In Search of an Ontology for Quantum Field Theory

Dissertation
zur Erlangung der Doktorwürde,
dem Promotionsausschuß Dr. phil.
der Universität Bremen
vorgelegt von

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Bremen, den 6. Juni 2000

Contents

Preface

Some parts of this book have been or will be published in extended or shortened versions and/or in a different arrangement. Parts of chapter 1 will appear as the introduction in Kuhlmann et al. (2000). Parts of section 3.1 and chapter 8 have appeared as “Processes as objects of quantum field theory” Kuhlmann (2000). Parts of chapters 5 and 9 have appeared as “Quanta and tropes: Trope ontology as descriptive metaphysics of quantum field theory” Kuhlmann (1999a) and as “Quanten und Tropen - Philosophie der Physik und Sprachphilosophie” Kuhlmann and Stöckler (2000). Parts of chapter 6 have appeared as “Was sagt das Vakuum über Teilchen aus? Neuere Ergebnisse aus der theoretischen Physik schaffen zusätzliche Probleme für den Teilchenbegriff” Kuhlmann (1999b).

List of Abbreviations

AQFT	Algebraic Quantum Field Theory
CCR	Canonical Commutation Relations
GRT	General Relativity Theory
prob	Probability
SRT	Special Relativity Theory
QFT	Quantum Field Theory
QM	Quantum Mechanics

Part I

Introduction

Introduction

Which questions will be explored? The philosophical topic of this thesis is *ontology* restricted to the investigation of the most general structures of what there is in the world. We will ask which kinds of things and modes of being there are in the most general sense. However, the questions which are of concern in the present work are only relative ones. What is being discussed are the ways to conceive of the world which are compatible with the mathematical formalism of QFT. No assumptions are being made about the truth of QFT or its relation to reality. Questions about truth, reality, "the world" and their connection have no direct impact on the study. Moreover, being as such will not be an issue at all. QFT is thus the unquestioned starting point of the following investigation. The only sense in which this procedure will be reflected upon is with regard to the conceptual consistency and maturity of QFT and the status of QFT within physics.

The immediate question why QFT of all scientific theories has been chosen for this enterprise has a straightforward answer. If any theory about nature can lay claim on being the most fundamental one it is QFT. This is not to say that everything can or should be reduced to QFT. However, when special sciences come under ontological consideration at all, QFT is of outstanding importance. Accordingly, it is of particular interest which picture of the world this theory paints.

The term 'ontology' is often used in a twofold way, at least in the tradition of analytical philosophy which is the philosophical background of the present work. Besides the search for or the theory of the most general structures of being, 'ontology' denotes the domain itself to which a language or theory refers. Following this tradition I will freely make use of both senses of 'ontology' as well.

It is not presupposed that there is one definite set of basic entitites to which QFT refers and which one could simply, or after some closer investigation, read off QFT. The only two things I will presuppose with respect to ontological questions is, firstly, that these questions make sense at all and, secondly, that special sciences like physics constitute objects whose conceptual analysis yields a valuable contribution to the general ontological questions.

What kind of answers should be expected? This thesis will hopefully purvey inspiring information about QFT and some ways one can and cannot imagine the world to be in line with QFT. However, it will not supply *the* right or appropriate ontology of QFT. Not only is the number of proposals as well as the number of issues to be taken into account almost impossible to exhaust. Moreover, there might never be a final unified answer.

Although a final answer to the posed questions should not be expected it will become clear in the course of this investigation that not all problems are equally important and not all options are equally viable. Eventually, I will introduce and explain a new option for the ontology of QFT and justify my preference for this option.

Historical and systematical background. The ontological analysis of QFT is a relatively new area of philosophical concern. Nevertheless it clearly has a well-known immediate historical and systematical background. In a sense it is a follow-up to the famous discussion about the *wave-particle duality* which originated with the formation of quantum mechanics (QM). Quantum objects seem to defy a representation in classical terms. With the *quantum measurement problem* the very idea of an objective ascription of properties to things came under suspicion. Finally, *Heisenberg's uncertainty relations* together with the non-classical behaviour of systems containing so-called *identical particles* endanger the individuality of quantum objects. All these questions still linger on in the present investigation.

There is, however, a much longer tradition of kindred questions in the history of atomism beginning with ancient greek philosophy. Here we have similar considerations about the building blocks of the world and their properties. Nevertheless, there is a pivotal difference between the old atomist's reasoning and the way we proceed nowadays. Except for its very last period the history of atomism consists exclusively of conceptual considerations. In contrast to that the ontological study of QFT starts with a theory which has been exceedingly well corroborated in a plethora of experiments.

Main results in this thesis. Besides an account of the current state of research and of some systematical as well as historical foundations this work contains four original contributions by the present author to the ongoing research. The first point is preparatory and consists in the embedding of the main topic of this thesis into philosophy of physics on the one side and general philosophy on the other side. Each of the next three contributions to the research concerns a different option for the ontology of QFT. The reference to different options is not the only feature which distinguishes these three contributions. Moreover, their nature differs in at least one respect which makes it possible to say that the first contribution is in a negative context, the second in neutral one and the third in a positive context.

The context of the first contribution is an argumentation against one option for an ontology of QFT, viz. particle ontology. It deals with localization problems of relativistic N-particle states. The relation of two conceptually important no-go theorems will be explored in section 6.3.2 and it will be shown that the analysis leads to a surprising result.

Other than the first contribution the second one as such is neutral with respect to the choice between different ontologies. Its purpose is to carve out interpretative consequences of the most radical proposal for an ontology of QFT, process ontology. The new study carried out in this thesis has to do with the interpretation of Feynman diagrams. It will show in sections 8.3 and 8.4 that and which interpretative differences follow from the choice of different ontological approaches.

The last one in the group of the three above-mentioned contributions has a different nature again. It is the proposal of and an argumentation for a new ontology of QFT, viz. *trope ontology*. In three steps I will show in chapter 10 why I consider the trope-ontological approach to be a very palatable new alternative for the ontology of QFT. I will argue that dispositional properties are pivotal in a trope-ontological interpretation of QFT.

By these contributions I try to push a subject further ahead which is vividly discussed in these days. I hope that my results will help to further stimulate the debate. Since there is still much more to explore about the ontological aspects of QFT I have no doubt that this will remain an area of lively research for many years to come. Accordingly, the exposition of the state of research as well as my own results represent only a small part of what can, and hopefully will, be done.

The choice of topics. The question concerning the choice of the topics is a two-fold one. The one side is about the choice of the ontological alternatives to be examined, the other side is the choice of aspects to be considered for each ontology. The following investigation does not aspire to completeness with respect to either side. My main intention is to describe which new results I found out during my own research. One of these results is about an already existing ontological interpretation of QFT, namely particle ontology. The other two results are attempts to establish and evaluate new alternatives for an ontology of QFT. These are process and trope ontology where trope ontology is the alternative which I will finally give my own preference.

The reason why I included field ontology in my exposition is not that I had anything new to say about them, leaving evaluative aspects aside. By including this ontological alternative I wish to sharpen the understanding for those alternatives which are my main concern. Moreover, an account about the ontology of QFT would be misleading if it did not comprise those conceptions which are held by many researchers after all. These remarks should make it clear that the length of chapters does not indicate the importance or popularity of the respective ontological alternatives considered.

It could be objected that a complete list of alternatives as well as of all the arguments for and against the single options would be heplful. One might further hope that by doing this one could sort out all but one option which would then be the right one. I agree. This would be a nice thing to have. However, currently we are by no means in a position to do that. We are just at the beginning of an ontological investigation of QFT. Moreover, even if we should finally reach a state of research when we know all the options and have all arguments and counterarguments on the table who tells us that there is one single alternative which would emerge out of this cost-benefit analysis? It may well be that we will have to live with different ontologies at the same time. In any case it is much too early to speculate about the end while we are just at the start. Nevertheless, despite of these restrictions I have tried to consider a range of ontological alternatives and topics which, at least to my knowledge, is not available so far within one monograph.

Structure and topics of the thesis. Leaving the 'Introduction' and the 'Conclusion' aside the thesis falls into four parts where the second part (chapters 5 - 7) and the third and fourth part (chapters 8 - 10) are the two halfs of the main study where chapter 10 is my own proposal. The first long part on 'Context, Methods and Presuppositions' (chapters 1 - 3) is the longest and prepares the ground for the ensuing investigation. Its topics will be introduced in the next few paragraphs before coming to the main study.

Although the study of ontological aspects of QFT is a rather new area of philosophical research the issue cannot even be nearly understood properly without a recognition and analysis of its historical as well as systematical background. A thorough preparation is indispensible for any further investigations. Accordingly, the four introductory chapters are more significant than a merely didactically motivated lead-in.

Historically, the discussion concerning atomism is the precursor of today's ontological examination of quantum physics. The ways of atomism and the role of its ideas in the research process of modern physics will be traced back and explored in chapter 1. The next stride in this line is the embedding of QFT into twentieth century physics. Within quantum physics, QM is conceptually prior to QFT since QFT is meant to reconcile QM with relativity theory. Historically, however, the urgent need for this reconciliation was felt and first attempts were being undertaken parallel to the formation of quantum mechanics already. Due to the intimate relationship between QM and QFT we have to give conceptual investigations of QM a closer look. This will be done in two steps. The first step in section 3.1 is a study of those ontological aspects and problems of QM which are of particular importance for the following investigation. In a second step in chapter 4.1 I will deal with the question why it is sensible to consider ontological matters concerning QFT before related questions with respect to QM are settled first.

Chapter 3 is comparatively technical and prerequisite only for some later chapters. Here an account of an axiomatic reformulation of QFT called *algebraic quantum field theory* (AQFT) will be given. It is of special importance for considerations in chapters 6 and 10. Section 4.2 reflects on the status of AQFT in relation to standard QFT. Since various books with introductions to QFT are readily available with any possible degree of difficulty no separate account of QFT will be given here. The 'Physics Glossary' contains various suggestions for further reading. Sections 3.2 and 3.3 will consider QFT only insofar as it is needed for an understanding of AQFT.

The more generally philosophical chapters and sections appear at different places in the introductory part as well as in the main study. The concept of ontology is a very intricate topic inside general philosophy already. Discussions concerning ontology are always apt to provoke much controversy. Some strands of tradition and current stances concerning ontology will be laid out in chapters 2 and 5 as well as in the introductory passages to specific ontological approaches.

The main investigation of different ontological conceptions for QFT falls into two parts. Part one (chapters 5 - 7) is concerned with classical ontologies, part two (chapters 8 - 10) with revisionary ontologies. The classical-revisionary-split is derived from the division into descriptive and revisionary metaphysics which stems from the philosophical tradition of Analytical Ontology. Although the idea behind this division will be intuitively clear to everyone the matter is not as easy as it looks. The origin and the meaning of these concepts will be given further thought in chapter 5.

The concluding part VI serves two purposes. In chapter 11 some thought will be given to the question whether and how the physicist and the philosopher can benefit from each other when ontological considerations are concerned. Chapter 12 is the final summary which collects and evaluates the main points and tries to place them in a comprehensive scheme. The list of references aims, instead of completeness, at catching the more recent publications which are of interest for the ontological investigation of QFT.

Part II

Context, Methods and Presuppositions

Chapter 1

Philosophical Background

The purpose of this chapter is to delineate the tradition of conceptual investigations about theories of nature from ancient until modern times. The emphasis lies on those strands which constitute the context of the present study.

There is a coherent tradition of philosophical thinking about nature from early ancient philosophy to our days. One indication for this coherence is the fact that some of the most outstanding twentieth century physicists like Schrödinger and Heisenberg[1] put considerable emphasis on the linkage between quantum physics and ancient Greek philosophy. However, something has changed in modern times which makes us less aware of this tradition. Before modern times there was, besides astronomy, no separate discipline corresponding to theoretical physics. The only equivalent in ancient and medieval times can be found in the work of thinkers which we classify as philosophers and theologians today. Although the distinction between philosophy and physics as subjects is relatively sharp today this is not always the case with respect to the people involved as we saw above. This is particularly so in regard to theoretical quantum physics where conceptual research takes place in a continuum from the physics to the philosophy community.

[1]The monographs Schrödinger (1954) and Heisenberg (1959) are just two of their explictly philosophical works.

Since the very beginning of western philosophy reflections about the material world which go beyond the directly observable play a central role in philosophy. Starting with the presocratics it has always been a point of debate what the fundamental characteristics of the material world are. Is everything constantly changing or can certain permanent features be separated? What is basic and what is merely a matter of appearance? In the course of time various answers have been given and conflicting views have often been alternating in their predominance.

There is no smooth process of cumulation or improvement until twentieth century physics finally revealed the "right view" about nature. This is not only due to the long coexistence of mutually exclusive views. Moreover, there is no and most probably never will be any "right view" about nature to be read off modern physics. The answer of modern physics to the old philosophical questions is not settled yet and maybe it never will. Some take this to be a sign that the very questions might not be sensible then. However, it seems many questions survive these doubts indicating that the doubts themselves must be seen with care. In any case one can arguably record that conceptual considerations about the material world have often led to fruitful clarifications even when no final answers to the "big questions" were found in the end.

The focus of human thinking about nature has shifted decisively from ancient to modern times. While originally it was mainly speculative one of the key concepts of modern science is experimental scrutiny. The development of and the debate about *atomism* is a favourable example in case. The turning point from speculative to experimental emphasis occurred in the seventeenth century. It is very instructive to realize that the elegance and purity of certain philosophical positions was now left behind in favour of eclectic conceptions which were mainly assessed by their explanatory power in view of observable phenomena. From that time onward speculative thinking about nature which did not take scientific results as their starting point came more and more under suspicion.

The history of atomism has some aspects which render it particularly interesting in the context of the ontological analysis of quantum field theory

(QFT) in this thesis. On the one side it is of exceptional methodological interest since it is one of the few cases of an interplay of philosophy and physics. On the other side not only this formal aspect of the historical development of atomism is closely related to the issues treated in this work but also the content. Firstly, it is a famous example for an ontological debate and, secondly, it can in some respects be seen as the forerunner of the questions which will be pursued regarding QFT. After all, the immediate candidates for the most basic entities to which QFT refers are the modern counterparts of atoms, namely electrons, quarks etc.

