science has shown that we were wrong in the past, making it plausible that we are also wrong in the present. Since 1981 every realist interpretation has to have a solution to this argument. Let us spell it out. Laudan tries to refute *Convergent Epistemic Realism.* This form of realism differs from the definition we borrowed of Psillos in Section 1.1. Let us go over the definition (Laudan 1981, p. 20-21, [68]):

- R1 Scientific theories are typically approximately true and more recent theories are closer to the truth than older theories in the same domain.
- R2 The observational and theoretical terms within the theories of a mature science genuinely refer.
- R3 Successive theories in any mature science will be such that the 'preserve' the theoretical relations and the apparent referents of earlier theories.
- R4 Acceptable new theories do and should explain why their predecessors were successful insofar as they were successful.
- R5 Theses R1-R4 entail that scientific theories should be successful; indeed, these theses constitute the best, if not the only, explanation for the success of science. The empirical success of science accordingly provides striking empirical confirmation for realism.

R1 and R2 account for our semantic stance, though there are a couple of differences. In R1, the convergence of theories is claimed without a good defence. R1 makes a claim about the convergence of truth. This is related to R3 and R4. If our previous theories are approximately true and according to R3 we preserve the relations and referents, the successive theory is at least as true as the former, we should claim convergence, because we do not want a lesser theory to be the successor. In R2 the term "mature" is mentioned; Laudan does away with this terminology

[9] Of course there are some continuities over theory change; electrons notably always had the same charge, mass and spin values. We come back to the parts that are retained over theory change later on in this Thesis.

in the same way as we did in footnote 6. The claim of empirical testability of realism rests upon the abductive reasoning in R5.

Laudan proceeds to show that R2 is untenable. Without R2 we cannot hold R3 and R1. He claims the failure of R2 by pointing at the history of science and stating his famous argument that was later dubbed the pessimistic meta induction:

> PessMi History of science shows that past theories posit different objects than present theories, it is therefore plausible that future theories will not possess the objects referred to in present theories.

Examples from the history of science are phlogiston and aether. These terms and the theories in which they functioned were abandoned and in our present theories we use different terminology. It is a lesson one can learn from the work of Kuhn and conventionalism as well. Different theories lead to different world views and what we regard as the best explanations in the present time will be overthrown just as the preceding theory was overthrown by the present one.

If we cannot claim that theories genuinely refer (R2), and we cannot claim continuity over theory change (R3), convergence is out of the question (R1). The only claim that we can retain here is R4, that newer theories should explain how older theories were successful. Notice that the meta-induction is only about terms referring to objects, this is where we are able to evade it. We will go deeper into this in subsection 1.3.

1.1.3 Realism vs. Anti-realism, a Mexican standoff?

Let us recapitulate the positions of the realists and anti-realists. They differ in statements about our epistemological access to the workings of the world. Physics purports to describe these workings, but over the course of history, physics has changed. The realists claim that the truth and genuine reference of our theories is the only thing that does not make the success of science a miracle (NoMir). A milder form of NoMir says that the theory has to latch onto the actual regularities in the world in order to not make the predictions miraculous. This form of the argument is due to Van Fraassen[10].

According to conventionalism every claim about the world is formed and shaped by a system of conventions. The same holds for scientific theories and their terminology. Old theories and new theories are incommensurable: the terms in the old theory referring to the unobservable part of the world cannot be reduced to the new terms. Therefore we cannot state continuity of reference of our theories over scientific revolutions. PessMi then finishes the job for the anti-realist: We were wrong in the past and we will probably be proven wrong again in the future.

Laudan fails to address the NoMir, the argument that can be seen as the main reason why people are scientific realists. When we cannot regard our best scientific theories as truly referring, how should we explain the theories that do posit unobservable objects and give true predictions? NoMir gives us the intuition that *something* in our theories is (approximately) true. We cannot claim genuine referral of our terms, but we cannot degrade our beloved science to a coincidental generalization of the empirical surface. At this point, both parties have undermined their position, for the knife cuts on both ends: no genuine referral means miracles and coincidences, while genuine referral is implausible given the historical facts. In 1989, John Worrall rejuvinated the debate by introducing a third position.

[10]see the quote on page 1.1.1.2

1.2 Structural Realism

In his 1989 article "Structural Realism, the Best of Both Worlds?", Worrall (re-)introduces structural realism [106]. The claim is that the terminology of our best scientific theories does not necessarily refer, but the structure of our best theories is isomorphic to the structure of the world. In this section we show how structural realism can resolve the problems of both realism and anti-realism. Then we give the different positions within structural realism and discuss the criticism on these different positions.

No one claims the existence of mathematical entities in the world, we always claim that our math represents THE WORLD. By employing mathematics as a representational tool isomorphism is always the best we can get. Isomorphism between structures A and B means that we can have a structure preserving mapping of each element in structure A to structure B. A and B are structurally identical. Because mathematics makes use of structures that need an interpretation, the interpretation can only successfully hold if the structure of the mathematical part is also exemplified in the interpreted domain.

Structure can be characterized in set theory. We speak of a ordered set $\langle U, R\rangle$, where U is a non-empty domain of elements and R is an indexed non-empty set of relations working on Cartesian product sets of the domain. This is a characterization of structure in which we can describe any logico-mathematical structures. We usually need some form of translation from the formalism used in the theory to set-theory. An example is the theory of Peano arithmatic consisting of $\langle \mathbb{N}, S\rangle$, where S is the successor function and $\mathbb{N}$ are the natural numbers.

This characterization might be helpful in the future, but for now, a naïve interpretation of structure will suffice: the structure of theories is about their logico-mathematical form.

Let us grant Van Fraassen and the logical positivists that the empirical adequacy of any theory is determined by its empirical results. Not that a theory is true when its results are true, but that empirical adequacy is a necessary condition for truth and that we have little more to go on. If we take empirical adequacy as our only grounds for truth while granting the intuitions behind NoMir, we are obliged to say that there is something in our theory that correctly describes the world. PessMi forbids it to be the entities; the ontologies of successive theories have always been changing. The first candidate that comes to mind is *Structure*.

1.2.1 Convergence and Continuity over Change

Different theories speak of different entities. Over the course of time, we have always worked with a different vocabulary, or at least ascribed different properties to terms with the same name. But while everything is changing, there is something that remains constant. The classical example, due to Poincaré, are Fresnel's equations that are preserved within Maxwell's electromagnetic theory [90].

$$A_{\perp}^{\text{reflected}} = \frac{-\sin(i-i')}{\sin(i+i')} A_{\perp}^{\text{incident}} \tag{1.3}$$

$$A_{||}^{\text{reflected}} = \frac{-\tan(i-i')}{\tan(i+i')} A_{||}^{\text{incident}} \tag{1.4}$$

Where A is the amplitude, with $A_{\perp}$ and $A_{||}$ the components perpendicular and parallel to the plane of incidence, the plane which is spanned by the incidence and reflected rays. The angle of the reflected rays is i and the angle of the refracted rays is i'. Fresnel's equations successfully described reflection and refraction by assuming that light was a wave propagating through an aether.

The interpretation of light does not matter for the application of the equation. Fresnel's equations can be derived from Maxwell's equations, they are preserved over theory change. In Fresnel's theory the equations describe light as a vibration of the ether; in Maxwell's theory, light is an electromagnetic field. In Einstein's theory Fresnel's equations describe the behaviour of energy quanta and in Feynman's theory Fresnel's equations describe the probability amplitude of a quantum electromagnetic field[11].

It seems as if the structure of Fresnel's theory somehow latched onto the structure of the world. We suspect that the structure of the equations is what is connected to THE WORLD, it surely is not the ontology, which has changed over the course of history. We can compare the different theoretical explanations of the optical phenomena because they all work with the same structure. It are these equations that makes sure that theories about optical phenomena make successful predictions. If we take this example as a typical example from scientific discourse, it is obvious to look for a connection between theory and THE WORLD in terms of structures.

Whether or not the Fresnel case is a typical example of scientific change can be debated. It has been argued by Psillos that the Fresnel case is unique in that the exact formulations of the equations can be used in different theories. It is not over every theory change that the equations of the old are *fully* preserved in the new theory. There is normally some limit in which the theories' structures reduce to each other. Part of this is accounted for by the correspondence principle:

> CorrP Any acceptable new theory should account for its predecessor by degenerating into that theory under those conditions under which the old theory has been well confirmed by tests. (formulation due to Post, p.228 [83])

CorrP is a requirement for new theories. Most scientists use CorrP as a guideline for formulating a new theory. One example of the CorrP is Bohr, who formulated his own correspondence principle to make sure that there is an agreement between the quantum mechanical and classical outcomes[14][12].

We already saw CorresP in **R4** of Laudan's depiction of convergent epistemic realism. It is an intuitively appealing principle to make sure we don't throw out the baby with the bath water. A new theory is a way of dealing with the anomalies in the old accepted theory. By employing CorresP, the new theory will, in the appropriate limit, structurally approach the old theory, there where the old theory was empirically successful. This is an uncontroversial claim and we want to stress its importance for structural realism. It gives us the handles which we can use to lift structural realism over the PessMi barrier.

By adhering to CorrP, we know that there is *structural* continuity over theory change. To let a successor theory degenerate into a predecessor theory, means that we can equate their structures, in those areas where the predecessor theory was well confirmed. The different ways in which there is structural continuity are covered by Votsis' formulation of the *continuity claim*: (Votsis 2011, p. 20-21, [105]):

[11] With thanks to F.A. Muller for pointing this out.

[12] Bohr's correspondence principle is different from the generalized philosophical lemma that we have dubbed CorresP, it is formulated in a specific form regarding either quantum mechanical frequencies, intensities or transitions corresponding to their classical counterparts. It is however a good example of a new theory that in its limit of $\hbar \to 0$ gives the old predictions.

1. Approximately all and only operative structural elements of scientific theories have been (and will be) preserved through theory change either (a) intact by derivation, or (b) via a transformation from new to old structure that is either (b.i) continuous or (b.ii) partially discontinuous or (c) intact but independent of any currently accepted structures.

2. Preservation is a reliable guide to (approximate) truth.

3. Non-preservation is a reliable guide to (approximate) falsity

∴ The preservation of approximately all and only operative structural elements of scientific theories through theory change either via (a), (b) or (c) is a reliable guide to their approximate truth. The non-preservation of non-structural elements and inoperative structural elements is a reliable guide to their approximate falsity.

This is a very dense formulation; let's go over it. In premise 1 Votsis mentions *operative* structural elements; a structural element is a statement about the world capable of a truth value whose content is purely structural, it is *operative* when it is responsible for a theory's genuine predictive and explanatory success. In the next Chapter we will investigate this notion of operativeness.

Preservation through intact derivation was already mentioned in the Fresnel-Maxwell case, the structure is preserved intact. A *continuous* transformation is a transformation that is completely translatable from one view to the other. An example is the use of different projections of the world which are all translatable.

A *partially discontinuous* transformation there are some essential structural elements that are not preserved over the transformation, e.g. from Minkowski space to Gallilean space-time, by letting $v/c \to 1$, we lose the relativity of simultaneity, but retain the relativity of position and absolute motion. A *fully discontinuous* transformation is a transformation in which no structural elements are preserved, for operative structures we cannot come up with an example of discontinuous preservation, possibly because of CorresP.

The "*intact but independent preservation*" mentioned in premise 1(c) occurs in the case of Kuhn loss; the successor theory does not incorporate an operative element of the preceding theory. If this element gives successful predictions, it will be preserved <u>outside</u> of the new theory. The operative element is not longer embedded in a theory, but is still in function. The term *Kuhn loss* is somewhat misleading here, because we do not lose the operative element. The only example Votsis gives for this is Poiseuille's law, a law on the flow of an incompressible fluid along a tube that cannot be reduced to quantum mechanics. This law is still in scientific textbooks on the matter, so it sustained the theory change.

That the preservation of structure is a reliable guide for approximate truth needs spelling out. It seems as if we can claim some form of convergence of structure by adhering to Votsis' Continuity Claim. Because our new structure will mimic the old theory when applied to the same domain (CorresP), and NoMir tells us that the old theory latched onto the structure of the world, we can infer that that part of the theory that is preserved into the next empirically (more) adequate theory, is the approximately true part of the theory. These are the structures that are sustaining through theory change.

On the same grounds, we can argue that the structure of successive theories converges as well. The claim of convergence leads to two questions:

1. How do we know that the structure converges?

2. Convergence to what? If structure converges, we want to know whereto.

Question 1 can be answered rather easily. We know that the structure becomes more precise because the empirical data generated by the new theory is more precise. The new theory necessarily has a greater empirical scope, if this is not the case, there is no need to change our theory and rewrite all the text books. We also know that, because of the CorrP and the resulting continuity, we will expand part of the old structure. By covering a greater domain more precisely, convergence is a plausible claim.

To question 2 we can answer that the changing structure approaches the structure of the world. Over the course of scientific change theories are getting more and more precise. The operative structural elements of the theories are growing and in combination with CorrP, we can infer that the growing structure is describing more and more the structure of the world (up to isomorphism). We can call this the *optimistic meta-induction of structure.*

While the structure of our theories is growing, the structure of THE WORLD does not grow (assumption). Still, to make sense of convergence of structures requires a deeper understanding of what the phrase "structure of the world" might mean. We will provide this understanding in the chapter on metaphysics, Chapter 2.6. Let's now go over the arguments for the different versions of structural realism.

1.2.2 Epistemic Structural Realism

Epistemic structural realism (EpSR) says that all we can know about the world is limited to structure. This needs to be explained, and there are multiple possible ways of explaining EpSR. First of all, there is the distinction between *direct* EpSR and *indirect* EpSR. Direct EpSR holds that we can have direct epistemic access to the observational data, which includes non-structural knowledge about the observable world, but only structural knowledge about the unobservable part of THE WORLD. Indirect EpSR states that our sense data are the outermost level of epistemic access, so that the objects in the observational world itself, the ones causing the sense data, are non-structurally unknown. Indirect EpSR can respond to the idealist how we can have any knowledge of the world-in-itself.

1.2.2.1 The Upward Path

The *upward path* starts at the information we get from our experience and then look at what information is genuine knowledge about the world. An obvious position for 'Upwarders' is indirect EpSR. There are a couple of arguments for the upward path, noticeably the perception argument and the transmissibility argument. We go over the argument from perception quickly, because the argument of transmissibility is more interesting, and will prove very useful later on in this thesis.

The perception argument was put forward by Russell. Russell claims that all we can know about the world-in-itself are the logico-mathematical structure of our sense-experiences. This is not a lot. Only the number of objects and the properties of the relations they exhibit in our representation, e.g. transitivity, reflexivity and the like. There is some more knowledge to be gained by virtue of the transmissibility argument.