1.1 The Development of Atomism in the History of Philosophy

Most expositions of the history of atomism simply presuppose that the atomistic account of matter has turned out to be the correct view so that historical studies can use this yardstick in order to evaluate how well former philosophers have come off in making the right guess even without empirical evidence. This procedure is flawed in at least two respects which mirror the more general arguments in the opening paragraphs of this chapter. Firstly, the 'atomistic account of matter' consists of a large spectrum of views and one could defend the position that there are non-atomistic accounts which are closer to the results of modern physics than some of the atomistic views. Secondly, if one takes atomism to be the view that the material world consists of unchangeable atoms (whatever they are) on the one hand and the void on the other hand then one has to conclude that modern physics actually arrived at a non-atomistic point of view. One can add as a third point that there is no fixed point of view of modern physics anyway.

By these considerations I wish to point out that an examination of various older atomistic views as well as the arguments for and against atomism might have more than just historical value. It may well be that looking back at ancient thinking about atomism reveals conceptual results which are helpful for an understanding of today's physics as well. The lack (and neglect) of empirical evidence in premodern times might even turn out to have some virtue in it. The variety of different conceptions is larger and the argumentation richer since their is nothing else one could appeal to.

Atomism has emerged as a proposal to solve the conflict between two opposite views in the sixth and early fifth century BC.[2] On the one side Heraclitus was famous for maintaining that everything is in a state of flux. Whether or not Heraclitus as a historical figure is correctly described by this statement is not very important in our context. What matters more is that this view was ascribed to him by his contemporaries - notably Parmenides - as well as later philosophers. Parmenides on the other side believed that the impression of change is just an illusion. Both Philosophers had convincing arguments for their views but obviously they could not both be right. In the fifth century BC Leucippus had an elegant compromise to offer which Democritus worked out to a consistent philosophy. They agreed with Parmenides that change is inconveivable on the fundamental level of the material world. Instead of then denying the possibility of any change, however, they assumed basic unchangeable building blocks out of which everything else is composed. Since these building blocks were thought of to be the smallest parts of matter they were called *atoms* (greek ἄτομος, uncuttable, undivisible). With the assumption of atoms it was possible for Leucippus and Democritus to give an account of observable change in the world without admitting any change on the basic level of atoms. The recombination of atoms is responsible for the change on higher levels. Things change but the atoms out of which these things are composed stay unchanged. Atomism thus allows to maintain the view that matter is basically or intrinsically unchangeable while at the time accounting for change in the world of experience without marking the impression of change as a mere illusion. [3]

[2]Dijksterhuis (1956) and Sambursky (1962) are two classical monographs. van Melsen (1967) is a good short account of atomism. Pabst (1994) although having atomism in the Middle Ages as its main issue contains a helpful and modern summary of ancient atomism as well as an interesting evaulation of references.

[3]Further ancient theories of atomism can be found for instance in the work of

Let us have a closer look at the origin and some details of the first atomistic theories. For Democritus atoms can only differ in shape and size but not in any other properties. Since ancient times it is a common practice to classify this opinion by saying that Democritus' atoms differ quantitively but not qualitatively.[4] The multiplicity of observable appearances stems from the infinite number of possibilities for their combination. The elegance of this atomistic theory of matter becomes clear on the background of some conceptual problems to which it provides a solution.

The Eleatic philosopher Parmenides and his favourite student Zeno considered paradoxes which still today confuse most people when they first learn about them. Zeno's most famous paradoxes have to do with an infinite division of a given space or time interval and the sum of these infinitely many ever smaller quantities. Zeno's arguments hinge on the implicit presupposition that an infinite sum of non-vanishing positive numbers, say $\frac{1}{2}+\frac{1}{4}+\frac{1}{8}+\frac{1}{16}+...$, must give an infinite result. Zeno has a twofold résumé. Firstly, movement is an illusion since any given process in time can be devided and summed up as above showing that it would have to take infinitely long. Secondly, divisibility is not conceivable since it would lead to the conclusion that things must have either infinite or zero size. These so-called *problems of the continuum* are a vital part of the background on which atomism appeared. Leucippus and Democritus had the idea to solve Zeno's paradoxes by saying that things are divisible but only somewhere, viz. in the void between atoms.[5]

Diodorus and Epicurus in the early third century BC. Conceptually their points of view do not differ very much from the one of Democritus with the exception of the introduction of the new distinction between physical and mathematical atomism.

[4]E. g. in van Melsen (1967), p. 194f. Although I can see the point I doubt that it is a good characterisation especially with respect to the property of shape. At most I would mark this difference as between extrinsic and intrinsic properties.

[5]In modern times it turned out that there is an easier solution to Zeno's paradoxes. Zeno was simply mistaken in assuming that an infinite series of non-vanishing positive numbers must always give an infinite sum. Whether or not there is a finite sum depends on how fast the terms in this series are decreasing. It is not the case that Achill never reaches the tortoise. In a way Zeno's thought experiment corresponds to a time-lapse process which is getting ever slower. But this does not make the observed process itself

In his amply discussed dialogue Timaios Plato seems to lay out an atomistic theory of matter which is reminiscent of highly mathematical physics theories of the twentieth century. Plato takes up Empedocles' famous doctrine (fifth century B. C.) which assumes four basic elements, viz. earth, water, air and fire, out of which everything is composed. While it is open whether Empedocles had a corpuscular theory of matter in mind Plato linked each element to a kind of atom which is characterized by a certain geometrical figures, for instance the tetrahedron in the case of fire. Using the somewhat problematic quantitive/qualitative-distinction again one can say that Plato proposed a hybrid between theories based on the permanence of qualitative properties - as Empedocles did - and theories where quantitive properties are taken to be basic - as in Democrit's atomism.

Evaluating Plato's theory, two cautions should be considered. Firstly, the similarity to the role of mathematical elegance and beauty in the development of theories in modern physics is superficial. In contrast to these theories Plato had no empirical basis for his thesis. Plato's theory was highly speculative and - in contrast to modern physical theories - it was not meant to be checked by later experiments. Secondly, more recent studies show that it is not clear whether Plato's atomism aimed at physics at all. It is possible that the objective is an ethical model rather than a physical theory.[6]

There are various opponents to atomism in antiquity. Most influential among them is Aristotle who, like the Stoics, defended the continuum thesis. The writings of the Sceptic Sextus Empiricus include a valuable collection of arguments against atomism.

Most expositions of the historical development of atomistic theories simply make a jump from late antiquity to early modern times without further commentary. The classical standard view about the history of atomism in

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infinitely long.

[6]Lothar Schäfer, emeritus professor of Hamburg University, propounded this thesis in his talk "Naturordnung und Herrschaft in Platons Timaios" at the University of Bremen, 2nd of February 2000.

the Middle Ages is that there is no such history.[7] However, the modern research on the significance and dissemination of atomistic ideas in the Middle Ages is surprisingly interesting, and a difficult issue in itself. The prejudices about the supposedly dark Middle Ages with little independent and productive intellectual life is largely responsible for this inappropriate evaluation. In the case of atomism the facts were almost turned upside down. In his recent study Pabst (1994) on the history of atomistic theories in the Latin Middle Ages Bernhard Pabst could prove that there were at least 18 medieval adherents of atomistic theories. According to Pabst one can claim that in a certain period of the Middle Ages atomism was more widespread and readily accepted than at any time in antiquity. And not only that. Contrary to the common belief that medieval thought was based on an uncritical trust in authorities neither did any of the medieval authorities held an atomistic view nor did any of the above-mentioned 18 medieval adherents of atomistic theories copy an ancient theory of atomism. Only the general idea of atomism was translitted from antiquity to the Middle Ages.

The heyday of medieval atomism was between 1100 and 1150. None of the atomistic theories was based on a materialistic view of the world which was a central trait of ancient atomism. This difference is clearly due to the predominance of religion and theology in medieval thought. The atomists of the Middle Ages aimed at pragmatic explanations for natural phenomena. It is not only this neutral attitude which renders medieval atomism as closer to modern thinking about nature than ancient theories. Various developments over ancient conceptions were generated and vividly discussed. From the modern point of view the major improvement was the qualitative charaterisation of atoms.

In the second half of the twelfth century the atomistic movement declined. Aristotle's works became accessible through translations of Arabic copies and with these translations Aristotle's arguments against atomism

[7]The most notable exception is Lasswitz' famous history of atomism from the Middle Ages until Newton Lasswitz (1890).

spread.[8] Since the medieval versions of atomism in the 1100-1150-period were particularly vulnerable for Aristotle's arguments atomism quickly lost its popularity.

1.2 Philosophical Versus Scientific Atomism

Atomism has a philosophical and a scientific dimension. Until the 17th century it was primarily a philosophical issue. From that time onward the focus shifted to the scientific interest. Central in this shift was the identification of kinds of atoms with chemical elements by Dalton around the turning point from the 18th to the 19th century. The shift from ancient, medieval and early modern philosophical theories of atomism to scientific theories of atomism can be characterized by an essential change of emphasis and aims. While philosophical theories of atomism tried to explain the very possibility of change on the basis of something stable, scientific theories of atomism aim at the explanation and prediction of quantitative details of observable phenomena. This fundamental difference of intentions brings about a difference in the character of reasoning as well.

Philosophical theories of atomism often had a tendency to be dogmatic about a number of aspects. It is simply postulated that at a certain level matter is not divisible any more. Moreover, it is assumed that there is a certain number of kinds of atoms with certain spatial structures. After all, no more was intended than to find arguments for the general conceivability of changing qualities without the need to assume that everything is in flux which would render the world utterly inexplicable and barred to cognition.

Scientific theories of atomism have a very different standard for the evaluation of atomistic theories. The detailed properties of atoms do matter a lot since they have consequences for the prediction of observable phenomena. Atomistic models are as good as they give accurate quantitative predictions for experiments. Philosophical inconsistencies are less accutely

[8]Plato's Timaios had no influence on this period of medieval atomism since the only available translation by Calcidius contains just the first half of the Timaios which does not comprise Plato's corpuscular theory.

felt than a lack of numerical precision. And since the experimental checking yields a very fine method of control for scientific theories of atomism there is less dogmatism to be found here than in the philosophical period of atomism. Due to experimental results the assumptions about atoms in scientific theories can undergo fundamental revision. As we see it today atoms are actually divisible and what takes their place as the smallest building blocks (maybe quarks and leptons, maybe superstrings) are not eternal entities. They can undergo change themselves and can even begin and cease to exist. The only reason why modern scientific theories of atomism are so different from philosophical theories is that it has turned out that these radically modified theories are most successful in predicting observable phenomena.

There is another characteristic change from ancient and medieval philosophical theories of atomism to scientific theories of atomism. While philosophical atomism is very figurative and visualizable, scientific atomism has a different emphasis. When looking at atomistic models it is rated much higher how mathematically elegant and simple its description is and how numerically manageable and precise the predictions are. One consequence of this scientific attitude is the fact that the resulting atomistic theories loose their connection to the way we conceive of the natural world. Instead, they are primarily predictive tools with little impact on our picture of the world. One of the aims of this thesis is the attempt to fill a part of this gap by pointing out which ways to imagine the natural world are compatible with current theories of modern physics.

1.3 Atomism and Reductionism

I conclude this chapter with some brief remarks about a general attitude behind the search for atomistic explanations and my own stance towards it. With its assertion that everything can be reduced to some basic building blocks atomism is one form of reductionism. In order to clarify possible ways to understand this assertion let me introduce the distinction between *methodological* and *ontological* reductionism. A *methodological* reductionist holds that all scientific theories can and should be reduced to a fundamental theory which is generally taken to be physics. One can express this claim the other way round as well: Whenever something is to be explained start with the most basic theory and derive the explanation for the phenomenon in question by specifying a sufficient number of constraints and boundary conditions for the general fundamental laws. An example of this procedure is the explanation of an atomic spectrum by calculating the excited energy states of a many-body systems containing the relevant constituents.

An *ontological* reductionist is somewhat more modest. He agrees with the methodological reductionist that the reduction of higher-level theories to lower-level theories is possible in principle. However, the ontological reductionist thinks that a reduction to the lowest possible level is often neither practically feasible nor even desirable. In order to explain the shift of power in the last election nobody is interested in getting information involving quarks, gluons and electroweak interaction. And even in the case of the spectrum of a uranium atom this is not the appropriate point to start. Note that methodological reductionism presupposes ontological reductionism but not vice versa.

Nevertheless, the attitude of the ontological reductionist, to which I agree, is not without consequences for the practice of science. Although an actual reduction might often not be completely feasible it can sometimes have a high *methodological fruitfulness*. The *Laser Theory* as established by H. Haken and others is a famous example. In this theory it was attempted to reduce the already known phenomenon of laser light to the most basic theory, i. e. QFT. Although certain less profound exlanations for laser light were available before the establishment of Laser Theory researchers felt that more could be done. My point now is that it is almost of secondary importance whether the aim of a complete reduction to the most fundamental laws was actually achieved since while attempting to get there numerous technically highly significant effects and modulation possibilities were discovered. This would never have been achieved if one had been satisfied by less fundamental explanations.

Closely connected with the issue of reductionism is the one of *realism* both of which are almost two sides of the same medal. Again I agree with the attitude of the realist and again out of the same main reason as above. I think that the realist's stance has a high heuristic value, no matter whether he is actually "right" with his attitude in the end. I think that the realist's believe in the existence and recognizability of an external world is methodologically much more fruitful than the point of view of an antirealist. The antirealist cuts off a lot of questions whose investigation can yield interesting insights and discoveries.

I think that the same is true for the philosophical investigation of scientific theories as well. Although the analysis undertaken in this thesis would loose some of its relevance without a realist's attitude I think it should still be of some interest for those who do not share this standpoint. It seems to me that the truth of realism or anti-realism is of minor importance in the end. What really matters is how fruitful each of these attitudes is for the actual reasearch whether it be in natural sciences or in philosophy.

Chapter 2

Ontology and Physics

Although the restrictions of the present study render it quite different from many other philosophical investigations which are labelled ‘ontology’, the very restrictions have their place and justification in the tradition of ontology. A proper understanding of the approach taken here thus necessitates a look at the history of ontology to which it is a reaction. It will become clear that this study is based on a Quinean stance on ontology.