1.2.2.2 The Transmissibility Argument and Underdetermination

The transmissibility argument was first posited by Poincaré. We quickly outlined it in the Preface of this Thesis (p. 4). The core of the transmissibility-argument is that it is possible for us to speak about our percepts. We can successfully transmit our perceptions of the world, but what is it we can transmit? A good example is stated in the introduction of the Thesis, it is imaginable that each of us experiences the colour 'purple' differently. Nevertheless we will attribute it to the same objects. Because we tend to agree on the extension of 'purple', there is information that is transmitted. It cannot be the individual impressions in our representations, because these are not translatable to language. It necessarily is structural. This structural knowledge defines the colour purple as a knot in the network of beliefs of colours. It is related to other concepts such as 'red' and 'blue'. Because of the successful transmission of sentences as 'Bring the purple sweater', we know that the structure of our representations has a shared component, and we agree upon the extension of the structure.

The transmissibility argument employs other premises than the perception argument. Where the perception argument is founded upon the premise that the structural elements of our perceptions give us information about the structure of THE WORLD, the transmissibility argument is founded upon the successful *transmitting* of information about those perceptions. Successful communication employs a form of NoMir, because we are able to successfully transmit sense perceptions, there is something in those sense perceptions that is shared between the people having a conversation, ideally this is public knowledge. Frigg and Votsis summarize the transmissibility argument as follows:

1. All knowledge is ultimately based on perceptions.
2. Perceptions consist of individual sensory experiences and their relations.
3. If something is public knowledge about the external world, then it is transmissible via language.
4. The content of individual sensory impressions is not transmissible via language (as in the 'purple' example).
5. The logico-mathematical properties of relations between sensory expressions are transmissible via language.

∴ Only the logico-mathematical properties of relations between sensory experiences but not the individual sensory experiences themselves can be publicly knowable.(formed after Frigg and Votsis, 2011, p. 239, [47])

Frigg and Votsis point out that there is no warrant for public knowledge in the transmissibility account, but *if* there is public knowledge, *then* it is structural. We would like to alter Poincaré's version of the argument to make room for non-public knowledge; scientific knowledge is only ideally public, but not public for all the people. Scientific knowledge is only accessible for people with the right background knowledge. To understand physics, we need to understand mathematics. We can understand something and thus transmit knowledge only with respect to a certain system of background knowledge.

1.2.2.3 The Downward Path

The downward defense of EpSR takes science as given and then strips away all the elements of which our knowledge is uncertain. What we are left with is structure. Direct EpSR is a plausible place to stop the downward analysis, though it is possible to go on until indirect EpSR. Let us give a description in terms of empirical equivalence and present an example from the history of science.

1.2.3 From Empirical to Structural Equivalence

Let us take an example from current science. The De Broglie-Bohm theory of quantum mechanics gives an alternative description of the quantum realm than the orthodox Copenhagen interpretation. The ontological consequences of both the theories are incompatible; they contradict each other.

Because we have a neutral observation language, that is we can agree on observable results, we can determine the empirical equivalence of these two theories. As stated before, empirical adequacy is one of the only indicators we have to the truth of any theory. The application of a theoretical structure to the world is necessarily accompanied by observational results. When we assume that the part of THE WORLD, which is structurally isomorph to the theory's structure is picked out by the observational results the theory produces, the structural equivalence of two empirical equivalent theories follows easily. When they have the same observational results, they speak about the same unobservable part of reality.

The two theories are ontologically different, but there are some structural parts that are equal. These parts are the Schrödinger equation, it's evolution and the Born rule, $|\psi^2|$. These are the operative structures governing this domain of THE WORLD. Both theories also describe non-local influence possible in entangled systems, it is explained/interpreted differently, but results from the shared structures alone.

This argument will be spelled out in detail in Chapter **??**, where we state how the structure of THE WORLD has to be, given quantum mechanics and our metaphysical position regarding structure.

The assumption that the empirical results of a theory determine which part of THE WORLD it represents is a controversial statement. this controversy comes from a living debate about Ramsey sentences capturing a theory's cognitive content. There has been a devastating argument delivered by Newman which keeps this debate alive. Let's go over the details.

1.2.4 Ramsey, Newman and Putnam[13]

The Ramsey sentence of a theory is the empirical reduct of the theory. We axiomatise our theory $\mathcal{T}$ in a formal first-order language. Let us assume that the number of axioms is finite. The axioms comprise $\mathcal{T}$'s core equations, the heart of the matter. Now let us conjunct all the axioms to a single sentence, T.

Now assume that the predicates in the sentence T are separated into two classes, P: the set of all P_i for observation predicates, and Q: the set of all Q_i for theoretical predicates. We can now express the theory as

[13]This subsection relies on the Section on Ramsey sentences in Frigg and Votsis' *Everything you always wanted to know about structural realism but were afraid to ask* [47]

$$T(P_1, P_2, ..., P_n, Q_1, Q_2, ..., Q_m) \tag{1.5}$$

Now we go to a second-order language. To create a Ramsey-sentence of T, we replace Q with a set X, containing variables X_j, with $j = 1, .., m$, ranging over predicates. The next step is that we existentially quantify over the the X_j, only claiming existence of the variables. There are no claims about unobservables in the Ramsey sentence of a theory. The Ramsey sentence will look like this:

$$T_R := \exists X_1 ... \exists X_m T(P_1, P_2, ..., P_n, X_1, X_2, ..., X_m) \tag{1.6}$$

The Ramsey sentence T_R states that there there are theoretical predicates such that $T(P, X)$ is true. T_R is related to T in the following ways: ($\vdash$ is the second-order deduction relation)

- $T \vdash p \longleftrightarrow T_R \vdash p$ where p is a sentence only using the observational vocabulary.
- $T \vdash T_R$ but not vice versa.
- When two Ramsey sentences have the same observational content, they cannot be inconsistent with each other.
- The Ramsey sentence does not eliminate commitment to things that fall under the predicates X_j, it eliminates commitment to *specific* things referred to by specific predicates.

A lot of EpSR'ists claim that the Ramsey sentence captures the cognitive content of a theory. This should be the empirical and structural content of a theory. The empirical part is clearly described by the P-part of T_R. What about the structural content of T? How is this described by T_R.

An attempt to formulate the structural content of T_R is by claiming that T_R says that there is a structure S that is a model of T, which is instantiated when T_R is true. The truth of T_R is determined by its empirical adequacy and ...

We said that structure is expressible in set theory, but when we are dealing with ramsified theories, we will have to modify our definition of structure from $\langle U, R \rangle$ to $\langle (U_O, U_U), (R_O, R_M, R_U) \rangle$. The indices $_O$ and $_U$ stand for the observable and unobservable objects/relations, while the index $_M$ is about the mixed relations between the observable and unobservable elements in the domain. $U = (U_O \cup U_U)$ and $R = (R_O \cup R_M \cup R_U)$ while $U_O \cap U_U = \varnothing$. We now know that our structure S can be characterized in this form: $\langle (U_O, U_U), (R_O, R_M, R_U) \rangle$ and the empirical substructure of S, S_e, is expressible as $\langle U_O, R_O \rangle$. Where R_U is the extension of Q and R_O is the extension of P, because R_M features unobservable relations, it is often seen as an extension of Q.

The kinds of objects between which the relations hold are a part of the description of the structure, while the relations themselves are not explicitly stated because of the ramseyfication. This leaves us with a problem when we want to claim the knowledge T_R yields.

The claim is that the EpSR believes in the truth of T_R; there is a real structure $S \models T_R$. This distinguishes the EpSRist from the realist, who believes in the truth of T instead of T_R and the empiricist/instrumentalist, who only believes in the truth of the observation part of T. By the assumption that the structure also satisfies the unobservable part, it raises the question what the Ramsey sentence can tell us about the structure S. The answer to this is that the structure S is not necessarily isomorphic to the ontological structure of the world. The only thing a true Ramsey sentence tells us about S, is

Cardinality Theorem The Ramsey Sentence of a theory T is true if, and only if, T has a model S which is u-cardinality correct and empirically correct. (from [47], p. 249)

U-cardinality correct means $\#S = \#U_U$. The Löwenheim-Skolem theorem guarantees there is an infinity of models that fit the T_R, when T_R has an infinite model; categoricity is exceptional. So the claim of any T_R is then that the target domain has the same cardinality as one of its models. This is related to the Newman Theorem:

> Newman's Theorem: Let C be a collection of objects and let S be a structure whose domain has the same cardinality as C. Then there exists a structure C_S, in the domain of discourse of the metatheory (set-theory), whose domain is C and which is isomorphic to S.

Newman's Theorem and the Cardinality Theorem tell us that the structure we find using ramseyfication will be satisfied by any collection of objects with the right cardinality. This follows from set theory, where we can easily construct a theorem that says

> Let X be a set/collection and let $\mathbf{M}$ be a structure such that $\#\text{dom}(\mathbf{M}) \leq \#X$. Then there exists a structure M_X whose domain is X with a substructure isomorphic to M. (from [61], p. 293)

The big question that rises is whether it is also the case when the domain has a (physical) structure that needs to be respected. When we make the claim that the world is describable by an uninterpreted structure, we mathematize physics in that we say that the world consists of sets. This is absurd.

One way out of this absurdity will lead us to an ontic structural realist claim in which there is a structure "out there" that has to be mimicked by our theories in order for them to be successful. We cannot just claim that a Ramsey sentence is trivially true, if we let this truth follow from set theory. The world does not consist of sets, and when we claim to have knowledge of *the structure of the world*, we hope to find that THE WORLD also exemplifies this structure *in itself*. Not that we reorder the world to make it fit our theories.

When we enrich set theory with (physically existing) objects, then U can be a *set of objects* in THE WORLD. In this version the objects are part of the metatheory instead of being represented by the set-theoretical objects. Nevertheless, the same problem will arise. We can reorder the objects within set-theory denoted by U, to form a structure isomorphic to T_R disregarding the actual structure in THE WORLD. What is absolutely necessary is that the structure of these objects is represented by T_R, or the knowledge about the world is limited to the cardinality of the objects and our ability to reorder objects in our metatheory.

1.2.5 Ontic Structural Realism[14]

One way to counter the Newman objection is by resorting to *physical structure*. In its ordinary use, *isomorphism* is a relation between set-theoretical structures. To claim that the a theory is partially isomorphic to the structure of THE WORLD is to claim that the worldly structure is a set-theoretic entity. We are all aware that set-theoretical entities 'live' in a mathematical universe

[14] This Subsection relies on the paper by Ainsworth, What is Ontic Structural Realism, [1]

and that our physical universe can very well be described by mathematics, but is not mathematical in nature.

The interpretation of mathematical entities to worldly objects leads to Newman-like objections. A solution to this problem is to take physical structure as a primitive. A claim that there is a structure in THE WORLD that is existing out there, with isomorphism of a mathematical structure to a physical structure. This position is called *ontic structural realism*, or OnSR. There are multiple claims as to what physical structure means of which we will spell out three.

1.2.5.1 Ladyman and French' Eliminativst OnSR

The eliminativist position of Ladyman and French states that there are no objects whatsoever. Relations are the only ontological primitives. The existence of objects and properties is dependent on the position in a structure (of relations). The main problem with this approach is that it changes the conventions we have about relations. In our traditional meaning of the word relation, a relation is something that holds between relata. Relata are objects or relations themselves, but they must exist prior to the relations they stand in.

To claim that relations are primitive to their relata is a conceptual change that is difficult to grasp. A possible interpretation of the ontology is that "it's relations all the way down" (Stachel, 2006, p. 54 [96]). Every object in a structure will be a structure itself. When we look at the ontologies posited by science over history, this seems not to be so far off. Molecules proved to exist of protons neutrons and electrons, these are themselves dissectible into quarks, which fall apart in strings or what have you. But to claim that a fundamental level necessarily *cannot* exist is not a position that attracts a lot of followers.

Another interpretation of relations without objects is in the light of the *bundle-theory of objects*. The bundle-theory sees objects as the knots in a system of relations. This is only possible when the relations are not only extensionally, but also intensionally knowable. The relation "being bigger than" can be known as it is, instead of only its transitivity, or else the resulting structure does not uniquely define a possible world.

French and Ladyman come to their conclusion that there cannot be individual objects through arguments from quantum mechanics. The indistinguishability of quantum systems or objects suggests that the subjects of quantum mechanics are no individuals. The tactics employed by French and Ladyman are to remove objects altogether from the ontology, because the objects cause the underdetermination of metaphysics by physics in quantum mechanics. This might be a bit rigorous, luckily there are other positions available.

1.2.5.2 Esfeld's Moderate OnSR

In Esfeld's *moderate OnSR*, there are objects in the ontological structures. The objects do not have intrinsic properties. The identity of objects is conferred upon them by the structure of which they are a part. This is a form of holism, in which the identity of objects is not intrinsic to the objects themselves.

The first problem is that it seems to be false. Even in quantum mechanics, the Hamiltonian operators depend on state-independent properties, so it seems unlikely that we can do quantum mechanics without properties. Esfeld and Lam claim that our knowledge of properties is necessarily of non-intrinsic properties. We know the charge of a particle because of its behaviour in a charged field. All traditional intrinsic properties are only knowable because they have some causal powers. It is plausible that there are multiple natural properties that exemplify the same causal powers.

An example by Ainsworth is jade. We now know that there are two different kinds of jade, but for centuries they have been classified under the same denominator. They both have the same presentations to us, they are both green, hard, etcetera, and therefore have the same causal powers.

There is something to state-independent properties that is not intrinsic, we assume that it is the causal powers these properties have. This will be investigated in the next Chapter.

1.2.5.3 Lyre's Extended OnSR

In Lyre's *Extended OnSR*, the objects are not individuals, but they do have intrinsic properties. This is precisely the opposite position of Esfeld and Lam's moderate OnSR. The intrinsic properties are the properties that are invariant under transformations. How we know that these properties are intrinsic is a mystery, this brings the form of 'intrinsic' into doubt. It is not the same 'intrinsic' as the term characterized by Langton and Lewis in their [67]. This leads to doubts regarding the claim by Lyre. We acknowledge the importance of properties invariant under transformations, but reserve 'intrinsic' for intrinsic properties as defined by Langton and Lewis.

Both Lyre's and Esfeld's position have something to it. But each ontology is a bit too strong in some points. We propose that properties that have causal powers should be considered as monadic relations.

1.2.5.4 Overview

The different OnSRs are motivated by two different types of argument[47]. The first argument form is that OnSR is better equipped than its rivals to certain forms of critique, notably Newman's Objection. The second argument is that in modern physics discussions about distinguishable objects, whether they are elementary particles or space-time points, motivates a different approach towards our classical metaphysics. The different positions will be analyzed more thoroughly in the Chapter on metaphysics, in which we will take up a position of our own in which relations are ontologically primitive.

	Eliminative OnSR	Moderate OnSR	Extended OnS
Objects	−	+	−
Properties	−	−	+
Relations	+	+	+

Where − and + either reject or affirm ontologically primitiveness.

1.3 Summary and Conclusion

In this chapter we have given an overview of the views that are common in the philosophy of science. Either we can, or we cannot have knowledge about the world. The classical debate focuses on scientific realism versus multiple forms of scientific anti-realism. The realists hold that we can have knowledge about "theoretical entities", while the anti-realists claim that we can only have knowledge about the empirical data.

The realist's NoMir gives us the view that only by (approximately) true theories we can explain the success of science. The anti-realist's PessMi makes us abandon all hope on continuity over scientific change; entities are gained and lost with the theories they belong to. These two arguments are both intuitively appealing.

Structural realism gives us a claim of approximate truth, complying with NoMir: the logico-mathematical structure of our theories is isomorphic to the structure of the world. By restricting truth to structures instead of entities, we can claim continuity over scientific change as well: the mathematical structure of the theories is approximately preserved. This is an answer to PessMi and gives us a condition that shapes our scientific progress; CorrP.

EpSR gives us a position we want to defend and expand. We can only have epistemic access to the structure of the world. Our understanding of the neutral observation language leads us to believe that we have at least structural knowledge of the world. Different successful[15] theories applied to the same empirical data, yield the same structures. These structures seem to be the parts of the theory that are related to the unobservable part of the world. Because they give correct new predictions, we can infer that they latch onto the actual structure of the world.

Newman's theorem and the cardinality requirement lead us to the suggestion that we can only know the world's cardinality. This works not only for ramsified theories; Putnam claims that it holds for any theory. So we need to find a way to show how the structures of our theories relate to the actual structures in the world to make sure that we do not have trivially true theories. This we will solve in this thesis by making the claim that the way our structural knowledge is related to the world is because it can only be applied, when the theory that is being applied has a similar structure as THE WORLD.

While EpSR tells us all we can know about the world, the knowledge we have should be spelled out. OnSR is one approach of saying how THE WORLD is. True knowledge about the world can tell us how that part of the world we know must be like. The parts we cannot know, non-structural parts, should not be a part of this ontology. The different approaches of OnSR are not satisfying in that they claim to be all there is, while our position is that the metaphysics compatible with a healthy epistemic attitude should not make claims beyond the knowable realm. This includes claims regarding the affirming or denying of non-structural elements in the unobservable part of THE WORLD.

When we have structural knowledge of THE WORLD, there should be something exemplifying this structure in THE WORLD. A physical structure is the only possible conclusion that is compatible with EpSR. This is what we will do in the next Chapter, look for the boundary conditions of such a physical structure. Such a structure and the way our different world views can have different views of such a structure also needs investigation.

The transmissibility argument on page 22 plays an important role in this Thesis. The Kantian roots of this argument are undeniable, it divides the world up in a personal representation of THE WORLD and our communication about it, leaving THE WORLD itself out of the conversation. How our own personal representation can only be structurally communicated to others because no-one has access to an other person's representation of THE WORLD, gives us an intuition on how to handle different world views.

We will investigate how different theories from different world views have similar (operative) structures. We will acknowledge the fact that world views can alter the form of the theories, but we will demand that the change in domain will respect some higher structure of which both theoretical

[15]Making novel predictions, that is.

structures are a derivative. The structure of the theories is not dependent upon the objects that it chooses and different theories will produce similar views in order to be successful. This will be exemplified in the specification of the growth or convergence of our theoretical structures.

Let's get to it.

Chapter 2

What is Structure? A Metaphysical Investigation

In this chapter we address two main issues. The first one is the most obvious and profound one: what does reality look like? The answer to this question is metaphysical. What we assume the primitive structure of the world to consist of is decided upon after careful assessment. The second issue makes it possible to evade most, if not all, of the anti-realist arguments. By showing how different theoretical paradigms relate to the same physical structure, we take the wind out of the sails of underdetermination founded on conventionalism and PessMI founded on incommensurability. It will give us an insight in how we can have different perspectives on how the world appears by referring to the same structural core from these different perspectives.

In the first issue we let our motivations for the choice of ontology be guided by the core of quantum mechanics that we find in the next Chapter. That core will exist of the operative structures of a theory that are similar in each interpretation of it, thereby addressing the second issue. In this chapter we will hope to settle that structural underdetermination is a non-issue by linking one physical structure one-to-one to a certain empirical data-set. Any set of data will yield one physical outcome.

2.1 Metaphysics and Epistemology

EpSR is an epistemological position. It makes a claim about the knowledge we can have of the world. OnSR is a metaphysical position that claims that there is only structure in the world, or at least, that the world is structural in nature, i.e. relations are primitive.

Though EpSR only tells us about the knowledge we can have about the world, there is nothing in EpSR that gives us access to the structured reality of which we have knowledge. The map is not the territory[1]. We can come up to knowledge morphic to the structure of the world. Knowledge implies truth, so there is *some* relation to THE WORLD. But we need to posit the level of ontic structural realism to *justify* our knowledge at the EpSR level.

EpSR and OnSR part at the ontological commitment. EpSR remains silent about the actual nature of the world. All it claims is that our knowledge of THE WORLD is structural. How is this

[1]This quote is originally attributed to Korzybski.

to be understood without an ontology of THE WORLD? EpSR-ists believe that we can have true knowledge about structures. The OnSR-ist expands this claim and states that there is an actual physical structure in the world.

The two positions do not necessarily disagree, in fact, they tend to work together. Traditionally, knowledge is seen as a *justified true belief.* Wherever there is knowledge to be had there is something in the world that is true, corresponding to our justified belief. The ontological structure of OnSR provides this level. It provides the ontological basis that unites the epistemological and metaphysical realm.

There is one more assumption to be made to let the two fields work together. In a recent article Muller gave us the assumption that makes the two theses, EpSR and OnSR, coincide [81]. The extra assumption, according to Muller, is *scientific optimism.*

Scientific Optimism (ScOpt) : Science will, in the end, provide us with everything that we, humans, can come to know about the physical world.

Given ScOpt and EpSR, OnSR is justified. Since OnSR implies EpSR and knowledge implies truth, we can deduce that if all knowledge we can get of the world (through scientific methods) is structural there is an existing structure in THE WORLD of which we have knowledge. This is all us mortals can access, anything beyond structure is necessarily obscure, but we can access it!

$$\text{ScOpt} \longrightarrow (\text{OnSR} \longleftrightarrow \text{EpSR}) \tag{2.1}$$

The theses OnSR and EpSR still mean something different, but from (2.1) it follows that if you believe OnSR, then also EpSR, and vice versa. Where EpSR speaks about the way we can know the structures and OnSR tells us that these structures are actual existing entities. If only we accept ScOpt.

Is ScOpt acceptable? It is a strong claim about what science itself is. When we concede that mathematical descriptions will be structural descriptions, to say that descriptions of the unobservable part of THE WORLD are structural is intuitive. ScOpt tells us that this description is exhaustive and that nothing knowable remains hidden. Science gives us knowledge of THE WORLD, and science is the only way of gaining knowledge about THE WORLD. That science would be the only way to gain knowledge is difficult to grasp because everyday life also provides us with knowledge about the world.

ScOpt is correct insofar as it is about the *physical* world. Everything that is knowable has some way of coming to us. Science is the most widely accepted method of gaining knowledge. If it would be possible for people to gain knowledge about the world in a non-scientific way, this knowledge would, arguably, also be structural. Why? Because of the transmissibility argument (see p. 22). When knowledge is (successfully) communicated to another member of the epistemic community, the only thing we can be sure of is that the structure is communicated. The way the knowledge appears in ones personal representation of the world can never be shared, only its structure.

When we concede that knowledge is something that is to be had by a community instead of single persons, the structural aspect comes up as a way of factoring out the different (cultural) colourings we might give to our personal sense data. When knowledge is able to give true predictions, the structure should be accepted by the community as morphic (within the boundaries of the application) to the world.

This is a very important claim in the remainder of this Thesis, we will investigate it not only as the residue after transmitting personal data from one person to another. We claim that different theoretical perspectives have the same basic structures if they have the same empirical data. To be successfully compared, different paradigms need to agree on a observation language. This is something we have established in the last mentioned Chapter 1.2.

2.1.1 Epistemological Constraints on Ontology

Assume we have a world of which we can gain structural knowledge, but the world is richer. It also contains non-structural elements. Why would it not be possible to gain knowledge about the non-structural elements? What non-structural elements are there?

The things-*in-themselves* are not knowable according to Kant. The part of the object that can be classified as the *-in-itself* part, is its the *haecceity* and the intrinsic properties. Haecceity and *quiddity* are terms that denote the *thisness* and the *whatness* of objects. It is good to have this distinction clear before entering metaphysics. Haecceity distinguishes an object's particular existence, while quiddities are about an object's properties as belonging to a kind or type. Intrinsic properties consist of quiddities and haecceities.

Intrinsic properties have been characterized by Lewis and Langton in 1998 [67].

- The property can be had or lacked independent of the object having it is accompanied or lonely.
- A property is intrinsic iff its duplicate has the same intrinsic properties.
- A property should not be the negation of a disjunctive property.

The first of these requirements is pretty straightforward. It states that it has to be the property of the thing itself, not depending of its surroundings. The second of these requirements depends on the idea of a duplicate. Duplicates come from Lewis' metaphysical multiverse in which each modal world refers to an existing world just as real as the present one. Every object therefore has a counterpart in other modal worlds. All the properties that do not hold for the duplicate, but do hold for the original, are not intrinsic[2].

The third requirement is that the property is not the negation of a disjunctive property, $\neg(F(x) \vee G()x)$ does not express a property. Non-disjunctive properties tend to pass the first two requirements, but they are no *natural* properties.

To define naturalness of properties is a different project we shall not go into. We trust Lewis and Langton in that the non-disjunctive form of the properties does not reflect genuine intrinsic properties. That set aside, why should we not be able to have knowledge of intrinsic properties? We go back to Kant. What Kant means by ignorance of things in themselves is, according to Lewis:

> ignorance of the intrinsic properties of substances. The substances that bear these intrinsic properties are the very same unhidden substances that do indeed affect us perceptually. But they affect us, and they affect other things that in their turn affect us, in virtue of their causal powers, which are among their relational properties. Thereby we find out about these substances as bearers of causal powers, but we find out nothing about them as they are in themselves. (Lewis 2001, §1)

[2] It seems as if the relation "is a duplicate of" is primitive.

In Lewis' interpretation of Kant, the intrinsic properties, that is the properties as they are *in-themselves*, does not affect us. What affects us, or our measuring devices, is only the causal powers, which might belong to intrinsic properties that lie beneath these relational manifestations. So where are the intrinsic properties in this picture and what is our access to them? An answer to this question is given by Frank Jackson:

> When physicists tell us about the properties they take to be fundamental, they tell us what these properties do. This is no accident. We know about what things are like essentially through the way they impinge on us and our measuring instruments. [This] does suggest the possibility that (i) there are two quite different intrinsic properties, P and $P*$, which are exactly alike in the causal relations they enter into, (ii) sometimes one is possessed and sometimes the other, and (iii) we mistakenly think that there is just one property because the difference does not make a difference (...). An obvious extension of this possibility leads to the uncomfortable idea that we may know next to nothing about the intrinsic nature of the world. We know only its causal cum relational nature. (Jackson 1998, 23-24, [59])

This quote is regularly used by Esfeld to defend his version of moderate OnSR [32][35]. It gives us the same image we get from Lewis quote but more explicit. We cannot have knowledge of the intrinsic nature of objects, we can only know their causal cum relational nature. When we try to build a metaphysics beyond that, that is try to defend the existence of a single property that is the source of the causo-relational profile we discovered, Jackson claims this is always underdetermined. In his example where multiple properties are attributed to the same object, but their difference does not make a difference in the causal profile of the object, we can never know what is actually "out there", all we can know is the causal profile.

That we cannot know the intrinsic properties themselves is called *epistemic humility*.

> *Epistemic Humility*: We are unable to know the intrinsic properties, we can only know their causal profiles, which are relational properties.

It is strange wording, if we are arrogant, we say to know the intrinsic properties, but when we cannot know, not knowing is not a sign of humility. A humble attitude is unnecessary if something is impossible. But let's accept it as it is.

It is possible to believe in the intrinsic nature behind the causo-relational profile of the objects, if we allow that metaphysics and epistemology drift apart. We would end up in an air castle contest in which the only possible way of judging the castles in the sky would be on beauty or tradition. This is not a desirable situation, we therefore propose to keep our metaphysics close to our epistemology.

This means that we do not allow intrinsic properties the way they are envisaged by Lewis and Langton to be a part of our ontological scheme. It is possible that these intrinsic properties exist, but there cannot be any decisive arguments, any discussions will therefore be without content.

This is how our ontology is constrained by what we concede to the EpSR-ist. The main goal of the EpSR-ists is to have structural knowledge about THE WORLD. Ontological structures are a must. We still need to know what composes our ontological structures. An Ockham-like constraint would minimalize the ontology with respect to our epistemology, denying the existence of non-structural elements. Also when these non-structural elements are a necessary part of the structures in the world. Let's investigate how substance exists, and how this can be unified with ontological structure.

2.2 On Substance

The Ladyman and Ross' "structures all the way down"-view of THE WORLD claims that our basic objects are structures themselves. There is nothing that can tell us that there are simples in the ontology.

Such a characterization of the "structures all the way down"-view makes radical claims about the non-existence of objects in structures. This form of eliminativism is too strict; its claims go too far beyond our epistemological reach to be vindicated. The position is however possible and does not lead to any inconsistencies.

To eliminate objects feels as if we eliminate substance altogether. All that is left are relations, and intuitively relations hold *between* things. But is this necessarily so? Let us go into different approaches to substance.

2.2.1 The Classic View

In the classic view, our most basic level consists of objects as particulars. The objects are the hooks on which we can hang our predicates; which express properties or relations. In this view we have objects as given, which happen to be related in some way or another. It is characterized by Armstrong (1989, p.59) as

> It is natural to distinguish a thing, an individual, a token, from any particular properties that the thing happens to have. The table is hard, brown, rectangular, and so on. But it is not identical with its hardness, brownness, rectangularity. These properties are rather naturally taken to be things it merely *has*. ... With thing and properties thus distinguished, even if very intimately connected, we have what may be called a [particularist] view. [2][3]

We call this view the *particularist* picture, to stress that there is a particular object of which we predicate properties and which stands in relations. The particularist picture has an ontology of particular things which are predicated and predicates express instantiations of universals. The thing itself can be a *bare particular*. Bare particulars have no properties or essence of themselves. There is some material substance that instantiates the properties. This substance is intrinsically unknowable, because it does not interact with us, only its (causal) relational properties have the power of influencing other objects and, in the end, ourselves.

Lewis has a special version of the particularist view in which all the relations in the world supervene on the non-relational properties of an object. The most basic example is the relation "larger than" which holds between objects X and Y, supervening on the values of property "length" attributed to each of the two objects. The relations, or properties, belonging to the set A, in this case, the "'larger than"-relation, supervenes on a set B of properties, in this case lengths. The slogan of supervenience is:

> There cannot be an A-difference without a B-difference. [**?**]

The particularist picture not only presupposes substance to exist as bare particulars, but makes the (intrinsic) properties the most important of the triad objects, properties, relations.

[3] Text between [square brackets] is altered to better fit the Thesis without altering the connotation of the text within the quote (much).