2.1 “On What There Is”: Notions of Ontology

Ontology is the philosophical subdiscipline whose concern is existence, or being, in generality. It “is a general theory of everything”.[1] The range of philosophical investigations which go by the name ‘ontology’ is large, in particular because of a wide divergence about what to consider as interesting and legitimate questions. The emphasis can be either on the meaning of the concept ‘being’ or on the more specific question of what there is in the world in the most general sense.[2] In the first case, the ontologist can be interested in the famous question “why is there something rather than

[1] Simons (1998a), 251.

[2] “On What There is” is the title of Quine’s famous paper Quine (1948) which is reprinted in Quine (1961).

nothing?" and he can further search for the principles or reasons of "being as being".

In the second case, the ontologist asks which types of objects and modes of being there are and which general properties they have, can have or must have. He considers which entities are the fundamental ones and which entities are only derived in whatever sense.

The present work is in the vein of this second emphasis in ontology since we start our investigations on the basis of a given theory, viz. QFT, and ask to which basic entities it refers. For now we leave it open whether this specific question is just one among various further equally important enterprises which consider other sciences and fields of reality. In order to explicate the associated understanding of ontology the following exposition about ontology will place the attitude taken here in its historical as well as systematical context. Before doing so, a number of examples of classical debates with at least strong ontological components may serve to illuminate the general orientation of this second approach to ontology.

The first exemplary debate is concerned with the ontological status of *properties*. While Plato maintained that properties like redness exist as universals outside of our mind others argued that there are only particulars like one red flower. These two traditional points of view are called realism about universals on the one side and nominalism on the other side. The vivid medieval debate about this issue is particularly famous.

Another discussion concerns the existence and relation of *mind and matter*. While the materialist claims that everything, including mental states, can be reduced to matter, the Cartesian dualist in his classical expression contends the dichotomy of res cogitans and res extensa as the two fundamental and thus irreducible parts of reality. On the very opposite side of materialism lies idealism, propounded by Berkeley, with the view that there are only mental objects, called 'ideas', which are in the mind of God.

A third and last example for a debate with largely ontological significance is the one about *space and time*. Is existence only possible in space and time? In connection to this question follows another one. Which kind of reality do numbers and laws of nature have? What is the ontological status of space and time themselves? Do they have an existence independent of material objects (substantialism) or are they only a means to describe the relation of these objects (relationism)? Kant argued that all appearances are in space and time but these are only the form in which the things-in-themselves are inevitably given to us.

As one can see there often is a broad spectrum of possible answers to ontological questions. When pursuing one specific ontological question it is helpful to place the questions as well as the solutions which have been proposed until now in their historical and systematical context. Hard questions usually reoccur in disguise so that a knowledge of other debates can help to evaluate the debate in which one is primarily interested.

The history of philosophical investigations which are explicitly labelled 'ontology' begins with scholastic philosophers in the seventeenth century. Nevertheless the enterprise itself was important in ancient times already. Parmenides considered 'being' as *the* central philosophical concept. And notably Aristotle was interested in 'being as being'.

The *relation of metaphysics and ontology* has long been and still is a point of disagreement. While in the seventeenth century both terms were mostly taken to be synonymous, in the traditional view (e. g. Christian Wolff) ontology is classified as a part of metaphysics besides cosmology and psychology. In the twentieth century there are strands which consider ontology to be metaphysically neutral[3] or they are even explicitly critical of metaphysics in contrast to ontology (Heidegger).

In the eighteenth century Christian Wolff canonized and completed ontology as a discipline. Since Wolff's time ontology is separated from natural theology in contrast to the Aristotelian tradition in which first philosophy and metyphysics in the sense of natural theology were seen as a unity.

In the Leibniz and Wolff tradition ontology was a matter of necessary truths which are derivable from unquestionable first principles like the principle of contradiction and the principle of sufficient reason. Thus in order to pursue ontology one does not have to look at the actual order of the

[3]For instance Simons (1998b).

world. According to this line of thought special sciences have no relevance for questions of ontology.

Kant considered this traditional understanding of ontology to be "presumptuous" and refuted it by showing that a priori enquiries can only find out something about the general form of possible experience. In Kant's view one cannot say anything substantial (i. e. synthetic) about the contents of experience without first making experiences. A vital step in Kant's argumentation against the derivability of ontological matters from first principles was his "second antinomy of pure reason" which demonstrates internal contradictions in the traditional conception of ontology. The intention of Kant was to replace traditional ontology by his - in comparison - moderate transcendental philosophy. Another famous part of Kant's philosophy is his argument against the ontological proof of the existence of God which will be discussed in a bit more detail in chapter 4.2. Kant argued that existence must not be considerd as a property which something can have in addition to other properties.

2.2 The Analytical Tradition of Ontology

Analytical ontology can be characterized as the rehabilitation of the old ontological questions while maintaining the new and powerful instruments of the philosophical analysis of language. It is mostly within this framework that the investigation of this thesis will be carried through. One important reason is the fact that the analysis of languages is structurally very similar to the investigation of scientific theories.

The three most important steps of the rehabilitation of metaphysics within the analytical tradition are marked by Carnap, Quine and Strawson, with an increasingly positive attitude.

Carnap's philosophy rests on a radical criticism of the very question of traditional ontology.[4] Carnap makes a distinction between internal and external questions about existence. Internal questions ask for the existence

[4] "Empiricism, Semantics, and Ontology" Carnap (1950), which is reprinted in Carnap (1956), is the classical source for his attitude towards ontology.

of an entity within a given "linguistic framework". An example for Carnap's broad notion of a linguistic framework is the order of space and time and the entities one can ask for could be material everyday things in space and time. External questions concern the existence of the very linguistic framework itself. In our example this would be the question whether (the points of) space and time exist. Carnap considers external questions concerning the reality of the framework itself as pseudo questions "without cognitive content". The choice of the linguistic framework is a matter of pure convention. The only sensible measure is how practical the choice is. According to Carnap, any further questions lead astray.

Quine rejects Carnap's view by denying the possibility of his basic distinction between internal and external questions. Instead, Quine prefers to speak of the "ontological commitments" of a theory. Suppose that a given theory T is a true theory, Quine asks which are the ontological commitments. One famous definition of ontological commitments of a theory runs as follows:

> a theory is commited to those and only those entities to which the bound variables of the theory must be capable of referring in order that the affirmations made in the theory be true. Quine (1948)

Somewhat more succinct is Quine's well-known slogan "To be is to be a value of a variable."[5] Another way to express Quine's attitude is to say that ontology asks for the *truth makers* of a given theory (or language). What is looked for are those entities which one has to assume in order to make a particular theory (or language) true. According to Quine the truth of the theory itself is not the question in philosophy. Quine argues that the most appropriate way to ontology is to look at the best science available at a time.

The attitude which underlies my following investigation about ontological aspects of QFT is in its rough outline akin to the Quinean approach.

[5] Quine in a talk in 1939.

I agree with Quine that the "best science available" is of pivotal importance for general ontological questions. And I agree with Quine that the attempt to dis-cover and unfold the ontological commitments of the relevant scientific theories is a fruitful approach. Nevertheless, there are some points where I disagree with Quine. I do not believe that the situation is as easy as Quine describes it. It is is not as if one could simply take the "best science available", determine its ontological commitments and there you have the best ontology available. It seems to me that there is no straightforward way to figure out to which entities a given theory is commited. I think that probably all one can achieve is to find out which ontological conceptions are compatible with a given scientific theory. In the case of quantum physics I believe the most one can hope for is that one finds an ontological conception which explains puzzling features most naturally. But I am afraid that such arguments will never have the power of a commitment.

2.3 Excursion: No-Go Theorems in Quantum Physics

Since no-go theorems are pivotal for some steps in the ensuing investigation I will conclude this chapter with some general remarks about no-go theorems, their role in quantum physics and their significance for ontological studies.

There are different ways to find out something about the ontology of a scientific theory. For QM and QFT a very precise and successful method is to look for no-go theorems like the famous one by John Bell which will be summarized later[6] on hidden variable theories or a more recent one found

[6]See "On the problem of hidden variables in quantum mechanics" Bell (1966) and "On the Einstein-Podolsky-Rosen paradox" Bell (1964). Interestingly, Bell himself seems to have been annoyed by this business and in "On the impossible pilot wave" Bell (1982), he wondered "[...] why did people go on producing 'impossibility' proofs [...]", p. 160 in Bell (1987), mentioning famous names like J. M. Jauch, C. Piron, B. Misra, S. Kochen, E. P. Specker, S. P. Gudder and, last but not least, himself!? Probably

by David Malament on the impossibility of a certain particle interpretation for relativistic QM.[7] The advantage of such no-go theorems is a very high degree of precision. Most no-go theorems suffer from a very limited scope, however. Malament's no-go theorem for instance only shows that non-relativistic QM of a fixed number of localizable particles cannot be reconciled with relativity theory. It thus does not rule out a particle interpretation for QFT because here the precondition of a fixed number of particles is not met. The relevance of this no-go theorem for the interpretation of QFT is not immediately clear therefore. Further thought is thus necessary for an understanding of its ontological significance with regard to QFT.

The origin of no-go theorems in quantum physics consists in the fact that there is no undebated correct way to understand various entities appearing in the formalism of QM. More on this can be found for instance in chapter 3. So far, the most successful way to handle this situation is the construction or discovery of proofs which demonstrate that certain sets of assumptions (e. g. locality, separability, determinism, value definiteness of all possible physical quantities etc.) lead to contradictions. Assuming that an interpretation of a (piece of) formalism can sometimes be condensed into a set of assumptions we can thus at least exclude some interpretations. Since we can by this exclusion procedure show that one or the other interpretative option is not an admissable way to go these results are called 'no-go theorems'.

There are three particularly famous examples for no-go theorems. The first one is *John von Neumann's* alleged proof of the impossiblity of *hidden variable theories*. Later it turned out that von Neumann's proof rested on implicit assumptions which narrow the applicability of his result considerably.[8] For instance, von Neumann's proof is not a legitimate argument

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the reason for this stance are almost ideological feelings concerning Bohmian Mechanics.

[7]See "In defense of dogma: Why there cannot be a relativistic quantum mechanics of (localizable) particles" Malament (1996).

[8]Jammer (1974) is the authoritative account of the historical background as well as of the change in the evaluation of Neumann's alleged proof.

against Bohm's version of quantum mechanics which is explicitly holistic or non-local.

The second famous example of a no-go theorem is Bell's theorem. (Derivation of *Bell inequalities* under certain conditions, proof of violation in QM). [9] The third example are non-objectification theorems against ignorance interpretation of QM (nonvanishing 'interference terms'.)

[9] Redhead (1987)

Chapter 3

Fundamentals of Quantum Physics

In this chapter I will deal with some salient features of quantum mechanics (QM), quantum field theory (QFT) and algebraic quantum field theory (AQFT), an axiomatic reformulation of QFT. Instead of aiming at any kind of completeness I will emphasize some issues which are of particular significance for ontological considerations. Moreover, I will introduce some pieces of formalism which prepare the ground for investigations in some later chapters. Nevertheless, the most important points will be taken up again in those chapters themselves. For general introductions to QM, QFT or AQFT the 'References' contain various suggestions.

3.1 The Legacy of Quantum Mechanics

As regards ontological considerations about QFT the legacy of QM is mostly a negative one. Most of the notorious obstacles for an ontological understanding of QM are equally troublesome in QFT. In section 4.1 I will reflect upon the question whether it is appropriate to start ontological investigations about QFT before corresponding matters with respect to QM are settled. For now, I put that concern aside.

Problems concerning the individuation and reidentifiability of particles, are the most fundamental ones for our context especially when considered together. They are concerned with the distinguishability of particles in its transtemporal and in its instantaneous aspect respectively. Both aspects have notoriously caused trouble for the idea of individual traceable particles. These problems arise in QM already and lose nothing of their importance in QFT.

The Problem of Individuation

The problem of individuation results from the study of systems with many quantum mechanical particles. The starting point for the statistics of such systems is the fact that the Maxwell-Boltzmann statistics (i. e. the energy distribution law) which is valid in classical statistical mechanics leads to false predictions for systems of 'identical' quantum mechanical particles. In QM, particles are called 'identical' when they have all their permanent properties (e. g. rest mass, charge, spin) in common. A set of permanent properties fixes a class of particles (e. g. electrons) rather than a particular particle.[1] It turned out that one gets the experimentally correct statistics when the possible micro states which lead to the same macro state are counted differently for systems of identical particles: Micro states which differ merely by the 'exchange of two particles' must be counted as just one state. This fact is referred to as 'non-occurrence of degeneracy of exchange'[2]or 'indistinguishability of identical particles.'

What are the consequences of the indistinguishability of identical particles for our main issue, the basic entities of QFT? The emerging problems become clearer after a short look at the symmetrisation postulate which follows from the indistinguishability of identical particles given some additional assumptions.[3] Depending on the spin of the respective particles the wavefunction of a many-particle system has to be symmetric or anti-

[1]Cf. Mittelstaedt (1986) (*Sprache und Realität in der modernen Physik*), chapter viii.

[2]In German: "Nichtauftreten von Austauschentartung".

[3]The logical connection of the indistinguishability of identical particles and the symmetrisation postulate is discussed in detail in Stöckler (1988), p. 12.

symmetric under the 'exchange of two particles,' or, to be more careful, under the exchange of two particle labels.[4] 'Non-symmetric' wavefunctions (which are neither symmetric nor antisymmetric) are excluded.

The symmetrisation postulate is only necessary[5] in the Schrödinger many-particle formalism which, despite the problems with indistinguishability, uses labels that are obviously meant to refer to individual particles of the overall system. Because of the symmetrisation postulate, however, not all wavefunctions of the 'overall' or 'compound' system, which could be constructed by the standard way of forming the tensor product of one-particle states, are allowed any more. Inside the Schrödinger many-particle formalism non-symmetric wavefunctions can be formulated but get excluded. The formalism is therefore richer than the experimental reality which it is designed to encompass.[6] This fact could be taken as an indication that the theory is built upon inadmissible assumptions which lead to a piece of structure that has to be excluded artificially.