Where and how universal properties exist is a tough question. The particularist picture does not have a solution to this problem, it assumes the universal properties as they exist in our language to exist in reality as well. How these attributable properties come into existence is a question left unanswered. The assumptions that bare particulars can exist while they are never encountered dwells in obscurity.

2.2.2 Neo-Aristotelians

The Neo-Aristotelians employ a particularist picture as well, but things are never bare particulars. The neo-Aristotelians claim that an object is always an object instantiating a kind or sortal. Lowe has a four category ontology [70]. The kinds are universals, characterized by *attributes*, the *objects* are the particular instantiations of the *kinds*, together forming *modes*. We focus on his view of substance. In his view there are objects which belong to certain kinds.

All we encounter is particular instances. That objects are of the same kind would imply an existing kind of which objects are an instance. Though each cat is different, their universal cat-ness is being instantiated by individual cats. What does it mean for kinds to exist?

According to Lowe empty kinds cannot exist; for instance the kind “pegacorn” (a pegacorn is a horse with wings and a horn) has a distinct meaning, it is not instantiated and therefore does not exist. When the last cat dies, the kind “cat” stops being instantiated and the universal “cat” ceases to exist. Our language has a way of ordering the domain in such a way that we can distinguish between *felis catus* and *felis leo*[4]. Instantiations of each of these kinds comes with the properties that are attributed to a member of the kinds and individual properties that distinguish it from other instantiations of the kind.

Each instantiation of a kind has essential properties, united in a criterion of identity. A criterion of identity is a collection of attributes characterizing a kind. An object is necessarily an instantiation of some kind, so it has some intrinsic properties, or quiddities, to make it identifiable as a member of that kind.

In Lowe’s ontology science tells us, through the use of language, the kind structure of the world which need to be instantiated to exist. So the use of language shows us, guided by scientific practice, what kinds are instantiated, ergo existing, and what the identifying properties of these kinds are. The instantiations of the kinds is done by objects which consist of matter also belonging to a kind, e.g. cats consist of feline matter.

We can also account for the changes of kinds and their instantiations over the course of history. That the lion has migrated from *felis leo* to *panthera leo* is something that can feed PessMI-like arguments against Platonic kind-realists and Neo-Aristotelians. It is possible that there are kinds “out there” while our language referring to those kinds will change; we can be wrong and that is what feeds the PessMI (we were wrong in the past and will be so in the future).

According to the Neo-Aristotelians the kinds recognized by our science and language do not have to correspond to the kinds in THE WORLD, creating a gap between our metaphysics and our epistemology. Here the structural realist has an advantage.

Lowe claims that universal kinds are “mere abstractions and do no serious ontological work on their own” (Lowe, 2006, p.39, [69]). Only instances of kinds exist in which universals are a part of objects but do not exist separately. That is a part of the Neo-Aristotelian framework that is useful for us structuralists.

[4]Linnaeus named the lion *felis leo*. Nowadays a lion is considered to instantiate the species *panthera leo*.

2.2.3 Bundle Theory

Bundle theory explains substance as bundles of universals. This is why we don't need bare particulars or other types of objects in the ontology. The bundle theory bundles the universals to a particular. This particular consists of only universals.

What is it that distinguishes two bundles of the same universals? We have to bare the burden of Black's balls. In his argument from 1952 Max Black gives us an impoverished universe in which only two iron spheres exist [11]. These two spheres are both one mile in diameter, solid iron and two miles apart. There are two spheres, but we cannot distinguish them. Each property of the one is possessed by the other.

The spheres are indiscernible, but there are two. This shows that Leipniz' identity of indiscernibles fails. When the identity of indiscernibles fails, there must be more to an object than a bundle of universals. This is a serious problem for the bundle theorist.

There is a way to weakly discern the two spheres. We can know the number of the spheres precisely because of the relations they stand in. If we allow relational properties, such as "being two miles from an iron sphere with a one mile diameter", each of the spheres has the same relational properties as well. But the asymmetry of the relation shows us that there are two.

We can count the spheres, precisely because of the relations they stand in. The spatial relation in this case serves to count them, but not to identify them. This way of discerning objects has been deemed question begging; to count the objects and map the relations to the objects, we first need to identify them [22].

Our structural realist approach can circumvent this critique on weak discernibility by taking the relations as primitive and discerning the amount of different objects from that.

2.2.4 Modes

The position advocated by Michael Esfeld is a causal modes theory. In his recent work (Esfeld and Lam, 2011, [38]) he claims that the distinction between objects and the relations (properties included) they instantiate is merely a conceptual distinction. This is similar to Lowe's use of universals which are only existing when instantiated. When an object instantiates a certain set of properties, they coexist in the way the object exists.

That is the central thought to this ontology; there is only one type of *object-thing*, where properties are the way objects act, not something the object has. When we combine this with the humility argument, we arrive at Esfelds ontology: objects exist as causal powers.

In this way there is a fundamental modality in the world; objects are real dispositions.

The structure of the world is a modal structure in which all the relations between objects are relations that would hold when the objects were in place. Our knowledge necessarily only comes forth through the causal relations between our measurement instruments and the objects themselves. But causality can be explained in a modal way as well,

A property confers a causal power to the thing it is attributed to [50]. The property "being hot" confers the capacity to let ice melt. The property "being spherical" confers the capacity to roll. The form is like this:

When X exists and X has a charge C, this means that X will respond to a charged entity B in way A.

The property 'charge', is only known from its interaction with our measurement devices (functioning with charges themselves!). We are therefore only able to distinguish the way objects causally interact. In our classical metaphysics we have added a property 'charge' that also applies to the object when there is nothing it responds to. This seems as a very natural thing to do letting the causal profile be caused by a property. The property explains how the causal profile works. But according to Esfeld:

> the fundamental physical structures are causal in themselves so that there is no need to postulate underlying causal properties(Esfeld, 2008, 13, [37])

So the level of properties is superfluous, just as quiddities or haecceities. We can deal with only the causal profiles and speak about the world. This is precisely the part of the metaphysics our epistemology can support. Our world now has a necessary appearance, because the causal profile is locked down, it is a part of the ontology. As opposed to neo-Humean approaches, notably Lewis' mosaic.[5]

The structures in THE WORLD consist of relational structures of modes. The relations are the causal powers relating different parts of the structure.

An advantage of the distinction between object and its relations being conceptual, is that we can incorporate successive theories. It is possible to conceive of the whole universe as one object as existing in a causal mode. The different objects we experience are conceptual parts of the whole structure being divided up into small causal parts.

Though this view dismisses the quiddities and haeccities in favor of a more modest ontology, there are some questions about whether Esfeld succeeds. It seems as if he replaces the superfluous metaphysical nature of objects with a causal profile, completely unjustified. Let us look at some of the critique.

2.2.5 Psillos: You must be quidding

Psillos makes a case for quidditism, specially attacking Esfeld's causal structural realism in his 2011 [85].

1. World $W1$ containing a single object with a causal power Q and $W2$ containing tandem objects with the same causal power Q are different, but we can only see the difference by going beyond causal roles, *even when we can never know the difference there might be one.* To know the difference between these two worlds, we need to go beyond the causal roles. Sticking to the causal roles is denying the existence of the metaphysical level altogether.

2. The argument that our theories are formulated using dispositions does no work for a dispositional ontology. We cannot infer from the way our theory is formulated that THE WORLD is also causal in nature.

3. The only argument for causality is the argument that we do not want to go with quiditism, where objects have qualities as in quiddities or haeccities. Esfeld does not solve a problem, he simply postulates an alternative account, When we take a close look, the strategy Esfeld employs in arguing for a causal structure metaphysics is inference to the best explanation. By ruling out

[5] In Lewis' theory the causal profile is constituted by the patterned relation emerging between objects in the mosaic that is the actual world. In different worlds, the causal relations emerging from the mosaic would be different.

quiditism he postulates physical causes to explain how the world works. There is no argument for the use of causes other than that it works and we cannot go with quiddities.

There is another account of the world possible. Lyre's account uses structures as primitive and depends upon properties. And the properties are not properties of objects, but of kinds. This is closer to the workings of scientific theories, because

> theories of physics represent particular objects in their models, they present kinds of objects rather than objects simpliciter when taken as a whole. According to Brading and Nounou p. 120 in [89]

Brading and Nounou state that scientific theories speak about kinds, and that objects are only present in the models, that is in the interpreted forms of a theory. When we model a situation we take a objects belonging to kinds and we apply the theory to objects as instantiating the kinds. What our best theories have to say is only about the relations between kinds. How objects instantiating the kinds can be individuated is something for the next Chapter. Let us first focus on the next Section in which we see how to deduce properties of kinds from the theoretical structure.

2.3 On Properties

Lyre claims that there are intrinsic properties that are knowable. His ontology lacks the primitivity of objects but has the primitivity of intrinsic properties. Let us focus on the kind of intrinsic properties Lyre does allow for, we already know that they cannot be the intrinsic properties as they are described by Lewis and Langton.

Lyre opts for a holist Humean supervening structure, in which the whole structure provides the base on which the laws supervene. In this view, structures are global regularities.

> Laws arent literally structures, and structures are only law-like in the sense that laws can be reduced to global regularities (which we call structures) p.13

In Lyres ontology, we find relata and structurally derived properties. The structurally derived properties comprise relational properties and invariants of structure as structurally derived intrinsic properties. Lyre derives intrinsic properties by means of symmetries.

> A symmetry of a domain D may be considered a set of one-to-one mappings of D onto itself, the symmetry transformations, such that the structure of D is preserved. The symmetry transformations form a group and exemplify equivalence relations to a partitioning of D into equivalence classes. From this we always get invariants under a given symmetry providing properties shared by all members of D. And insofar as such properties belong to any member of D irrespectively of the existence of other objects, they are 'intrinsic'. On the other hand, they do not suffice to individuate the members, since all members share the same invariant properties in a given domain. (Lyre 2011, p.1-2, [74])

The invariant properties are intrinsic in that they belong to any member of D irrespective of the existence of any other entities. We cannot individuate the object with invariant properties, for all members of D share the same invariants. The derivation of properties from symmetries is also sketched by Muller in his [81], §4. The properties are derivable, but what kind of properties are they?

These are not the intrinsic properties as defined by Lewis and Langton, because those individuate an object. They seem to be the properties of a *kind* of objects. We claim that they are relational properties; properties that express the relation of something to something else. As a mass can be seen as the cause of the curvature of the gravitational field (or the other way around), but it is necessarily connected to a property translatable to something related to something else. If it isn't we would be back at quidditism, which contrasts with our epistemological constraints.

The structural properties are the relations and the structurally derived properties. Structures are *global* entities. They are concrete entities encompassing everything. This makes them act as universals. The local particulars are derived from these structures of the world *in toto*. The structures are not abstract, as universals, but they can function this way. A property derived from the structure acts as a universal within the structure describing the whole of reality, but it loses its meaning outside the structure.

So Lyre's ontology

> ... takes whole structures as basic and structural properties relations and intrinsic invariants as features of such structures. From them relata can be derived or reconstructed in the following sense: they are the placeholders between the relations and they are domain-wise individuated by the structural invariants which serve as structurally derived intrinsic properties of the relata. (Lyre, 2011, p.6, [74])

The relata in the structure are accounted for by a bundle theory. The objects are bundles of the relations dependent on the global regularities. The global structure can only be approximated by local parts. The structurally derived intrinsic properties provide us with a natural kind structure of the world.

In a different book, of Ladyman and Ross, Lyre is paraphrased to say that objects of a theory are members of equivalence classes and no further individuation is possible(p.147 [65]). Lyre is cited in the passage where Ladyman and Ross explain how they account for objects from invariants in group theories, much the same way as Lyre funds his intrinsic properties:

> The idea then is that we have various representations of some physical structure which may be transformed or translated into one another, and then we have an invariant state under such transformations which represents the objective state of affairs. Representations are extraneous to physical states but they allow our empirical knowledge of them. Objects are picked out by the identification of invariants with respect to the transformations relevant to the context. Thus, on this view, elementary particles are hypostatizations of sets of quantities that are invariant under the symmetry groups of particle physics. (p.146-7 [65])

Ladyman and Ross say that the invariance of the permutations of our different representations gives us the sets of invariant quantities (i.e. Lyre's intrinsic properties such as mass, charge, total spin).

Muller also takes properties and relations to be automorphic subsets of structure-domains [6].

A problem for Lyre's ontology is that causality is not a part of THE WORLD. Just as in Humean supervenience approaches, the causality comes from the relations that are in the actual structure. Other structures would mean a different causal explanation. Since the actual properties also

[6] From Muller's talk on Structural Explanation, September 2011, Ghent.

depend on the actual structure, properties can still be associated with a causal profile. Whether there exist properties that have no causal influence is a question we will not answer.

There is one risk to Lyre's method. When we have a symmetry on G, we can move up to $\mathsf{Aut}(G)$, the group of all automorphisms on G, then to $\mathsf{Aut}(\mathsf{Aut}(G))$ and so on. This leads to an infinite regress of symmetries. The solution Lyre proposes is to stay close to our own physics, a solution a true scientific realist can relate to while the answer evades the critique.

2.4 Using Models and Preferring Structure

Now for something completely different. Let's present an analogy from modeling. Modeling is a method that is often used in science. We create something that can be used as a surrogate world. By altering something in the (often theoretical) model, we can learn something about the world. In the best cases this can be verified and we are talking about correct predictions. A sophisticated model can be connected to a data set, e.g a mathematical pendulum gives a family of solutions that can be used to describe some characteristics of a physical pendulum.

This way of using models is interesting because it gives us a place where empirical data are linked, *through theoretical structures*, to THE WORLD. Let us see how this works and how it can give us insights into the use of structures.

When we are able to map the city of Amsterdam to the tiny irregularities on a blank sheet of paper, the sheet does not count as a model of the city. If we have the same sheet *and* use it to navigate through the city, there should be something in the *mapping* that is also in the city of Amsterdam. To successfully use a model, there should be relations in the model in such a way that these relations can be mapped on the city. The different parts of the paper should not necessarily be ordered in the map as in the city itself, but the way we *use* this model, defines some relations in the model that are *actual* relations between places in Amsterdam.

We claim that the same holds for models of the unobservable world. The *use* of a model picks out a specific internal relation[7] in the model, that is actively used in the making of predictions. To use a theory to make certain (true) predictions, makes sure that something of that theory is of the same form as something out there. The use of the theory picks out the preferred relations.

When we can use a model as a surrogate world, we can use a model to make novel predictions. The novel predictions are not already in the model, they are products of the structure of the model in its intended form, that is the way in which it is being used, as correctly describing the structure of THE WORLD.

Our theory of Brownian motion is useful for predicting the distance a particle in a liquid can travel *as well as* for predictions of fluctuations in the stock market. The different uses designate different structures in THE WORLD that can be represented by the same mathematical structure. There is no question on the right interpretation of the structure, the *use* fixes the interpretation.

So we can safely assume that there is a part of a theoretical structure that relates to a certain data set, or abstraction thereof[8]. The connection of the theory, and thereby its operational structures,

[7]Internal relation is a relation that is necessary, a change in one of the relate immediately changes the other relatum. This as opposed to external relations that merely supervene on the properties of the relatum.

[8]No particular data set would apply to the theories of physics due to imprecise measurements and individual mistakes in the data. How to do a good abstraction of the data to a data set that fits the ideal, as in theoretical, case, is a question outside the scope of this Thesis. It is a question that should be answered in the philosophy of experimentation.

to a set of data, is governed by our (successful) use of the theory to explain the data.

The successful use of a theory picks out a preferred theoretical structure

Upon acceptance of this claim, we have established the relation of a structure in a theory to empirical outcomes. The use of a theory links the structure itself to empirical sense data.

This relation is one side of the coin, it relates the observable results to a specific theoretical structure. The other side that we want to establish is how the theoretical structure relates to THE WORLD. We recall this quote from Esfeld:

> if the fundamental physical structures are modal structures, being the power to produce certain effects, then (...) any difference in the fundamental structures, accounting for there being two different types of arrangements of fundamental structures in two possible worlds, automatically leads to some difference in the effects that these structures produce and thereby also to some difference in the domain of observable phenomena. (Esfeld, 2009, p. 187)

Let us take a good look at this quote. Esfeld claims that any difference in the observable level is the result of a change in the unobservable causal structure in THE WORLD. When we have dismissed talk about quiddities and stick with the causal structures as our ontology, we can state that the way the observable world is, supervenes on the causal structure of THE WORLD.

Psillos explicitly denies that different structures lead to different observable results.

> Take Newtonian mechanics, where $F = ma$, and compare it with a reformulation of it, according to which F is always the vector sum of two more basic forces F_1 and F_2. Suppose further that F_1 and F_2 are such that they sustain each other and can act only in tandem to produce acceleration. Suppose further that F_1 and F_2 have no other effects. We have two modally-laden structures which are non-isomorphic but, nonetheless, empirically equivalent.(from Psillos, 2011, [85])

In this quote Psillos states that there are two ways of formulating Newtonian mechanics. There is, however, a problem with the second formulation. It lacks explanatory power. When asked what the F_1 and F_2 consist of, we cannot but answer that there are at least four smaller forces, two of each composing F_1 and F_2. This formulation begs the question.

The other problem with the second formulation is that F_1 and F_2 can only act in tandem. That means that they cannot be observed alone, in fact, they cannot act alone. They are bound to act together with their predestined counterpart in order to produce F itself. When F_1 and F_2 are allowed to exist but not allowed to act alone, our ontology would grow unnecessarily. The F_1 and F_2 can only act in tandem, because they are components of the same force. The real causal power acting here is F.

We can already see that F_1 and F_2 are not existing, because they can be chosen at will. We can choose F_1 and F_2 with the only constraint that they add up to F, were this a good reformulation. When they are physical objects, we cannot choose them, can we?

When objects are nothing over and above their causal profile, we can safely assume that there is a causal chain from the causal objects to our measurement devices. When two objects differ in their causal profile, the existence of one of the two in the chain, will alter the chain end therefore alter our experiences/measurements. When they do not alter our measurements, the causal objects are not operative; i.e. not necessary within this structure's domain.

An example from the observable realm is the use of a map to find your way through town. We know that the map works, because we can determine the (shortest) route from A to B. The relations of different streets to each other in the model and in reality correspond. If the relation did not correspond correctly, but it is possible to find the correct route, the incorrect description must not have been part of the followed route.

When we see this in the observable realm and we believe that, as realists, the way we describe the unobservable realm is similar to the way we describe the observable realm, we can hope to find a core structure in an empirically working model. By letting the use of a theory "pick out" the vehicle structure in THE WORLD, we can retain even the structure of Newtonian mechanics as (approximately) true within its realm of applicability. The use of a theory is necessary linked to evidence. This evidence settles the domain question: it makes sure that the theory is not correctly corresponding to the whole worldly structure, but only approximately to a limited domain, validated by the use of the theory as applied to the particular (limited) data-set.

Newtonian mechanics is useable in the earthly realm with objects with a size $\gg h$ and speeds $\ll c$. In this part of the world the structures of the theory of Newtonian mechanics are similar enough to the structures of the world to give us proper usage. Let us rephrase the lessons from this passage in a oneliner:

> **Structure-Observable Link: There is a worldly structure connected to every grouped set of outcomes.**

Upon the acceptance of this assumption, we have a clue regarding our metaphysical framework, as well as a clue regarding where to look for theoretical structures that can be linked to ontological structures, namely in empirically equivalent theories.

2.5 Structural Ontology

In this section we give a definite description of the ontology we are committed to. The chosen ontology not only allows us to describe the metaphysics of physics, but of the special sciences as well.

2.5.1 The Metaphysics of Structure

When addressing the structure of THE WORLD, we have to be careful to distinguish mathematical structure from physical. An often made mistake is being realist about mathematical entities. This is something we must be aware of. Structural realism is a semantic thesis, the theoretical structure refers to the worldly structure. That being said, we can spell it out.

First notice that our only access to anything worldly passes through our senses. That our representations map our empirical input is therefore not a surprise. There are necessary connections between sensory input and theoretical structure.

Examples from the macro-realm are always directly connected with observation sentences. Our theoretical macro-realm structure doesn't reach too far beyond the mere empirical. When we work with structural concepts like electrons, this is not so obvious. An electron is a structure that has properties related to measurement set-ups. Examples include mass, charge, spin, position, momentum, et cetera. We can employ these properties, attributed to something we cannot sense directly (we can only experience the outcomes of the measurements), to gain fresh new observations.

We can use these invisible sources to excite other unobservable objects. By employing the theoretical structure that refers to the unobservable, we can produce novel observations. To claim that the relation between a button turned here and an interference pattern appearing on a photographic plate there is only a correlation between instruments in a laboratory is absurd. We know something about the workings of the unobservable structure. We know of our theoretical models successfully describing the wave structure of reality interacting with the machinery we use, both the PEGGY II and the photographic plate[9]. Through the manipulability of the unobservable we can gain knowledge of the unobservable relations.

To describe the nature of these unobservable relations we have described two possible candidates: Esfeld and Lyre.

Lyre's ontology is more beautiful than Esfeld's causal structuralism. Esfeld's causal structuralism is not motivated by scientific arguments, but by the denial of quidditism (This is some valid critique by both Lyre and Psillos on Esfeld). Lyre's ontology has a very beautiful aspect in which the parts are depending on the whole, they emerge from it, as it were. The structure as primitive touches on the essence of structural realism. Relations are necessary as primitive entities in our metaphysics. With structure we can form properties and relations (as automorphisms on the structure) and objects, by bundling the properties and relations.

Relations deserve a special place, it is, in the light of quantum mechanics, no longer possible to think in a particularist framework. Let us go over some arguments from quantum mechanics, arguments that will be spelled out in detail in the next Chapter 3

In the particularist view, combined with Humean supervenience, we have objects and their non-relational properties and on these properties there supervenes the relations of the properties. In classical Humean supervenience account of the world as a depending on intrinsic properties, the relation x *is longer than* y depends on the non-relational properties of x and y, that is their length. Quantum mechanics gives us a reason to drop supervenience and the particularist view and adopt a relational holism that has a lot of elements of Lyre's ontological framework.

An argument to allow relations as more primitive than objects was found in an article by Teller [97]. In an entangled quantum system we have a clear cut example of a relation that does not supervene on non-relational properties. Teller gives us an argument for relational holism on p. 214 of his [97]. Let us recapitulate the argumentation. In quantum mechanics a state gives us the probabilities to find a property p on measurement of a system A. In an entangled system, we can form a state expressing the property q to a superposition of systems, any of the properties of the combined system are captured bny this state, or rather probability to find a property on measurement. This state expresses a correlation between the two systems. The state of the whole system; the two related subsystems, can never be constructed by supervention of the states of the parts, we miss the characterizing relation defining the correlation between the two subsystems. It is in fact the other way around. The relation of the pair suffices to find any of the part's states by using a partial trace.

Relational holism does not deny that there are relations that supervene on properties, but it does deny that this is necessarily always the case. There are relations that exist as a part of the global structure. This global structure is the primitive, it is what gives us the intrinsic properties. On these intrinsic properties a lot of relations supervene, e.g. "being longer than", "being heavier than", et cetera. This is a different kind of relation than the intrinsic relations that also follow from the global structure.

[9]Peggy II was popularized by Hacking who used the manipulability of the unobservable through experimental machinery to be proof of *entity realism*, being realist only about the entity and not about the governing laws.

When our supervenience base consists of the intrinsic relations and structurally derived intrinsic properties, the global structures are the primitive objects that give us these relations and properties. It cannot be that a global structure is related to its derivatives is a classical relation way, because that keeps the possibility open that the structure is a mere relatum of this relation! It would make the structure an abstract entity and we do not allow *ante rem* structures, only *in re* structures [73]. The intrinsic properties/relations and the theoretical structures of which they emerge are inseparable.

To make a distinction between the supervenient relations dependent on the properties and the intrinsic relations inseparable from the structure, we propose the term *internal relationship.* Internal and external relationships are terms that date back to British philosophy in the early 1900s. Internal relationships are relationships that are intrinsic to an object in that they could not be changed in any way without changing the object itself. Examples are the relation between the arc of a circle and the center of said circle, it cannot be the arc of this circle without being related to the center in a specific way [10]. *External relationships* are the classical Humean supervenience relations in which the relation does not alter the identity of the objects themselves.

We propose that internal relationships exist out there. Examples from quantum mechanics would include the Bell correlations. The relations are not alterable without altering the subsystems, in fact, the correlations between the subsystems are existing in nature. Internal relationships are often dismissed because of their modal content (their essentialism) [10]. This is a key aspect of a Humean view, even of the Humean view that Lyre holds. But it is not possible to flee the notion of internal relations that easily.

Abstract notions, such as the logical connectives always exemplify these internal relations, deduction implies necessity. To deduce properties and relations from a global structure smells like essentialism. If we were to allow internal relations in physical structures as well, we would undermine the Humean program Lyre had in mind. Lyre however explicitly refrains from the way the intrinsic properties are ‘parasitic’ on the global structures [74][73]. He tries to keep a Humean program, without realism about modalities, acknowledging that the way the properties and relations that emerge from the global structure are necessary, given that the corresponding global structure is in place.

So, when we acknowledge the internal (intrinsic) relation as an addition to the normal (external) relation to be a part of our ontology, our ontology looks like this:

	Ontological Status
Objects	Bundles
Global Structures	Primitive
Intrinsic Properties (of kinds)	Derived
Internal Relations	Derived and found through manipulability
External Relations	Supervenient on Properties and Relations

The internal relation is the primitive ontological entity that we add as existing in the world, it is the type of relation that cannot be created out of the identity of its parts, it is the other way around. The internal relations fix the parts the way they are (we see this in quantum mechanics). Another good example is the bundle theory, where objects are bundles of relations, a change in the relations changes the relata, for they are nothing but bundles of the relations. The relations we discover are necessarily a part of the discovered structure, and we are the ones bundling them into objects, depending on our application of the different relations.

2.5.2 Zooming Out of Physics Into the Special Sciences

The whole, that is the global structure, determines the way we dissect it. Lyre's ontology gives us a preferred kinds ontology, it makes the resulting kinds necessary with respect to the actual structure. What we have in THE WORLD is theoretically described by equivalence sets of properties and we are the ones grouping them into kinds. Kinds only exist as a set with contrasting properties of another. It is the difference between something and something else that creates the kinds, we are the ones looking for the differences[10].

We state that objects are nothing but bundles of relations, but who is the one deciding which bundles we acknowledge as genuine objects? When we deny the existence of predefined objects and hold fast to an ontology of relations, the size of the objects depends on the bundles we interact with. Different levels of interaction, different theoretical structures mapped on the world, leave us with different invariants and thus different kinds. We can talk about trees, forests, plant cells or galaxies, all depending on the point of view one takes and the theories in use.

What we call an object depends on the context of our decision what to call an object. Different fields of science have different global (theoretical) structures they employ, and therefore employ different natural kinds in their addressing of THE WORLD. How the different fields of science are related depends on the way the different empirical data is related. We can speak about forests as objects in ecology, we talk about single trees in the biology of trees[11]. The structure of THE WORLD is rich enough to allow these different subdivisions to be mapped onto it, the same way as we can allow classical mechanics to be approximately true for macro objects on earth, while maintaining that quantum mechanics is the way to go to describe their microscopic parts. These different abstractions give us different divisions of THE WORLD.

Since we can, through interaction with the world, reveal relations about the world and our knowledge about the world is growing, what we consider to be elementary particles is changing. The use of the word 'elementary' denotes an object that is considered a simple, that is an object that has no parts. To assume the existence of simples seems too optimistic within the light of our ontology. We can see how different natural kinds emerge from our different global structures, the partial applicability of different views might give us different simples per theory, allowing them to exist in the world. Each area of application is related to one ultimate structure in the world. In the end all these views are interconnected, for they are different representations of the same world, nevertheless all describing real structures existing in the world.

To end this section, let's focus on a quote by Gregory Bateson on ecology

> The horse isnt the thing that evolved. What evolved actually was a relationship between horse and grass. This is ecology. If you want a lawn, which is the equivalent in the suburbs of a grassy plain, there are certain steps you have to take. First of all you go and buy a lawn mower. This is the equivalent of those front teeth of the horse. And you have to have this in order to prevent the grass from going to seed. If the grass goes to seed, it dies. Its done its thing, it thinks, and it dies. So you keep it from going to seed with a mower. Secondly, if

[10] Zoological footnote: *Drosophila Melanogaster*, the fruit fly, is being used in genetics experiments since 1910. In the past century there have been artificially created mutation strains that are now considered different kinds of flies. Differences include different wing shape or colour, for the naked eye, before lab cultivation and grouping, the species was known as one sort. Now our researchers know what to look for, they can distinguish different types.

[11] Note that a forest is more than an aggregate of trees! It exhibits complex interrelations and objects in a forest depend on each other. They are viable objects precisely because of the non-equilibrium state they have to maintain within the whole, when this ceases to be the case, the forest is nothing but an aggregate of (dead) trees. A healthy forest will be more than that, it will be an ecosystem. Living organisms exhibit a wholeness that makes them all quite complex. Artifacts do not seem to exhibit this natural complexity, on first glance.

> you want to make a tight turf, you have to squash it down, so you buy a roller at best one of those rollers with sort of fists on it all over thatll knock it down. This is a substitute for horses hoofs. And finally, if you really want to have a good lawn, you go and buy a sack of manure and substitute it for the back end of a horse in order to deceive the grass into doing ecologically what it would do if it had hoofed animals living on it. Thus the unit of whats called evolution out there, is really not this species or that species. It is an entire interlocking business of species. (Gregory Bateson, 1991, p. 276)[5]

This quote gives us a way in which our ontology can be appropriate for other fields than physics. We can assign properties to subsystems, in this case the grass growing on the tundra and the Przewalsky horses living on these grassy plains. They exhibit some sort of intrinsic properties and in the light of the whole, the ecological structure of the tundra, they exhibit internal relations as well, they are connected in such a way that we have to fulfill the relational requirements. Albeit a mere simplified example, the existence of a relation of this sort seems quite plausible.