A closer look at a symmetrisized wavefunction of a compound system hints at a reason for these difficulties: An anti-symmetric wavefunction of a system of fermions is a superposition of product wavefunctions, i. e. a sum of tensor products of one-particle states. A sufficient example is the wavefunction of a system of two identical fermions (e. g. electrons):

$$\Psi(x_1, x_2) = \frac{1}{\sqrt{2}}\Big(\psi_\alpha(x_1)\psi_\beta(x_2) - \psi_\beta(x_1)\psi_\alpha(x_2)\Big), \tag{3.1}$$

where $\psi_\alpha(x_1)$ and $\psi_\beta(x_2)$ are energy eigenfunctions of one-particle Hamiltonians and α and β represent sets of quantum numbers characterizing one-particle states. Since x_1 and x_2 are variables of the "single particles" 1

[4]Pauli's well-known 'exclusion principle' is thereby fullfilled automatically: The wavefunction of two fermions in the same single state, i. e. with the same quantum numbers, vanishes as can be seen in equation (3.1) on p. 37. In other words there is no compound state where two fermions have the same quantum numbers.

[5]The symmetrisation postulate is true but trivial in the so-called 'occupation number representation' which I am going to discuss later.

[6]Especially M. Redhead worked on the so-called "surplus structure" of scientific theories: Redhead (1975), Redhead (1980).

and 2 it is natural to ask what the states of these "single particles" are. It turns out that it is impossible to give a satisfactory answer to this question if one holds on to the conception of individual particles. Each "single particle" is in the *same* state as a part of the compound system even though in the wavefunction of the compound system *different* one-particle wavefunctions are used. The location of a "particle exchange" has obviously become problematic. The usage of labels for individual particles in the usual sense might lead one astray. We thus have an ontological problem since on the one hand we can successfully use labels which seem to number something but on the other hand we are not dealing with particles in the usual sense any more for whom the labels were introduced originally.[7] In section 10.2 I will elaborate on this issue in more detail.

The Problem of Reidentifiability

The problem of individuation exerts its full force only in connection with the second one, the problem of reidentifiability: If in certain classes of microparticles we cannot distinguish individual particles by permanent properties why do we not simply look where they are and keep track of their location while time elapses? The following argumentation shows that even this way is obstructed.

On first sight the claim that we cannot follow a particle in space-time is astonishing since we seem to have exactly these looked-for tracks of particles in cloud-chamber photographs, showing, for example, charged particles on curved trajectories. A closer look reveals, however, that these 'particle tracks' have very little in common with sharp trajectories of classical physics. On the micro level we have smeared tube-like objects. Each of these tube-like trajectories is the result of a vast amount of unsharp quantum mechanical position measurements[8] in close succession. The de-

[7]Problems with particle labels are discussed extensively in Teller's recently published book Teller (1995) on some philosophical problems of free QFT, with main emphasis on QED.

[8]In our context a measurement is every interaction of a quantum object and a macroscopic system with a definite result, e. g. a dot on a photographic plate.

gree of unsharpness or "smearedness" is even far bigger than the theoretical minimum which is given by Heisenberg's uncertainty relation for position and momentum.

With a particle track being the result of many successive measurements, the immediate suggestion is that one and the same particle gave rise to the track because numerous measurements were performed on this particle. Unfortunately we have difficulties with this assumption in QM: Even if the time interval between two quantum mechanical position measurements that contribute to one particle track is extremely small we cannot be sure to have measured the same particle. The reason for this is the fact that even in the case of a sharp position measurement after an arbitrarily small time interval the measured object can be detected infinitely far away from the first point of detection.[9] Between the results of two quantum mechanical measurements of a continuous observable - like position - there is in principle no deterministic connection.[10]

The problems discussed above partly reflect a general difference between classical and quantum mechanics. In classical mechanics when position and momentum of a free particle are given both is fixed for any later point of time, we have a so-called 'path law.' In quantum mechanics, however, we do not have a deterministic law of this kind. The first reason is that a quantum object cannot have a sharp position and a sharp momentum at the same time. The second reason is more fundamental: There is, in general, no deterministic connection between single (or groups of) measurement outcomes. All we have in quantum mechanics is a law for the evolution of the statistics of measurement outcomes: The stastitics is given by the

[9]See for example Hegerfeldt and Ruijsenaars (1980).

[10]In contrast to that for discrete observables (i. e. where the measurement outcomes are discrete numbers) 'repeatable measurements' are possible if we are dealing with 'state preparation measurements.' In this case after the measurement the measured object can be found in that eigenstate which corresponds to the measured eigenvalue. A repeated measurement leads with certainty to the same measurement outcome (this is the defining property of a 'repeatable measurement'). For a proof of the impossibility of repeatable measurements of continuous observables see the classical paper Ozawa (1984).

'state function' and the deterministic law according to which it evolves in time by the Schrödinger equation. We know, therefore, how the statistics of possible measurements are connected, but we do not know in general how single measurements are connected. This means that a particle track cannot be interpreted as a succession of connected measurements on one object. The possibility to identify an object by tracing it through space-time is excluded.

Problems concerning the individuation and reidentifiability of quantum mechanical particles cause severe difficulties for the conception of individual quantum objects. Because of the problem of individuation it is impossible to distinguish individual quantum objects which are specified by the same permanent properties. The immediate proposal for a solution to this obstacle is ruled out by the problem of reidentifiability: Quantum objects cannot be identified as individual entities by localizing and tracing them in space-time.

3.2 The Standard Formalism of QFT and its Problems

In this section I have picked out two particularly surprising features of the formalism of QFT which are helpful for a deeper understanding of some later investigations. The first subsection on "Creation and Destruction Operators" introduces an issue which has an obvious significance for ontological questions in general and which is of particular relevance for the discussion of particle and process ontology. The second subsection on "The Representation Problem" is primarily a preparation for the introduction of Algebraic QFT in section 3.3 and 3.4.

Creation and Destruction Operators

Creation and destruction operators are widely used in QFT for all kinds of particles and in various different contexts. The first and most well-known example are the creation and destruction operators for photons. In Dirac's famous 1927 paper on "The quantum theory of the emission and absorption of radiation" (see Dirac (1927)) photons appear in the quantization of the electromagnetic field. Later Dirac's procedure was a model for the quantization of other fields as well.

In classical QM creation and destruction of photons are implicitly contained in the emission and absorption processes which have to be postulated, for instance, when one of an atom's electrons makes a transition from a higher to a lower energy level or vice versa respectively. The formalism of QFT, however, contains an explicit description for the creation and destruction of particles like photons. In order to derive the corresponding creation and destruction operators I shall give a very brief description of a non-covariant approach to the quantization of the electromagnetic field.

The easiest way to quantize the electromagnetic (or: radiation) field consists of two steps: Firstly we Fourier analyse the vector potential of the classical field into normal modes (using periodic boundary conditions) corresponding to an infinite but denumerable number of degrees of freedom. Secondly, since each mode is described independently by a harmonic oscillator equation we can apply the harmonic oscillator treatment from non-relativistic quantum mechanics to each single mode. As the result we get for the Hamiltonian of the radiation field:

$$H_{\mathrm{rad}} = \sum_{\mathbf{k}} \sum_{r} \hbar\omega_{\mathbf{k}} \Big(a_r^\dagger(\mathbf{k}) a_r(\mathbf{k}) + \frac{1}{2} \Big), \tag{3.2}$$

where $a_r^\dagger(\mathbf{k})$ and $a_r(\mathbf{k})$ are operators which satisfy the following commutation relations

$$\begin{aligned} [a_r(\mathbf{k}), a_s^\dagger(\mathbf{k}')] &= \delta_{rs}\delta_{\mathbf{k}\mathbf{k}'} \\ [a_r(\mathbf{k}), a_s(\mathbf{k}')] &= [a_r^\dagger(\mathbf{k}), a_s^\dagger(\mathbf{k}')] = 0. \end{aligned} \tag{3.3}$$

The operators $a_r^\dagger(\mathbf{k})$ and $a_r(\mathbf{k})$ as well as their product $a_r^\dagger(\mathbf{k})a_r(\mathbf{k})$ have interesting physical interpretations. In order to see this one has to examine the eigenvalues of the operators

$$N_r(\mathbf{k}) = a_r^\dagger(\mathbf{k}) a_r(\mathbf{k})$$

which are the essential parts in H_{rad}. Due to the commutation relations (3.3) one finds that the eigenvalues of $N_r(\mathbf{k})$ are the integers $n_r(\mathbf{k}) = 0, 1, 2...$ and the corresponding eigenfunctions are

$$\mid n_r(\mathbf{k})\rangle \propto [a_r^\dagger(\mathbf{k})]^{n_r(\mathbf{k})} \mid 0\rangle \tag{3.4}$$

where $\mid 0\rangle$ is the state vector of the vacuum with no photons present. The interpretation of these results is parallel to the one of the harmonic oscillator: $a_r^\dagger(\mathbf{k})$ is interpreted as the creation operator of a photon with momentum $\hbar\mathbf{k}$ and energy $\hbar\omega_{\mathbf{k}}$ (and a polarisation which depends on r and $\mathbf{k}$). In the light of this interpretation equation (3.4) can be understood as expressing that we get a state with $n_r(\mathbf{k})$ photons of momentum $\hbar(\mathbf{k})$ and energy $\hbar\omega_{\mathbf{k}}$ when the creation operator $a_r^\dagger(\mathbf{k})$ operates $n_r(\mathbf{k})$ times on the vacuum state $\mid 0\rangle$. Accordingly $N_r(\mathbf{k})$ is called the 'number operator' and $n_r(\mathbf{k})$ the 'occupation number' of the mode which is specified by $\mathbf{k}$ and r. The corresponding interpretation for the destruction operator $a_r(\mathbf{k})$ is parallel: When it operates on a state with a given number of photons this number is lowered by one.

The Representation Problem

Innitially there were two firstly independent starting points in QM, Heisenberg's *matrix mechanics* and Schrödinger's *wave mechanics*. Schrödinger, Dirac, Jordan and von Neumann realized that *matrix mechanics* and *wave mechanics* are just two (unitarily) equivalent representations of the same underlying abstract structure, i. e. an abstract *Hilbert space* $\mathcal{H}$ and linear operators acting on this space, where eigenvalues of self-adjoint operators (corresponding to observable quantities) are possible measurement outcomes. One can switch back and forth between such representations by the use of unitary transformations without changing the described physics since eigenvalues, expectation values and the like stay unchanged (just as in classical mechanics the modulus of vectors is invariant under orthogonal transformations).

Von Neumann and others (e. g. Stone) showed that the *canonical commutation relations (CCRs)* for coordinates and their canonical momentum coordinates in configuration space fix the representation of these two sets of operators in Hilbert space up to unitary equivalence (*Von Neumann's uniqueness theorem*).[11] This means that the specification of the CCRs suffices to describe a particular physical system.

Von Neumann's uniqueness theorem looses its validity for systems with infinite number of degrees of freedom. This is exactly the case with quantum *field* theory, however, since an infinite number of degrees of freedom is the core property of a field. Now we suddenly have many inequivalent irreducible representations of the CCRs.[12] It is not immediately clear what this means and how one can cope with this situation. This situation is one of the starting points for the establishment of Algebraic QFT which is the topic of the next two sections.

3.3 The Relation of QFT and AQFT

Algebraic Quantum Field Theory (AQFT) is arguably the most successful attempt to reformulate QFT in an axiomatic manner.[13] It originated at the end of the fifties by the work of Rudolf *Haag* and quickly advanced in collaboration with H. *Araki* and D. *Kastler*. Other prominent attempts to axiomatise QFT are Arthur *Wightman*'s *field axiomatics* (using quantum fields smeared out with test functions), the *S-Matrix-approach* by *Bogoliubov* and the more recent *Euclidean QFT*. A famous equivalence proof is the *Osterwalder-Schrader Theorem* which shows that the 'axioms of Euclidean QFT'[14] are equivalent to Wightman's axiomatics. AQFT and Wightman's

[11]Von Neumann's uniqueness theorem rests on some justifiable assumptions, viz. irreducibility and sufficient regularity.

[12]The significance of this remarkable fact for QFT was first noticed by K. O. Friedrichs in one of the first attempts to formulate QFT in a more systematic way in Friedrichs (1953) although von Neumann himself was aware of the restriction of the uniqueness theorem to a finite number of degrees of freedom already in 1938.

[13] For comprehensive introductions to AQFT see the monographs Haag (1996), Horuzhy (1990), Baumgärtel (1995) and Baez et al. (1992) as well as the two overview articles Haag and Kastler (1964) and Buchholz (1998).

[14]Cf. Haag (1996) p. 75.

axiomatics are not equivalent, however.[15] AQFT itself is split into two versions, *concrete AQFT* (*Haag-Araki*) and *abstract AQFT* (*Haag-Kastler*). The concrete approach uses von Neumann algebras, the abstract one C*-algebras. The adjective *abstract* refers to the fact that in this approach the algebras are characterized in an abstract fashion and not by explicitly using operators on a Hilbert space. In standard QFT the CCRs together with the field equations can be used for the same purpose, i. e. an abstract characterization.

All these axiomatisations of QFT have at least one aim and one problem in common.[16] As to their aim they all want to avoid the usual approximations in standard QFT. Trying to do this in a strictly axiomatic way, however, they only get 'reformulations' which are not as rich as standard QFT from a physical point of view. In the case of AQFT it is the lack of quantum fields which makes it hard to reproduce phenomena like the existence of antiparticles and the relation of spin and statistics.[17] As Horuzhy puts it, a purely axiomatic version of AQFT with observables and states as its basic entities is not sufficient to produce a *dynamical theory* in the sense that not only measurable properties can be described but also the underlying, sometimes unobservable (as in the case of fermion fields), physical mechanisms.[18] AQFT therefore has to be enriched by non-axiomatic concepts which has been done in the course of its development. Since in this sense AQFT cannot be called an axiomatic theory any more Haag prefers to call it *Local Quantum Physics* stressing the physical rather than the axiomatic/mathematical ingredients. This should be seen as a signal that AQFT is not merely a mathematical reformulation of QFT but rather one among different schools in physics with certain physical and conceptual

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[15]Cf. Haag (1996) p. 106.