2.6 Converging and Parallel Perspectives

When we allow for a basic ontological level in the world, we can see how it relates to our different theoretical views. The most interesting scenarios in science are when there is either a scientific revolution or when there are multiple successful conflicting views on a part of reality. In each of these scenarios there are multiple perspectives on the same ontological structure. Let's employ disjunct elimination again!

Classically we assume that there are multiple interpretations of the same, or similar, formalism. Whilst the formalism indeed determines the structure of a theory, in the old view the interpretation of the formalism makes the ontological claims. When we can have a separate debate about ontology, we are able to see which parts of the theories is ours to keep and which part is "merely interpretation" and does no ontological work[12].

Convergence of perspectives occurs in scientific revolutions. We then have two empirically comparable theories, of which one is the predecessor and one the successor. Because the theories are related to the same ontological structure in the world, the theoretical structure should converge. It becomes more accurate in its similarity to the ontological structure.

A clear cut example is the succession of Lorentz' aether theory by Einstein's special relativity theory. The formalism of both theories is very much alike. The main differences are in the existence of a preferred frame. The preferred frame exists in Lorentz' theory, i.e. the aether frame. Of course the convergence can only be claimed with hindsight, when we have agreed upon the "right" theory.

The fact that a structure which is similar in form will be expanded when we go from predecessor to successor makes the predecessor's structure less similar to the world. Its truth depends on its similarity to the worldly structure and is therefore applicable. Lorentz' aether theory was able to give similar outcomes as Einstein's special theory of relativity. Lorentz' theory had the outcomes relative to the aether frame, an assumption which was dropped by Einstein.

In the convergence case it is necessary to see that the successor perspective is the stronger one and the one that is more similar to the structure of THE WORLD. The convergence will be apparent by virtue of the continuity claim Votsis gave us in Chapter 1.2. Scientists will try to keep the

[12] Or at least cannot be verified to do ontological work.

operative structures, because the empirical adequacy of the predecessor theory needs explanation. Even though the convergence case is quite interesting, the more interesting case is the one of parallel perspectives.

Parallel perspectives are similar cases as the predecessor successor case, but there is no possibility to make this distinction. The empirical equivalence of the theories makes us infer, through the structure-observable link (see p.42), that there is a single worldly structure behind the two paradigms. Unlike the convergence case, we cannot claim (yet) that one is better than the other. The conclusion being that the different theories are sharing a physical structure to which they both refer. The intersection of the two structures is the *operative structure*: that part of the theory that connects the theory to its empirically successful predictions.

Our next mission consists in the description of this operative structure. The epistemic structure that emerges as the intersection of a set of empirically equivalent theoretical structures and is morphic to the ontological structure. We will use multiple interpretations of quantum mechanics to find the operative structure and infer its reality. In the end we shall express this operative structure in our ontological framework

To recapitulate, we have made a case for Ontic Structural Realism and argued for a plausible form of our ontology. We can now go and see how accepted conflicting theories are manifested within this ontology and from there infer how the world is.

Chapter 3

Application to Quantum Mechanics

In this chapter we shall see an example of our ontology backing up various scientific theories of the quantum realm. The convergence of structures depends on the convergence of successive theories and the structural convergence is guided by the correspondence principle. The only things that remain of a theory after a shift are the operative structures. To find the operative structures of the quantum realm, we take two different, parallel theories and see what remains, this is the operative structure.

Parallel perspectives provide us with different ontologies, but with the same empirical outcomes. Both theories will, in their own terms, explain why the other makes successful predictions. At the moment there is no crucial experiment available, since the empirical predictions are the same[1]. Our continuity claim states that when we have successive theories, it is possible to switch from one to another to find the operative structure, (see p. 19). By employing the same tactics on parallel perspectives, in this case different interpretations of quantum mechanics, we find the operative structure connected to the empirical data.

This operative structure does differ from a "normal" theory. Scientists in the field (not me) accept the complete ontology posited by the theory, only for working purposes. As structural realists, we acknowledge the superfluous posits to be purely instrumental, only allowing the ontological structures to have metaphysical weight.

Once we have accepted OntSR on the basis of other reasons than being singled out by science, we do not have to go over the normal connection between quantum mechanics and OntSR. The argument from quantum mechanics is that it supports claims about indiscernibles, which are objects that cannot be distinguished by their (intrinsic) properties. Indiscernibles can more easily be interpreted in a structuralist ontology than in a classical ontology. Since we look at the operative structure behind multiple interpretations, this argument loses its power.

In the Bohm theory any two objects are always discernible, because every object has a unique position at every time. The indiscernibility of elementary particles in quantum mechanics that is claimed to favour one or the other version of OntSR fails for the Bohm theory. Because we take the overlapping structures of the two theories to be the actual, operative structure, arguments on

[1] If any crucial experiment is available at all, remember the Duhem-Quine underdetermination thesis described in Chapter 1.2.

indiscernibility cannot give us a direction within OntSR.

We go and explore the *operative* structures of the quantum domain. When the operative structures point in the direction of a particular metaphysical framework, then that is the one which is favoured over the others. It turns out that the operative quantum structure allows us to find properties through automorphisms on partial structures, favouring Lyre's ontology.

A problem when comparing two different ontological frameworks is that the resulting structures have no meaning assigned to them. They get the meaning by functioning in the interpretations. An example is that a differential equation does not do anything until you link it's terms to something in THE WORLD, only then it becomes an equation of motion. Since we allow ontic structures, the structures retain their definite meaning. We have explained this in Section 2.4

We assume familiarity with the formalism of orthodox quantum mechanics. The characterising features that distinguish quantum mechanics from classical mechanics will be mentioned in Section 3.1, for the sake of convenience. We will recapitulate the causal quantum theory of De Broglie and Bohm in full in Section 3.2.

3.1 Orthodox Quantum Theory

3.1.1 Key Concepts

The primitive concepts we have in orthodox quantum mechanics are *states, physical quantities, systems* and *measurements*. Electrons, photons, neutrons and macro-systems such as a photon-box on a spring and trees are considered quantum systems. A *quantum system is anything that is described by quantum mechanics.*

The systems have states that determine probabilities of the possible measurement outcomes of different physical quantities[2], as an example we take A as a physical quantity. Physical quantities are represented by operators. Operators have a small hat, like this: $\hat{A}$.

There are state-dependent and state-independent properties of a system which are all physical quantities. *State-independent properties* are *charge, mass* and *total spin*. These are the properties we use to characterize different quantum systems, we can use them to differentiate e.g. electrons from positrons (opposite charge) or electrons from photons (different spin, mass and charge).

To explain what *state-dependent properties* are, we first have to describe what a quantum state is. To describe how radically different this is from the classical case, we explain quantum states through the analogy with classical states.

In classical mechanics, a state of a system in phase space completely determines the past and future of the system. Phase space assigns three position and three momentum values to each system. The deterministic laws of classical mechanics then fix the trajectory of this system in phase space. Phase space with its $6N$ dimensions, where N is the number of systems described, uniquely translates to trajectories in (assumed Euclidean) 3 dimensional space.

It is easy to see how classical mechanics relates to a particularist metaphysics (see p. 34), a metaphysics in which each object has its properties, position and momentum, as the state and its state-independent intrinsic properties, mass and charge. Relations come into play through

[2] The term "physical quantity" denotes what in other texts is called an observable. The term "observable" is misleading, because we can measure the position, an observable, of an electron, which is an unobservable item. The term quantity is preferred.

comparison of the state-independent properties and each micro system has its own defined path that depends on its the state-dependent properties.

Where in classical mechanics the state of a system exactly describes the properties of a system's state-dependent properties, in quantum mechanics, this is not the case. In quantum mechanics, the state vector, a vector in Hilbert space, exhaustively describes the properties of the system. They do not fix the system in a unique way, however.

In quantum mechanics, the state of the system gives rise to the properties of the system through the operators. Every operator representing a physical quantity has a spectrum of eigenvalues with corresponding eigenvectors. An operator acting on a state decomposes the state in a combination of eigenvectors of the operators. When a system is in an eigenstate of the operator, we can assign a value to the corresponding quantity with probability 1. Eigenstates are defined as states connected to eigenvectors depending on the corresponding eigenvalues. A quantum system in an eigenstate of a physical quantity, has the corresponding property, described as $\langle \hat{A}, a \rangle$ where a is the value of the physical quantity A, corresponding to $\hat{A}$. *Not* being in an eigenstate is not possessing the property.

In quantum mechanics, there are incompatible physical quantities. Every two operators that do not commute represent two incompatible physical quantities. Operators that do not commute have mostly non-overlapping eigenstates, meaning that the system can be in an eigenstate of $\hat{A}$ while it is not an eigenstate of $\hat{B}$. So the system cannot have a value of A and B simultaneously.

Two physical quantities represented by two operators that do not commute cannot be measured with arbitrary precision. Position and momentum are a pair of non-commuting physical quantities. Other pairs are time and energy, or any set of orthogonal spin directions. The precision that can be determined for one of those pairs, position and momentum, is written down in the *Heisenberg uncertainty relation* [56];

$$\Delta P \Delta Q \geq \hbar/2 \tag{3.1}$$

Therefore a quantum system can only have a definite property of one of a set of two incompatible physical quantities; the state cannot be in an eigenvector of two incompatible operators.

We can, however, know the *probabilities* to find any of the possible values from the spectrum of either A or B if we were to measure the incompatible operators. The state vector can be decomposed into any basis of eigenvectors with coefficients. When we decompose the state vector into the spectrum of the incompatible operator (which is a basis), the coefficients correspond to probabilities to find the state of the system in any of these eigenvectors upon measurement. These probabilities do not refer to our ignorance of the actual value, as in classical statistical mechanics. According to quantum mechanics they are the ontic probabilities, known as the *Born-probabilities* or the *Born measure*.

The Born measure gives us the probabilities of finding value a corresponding to an eigenstate $|a\rangle$ of the measured physical quantity $\hat{A}$. The probabilities to find any of the values of A are found by taking the square of the absolute value of the inner product of state and eigenstate

$$\mathrm{Pr}_A^{\psi(t)}(a) = | \langle a|\psi\rangle |^2 \tag{3.2}$$

The probabilities depend on the wave function ψ. The Schrödinger equation gives us the evolution of the wave function governing the probabilities of any possible measurement.

$$i\hbar\frac{\partial\psi}{\partial t} = \hat{H}\psi(t) \tag{3.3}$$

Here $\hat{H}$ is the Hamiltonian, the operator corresponding to the physical quantity total energy of the system. The Schrödinger equation only describes the evolution of a quantum system when there is no measurement made.

After a measurement of a physical quantity has been performed, the state of the system is in one of the eigenvectors of the spectrum of the operator corresponding to the measured physical quantity with a probability $\in \mathrm{Pr}_A^{\psi(t)}(a_j) = |\langle\psi(t)|a_j\rangle|^2$, where the spectrum $(a_0, a_1, ..., a_j)$ is given by $\sigma(\hat{A})$, when $\hat{A}$ has a discrete spectrum. The relative frequencies of the measured quantities correspond to the Born-probabilities. How, why and if this collapse happens is the subject one of the greatest still running discussions of quantum theory. For more information on the measurement problem we refer to the author's earlier work [98] and the syllabus on foundations of quantum mechanics [56].

3.1.2 Entanglement

Having cleared up the terminology of states, physical quantities, systems, measurements and probabilities, there are some states that deserve some extra attention. These are entangled states.

A state is *entangled* if and only if it cannot be ⊗-factorized. Any composite system is *entangled* at time t if and only if its state is entangled at t. We already noticed the possibility to decompose a state into eigenvectors with appropriate coefficients. It is also possible to assign a state to a combined system and to decompose this state of the combined system into eigenvectors belonging to physical quantities of the combined system.

This composite system contains two subsystems. When the composite system cannot be ⊗ factorized, the state of the combined system determines correlations between measurement outcomes pertaining to the separate subsystems. The nature of these correlations is best described by means of an example. If we take two spin 1/2 systems we can prepare them in the singlet state, part of this preparation is that the two systems interact in a special way before they are sent off.

$$|\psi\rangle = \frac{1}{\sqrt{2}}(|\uparrow\rangle_1 \otimes |\downarrow\rangle_2 - |\downarrow\rangle_1 \otimes |\uparrow\rangle_2) \ \in \mathbb{C}^2 \otimes \mathbb{C}^2 \tag{3.4}$$

Here the subscripts $_1$ and $_2$ correspond to the different subsystems and the arrows represent either z-spin up or down, $|\uparrow\rangle$ and $|\downarrow\rangle$ are eigenstates of the z-spin operator, with eigenvalues $\hbar/2$ and $-\hbar/2$, respectively.

When we now make a local measurement on one of the subsystems, say a spin-z measurement on system 1, we will still find a maximal correlation with the other subsystem, even though the systems are spatially separated in a way that does not allow them to interact. The restrictions imposed by this correlation are maximal in this example: system 2 will have a definite quantity of spin in the x-direction attributed to it at the moment we make a measurement at system 1, namely the opposite value. It is not always such a strong correlation, but in every entanglement the state of a system depends on measurement performed at another system, even though these systems can be lightyears apart.

This sounds quite bizarre. It becomes even more bizarre when we realise that the singlet state (3.4) is an eigenstate of the total spin of the combined system. None of the subsystems is in a spin eigenstate at the moment! This is not necessarily bizarre: classical objects can have properties their parts do not have. The bizarre thing is that the parts *do* have a spin value after a measurement. The state of the combined system tells us something about the parts that the parts do not tell us, namely that the total spin is 0, the parts are always anticorrelated, measuring spin up at $_1$ means that $_2$ has spin down and vice versa.

The correlations between the two subsystems cannot be expressed in mixed states of the subsystems. A mixed state of subsystem $_1$ would correspond to a density matrix, resulting from the partial trace on the complete system:

$$\mathrm{Tr}_1 \left|\psi\right\rangle = \frac{1}{2}(\left|\uparrow\right\rangle_1 \left\langle\uparrow\right|_1 + \left|\downarrow\right\rangle_1 \left\langle\downarrow\right|_1) \tag{3.5}$$

which is a sum of two projector operators for spin up and down respectively. It is possible to get the mixed state describing subsystem $_2$ from the singlet state in the same way (a partial trace), but it is impossible to get the singlet state when we combine these two mixed states. The correlation between the two subsystems cannot be retrieved.

We therefore have to conclude that the entanglement of the two states is what determines the properties of the subsystems and not conversely as in a Humean mosaic, that the relation between the two supervenes on the subsystems. This is an essential part of quantum mechanics which fuels our choice of ontology. Let us now see how the Bohm theory deals with this feature of the quantum realm.

3.2 Causal Quantum Theory

In this Section we overview different strands of Bohmian mechanics. We start with an historical interlude about de Broglie's ideas during the birth of quantum mechanics, after which we will give Bohm's 1952 version of the theory. In the end we give the present day Bohmian interpretation, which is a bit smaller than Bohm's 1952 version.

3.2.1 De Broglie's Theory (1927)

In 1927, Louis de Broglie constructed a deterministic quantum theory. He conceived his distinction of matter in waves and particles as early as 1923 and wrote his doctoral dissertation on this subject [3]. In his doctoral dissertation, he coined the De Broglie hypothesis, claiming that all matter displays wave-like behavior. This is imaginable when the matter is guided by waves. It explains the wave-like behavior as well as the particle-like features we encounter in measurement: both exist.

At the Solvay conference Pauli criticised de Broglie's theory concerning inelastic scattering. Pauli could not see how the trajectories could account for discrete energy exchange in inelastic scattering[3]. De Broglie's defence was found inadequate by the audience, even though it was later shown that all necessary elements were present [3].

In 1928, de Broglie said that

[3]In the book by Valentini and Bacciagialuppi, *Quantum Theory at the Crossroads*, the criticism is extensively investigated. Their analysis is that a confusion on Pauli's part by using an optical analogy introduced by Fermi in 1926 left de Broglie's solution to the problem obscured.

> [p]ropagation in a configuration-space of purely abstract existence is, in fact, out of the question from the physical point of view. The wave representation of our system ought to involve N waves propagated in real space instead of a single wave propagated in the configuration space (p. 131)[19]

There is some friction between his idea about the ontology and the theory he founded. In his early theory, he explicitly separated the particle and the wave and gave them both ontological weight. In his later views, after extensive discussions with Einstein, he opted for the interpretation in which the wave does not exist, but is a mere theoretical entity [8]. In this interpretation we lose the causal effect of the wave on the particle. De Broglie gave up on his own visionary view of particles and waves both existing.

De Broglie taught the orthodox quantum theory from 1932 for twenty years [13]. In 1932, von Neumann published a book in which every hidden-variable theory seemed to be refuted [103]. This refutation was proved to be based on too restrictive assumptions [56].

In 1952, Bohm published two papers setting forth a theory as de Broglie. De Broglie recognized Bohms ideas as his own and became one of the few early proponents of the theory.

3.2.2 Bohm's Theory (1952)

De Broglie's deterministic theory is essentially the same as Bohm's. The particle's position is a hidden variable, the probability the measurements predict reflects our ignorance of the actual, hidden, position. The particle is propelled by a so-called 'pilot wave'. The equations are similar to the classical Hamilton-Jacobi equations with an extra potential term.

In 1952, David Bohm reinvented the causal quantum theory program. He was unaware of the fact that De Broglie already thought up this interpretation of the quantum formalism [12]. He suggested that it is possible to talk about particles just in 'completing' the Schrödinger equation by entering for $\psi(\mathbf{q},t)$, the complex wave function, a complex number in its polar form:

$$\psi(\mathbf{q},t) = R(\mathbf{q},t)\mathrm{e}^{\mathrm{i}S(\mathbf{q},t)/\hbar} \tag{3.6}$$

The rest of the theory then follows without many problems, as long as one is willing to interpret the equations in a particular way.

We start from the Schrödinger equation:

$$\mathrm{i}\hbar\frac{\partial\psi(\mathbf{q},t)}{\partial t} = -\left(\frac{\hbar^2}{2m}\right)\nabla^2\psi(\mathbf{q},t) + V(\mathbf{q})\psi(\mathbf{q},t) \tag{3.7}$$

where $V(\mathbf{q})$ is an arbitrary potential depending on $\mathbf{q}$, the configuration-variable of the particle.

Filling in the polar form of the wave function, and then splitting the resulting formula in its real and imaginary parts, we have two new equations. One for $R(\mathbf{q},t)$ and one for $S(\mathbf{q},t)$:

$$\frac{\partial R}{\partial t} = -\frac{1}{2m}[R\nabla^2 S + 2\nabla R\cdot\nabla S]\text{ , and} \tag{3.8}$$

$$\frac{\partial S}{\partial t} = -\left[\frac{(\nabla S)^2}{2m} + V(\mathbf{q}) - \frac{\hbar^2}{2m}\frac{\nabla^2 R}{R}\right]. \tag{3.9}$$

We see that the only term involving $\hbar$ is the second term in equation (3.9). If we set this term to zero, we are left with the classical Hamilton-Jacobi equation:

$$\frac{\partial S(\mathbf{q},t)}{\partial t} = -\left[\frac{(\nabla S(\mathbf{q},t))^2}{2m} + V(\mathbf{q})\right]. \tag{3.10}$$

$S(\mathbf{q},t)$ is interpreted as the 'pilot wave', similar to the Hamilton-Jacobi interpretation. The rest term that we had set to zero, we call $U(\mathbf{q},t)$, the *quantum potential.* It is defined as:

$$U(\mathbf{q},t) \equiv -\frac{\hbar^2}{2m}\frac{\nabla^2 R(\mathbf{q},t)}{R(\mathbf{q},t)} \tag{3.11}$$

We see that the quantum potential only depends on $R(\mathbf{q},t)$ and $\hbar$, not on $S(\mathbf{q},t)$, and that it does not diminish over distance. Where classical potentials, such as the gravitational potential, diminish with $1/r$, the quantum potential does not. The quantum potential depends on the wave field, and the wave field has no source.

$R(\mathbf{q},t)$ is the square root of the probability density $R(\mathbf{q},t) = \sqrt{\psi(\mathbf{q},t)\psi^*(\mathbf{q},t)}$. That means that R^2 is, just as in the orthodox quantum theory, the position probability density. The probabilities in the Bohm theory *do* reflect our ignorance, just as in the classical case. There are multiple particle trajectories possible of which only one is actual.

The particle's velocity is found by the gradient of the wave front, giving only trajectories perpendicular to the wave field. A common interpretation is that the particles are carried or pushed around by the wave. The wave is seen as a real entity in Bohm's theory, working in real space through the quantum potential, although the wave is in configuration space. The velocity of the particle is given by

$$\mathbf{v} = \nabla S(\mathbf{q},t)/m \tag{3.12}$$

The contradiction with orthodox quantum mechanics stands out; not only does every system always have a position independent of its state being in a position eigenstate, it is also possible to calculate the momentum if we know the position. In orthodox quantum mechanics these two incompatible physical quantities cannot simultaneously be had by the same system.

The ontology of Bohm theory is constituted of waves and the particle positions. The wave lives in configuration space while the particles live in Euclidean three-dimensional space. The quantum potential acts via the wave field on the particles, and since the wave depends on all particles, the quantum potential is non-local. Bohm uses the quantum potential to explain the entanglement correlations in a *causal* way. A change in one of the particles alters the wave function, giving a change in the velocity of the other particle.

Supervenience is not necessarily violated, because the we can ascribe the different particles a different actual position and claim that this is what creates the non-local pilot wave. A non-local instantaneous interaction between the particles is still describable in a particularist frame. Noticing that the wave does depend all the particles and is a necessary ingredient to describe the interaction, we have to concede that supervenience is violated.

3.2.3 Present Day Bohmian Mechanics

Present day Bohmian mechanics does not mention the quantum potential. Nowadays, the Bohmians give the Bohmian description of quantum mechanics compactly, without the causal framework

Bohm gave. This description is given in multiple works by Bohmians Dürr, Goldstein and Zanghi [24][**?**][25][9] and will be reproduced here.

The state of the particle is given by $(\psi, \mathbf{Q})$, where $\psi(\mathbf{q}, t)$ is the quantum state: its evolution is described by the Schrödinger equation (3.3), with $\mathbf{q} \equiv (q_1, q_2, ..., q_N) \in \mathbb{R}^{3N}$, and $\mathbf{Q} \equiv (Q_1, Q_2, ..., Q_N)$ with $Q_k \in \mathbb{R}^3$ the real position of the kth particle.

The velocity is given by $v^\psi(\mathbf{Q}) \equiv \dot{\mathbf{Q}}$, with $v^\psi(\mathbf{Q}) = (v_1^\psi, v_2^\psi, ..., v_N^\psi)$ is a velocity field in $\mathbb{R}^3$, evolving according to

$$\dot{\mathbf{Q}}_k = \frac{\hbar}{m_k} \mathrm{Im} \frac{\nabla_k \psi}{\psi} = v_k^\psi(\mathbf{Q}) \tag{3.13}$$

The equations (3.12) and (3.13) are similar in nature, even though the explanation is different. In Bohmian mechanics $|\psi^2|$ gives the probability of finding the positions of the particles. Since $|\psi^2|$ is invariant under the dynamics, it is an appropriate way of describing, if and only if it was fulfilled in the initial set up of the system. The system is in quantum equilibrium, analogous to classical equilibrium in which the distribution of microstates is concerned with the notion of equilibrium. All other physical quantities are expressed in terms of position and are therefore secondary. Momentum measurements and spin measurements are very complex position measurements.

In modern day Bohmian mechanics, the causal story of the quantum potential made room for an equation describing the particle trajectories. The quantum state works in configuration space and describes the quantum correlations and whatnot, but the causal explanation de Brogle and Bohm explained is lost. Nevertheless, this minimal Bohmian interpretation is in use and is the one of the popular alternatives for orthodox quantum mechanics (the other being the many worlds interpretation).

3.3 The Bare Necessities

Look for the bare necessities of Mother Nature's recipes –Balou the Bear, Jungle Book, 1967

In the children movie *Jungle Book* the character Balou the Bear sings about finding the bare necessities. The bare necessities of Mother Nature's recipes do not involve the interpretative parts. When we take two theories to denote the same physical structure, the operative part is the necessary part of each theory referring to the same actual structure. We have defined operative structure in the first Chapter (p. 19), and here we will look for the core. No more interpretations, no more unnecessary additions, we just look for the operative core.

This is the idea we want to defend: two theories, the Bohm theory and the orthodox quantum mechanics, refer to the same physical structure in the world. The ontological claims of either theory should be set aside; we have our own ontology. Some things that differ between the two theories are:

- The collapse in orthodox quantum versus a measurement in terms of position in Bohmian mechanics.
- The hidden variables in Bohmian mechanics, $\mathbf{Q}, v^\psi$.
- The wave function is not real in orthodox quantum mechanics, but is real in the Bohm theory (not in Bohmian mechanics, mind you).

- Ontological probabilities in orthodox quantum mechanics versus determinism combined with epistemic probabilities in the Bohm theory.

Most of these differences will not come back in our structural quantum core. Since the two theories differ on the account of determinism, and the claim that a theory is or is not deterministic is settled by an interpretation, this is a part we have to be agnostic about.

To find out what part of the theories is the operative part, we take the theories under consideration and see which structure they share. Parts of the theories are significantly different, which leads us to suspect that these parts are not necessary for making correct empirical predictions. To find out which parts they have in common we will look at the similar structures. In this section we will discuss three structures they have in common.

1. $L^2(\mathbb{R}^{3n})$
2. The emerging state-dependent properties.
3. The Born measure

3.3.1 State Spaces

Comparing the two theories, the first thing we see is the isomorphic descriptions of the dynamics of the quantum system. The Schrödinger description, which is the way physics students are first taught quantum mechanics, is a valid description of the quantum state dynamics.

Where in orthodox quantum mechanics the state is completely described by $\psi \in L^2(\mathbb{R}^{3N})$, in Bohmian mechanics the state is described by the two-tuple $\langle\psi, \mathbf{Q}\rangle \in L^2(\mathbb{R}^{3N}) \times R^3$.

We immediately see that the overlapping part of the state spaces consists of $L^2(\mathbb{R}^{3N})$. This will be considered the operative state space structure. It should be noted that the Bohm theory is founded on the Schrödinger formulation of orthodox quantum mechanics with the addition of particles, and we again drop the particles.

What both theories have in common is the evolution of the Schrödinger equation, and corresponding to the structure $L^2(\mathbb{R}^{3N})$, in which the wave functions live.

3.3.2 The Emerging State-Independent Properties

The state independent properties in our quantum structure are mass, charge and spin. In science we use them to classify our elementary particles. These properties emerge from automorphisms on Our state space $L^2(\mathbb{R}^{3N})$. The set of all unitary and antiunitary operators forms the automorphism group of the Hilbert space.

An easy way to visualize the power of automorphisms is to consider that the wave function is invariant under spatial rotations (described by a unitary operator), it is easy to see that we can distinguish systems with a different orbital angular momentum.

$$\hat{R} : \psi \mapsto (\hat{R}\mathbf{q}) \text{ such that } \hat{R}\psi(\mathbf{q}) = \psi(\mathsf{R}\mathbf{q}) \tag{3.14}$$

Where $\hat{R}$ is an operator on $L^2(\mathbb{R}^{3N})$ and R is the 3×3 rotation matrix to which operator $\hat{R}$ corresponds, acting on $\mathbf{q}$. When $\hat{R}$ is any unitary rotation operator around an axis working on

ψ, the resulting $\tilde{\psi}$ preserves orbital momentum. We can distinguish all systems by their orbital angular momentum, which is preserved under rotations.

Mass and charge follow from different automorphisms. Linear momentum is preserved under boosts, mass is a part of that, while charge comes from internal symmetries. Charge follows from unitary rotations in the electromagnetic field. This way we can carve our domain into natural kinds.

Spin is a more complicated property that emerges from a combination of some other automorphisms, my training is limited and the time required to fully understand this is not there. The beautiful result is that this property gives rise to novel predictions.

Since unitary operators keep the inner product intact, they keep the probabilities intact. They divide up Hilbert space into equivalence classes: e.g. transformed states that under symmetry transformations keep the probabilities intact:

$$|\langle \hat{U}_R\psi|\, P(\Delta)\, |\hat{U}_R\psi\rangle\,|^2 = |\,\langle\psi|\, P(\Delta)\,|\psi\rangle\,|^2 \tag{3.15}$$

where $\hat{U}_R$ is a unitary operator representing a symmetry R.

3.3.3 Born Measure

Both quantum mechanics and Bohm's theory contain the Born measure. The probabilities were first proposed by Born in his now famous *"Zur Quantentheorie der Stoßvergänge"* in 1926 [15]. The probabilities are a feature of the quantum theory that breaks with the traditional conception of probabilities.

In classical mechanics, probabilities are epistemological, they represent our ignorance of the actual state of affairs. In orthodox quantum mechanics the probabilities are ontic. There is nothing of what the probabilities range over beyond the probabilities[4], in contrast with classical probabilities where probabilities describe our ignorance of the actual state over an ensemble of possible states.

In Bohm's theory the probabilities are no longer ontic, they are epistemological and exemplify our ignorance over the actual state of affairs. The actual state of affairs being the hidden variable that is the case. All other state-dependent observables depend on position and are covered by this rule.