[16]See Horuzhy (1990), p. ix.

[17]First successful attempts to overcome these shortcomings have been made by *Doplicher, Haag and Roberts* around 1970 and were improved e. g. by Buchholz and Fredenhagen to include in particular so-called '*topological charges*'. The adjective 'topological' refers to the topological structure of space-time. Cf. Horuzhy (1990), pp. ix f., 157 f. and Haag (1996) p. 153 and ch. IV.3.

[18]Horuzhy (1990), pp. 2 f.

preferences.

AQFT is expected to reproduce the main phenomena of QFT, in particular properties which are characteristic of it being a field-theory, like the existence of antiparticles, internal quantum numbers and the relation of spin and statistics etc. This aim could not be achieved within AQFT on a purely axiomatic basis. A major obstacle consists in the fact that the connection between the respective key concepts of AQFT and QFT, i. e. observables and quantum fields, is not at all clear. It turned out that the main link between the theory of local observables and quantum fields of standard QFT is the notion of *superselection*. Superselection rules are certain restrictions on the set of all observables.

3.4 Basic Ideas of AQFT

The motivation for AQFT:

Let A be an observable and $F(A)$ a real valued function of one real variable. It can be shown that $F(A)$ is just another way to label the same measurement outcomes. It is thus reasonable to consider the algebra generated by A as physically more basic than A itself or any other way to refer to possible measurement outcomes. *Segal* generalized this insight by saying that the C*-algebra generated by all bounded[19] operators (together with the norm topology) should be the basic entity in the mathematical description of physics. While in standard QM the Hilbert space representation and the C*-algebra formalism are equivalent this is no longer the case in QFT.

Quantum fields itself are not in general observable, but rather the local observables which are built from quantum fields. Two quantum fields are therefore physically equivalent when they generate the same algebras of local observables. It is thus reasonable to take these algebras as the starting point.

[19] See footnote 3 on page 169.

Basic Ideas of AQFT

One of the main traits and possibly the most unusual one of AQFT is the idea that all the physical information is contained in the mapping

$$\mathcal{O} \mapsto \mathcal{A}(\mathcal{O})$$

from (bounded) space-time regions to algebras of local observables. This is to say that it is *not* necessary to specify observables explicitly in order to get physically meaningful quantities.[20] The very way how algebras of local observables are linked to spacetime regions is completely sufficient to supply observables with physical significance. To express this idea in a slightly different way let us introduce the notion of the *algebra* $\mathcal{A}_{loc}$ *of all local observables* in the sense of set theoretic union, i. e.

$$\mathcal{A}_{loc} = \cup_{\mathcal{O}} \mathcal{A}(\mathcal{O}).$$

We can now say that it is this partition of $\mathcal{A}_{loc}$ into subalgebras which contains all the physical information about the observables. In this sense the primary concern of AQFT are the local algebras as wholes and the partition of $\mathcal{A}_{loc}$ into such algebras.[21] At this stage nothing is said which would physically discriminate observables within any one algebra. This is not to say that there are no differences between observables of one algebra. The claim is that the allocation itself of observable algebras to finite space-time regions suffices to account for the physical meaning of observables. It is not necessary to start with any such information explicitly.

[20] The knowledge of this correspondence allows one to calculate e. g. collision cross sections.

[21] The so-called *quasilocal* C*-algebra $\mathcal{A}$ generated by all local algebras $\mathcal{A}(\mathcal{O})$ is the C*-inductive limit of the system $\{\mathcal{A}(\mathcal{O})\}$ which is the completion of $\mathcal{A}$ in norm topology:

$$\mathcal{A} = \overline{\mathcal{A}_{loc}}.$$

This means that $\mathcal{A}$ is the smallest C*-algebra containing all local algebras. $\mathcal{A}_{loc}$ is an algebra as well but not a C*-algebra. It is for this reason that $\mathcal{A}$ and not $\mathcal{A}_{loc}$ is used in other contexts when reference to the set of all possible observables is made. In the concrete approach using von Neumann algebras the equivalent of the *quasilocal* (abstract) C*-algebra $\mathcal{A}$ is the so-called *global* algebra R.

The physical justification for this approach consists in the recognition that the experimental data for QFT are exclusively space-time localization properties of microobjects from which other properties are inferred. The Stern-Gerlach experiment may serve as an illuminating example: All one gets in this experiment are certain space-time distributions of dots from detected particles originating from a particle source and hitting a photographic plate. Only in a second step one recognices particles with certain spin directions after having passed an inhomogeneous magnetic field. This example might help to imagine that space-time localisation can be the basis for all other physical properties.

Physically the most important notion of AQFT is the principle of *locality* which has its effect both on the external as well as the internal structure of AQFT.[22] The external aspect is the fact that AQFT considers only observables connected with finite regions of space-time and no global observables like total charge or the total energy momentum vector which refer to infinite space-time regions. The physical idea behind this is that QFT is a statistical theory and that the experimental information comes from measurements in certain always finite space-time regions. Accordingly everything is expressed in terms of *local algebras* of observables. The internal aspect is that there is a constraint on the observables of such local algebras: All observables of a local algebra connected with a space-time region $\mathcal{O}$ are required to commute with all observables of a second algebra which is associated with a space-time region $\mathcal{O}'$ that is spacelike separated from $\mathcal{O}$. This principle of (Einstein) *causality* is the main relativistic ingredient of AQFT.

The *Assumptions of AQFT* are explicitly stated in appendix B together with various remarks about their contents and significance. It is instructive to have a look at the *isotony* condition which looks like a truism but which is arguably one of the two most important assumptions.

[22]Slightly different expositions of the twofold meaning of *locality* can be found e. g. in Haag and Kastler (1964), p.848 and Horuzhy (1990), p. 3.

Chapter 4

(A)QFT as Objects of Philosophy

Before beginning with my main study I will address two questions which might occupy the thoughts of some readers by now. Why do I look at QFT while the much less complicated quantum mechanics (QM) already displays the same problems in a far clearer way? Why does algebraic quantum field theory (AQFT) play such a prominent role in my investigation? I will try to answer these questions in the following three sections.

4.1 Quantum Mechanics versus QFT

Beginning with the formation of quantum mechanics (QM) in the twenties there has been a broad discussion about its conceptual foundations. At least three characteristics of QM have been and still are responsible for these discussions. First, QM is in many respects in sharp contrast to classical mechanics. Heisenberg's uncertainty relations and the EPR-"paradox" are only two very prominent examples. Second, QM has severe internal problems connected with the measurement problem. And third, there is the question of the compatibility of QM and relativity theory which has been partly resolved with the development of quantum field theory (QFT).

On the one hand the extensive discussions and analyses led to some clarification about the location and interconnection of various problems. The use of no-go-theorems was particularly valuable and these results are arguably the highest achievements in this area of research. Outstanding examples are the Gleason and the Kochen-Specker theorems[1] , EPR/Bell inequalities, non-objectification and probability theorems.[2] On the other hand none of the proposed solutions has led to a proper solution which is satisfactory in all respects. The most prominent proposals are the decoherence approach, consistent histories, modal interpretations, many worlds, many minds, Bohmian mechanics and nonlinear alternatives of the Schrödinger equation. Each particular proposal solves certain problems at the cost of having new problems at a different place.[3] To use a picture by David Armstrong in another context, each solution can only flatten the bulge in the carpet to the effect that the bulge appears somewhere else again. The impression is getting ever stronger that there will not be sweeping new results on the foundations of QM in the foreseeable future.

On first sight it might be surprising that the discussion on the conceptual foundations of the quantum domain has always been primarily concerned with QM and not with QFT. After all QFT is, in a certain sense, more comprehensive than QM and in particular relativistically invariant in contrast to QM. There have been at least two reasons for neglecting QFT in favor of QM for conceptual reflections. First, for a long time the attitude was dominating that the decisive philosophical problems show up in QM already. Accordingly a conceptual analysis of QFT appeared not to be necessary. It even seemed that looking at QFT would only blur the view on the central features since QFT is much more complex and mathematically advanced than standard QM. A second reason for neglecting QFT

[1] Redhead (1987), section 1.5 and chapter 5, gives a very systematic exposition.

[2] Mittelstaedt (1998), chapters 3 and 4, is a very recent state of the art source for details.

[3] Barrett (1999) is a very instructive and comprehensive current exposition of problems faced by new interpretations of or alternatives to QM. An impressively short and persuasive analysis of the stalemate reached in the interpretation of QM can be found in Peres and Zurek (1982) where only the most general features of different approaches are used. Barrett (1996) reflects on certain aspects of some formulations of QM.

was the fact that QFT has not yet reached the status of a consistent and complete theory. The lack of a quantum field theory of gravitation is felt as a pressing need. Since it cannot be excluded that the incorporation of the fourth force might lead to deep changes of QFT as a whole, the current version of QFT must be seen as a preliminary theory.

There have been various studies on the historical development of QFT and in particular Quantum Electro Dynamics (QED).[4] This is partly due to some charismatic figures involved, especially Richard Feynman, and some spectacular successes of methods like renormalization, Feynman diagrams and the extensive use of symmetry groops. For the preference of historical studies on QFT over philosophical ones it might have been more important, however, that history does not change afterwards like theories do. QFT as an object of philosophical reflection only began to receive more thorough attention around 1990. Apart from a certain saturation in the research on the conceptual foundations of QM the two above-mentioned arguments against QFT as a philosophical topic were weakened for the following reasons. First, a careful analysis of the specifically relativistic traits of QFT led to results which at least aggrevate the conceptual problems of QM severely. Possibly they even surmount those problems qualitatively. Second, due to the development of QFT and of the theory of super strings in the last decade the initial hope is fading away that QFT is near to its final completion. This hope flourished in the aftermath of the electroweak unification which seduced some people to euphorically anticipate the achievement of the final theory of everything. Today, string theorists like Dieter Lüst cautiously estimate some 15 years before there will be any contact between string theory and experimental testing of it.

There are not only indirect or negative arguments in favour of QFT as an object of philosophical research. Some further arguments support the hope that a conceptual analysis of QFT will deliver results which finally enable us to tackle problems which seemed insoluble when looking at QM. However, looking at QFT the fundamental difficulty to find and to under-

[4]Darrigol (1986), Schweber (1994) and Cao (1997) are arguably the most famous ones.

stand the nature of the basic entities of the quantum regime might lead to a solution which only makes it necessary to explain why we have the *impression* of "elementary particles". In that case there would be no need to take "elementary particles" ontologically serious.

One often encounters the opinion that quantum *field* theory is just as well a particle as a field theory despite of its supposedly misleading name. Some newer results, however, seem to make it almost impossible to maintain that view. In particular the Reeh-Schlieder theorem and the Unruh effect seem to display features which show that QFT is essentially a field theory. Further results like a no-go theorem by David Malament and e. g. Robert Wald's research on QFT in curved space-time strongly support such a view.

One problem for investigating the conceptual aspects of QFT consists in the fact that many results with conceptually important consequences can only be stated within a formalism which is mathematically involved, namely algebraic QFT (AQFT), even if it is physically clearer than the standard formalism of QFT in at least some respects. Philosophical aspects cannot always be seen immediately, however. It is instructive to realize that e. g. the Reeh-Schlieder theorem is already nearly 40 years old without having received any notice from philosophy of physics for most of that time.

At least until recently one (if not the) longest and most intensive track of discussions on the philosophy of QFT was an investigation by Paul Teller and Michael Redhead on different formal descriptions of many particle systems containing identical particles.[5] This discussion which was initiated in the late eighties finally became a central part in Teller's *An Interpretive Introduction to Quantum Field Theory* (1995) which is the first systematic monograph on the philosophy of QFT.[6] Teller's book displays two deficiencies, however. First, a major part of his studies can already be performed

[5] Redhead (1975), Redhead (1980), Redhead (1983), Teller (1983), Redhead (1988), Redhead and Teller (1991) and finally Teller (1995) is a selection of publications dealing at least partly with this question.

[6] The anthology *Philosophical Foundations of Quantum Field Theory* Brown and Harré (1988) was the first book to appear about this field of research.

with respect to non-relativistic standard QM. Second, the formalism upon which Teller reflects is on the one hand somewhat out-of-date (about from the fifties) and on the other hand too restricted in its scope of application since only free field theory is considered. It can be seen as partly Teller's merit, however, that a broad discussion on the conceptual foundations of QFT has begun in the recent years.[7]

4.2 QFT versus Algebraic QFT

Today, most investigations on the interpretation of QFT are perceived within the algebraic formulation of QFT (see chapter 3), called AQFT. AQFT is not the most convenient formalism for working physicists who are interested in calculating scattering cross sections and other empirically relevant quantities in high energy physics.[8] Despite its limited practical usefullness AQFT is a very fruitful and effective formalism in order to address conceptual questions. The program of AQFT can be compared to ideal language projects in the analytic tradition of philosophy. It started with a theory/language, i. e. standard QFT, whose formulation is generically historical, a conglomeration of various old and new techniques and theoretical approaches which is solely unified by its remarkable success in predicting empirical quantities. This is a parallel feature to ordinary languages which obviously work very well in practice.

Leaving the regime of practical purposes, however, it becomes evident that various ambiguities, disparities and the openness for unintended ex-

[7]Sunny S. Auyang's book *How is Quantum Field Theory Possible?* which appeared in 1995 as well had fewer effects than Teller's in the first time. This might be partly due to the fact that it is remarkably little involved in any recent contexts of discussions. In the last time Auyang's book has received more attention because of a new interest first, in event ontology and second, in the role of symmetries in connection with the discussion on gauge theories.

[8]Only recently theoretical physicists working on AQFT made some successful attempts to calculate standard "every-day quantities" using the AQFT-formalism with an expenditure comparable to that in conventional QFT. Private communication with K. Fredenhagen at DESY, Hamburg.

tensions are very inviting for conceptual considerations which lead astray. The so-called ontological proof of the existence of God is an interesting example. Taking God as the epitome of the most positive attributes and assuming that *being* is an attribute which is supposedly better than *not-being* one concludes that God must necessarily exist. Obviously, the accidental structure of historically grown western languages gave rise to such a heavy ontological conclusion.