The structure related to the Born probabilities is $\langle \mathfrak{B}(\mathbb{R}),\ Pr_A^{\psi(t)},\ [0,1]\rangle$; it depends on the wave function ψ and we can construct a different one for every operator $\hat{A}$ that corresponds to an observable A.

$$Pr_A^{\psi(t)} : \mathfrak{B}(\mathbb{R}) \mapsto [0,1] \tag{3.16}$$

$$Pr_{\hat{A}}^{\psi(t)}(a_j) = |\,\langle\psi|a_j\rangle\,|^2 \tag{3.17}$$

Each probability is connected to an eigenvalue of the operator of the observable. Call $\sigma(\hat{A})$ the spectrum; the set of eigenvalues of to the operator $\hat{A}$. It gives us a way of connecting ψ to our data set D. The data set D contains the empirical outcomes, in this case the relative frequencies of our measurements. For all observables there is a relative frequency data set D as well as a corresponding probability measure $Pr(\hat{A}\psi(t))$ connecting the corresponding operator to the wave function.

[4]There are of course state-independent properties that are attributed to physical systems and described by states, all existing with certainty.

The predicted probabilities, (3.17), are equal in both theories, the ontological commitments from within the theories is different. Since we are operating from outside of either theory, we can disregard the different parts and only look at the common parts. For each theory the structure $Pr_A^{\psi(t)}$ is necessary to map the theory to D. The Schrödinger equation governs the way the probabilities change over time.

To go from the pre-measurement dynamics to the actual outcomes, we have to tackle the measurement problem. A solution is not a part of our operative structure of QM. The projection postulate of quantum mechanics that governs the collapse of the wave function upon measurement is not a part of the operative structure of quantum mechanics. Bohm's theory explicitly lacks the projection postulate and the collapse of the wave function.

In Bohm's theory, the probabilities are epistemic, there is one actualized trajectory. The possible trajectories are governed by the probability current. The probabilities are important in Bohm's theory. If the operative structure of quantum mechanics is the shared structure of the theories under consideration, we need to incorporate the probabilities and have an *ignorance interpretation* towards the actualization.

Our resulting minimal quantum structure is

$$\mathfrak{Q}_0 \equiv \left\langle s,\ L^2(\mathbb{R}^{3N}),\ \psi(t),\ \sigma(\hat{A}),\ Pr_{\hat{A}}^{\psi(t)} \right\rangle \tag{3.18}$$

Where s is the state-independent properties given by the unitary operators on $L^2\mathbb{R}^{3N}$, $\psi(t) \in L^2(\mathbb{R}^3)$ is the wave function and the state space it lives in. $\sigma(\hat{A})$ denotes the spectrum of $\hat{A}$, and $Pr(\hat{A}\psi)$ denote the probabilities to find any of the eigenvalues of $\hat{A}$.

3.4 Structural Explanation

The main advantage of realism over anti-realism is that realism provides us with an *explanation* of the empirical and technological success of science. Realism provides us with an explanation that keeps miracles at bey. Why we can predict the phenomena under consideration is explained by the reference of our theories to something in THE WORLD leading to the predicted phenomena[5].

To explain is to answer a why-question. We explain by answering *why* something happens. There are many theories of explanation, giving different answers to these questions. Let us go over some of history's fanciest theories of explanation and see where our structural realist ontology fits into the picture.

The classical account of explanation is the *deductive nomological model* of Hempel and Oppenheim [52]. The Hempel-Oppenheim Deductive nomological model takes a law and deduces the explanandum from the laws in conjunction with empirical facts. The sentences connecting the explanandum to the explanans must be true. The problem here is that the role of laws makes the explanation symmetrical, while the explanation is asymmetrical. The use of a law makes it possible to explain the height of a flag pole by the length of this shadow, the sun's position and the laws governing light.

Since causality is asymmetrical and laws can be used in a symmetrical way, this account of explanation leaves us with questions about cause. Also the notion of a law is not unproblematic. A

[5]This Section is based largely upon a presentation by F.A. Muller held in September 2011, Gent.

non-true explanation can be explanatory, e.g. Newtonian mechanical explanations are non-true, but are explanatory precisely because they *do* capture the partial structure of the physical system.

Another possibility is *explanation by models* which are somehow similar to the world, this position was notably taken by Mary Hesse [53]. Here we are in realist atmospheres. Models function as connections between the theoretical and THE WORLD. They are abstractions from the real and specifications of the theoretical. By employing a model, we appeal to an underlying structure of THE WORLD. The underlying structure of THE WORLD should look like our model in such a way that our explanation with the model is a close enough description of *some* feature of THE WORLD. To use a model as a surrogate world, we use it to map only the relevant substructure to THE WORLD. A crucial factor of a model is that it gives an abstraction (if it wouldn't give an abstracted view, we would be working in a copy of THE WORLD, which is not more insightful than the world itself), it focuses on the relevant part of the world and it neglects the irrelevant parts (we can for instance neglect the gravitational pull of the rope to the bob of the mathematical pendulum). A model focuses on the specific parts of the world we use for explanation.

A *unificationist* explanation tries to trim down the number of basic explanatory building blocks, this position was made famous by Kitcher [62]. We try to reduce the number of facts by accepting a rigid set of argument patterns that, when accepted, allows us to deduce more facts from a smaller number of facts. How the unificationist explains is not that obvious; it reduces and interconnects our knowledge, but the intuitive explanation is missing. The part that misses is the appeal to any mechanics inside the explandum. A unificationist always has to rely on similar argument patterns and misses the realist boat referring to the actual workings of nature.

The *causal-mechanical* explanation does have precisely this reliance on an underlying mechanism, Wesley Salmon is the grandfather of this position [91]. Its basic explanatory qualities lay in the inner workings of a process. Of course to resort to causality is quite problematic, but intuitively there are some candidates to explain causality e.g. the transmission of a conserved quantity, energy momentum transfer, et cetera. This gives us some insights in the inner workings of a phenomenon and thereby we can explain it.

Most of the types of explanans rely on some *inner workings* of the explanandum. It is not enough to merely save the phenomena as the empiricist or the instrumentalist wants. There is actually something in THE WORLD, we know and use to explain the phenomena.

Our ontological structure $\mathfrak{Q}_0$ can explain *why* the phenomena occur the way they occur. How does this work? Through observation and experiment we create a data structure D. D contains relative frequencies of outcomes in the spectrum of the physical quantity measured, as well as values of the state-independent properties s. Our theory contains the theoretical structure $\mathfrak{Q}_T$ which we claim is isomorphic to the ontic structure $\mathfrak{Q}_0$. Now let us take the empirical substructure of $\mathfrak{Q}_T$ and call it $\mathfrak{Q}_{\text{emp}}$:

$$\mathfrak{Q}_{\text{emp}} = \Big\langle s,\ \alpha(\hat{A}),\ Pr(\hat{A}\psi(t))\Big\rangle \tag{3.19}$$

If D is embedded in $\mathfrak{Q}_{emp}$, it is embedded in the theoretical structure $\mathfrak{Q}_T$ that represents an ontological structure $\mathfrak{Q}_0$. Now $\mathfrak{Q}_0$ explains why D occurs, for it gives us the *actual* structure of THE WORLD behind the measured phenomena of D.

3.5 Why Interpretative Sauce?

We made a plausible case for a metaphysics of structures in which properties (1-place relations) and relations (n-place relations) were derived from a structure. We applied this metaphysics to quantum mechanics, a field in which the different interpretations seem to live side by side, unlike the progress of science, where different theories succeed each other.

In Section 1.2, we looked at the way different theories succeed each other and we are, in retrospect, able to point out the operative structures that are preserved over theory change (Votsis's continuity claim, see page 19). The realm of quantum mechanics allows us to find the operative structures without the need of a successor. Because the different interpretations are not succeeding each other, they provide us with a deeper form of understanding of the core. A clear grasp of the physics of the very small.

What we end up with is the basic structure of quantum mechanics; to take this structure to be uninterpreted would claim that it is nothing but a mathematical structure. It is more than that. It refers to the ontological structure in the world, by acknowledging the overlapping structure from the different perspectives we have on quantum mechanics. When the overlapping structure is the operative structure, and we adhere to the no miracles argument, we can infer the reality of this structure.

By solely adhering to the existence of structures, we believe in a minimal ontology. Most theories have more meat than just the bone structure. We tend to give the structures more bite than they have, we alter our interpretations until they look a lot like the world around us, or something we are familiar with. Such interpretations alter at the epistemological level. When we accept Bohm's theory, knowledge about trajectories is possible, within this framework. In an orthodox quantum mechanics framework talk about the collapse of the wave function is allowed. An accepted interpretation comes with a view of what we accept to be knowledge of the world[6].

Usually, to interpret a theory is to assign meaning to the terms of a theory. In quantum mechanics we agree on most of the terms, the interpretations differ on other statements. The different interpretations of quantum mechanics differ in what is regarded determinately true. We want more knowledge of the world than $\mathfrak{Q}_0$ provides. We want THE WORLD to tell us whether Schrödinger's cat is dead or alive. Unfortunately, our ontology is not that substantial. Our structural view is able to explain the empirical adequacy by referring to an ontology, but it does not give us such a "complete" view as a classical ontology gives.

A classical ontology takes objects as the primitives. In our structural view objects are not a pre-determined primitive. They are bundled relations and the bundles formed are determined by the theoretical structure in place. Bohm's theory and orthodox quantum mechanics would create different bundles from the same relations, e.g. the Bell-correlations with particles and non-local causality or collapsing states. Each of these views gives us a greater understanding of the quantum structure, we expand what we allow to be true statements on the content. This expanded truth is depending on the interpretation we choose.

To interpret quantum mechanics allows us to make more *Anschauliche* claims about the world. We extend the vocabulary or we add postulates to make the theory more manageable with a view we accustom ourselves with, be it beables or bra-kets. We create a world we can easily maneuver and we say it's THE WORLD.

[6]Thanks to F.A. Muller for clearing this up during a recent presentation titled *"What do we do when we interpret quantum mechanics?"*, Utrecht, February 29 2012.

> Man tries to make for himself in the fashion that suit him best a simplified and intelligible picture of the world; he then tries to some extent to substitute this cosmos of his for the world of experience, and thus to overcome it. [26]

This quote by Einstein gives us what we normally do within physics, we substitute our intelligible picture of the world for THE WORLD. By comparing all the different (working) pictures, we find the core of the picture, a structure that latches onto THE WORLD and therefore is effective. Our claim is that THE WORLD is shaped as this structure. We cannot go beyond structure without substituting our own world for THE WORLD.

To claim that we can go beyond structure is to claim an obscure view from nowhere that gives us direct knowledge of the essence of THE WORLD. Any interpretation expands the truth content by expanding the theory with something more. Each theory contains different narratives explaining its own extension, extending the epistemological boundaries by allowing the theory to be greater. This need for a greater understanding of THE WORLD is itself understandable, but it is not warranted, only our operative structure can be accounted for.

Chapter 4

Conclusion

In this Thesis we followed an unusual path for a scientific realist. For ordinary scientific realists, the metaphysics to be realist about often is suggested by our best scientific theories. In this Thesis the path was different. We have argued for structural realism beginning from epistemic considerations. The transmissibility argument shows us that if we can have knowledge, it must be structural. Next to that, the structural thesis resolves the deadlock between the pessimistic meta-induction and the no miracles argument by balancing between these arguments.

After we established the fact that we can have structural knowledge, ontological structure is the way to get to a true realism. Knowledge implies truth, ergo there is a structure of THE WORLD and anything beyond structure is obscure and unknowable.

To get to know THE WORLD, we went and looked for a fitting metaphysics, one that is close to our knowledge. It has to be close to our knowledge to minimalise the gap between epistemology and ontology. To keep this gap as small as possible keeps us away from obscurity. We went with Lyre's view, the view that takes the whole structure as primitive, allowing us derive intrinsic properties and relations. The structure gives us a network of relations and relational properties that are necessary within this actualized structure. Any other structure would give us different relations. This is not founded when we look at the quantum mechanical structure. When the structure is actualized, the resulting relations come with necessities for the relata.

The objects within this structure are bundles of relations and properties that result from automorphisms on the global structure. There is a top-down approach of description. The structure determines the properties of the natural kinds as well as the relations between objects. The objects are built as bundles from relations and properties.

Of these properties we only know their causal *cum* relational profile. This was explained by Esfeld. Esfeld then made the mistake to reduce everything to causal relationals. Esfeld is partially correct in his claim; e.g. we can only speak about mass as how it acts in a gravity field. But we can also know that an object has the property mass when it is alone. We can for instance permute the objects of the kind of objects that all have mass **m** and nothing would differ in our measurement setup. We can thereby infer that the property is also had outside of interactions. To have mass entitles the object to a dispositional relational property allowing us to measure the property whenever it interacts with e.g. scales.

To speak about unknowable intrinsic properties is not done. The intrinsic properties that Lyre dissects are not the quiddities against which Esfeld argues. They are what was called intrinsic by the physicists, not the intrinsic properties of Lewis and Langton, which are intrinsically unknowable.

By comparing two interpretations of quantum mechanics, we found the minimal quantum structure $\mathfrak{Q}_0$. This quantum structure is the only structure we can be certain of to exist connected to the corresponding quantum data set D. This modest structure $\mathfrak{Q}_0$ seems to lack an interpretation, because of its mathematical character, but it is connected to THE WORLD, as well as our empirical data. The mapping of the dataset to the empirical part of the structure fixes the structure in THE WORLD.

The structure leaves us with a set of structurally derived intrinsic properties and relations used to classify and discern objects. Relations bind us to some form of holism in which we cannot describe separate parts without throwing away information about the whole. This view depends on the relations that define the objects. We can have different global structures that would carve up THE WORLD differently, but they have to respect the worldly relations. The different carving would consist of different bundling. A property distinguishing fermions is not needed when distinguishing different atoms.

If we zoom out of the quantum territory, it is still a viable ontology. The kind "tree" consists of properties and relations. Its roots are related to its branches and the bark is related to the leaves and so on. But to claim that the tree stands on its own and is an object that can be separated of the non-tree part of the world, is unintelligible. The tree is also related to the soil around it and the sun above it, the rain providing it with water and even the bacteria and other protozoa that might live in symbiosis with this particular tree. The life of a tree depends on its state of disequilibrium within its surroundings. If it were in total equilibrium, it would be dead.

We are the ones bundling this specific part of the worldly structure in the natural kind "tree". On molecular level the end of the tree is not that easily found, since it is in constant reciprocity with its environment. Different views give different world views, which does not mean that they are contradictory.

This Thesis is not finished. It will never be finished. This project can go on for ever. Spelling out different structures as described by different fields of science. Maybe eventually even describing the social sciences? Since each field of science deals with different empirical data, it is linked to a different physical structure. These structures all exist and all of the scientific fields associated with them are approximately true in their linking of the theoretical structure to reality.

When science improves, our theoretical structures will need to be finetuned as well. They will not change too much, because the core structure should be approximately correct. A new theoretical structure might change the way we group relations into objects, or replace a relation for nuanced distinguishable relations.

Having made plausible the structural view, the world will never look the same again. Structural interactions of parts and wholes will keep popping up throughout life. And it is a nice way to look at things, somehow it's strangely satisfying. But I bet it's only satisfying for the believer, the one who has substituted a structural universe for THE WORLD in order to make it intelligible.

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