An example from quantum physics may serve to illustrate the same point within a physical formalism. The Schrödinger many-particle formalism for systems of identical particles contains an important index which clearly stems from the idea of labelling the different particles in such a "many-particle-system" (see section 3.1). Unfortunately, it turned out that these "particle labels" cannot refer to different individual particles. In the sense of labelling anything in the world they clearly lost their original historical meaning. Nevertheless, "particle labels" still linger on without a definite interpretation or, to put things more strongly, they remain as a piece of merely historically justified formalism.[9] A last example from QFT is the confusion about the so-called "second quantisation".[10]

The idea behind the ideal language project now was to construct a new language which makes it impossible to even formulate sentences which are ambiguous and whose parts have no clear reference and/or function. Carnap's often polemical writings on the connection between the vagueness of ordinary languages and pseudo problems in philosophy and his own attempts to build a better formal language can be seen as the most influential ones in Analytical Philosophy. His famous paper on "The elimination of metaphysics through logical analysis of language" Carnap (1931) contains some nice examples - e. g. on the use of "nothing" - which, despite their

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[9]Redhead introduced the notion of *surplus structure* in this context in Redhead (1975).

[10]Cao (1997), section 7.3, gives a detailed historical discussion of the misunderstandings and ambiguities. A critical examination of the notion of "second quantisation" can be found in Haag (1996), p. 47 ff. A comprehensive monograph on the matter is Berezin (1966).

harsh exaggeration, display the main point in a clear way.

Let me now describe the parallels and the differences between this project in modern philosophy of language and similar traits in modern physics. The first attempts to structure quantum physics in an axiomatic fashion originate in the late twenties so that there is an interesting temporal coincidence between the beginning of the philosophical and the physical program. The extension from a concise and abstract reformulation of QM to an attempt to reformulate QFT began in the late fourties and has been caried on up to now.

The founders of AQFT proceeded in a fashion which is comparable to the ideal language program at least in its general outline and some of its original motives.[11] It was tried to reformulate QFT in a way which is (mathematically) rigorous, as economical as possible with respect to its basic concepts and which displays a clear structure. In concrete terms these maxims were carried out in an axiomatic fashion by imposing fundamental, in particular relativistic, physical conditions on the set of observable quantities. One hope was to get rid of the notorious infinities for quantities like mass and charge. The opinion was that such infinities are mathematical artefacts which should disappear in an ideally constructed formalism rather than being improperly wiped out from a dirty formalism by the method of renormalisation. Starting with axioms like (Einstein) locality and relativistic covariance it was hoped that everything could be derived in a systematic way without ad-hoc moves and approximations.

Given the original idea of reformulating QFT in an axiomatic manner and thus overcoming various problems, AQFT had only a partial success. First, it turned out that a purely axiomatic version of QFT could not be established since it would not be rich enough from a physical point of view. The approach therefore had to be enriched by non-axiomatic elements in order to get into contact with “real physics”. Second, on the one hand, problems e. g. with infinities appeared in AQFT as well and, on the other

[11] The most prominent people of this era of search for an axiomatic reformulation of QFT are I. E. Segal, A. Wightman, R. Haag, H. Araki and D. Kastler, in roughly chronological order. For more details see chapter 3.

hand, the techniques in standard QFT for getting finite quantities by means of renormalisation procedures became ever more refined and systematic so that the unease became smaller.

With respect to the similarities between the ideal language project and axiomatic reformulations of QFT one can finally conclude that both programs turned out not to be as easy as one was hoping after the early successes. In both cases one had to realize that it is extremely difficult to construct a perfectly systematic and clear language or formalism which fulfils all the needs that an ordinary language or grown formalism does. It is possible to build such a system but at the risk of loosing contact to reality.

In contrast to the philosophical ideal language project, however, AQFT should not be considered as a failure. After all, AQFT is an area of ongoing and successful research, and rightfully so. There are points of divergence between the ideal language and the axiomatisation program and they might be the most interesting ones for our context in the end. At least one feature remained as a valuable improvement over standard QFT and in this respect we can see a fundamental difference between axiomatic reformulations of QFT and the aim of an ideal language in analytical philosophy. AQFT is not only meant to be a systematic and concise formalism in the sense of a language. On a realistic reading, QFT as well as AQFT are meant to say something about the "building blocks" and the structure of the world. Unless one takes a purely instrumentalist attitude one expects a physical theory to render more than a mere prediction of measurement results. Accordingly, a physical formalism would be more than a convenient machinery to calculate measurable quantities. One expects the formalism to somehow represent how nature works. The hope is to understand the underlying mechanisms which produce what we measure.

It is in these respects that AQFT comes off better than standard QFT. Although ironically AQFT was initially meant as a stricly positivist theory in which only measurable quantities occur, it has over the time been realized by a number of people that there is no need to stick to that attitude.[12]

[12] To my knowledge Simon Saunders was the first philosopher of physics who explictly

Apart from attitude it would arguably be a point of debate whether the positivist aim could actually be carried through in AQFT. It clearly failed in the connected S-matrix-program.[13]

However, rigorous formalism and positivist attitude is not all there is to AQFT. It is a serious attempt to reformulate QFT by putting fundamental physical ideas first and by trying to stick to one class of quantities in terms of which everything else is expressed. For these reasons AQFT is in a sense a lot more interesting from an ontological point of view than standard QFT. One of the highest aims in QFT has always been to calculate physical quantities most effectively. It is no coincidence that Richard Feynman is one of the most celebrated people in the research on QFT although conceptual rigour was never amongst his highest concerns. One could argue that explicit ontological attitude in QFT and AQFT and the actual successes in carrying it through are crosswise. Whereas elementary particle physics and likewise its underlying theory, viz. QFT, proclaimed to be "In Search for the Ultimate Building Blocks of Nature" t'Hooft (1996), AQFT stressed to only talk about measurements in finite regions of space-time. Effectively, however, it was in QFT that efficient prediction of measurable quantities always played a higher role than in AQFT. AQFT has more to offer since it is a rigorous attempt to keep basic and derived concepts apart.

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pointed out the possibility of a realist interpretation of AQFT in his rich article Saunders (1988).

[13]The S-matrix-program dates back to Heisenberg's 1943 proposal to take the scattering (or S-) matrix as the prime object of study and not the Hamiltonian. Heisenberg's initiative was explicitly grounded on positivist arguments as can be read off from the title "The observable quantities in the theory of elementary particles" of his two first papers Heisenberg (943a) and Heisenberg (943b) on this topic. Cushing (1990) is a thorough and comprehensive historical analysis. Illuminating studies of the relation of the S-matrix program to other approaches in QFT can be found in Cushing (1986) and Redhead (1980), p. 293 ff.

4.3 The Philosophical Interest in (A)QFT

We can thus - at least in some respects - learn more about nature at its most basic level from AQFT than from standard QFT. This does not mean that we can neglect standard QFT for our philosophical analysis. First, AQFT is not (yet) as rich as standard QFT. And second, since both approaches clearly have a preliminary status, it would not be wise to fade out potentially valuable information. We can not be sure which structures will survive. Accordingly, both standard QFT as well as AQFT will be taken into consideration in this work. Since they are not in conflict with one another there seems little risk to shed more light on one or the other depending on the context.

The interest of the philosophy of physics community in AQFT has been born roughly a decade ago.[14] Since then the most fruitful discussions have mostly been stimulated by reexaminations of some older physical theorems from the sixties and seventies. Outstanding is the Reeh-Schlieder theorem. Further sources are Haag's theorem, a lemma by Borchers and a number of closely connected investigations by Hegerfeldt. All of these results will be explained and discussed in more or less detail particularly in chapter 6 and appendix C. The properties of the relativistic vacuum often play a central role in these discussions[15]. Reasons for this interest are, first, the peculiar properties of the vaccum state and, second, the fact that all N-particle states can be "built up" from the vacuum state so that it is not just one exotic state. Central issues in the philosophical debate are questions about

[14]To my knowlwdge is was Simon Saunders' deep insight into and his constant interest in AQFT which to a good part initiated the philosophical debate. Already in the sixties Gordon Fleming was investigating questions of locality and covariance in the construction of position operators e. g. in his articles Fleming (1965a) and Fleming (1965b). Although today he is active in the philosophical discussion with contributions on the connection of superluminal signaling and hyperplane dependence, e. g. Fleming (1988), and lately together with Jeremy Butterfield on localization and Lorentz-invariance Fleming and Butterfield (1999) I consider his earlier work as part of the physics debate.

[15]E. g. Redhead (1995b), Redhead (1995a) and the monograph on *The Philosophy of Vacuum* Saunders and Brown (1991)

locality/localization and causality.

One problem and threat for ontological considerations with respect to QFT is the preliminary status of this most fundamental theory of Physics. The lack of a quantum theory of gravitation, the questioned legitimacy of the unavoidable renormalization procedures and the still unsolved inconsistencies in connection with the measurement problem are the most prominent examples. QFT as it stands cannot be the final theory. How can further thought about its interpretation then be justified before the final consistent version is found? Firstly if were to wait for this completion we are very likely to never even start with anything further. Besides some "Dreams of a Final Theory" there is nothing which suggests that the basic theories of physics will be competely discovered in the near future. Secondly interpretational reflections on the foundations of physics and its inconsistencies might help in the search for the final theory. Thirdly some quantal structures have been very 'steady' for more than 70 years now and lead to strikingly good predictions so that the belief is well-grounded that we will keep at least a good part of these stuctures.

Part III

Classical Ontologies

Chapter 5

Classical vs. Revisionary Ontologies

I now come to the main parts of the investigation about different ontological conceptions of QFT which is subdivided into classical and revisionary ontologies. Before starting to consider separate ontologies this chapter will reflect upon the division itself into classical and revisionary ontologies. I will go into two connected aspects. One aspect is the historical forerunner of this division in content as well as terminology, namely Strawson's distinction of descriptive and revisionary metaphysics. I will deal with the concept of descriptive metaphysics in the following introduction 5.1. The other aspect to be explored about the classical (or descriptive)/revisionary-distinction is the fact that classical ontologies, the term used in this thesis, as well as Strawson's descriptive metaphysics are related to the concept of substance. It is an important link between the classical/revisionary- and descriptive/revisionary-distinction that for both classical and descriptive ontologies the notion of substance plays a central role which it either does not or in a highly non-standard fashion in revisionary ontologies. In sections 5.2 and 5.3 I will consider some diverging ways to understand the notoriously elusive notion of substance.

5.1 Introduction

In his book *Individuals - An Essay in Descriptive Metaphysics* P. F. Strawson introduced the notion of *descriptive metaphysics* as opposed to *revisionary metaphysics* Strawson (1959). He describes his basic idea as follows:

> Descriptive metaphysics is content to describe the actual structure of our thought about the world, revisionary metaphysics is concerned to produce a better structure.[1]

Without much further justification and discussion Strawson then proceedes to present his own contribution to the corpus of descriptive metaphysics. One part of his investigation are detailed studies about how we conceive of everyday "things" like sounds and persons. Although Strawson hardly uses the expression 'ontology', what he actually does is ontology albeit in the tradition of analytical philosophy of language.[2]

The term 'descriptive metaphysics' seems to display a contradiction in itself. Is it not that *meta*physics tries to go beyond mere description? Although Strawson's concept of metaphysics looks modest it is provocative in its context.[3] It entails the reproach that various other metaphysicians were at least presumptuous if not misguided. Strawson names Descartes, Leibniz and Berkeley as historical examples for revisionary metaphysicians while he places himself in the tradition of Aristotle and Kant. Nevertheless, in 1959 it was obvious that Strawson's "descriptive metaphysics" was a repudiation of certain strands in contemporary analytical philosophy. To make things even more controversial, Strawson adds a little later in his book about the metaphysician's work:

> The structure he seeks does not readily display itself on the

[1]Strawson (1959), p. 9.

[2]In his more recent article "Semantics, logic and ontology" Strawson (1975) he explicitly elaborates on the close connection between semantics and ontology beyond the existence of merely structural resemblances.

[3]P. Simons' recent "Against modesty: claims of revisionary metaphysics." Simons (1999) is one of the latest reactions Strawson has provoked.

surface of language but lies submerged.[4]

Quite naturally, this last qualification of descriptive metaphysics arouses suspicion about the very possibility of descriptive metaphysics thus conceived. If descriptive metaphysics has to neglect certain traits of how our conceptions of the world appear to be in favour of structures which are then against our first intuition how are we to distinguish descriptive metaphysics from revisionary metaphysics? Provided that this suspicion is legitimate the dinstinction between descriptive metaphysics and revisionary metaphysics would be a matter of degree rather than being fundamental.

Criticism of this sort can be met at least partly. Strawson's question is *why* we look at the world in the way we do. Strawson wants to describe the structures which yield an answer to this question and not the immediate surface of how we speak about everyday things. Descriptive metaphysics construed in this sense is descriptive *relative* to a certain level of what it tries to describe.[5]

The division of the following investigation into classical and revisionary ontologies has two reasons. The first reason is that each ontological conception within either group can be understood much better with an eye on this classification than in isolation because the historical and systematical background of the respective ontologies is very similar. Process and trope ontology, for instance, can both be seen as reactions on problems with classical substance ontologies. Whereas they agree, at least partly, about their negative diagnoses of classical ontologies, they differ on the positive side, i. e. about the question what the appropriate remedy is. Quite naturally, this common background leads to a certain direct competition between process and trope ontology.

The second reason for dividing the following investigation into two parts is that it makes the discussion of different ontological approaches to QFT more effective. Motivations and problems are far more homogeneous within each group than across groups. One could almost say that the real compe-

[4]Strawson (1959), p. 10.

[5]Tugendhat (1967) is an excellent early classification and evaluation of Strawson's place in philosophy.

tition begins only once you have chosen your group. For instance, particle and field interpretation of QFT are here taken together into the group of classical ontologies. They are *the* two standard options for the ontology of QFT. Accordingly, many investigations are taken to be of importance for this pair of alternatives rather than for one or the other alternative in isolation. It is convenient, therefore, to have the respective arguments close together.

However, since the classical/revisionary-grouping still has, as many other distinctions, a certain degree of arbitrariness this cannot be the whole story. It is only meant as a first approximation which has to be refined and corrected. To this end a comprehensive evaluation and discussion of all the considered ontological alternatives for QFT will conclude this study.

I have preferred to speak of classical versus revisionary ontologies rather than speaking of *descriptive* versus revisionary. One reason are the above-mentioned problems with the notion of descriptive metaphysics. Another reason has to do with one of my later results in the context of QFT. This result indicates that it is possible that an ontological approach which is commonly considered to be revisionary can turn out to be descriptive in certain cases. "So why don't you put this ontology into the first group of classical or descriptive ontologies then?" you could ask. The answer is simple: because besides the possible appropriateness of the label 'descriptive' the above-mentioned reasons speak against this classification, i. e. because its background and its problems are similar to the ones of the other ontologies in this group. To be more concrete, I will argue that with respect to a certain formulation of QFT trope ontology appears to be descriptive while it is commonly rated as a revisionary ontology.

As I mentioned already concept of 'substance' is intimately connected with classical (or descriptive) ontologies. It is often taken to be the philosophical counterpart of the everyday notion of material things including ourselves. This makes it understandable why it is rooted at the centre of classical ontologies. While "substance ontology" is so deeply rooted in classical ontologies it is often the negative background for revisionary ontologies. Some versions of process ontology even make the negation of all "substance-ontological presuppositions" their very starting point Seibt (1997). Since the notion of substance is thus central for both descriptive and revisionary metaphysics the next two sections will deal with the question of how the concept of substance is to be construed.

5.2 Aristotle's Theory of Substances

Although the notion of substance plays a central role in metaphysical writings from ancient times up to now there is little agreement among philosophers about its meaning. There is no single clear-cut meaning of the concept of substance to which even most philosophers would agree.

Nevertheless, the everyday use of 'substance' yields a first approximation. When we say that something, say a business, has got a lot of substance we want to express that it has a particularly strong basis which renders it to be in a better position to survive rough times than another business with less substance. A business with a lot of substance is more likely to survive change since it is more independent from the ups and downs of the market due to its substantial basis. Even if it changes some features of its habit and some of its appearance it can stay basically the same. This illustration gives a first rough-and-ready idea of what is meant by substance.[6] I will now proceed with the philospher who is more than any other connected with the idea of substances, namely Aristotle.

The notion of substance was introduced by Aristotle using the already existing term $o\grave{\upsilon}\sigma\acute{\iota}\alpha$ (which goes back at least to Plato). Although Aristotle's reflections about substances are a pivotal part of his metaphysics and there is ample material about the issue in his writings, the totality of Aristotle's statements is apt to increase rather than diminish the despair about the lack of a uniform understanding. There are at least three aspects which contribute to this situation. It is not immediately clear what Aristotle's view was and whether he had one consistent view at all. To make things worse, there is a plethora of features which different philosophers consider

[6] A very accessible introduction to various historical and systematical questions about the concept of substance is the monograph Hoffmann and Rosenkrantz (1997).

to be at the heart of the concept of substance. And finally, the relation of later versions of the concept of substance to Aristotle's idea(s) is opaque.

In order to cope with this situation there is a tendency to dispose of the problem by using 'Aristotle' as a mere label without claiming that a conception which is called 'Aristotle's view' is exactly matching Aristotle's actual view. On the one side this is a legitimate and fruitful way to get beyond philological debates about Aristotle. On the other side this procedure entails the risk that not viable notions of substance ontology are constructed for the purpose to be refuted elegantly. In order to meet this risk I will discuss three contrasting current points of view. The first one is a modern and benevolent reconstruction of Aristotle's view as a consistent and convincing theory of substance put forward by M. Frede and G. Patzig Frede and Patzig (1988). It is the main issue of this section. The two other two accounts of the notion of substance have a negative diagnosis about its consistency and fundamentality and argue from the point of view of process ontology Seibt (1997) and trope ontology Simons (1998a) respectively. I will elaborate and comment on them in the next and last section of this chapter.

There are a number of interesting and important questions about Aristotle's theory of substances which - in favour of other questions that are more important in the context of the present investigation - I shall not even touch. To what extent and in which sense is Aristotle's theory a reaction and correction of Plato's theory of forms? How is the fact that substance is one of Aristotle's categories besides nine others related to his view that substances are those entities which have primary existence? Is there a development and change of ideas to be found in Aristotle's writings so that one can say, for instance, that the books of his *Metaphysics* display his mature ontology while his *Categories* must be seen as the result of an early stage? How well is the term 'substance' suited as a translation of Aristotle's term '*ousia*'? Detailed discussions can be found in the works cited in this section and the respective references therein.[7] In what follows I will restrict

[7] A good and neither very technical nor philological recent account of Aristotle's conception of substances can be found in the section "Aristotelian substances" (p. 117-127)

myself to the discussion of the final results of the above-mentioned three contemporary authors about ‘Aristotle’s theory of substances’ in the sense of the most fundamental entities in the world. The first interpretation to be considered here is the one put forward by M. Frede and G. Patzig in their introduction, translation and commentary for the famous book Z of Aristotle’s metaphysics Frede and Patzig (1988).[8]

When we consider the existence of concrete particulars like horses or human beings, asks Aristotle, what is it that has primary existence. ‘Primary’ here means that everything else which is not an entity of primary existence is dependent on these primary existing entities. Is the matter which a human body is composed of primary or is it its form? Of the two candidates for primary existence - form and matter - matter can be excluded since matter is always matter of an object. For matter to exist there always has to be something concrete and some form presupposed.

One could argue now that something similar holds for forms as a well. The form of human beings or of horses is something which can be realized many times just as universal properties like redness can. However, according to Aristotle’s stance in opposition to Plato, universals do not exist before and apart from individual things in a separate realm of eternal ideas. Due to his own doctrine about universals Aristotle is thus blocked to say that universal forms have a primary existence. For Aristotle universal forms depend on the existence of concrete things and hence on matter.

Both matter and universal forms are therefore dependent entities so that we have not been successful yet in our search for entities with primary existence which are not dependent on anything else. As to the choice between matter and form we seem to have reached a stalemate. Both seem to be somehow dependent on the other. Neither seems to be a viable candidate for primary existence.

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of Loux (1998). A more detailed study by the same author is Loux (1991). A comprehensive and accessible authoritative introduction to Aristotle’s philosophy is Ackrill (1981).

[8]Frede (1987), chapters 2-6 will be helpful for readers who are not familiar with German, in particular ‘Substance in Aristotle’s *Metaphysics*’.

Frede and Patzig offer the following solution. They argue that with respect to the choice between matter and form not all alternatives have been considered yet. The arguments against the primary existence of form which were put forward so far refer only to forms taken as universals. This leaves room for a further possibility when universals are not construed as forms but as individuals. According to this conception Aristotelian substances (or better ousiai) are individual forms. Only in a wider sense substances would be concrete things like horses or human beings where we have individual form and matter together.[9]

One can get an idea about this conception when thinking of a human body. Due to the natural metabolism every single molecule of a human body is replaced by a new one after some seven years, to my knowledge. Despite of this fact we still think that we are dealing with the same human being. Since the permanence of a human being's identity through this kind of change can thus neither be attributed to the material out of which he is composed nor to the general fact that he is a human being it must be his individual form that accounts for his persisting identity.

I finish this section with some comments and critical remarks. For my first point I need to anticipate some later terminology and ideas whose explanation can be found in chapter 9 on trope ontology. It seems to me that one could call the interpretation of the Aristotelian notion of substance by Frede and Patzig something like a 'singular trope theory'. From the point of view of trope theory an Aristotelian individual form could thus be characterized as a bundle of tropes which happens to consist of just one trope, namely the comprehensive form trope. Note that this is a characterization of the individual forms interpretation of substances *in terms of* trope ontology. It is a 'perverse reading', however, since one of the main goals of the individual forms view consists in getting away from somehow bundling properties. It is the very opposite of a bundle theory. Again, there will be more on bundle theories in later chapters on revisionary ontologies.

[9] A concise but rather technical study of Aristotle's theory of forms is Nortmann (1997). Chapter 11 is an illuminating evalutation from a modern point of view leaving all philological considerations aside.

For a first introduction to bundle theories confer the general chapter 2 on ontology.

The characterization in terms of trope ontology brings me to something which seems like a weak point of the individual forms interpretation of substances (or ousiai) to me. To use an expression coined by D. Armstrong Armstrong (1989) the construal of substances as individual forms is a "blob theory". The advantage of blob theories is that they are very simple and afford little ontological expenditure. However, these advantages bring about an unpleasant disadvantage. The price blob theories have to pay is a certain shortage of explanatory power. There are a number of undebateable facts about the world which they cannot grasp. In the case of the individual forms interpretation of substances, it seems to me at least, is is hard to explain what it means that two substances resemble each other. If the individual form of an object is on the most fundamental level already I cannot see what is left to analyze the resemblance of two substances. It is not satisfactory to say that two human beings resemble each other more closely than two others and to take this as a brute fact. One would like to refer to certain features of these people which are somehow aspects of the whole individual form. In an individual forms theory of substances, however, there is nothing actually existing one could refer to below the level of the individual forms.

Even apart from the mentioned criticism of the individual forms interpretation of substances we are left with the problem that this construal of the Aristotelian theory of substances might be too closely tailored for living organisms. Aristotle's prime examples for substances refer to living organisms like human beings or horses. Their physical parts in an everyday sense, e. g. the kidney, are not substances since they are not independent of the organism as whose organ they function. Parts in a scientific sense, e. g. electrons and quarks, are only potential substances as long as they are a part of a living organism. For ontological investigations regarding physical theories it seems to be more appropriate to consider other characterizations of substances.[10]

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[10] In his paper "Substances, physical systems, and quantum mechanics" E. Scheibe

It is important for the context of the present investigation how the notion of substances has been construed by those philosophers who try to use it as a matrix from which to construct alternative conceptions either to the traditional notion of substance or as an alternative to substance ontologies altogether no matter of which flavour. However, it should be clear by now, that argumentations against purported traditional notions of substance should be handled with high care. In the end, there might not be anything like a traditional notion of substance. Nevertheless, I believe that it is legitimate and fruitful in this situation to argue that certain construals of substance cannot be maintained and to try more viable or even completely diverging options. The next section is devoted to some of these attempts. They are of particular importance for part IV of this study since they are the traditional starting point for revisionary ontologies.

5.3 Substances under Attack

Generally, ontologists who rate themselves as revisionary[11] repudiate the view that the notion of substance is indispensible and basic for our ontological thinking about the world, even on the everyday level. The elusiveness of the concept of substance makes it particularly hard to evaluate the legitimacy of this repudiation, however. Since there is a large diversity in the way to construe the concept of substance it is difficult to argue for or against its applicability. These problems led to the following strategy on the side of revisionary ontologists. In a first step they pick out a certain set of characteristics which they consider to be indispensible for the concept of substance. In a second step they show that substance when understood in

has argued that it is "the modern concept of a physical system which comes nearest to the traditional notion of substance" Scheibe (1991), p. 215. He discusses four aspects of this "traditional notion of substance", independent existence, monadic predication, completeness and individuality.

[11]Note that the self-assessment does not always match with the mutual assessment. For instance, process-ontologist Johanna Seibt rates trope ontology as conservative Seibt (2000), paragraph 4, whereas trope-ontologists see themselves as revisionary Simons (1999).

this way either leads to contradictions or has no or almost no cases which would fall under this concept. Argumentations against 'substance ontology' do mostly not maintain that each single ingredient of the notion of substance has to be dropped. It is rather that certain sets of ingredients are either contradictory in themselves or of (almost) no help since they have an (almost) empty extension.

Peter Simons, in his article "Farewell to substance: a differentiated leave-taking" Simons (1998a), concedes that substance is legitimate and "harmless" as an everyday notion. However, he maintains that substance forfeits its status of being primitive, i. e. unanalysable, after metaphysical reflection in general as well as with respect to special sciences. Simons' stance is of particular value to the present ontological investigation of QFT because he considers the results of special sciences as a pivotal source and guide line for metaphysics.

Simons discusses the following "Strands of Substance":[12] "Independent Beings", "Ultimate Subjects", "Individuators", "Survivors of Change" and "Basic objects of Reference". I will explain them now one after the other.

Independence denotes the ability to subsist alone." Some examples for *dependent* entities may help to understand what is meant by its opposite. A property, a state or a boundary is not independent because it always is the property of something, the state in which something is and the boundary by which something is limited. Properties, states and boundaries could not exist if there was nothing else. Certainly, this is in fact true of a horse as well which is one of Aristotle's examples for a substance. However, it is at least conceivable that there is nothing but one horse whereas a boundary could not even be imagined without something else whose boundary it is. The boundary depends on that which it limits. Simons distinguishes different senses of independence, in particular what he calls weak and strong independence.[13]

A further feature which is often taken to be characteristic of substances

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[12] Simons (1998a) p. 236-239.

[13] Note for later purposes that a *trope* is defined as an *dependent* concrete particular in contrast to a substance which is an *independent* concrete particular.

is their being the *ultimate subjects of predication*. A substance is something to which predicates can be ascribed but a substance cannot itself be ascribed as a predicate to anything. One can say that Paul Fitzgerald in Liverpool is tall but it makes no sense to say that someone is *a* Paul Fitzgerald unless we take it to refer to a kind of person rather than one particular person. As Simons points out ‘being the ultimate subject of predication’ is by itself a characteristic of particulars rather than substances.

I now come to *individuators*: Something is needed which is responsible for an individual’s being an individual. Simons points out that a collection of universal properties can never guarantee not to be realized twice no matter how specific these properties are.[14] An individuating factor is needed. Several proposals have been put forward. Some examples are Aristotle’s *prime matter*, Duns Scotus’ *haecceitas or thisness*, *bare particulars* by the early Bertrand Russell and Gustav Bergmann and *spatial location* as defended by Strawson.

One can only conceive of a concrete particular to change when something survives the change about which one can say that it has changed. Substances are *survivors of change*. During a change some attributes are interchanged by new ones. Simons stresses that considering substances primarily as that which survives any change entails that the ultimate substances are indestructible.

The description of substance ontology by Simons which I just set out comes under the title “Farewell to substance”. Simons main point is that substances do not have the fundamental status that is commonly ascribed to them. He argues that substances can be further analysed in terms of tropes. Since I will set out trope theory in general in chapter 9 and Simons’ version of it in chapter 10 I will not go into any details here. I just wish to stress that Simons’ point against the notion of substance is *not* that it was

[14]The possibility of multiple realization of “bundles of universals” is the main argument against an ontology in which particulars are analyzed as bundles of universals which stand in the so-called *compresence relation* to each other. A good discussion and further references to this view - which was proposed by Russell in the fourties - can be found e. g. in Armstrong (1989), chapter 4 and in Loux (1998), chapter 3.

inconceivable or even inconsistent. He only claims that substances are not basic. I will come back to this point several times during my investigation.

J. Seibt's critique of substance ontology is much more radical than Simons'. She does think that the notion of substance is inconsistent and that there is no remedy. She thinks that there are three basic ontological problems, the problem of individuality, the problem of universals and the problem of persistence. According to her view, all ontological concepts fail in the face of these problems as long as they adhere to the so-called "substance-ontological paradigm".[15]

[15] For details see Seibt (1995) and Seibt (1997).

Chapter 6

The Particle Interpretation of QFT

The particle interpretation of QFT is not only the oldest ontological attitude towards QFT, it seems almost impossible to think of QFT without thinking of particles. Learning that the top quark has been "observed" leaves little doubt that we are finally dealing with particles even when these particles have "strange colours and flavours". Why should have billions of dollars been spent on particle accelerators when there are no particles to accelerate?

Although it seems undeniable that modern physics is to a large extent making theories and experiments involving particles it is this very interpretation which has the most fully developed arguments against it. Why not simply dismiss the particle interpretation then? I can see at least two reasons. Firstly, the immediate evidence speaks in favour of the existence of particles. Secondly, it turned out to be a difficult task to say what the indispensible characteristics of *the* particle interpretation are. The dismissal of the particle interpretation is not the only way to react to the arguments against it. There still is the option to say that our classical concept of a particle is too narrow and that we have to loosen some of its constraints.

Allowing for these options various arguments against a particle interpretation of QFT will be explored and evaluated in this chapter. Before doing so, the first section is reserved for some reflections about the particle concept itself.

6.1 The Particle Concept

Even in classical physics the concept of an (elementary) particle is not as unproblematic as one might expect. On the one side, conceiving of a classical particle as akin to a tiny golf ball immediately prompts the further question for its parts. On the other side, the assumption of point particles leads to physical problems when charged particles are considered: If the whole charge of a particle was contracted to a point, an infinite amount of energy would be stored in this particle since the repulsive forces become infinitely large when two charges with the same sign are brought together. The so-called *self energy* of a point particle is infinite.

These reflections may suffice to indicate that the particle concept has to be construed before it is put to use. Since it might not be the most appropriate way to start with a rigid definition of a particle we will, in this section, only collect and reflect upon some possible ingredients of the particle concept. At this stage no final decision is attempted as to the question what constitutes necessary conditions, whether one can find a sufficient condition and which features should be rated as only contingent.

Probably the most immediate trait of particles is their *discreteness*. Particles are countable individuals in contrast to a liquid or a mass. Obviously this characteristic alone cannot constitute a sufficient condition for being a particle since there are other things which are countable as well without being particles. Money is countable but one would not say when three hundred Euro are paid into an account that three hundred discrete individuals have been added to the other individuals on that account. A physical example are the countable maxima and minima of the standing wave of a vibrating string. The reflection on wave phenomena will be continued in the next paragraph.

It seems that *primitive thisness* or *haecceity*[1] is missing to make up a

[1] The notion of *haecceitas* or thisness has been introduced by Duns Scotus around 1300.

sufficient condition. In addition to being countable it seems to be necessary that it is possible to say that it is this or that particle which has been counted. The qualification "primitive" indicates that the "thisness" of something which is qualified in this way cannot be analysed any further. There is nothing else which is responsible or explains its thisness. An example from physics may serve to underline what is meant as well as a prepare for a later discussion. Disturbances of a medium can result in the propagation of a regular pattern of ups and downs, e. g. after a stone has been thrown into a pond. It is a characteristic feature of such a wave motion that different disturbances which are propagating in opposite directions (e. g. when two stones have been thrown) produce additive results when they meet and remain their undistorted shape when the wave pattern have passed each other. Although the ups and downs of the displacement of water can be counted one would hesitate to say that we are counting the same discrete individuals, say before and after the two wave patterns have passed each other. There seems to be a fundamental difference between ups and downs in a wave pattern and particles. It is primitive thisness what particles seem to have in addition.[2]

There is still another feature which is commonly taken to be pivotal for the particle concept, namely that particles are localizable in space. As was argued in the first paragraph in this section *localizability* should not refer to point-like localization. However, it will turn out in section 6.3 that even localizability to an arbitrarily large but still finite region can be a strong condition for quantum particles.[3]

Eventually, I wish to mention possible ingredients of the particle concept which are explicitly opposed to two corresponding (and therefore opposite) features of the field concept. Whereas a field is often defined as a

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[2]In Teller (1995) p. 103f and p. 112f primitive thisness as well as other possible features of the particle concept are discussed in comparison to classical concepts of fields and waves as well as in comparison to the concept of field quanta.

[3]The introduction in Wightman (1962) is a good account of the first period of research about problems with localizability in quantum physics. References of more modern investigations will follow in section 6.3.

system with an infinite *number of degrees of freedom* the very opposite is true of particles. A particle is for instance commonly referred to by the specification of the coordinates $\underline{x}(t)$ which pertain e. g. to its center of mass. The number of degrees of freedom of the particle is then given by the number of these coordinates. In contrast to a particle, a field $\phi(\underline{x}, t)$ has to be specified by its quantity for each value of $(\underline{x}, t)$, $x_i, t \in \mathbb{R}$ i. e. for an infinite number of values.

The last feature of the particle concept to be mentioned in this section is connected to the last point and again explicitly in opposition to the field concept. In a pure particle ontology the interaction between particles can only be understood as an *action at a distance*. In contrast to that, in a field ontology or a combined ontology of particles and fields *locality* is implemented by mediating fields.[4]

I will end this section with some hints and references on further more technically involved issues connected with the particle concept. Eugene Wigner's famous technical identification of particles in Wigner (1939) with the *irreducible unitary representations of the Poincaré group* (called "inhomogeneous Lorentz group" as well) is explained e. g. in Haag (1996), p. 28ff and its significance is further discussed in Streater (1988), p. 144ff and in the introduction of Buchholz (1994). Various extensions of the particle concept have been considered in AQFT over the past decades. Some keywords are infra- and *quasi-particles* as well as the particle content of a quantum field theory and asymptotic particle states.[5] To give just one example, B. Schroer introduced the notion of *infraparticles* Schroer (1963) in order to cure the restricted applicability of Wigner's particle concept to particles which do not carry electrical charge.[6]

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[4]In Haag (1996) considerable emphasis is put on this feature of fields. See for instance p. 7f.

[5]A non-trivial account of these developments can be found in Buchholz' overview article "On the manifestations of particles" Buchholz (1994). A decisive early study was published in the article "When does a quantum field theory describe particles?" Haag and Swieca (1962).

[6]The term *infra*-particles refers to the fact that the infrared problems are avoided which made the extension of Wigner's particle concept to electrically charged particles

The next section deals with the best-known scientific context in which elementary particles are investigated. The point of concern will be the tension between this experimental basis of QFT on the one side and the conceptual investigations about the corresponding theory on the other side.

6.2 Theory and Experiment in Elementary Particle Physics - Is a Particle Track a Track of a Particle?

In today's most basic theory of the material world, quantum field theory (QFT), there seems to be an insurmountable hiatus between two apparently incompatible conceptions of the fundamental entities: fields and particles. On the one hand there is a long and successful tradition of scattering experiments in particle accelerators. The observed 'particle traces', e. g. on photographic plates of bubble chambers, seem to be a clear indication for the existence of particles. On the other hand, however, the theory which has been built on the basis of these scattering experiments, viz. QFT, turns out to have considerable problems to account for the observed 'particle trajectories'. Not only are sharp trajectories excluded by Heisenberg's uncertainty relations for position and momentum coordinates which hold for non-relativistic quantum mechanics already. More advanced theoretical examinations in AQFT[7] , which will be decribed and scrutinized in the present chapter, show that quantum particles which behave according to the principles of relativity theory cannot be localized in any bounded region of space-time, no matter how large. This result excludes even tube-

impossible.

[7]Chapter 3 is mostly an account of algebraic quantum field theory, in short AQFT. Section 4.2 explains and discusses the relation between QFT and AQFT. The present chapter is, together with chapter 10, the most important reason why AQFT has been introduced. At least some parts of section 6.3 as well as the appendices presuppose these accounts.

like tajectories which are allowed (provided their boundaries are unsharp[8]) when only the constraints of Heisenberg's uncertainty relations are taken into account.[9] From this theoretical point of view it thus appears to be impossible that our world is composed of particles when we assume that localizability in any region of space-time is a necessary ingredient of the particle concept. Surprisingly, the very theory which excludes localizability is remarkably good in predicting experiments which apparently involve localizable particles.

For the working physicist this contradiction is not an important issue because it does not cause any problems, neither for the theoretical nor the experimental physicist, as long as conceptual questions as such are not at stake. In the last few decades Rudolf Haag and his colleagues, a group of theoretical physicists which puts much emphasis on conceptual clearness in their often pioneering work, have tried to fill this longstanding gap between theory and experiment. Within the framework of AQFT they proposed a mathematical model for 'almost localized' particles as they appear in scattering experiments[10]. The main ideas are firstly to describe scattered particles in terms of measurement results of a certain arrangement of particle detectors and secondly to assume only approximate localizability. Before coming to more details of this model the next few paragraphs will give some necessary background information about experiments in High Energy Physics and the sense in which there is a gap between the achieved results and their theoretical description.

All the experimental information which was used to test QFT comes from particle detectors. These are employed in target regions of particle accelerators where very fast and therefore very energetic elementary particles can hit each other and sometimes give rise to new particles which emerge

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[8]The requirement that the tubes are to have unsharp walls is due to Jauch's theorem. For details consult Jauch (1974).

[9]The blurredness of real particle tracks, however, is much larger than the minimum which is required by Heisenberg's uncertainty relations.

[10]Haag (1996), pp. 75-94, 271-289, is an introduction in two steps with an increasing degree of complexity.

from the scattering process. Since the aim of these scattering processes is to break the involved particles apart, one has to use very high energies and therefore very high velocities in order to exceed the binding energies. Since the velocities can be of the order of the velocity of light (though of course smaller) one has to take relativity theory into account for an appropriate theory of these processes, whereas ordinary quantum mechanics is non-relativistic. The founders of QFT proceeded in a somewhat conservative fashion: They used the formalism and the methods of classical Lagrangian mechanics and only modified it where necessary which is in particular due to the fact that some formerly scalar- or vector-valued functions had to be replaced by operators (see physics glossary). The result of this procedure were operator-valued quantum fields corresponding to different kinds of elementary particles and certain quantum states which these quantum fields can be in.

A surprising result was that particles themselves no longer appear in this theory. Although there are entities like "N-particle states" (see physics glossary) among the possible states of QFT it is not clear how these states relate to N particles. This is not only due to problems with the lack of individuality in systems with superposed identical particles. There is another essential characteristic of the particle concept which gets lost in QFT, viz. localizability. Since this topic is mathematically involved and not easy to display separately I wish to demonstrate the problem together with the way it is addressed in advanced QFT by using a mathematical model which is directly linked to modern detection devices for elementary particles.

The well-known cloud chamber photographs show particle tracks which are e. g. split after collisions or after a creation of new particles or which are curved due to a magnetic field. This detection method from the early days is visually compelling but has disadvantages in the numerical analysis because the only data it is based upon are graphical. Today one uses much more elaborate detection devices which directly supply the elementary particle physicist with electrical signals that can be processed by computers. This procedure allows of various possibilities to improve the exactness and value of the experimental data. A serious problem for the selective detection of elementary processes consists in the fact that there is always a large proportion of signals which are irrelevant for the process in which one is interested. A method to suppress background signals lies in the use of energy thresholds which have to be exceeded before the detector responds. The more intricate task is the discrimination of different elementary processes which occur in the same region at a similar time. A very successful way of achieving this aim is a coincidence arrangement of detectors: Only those signals are assumed to originate from one and the same process which were detected at exactly the same time.

In AQFT this detection method has been employed to tackle a conceptual question by modelling the described experimental situation in a mathematical way. The detector model is meant to demonstrate that a relativistic N-particle state after a scattering process can be understood as a state of N "singly localized" particles at least in the asymptotic limit, i. e. when time goes to infinity. The coincidence arrangement of N detectors is described by a product of N operators. Due to the Reeh-Schlieder theorem (see section 6.3.1) these operators can only be "almost localized", since strict localization is incompatible with the condition that the detectors must not respond to the vacuum. Operators are said to be almost localized when they are smeared out with test functions which vanish quickly when their arguments go to infinity.

The significance of the described detector model and in particular of the notion of almost localized operators for the tenability of a particle interpretation will be discussed in subsection 10.4. The reason why I do not consider this question here already is that I will have arguments why an answer depends crucially on certain philosophical presuppositions which are investigated somewhat better in the context of chapter 10.

6.3 Localization Problems

So far there is no strict proof against the possibility of a particle interpretation for QFT. The pieces of circumstantial evidence are strong, however.

The core of these pieces consists in problems to localize "particle states" in any sensible way. This will be the issue of the following section.

Section 6.1 showed that the very definition of what it is to be a particle is more involved than one would expect at first glance. There are various features which are commonly connected with the particle concept. However, which of them taken together make it up to a sufficient condition and, even more importantly, which of them are necessary? The advantage of a clear-cut necessary condition is that it allows for the possibility of no-go theorems to the effect that a conception which rests on this condition can be ruled out. Exactly this way has been gone with respect to the particle interpretation of relativistic quantum mechanics. The results are generally considered to be among the firmest foundations of ontological investigations about relativistic quantum physics. Reeh and Schlieder, Hegerfeldt, Malament and Redhead all gained mathematical results, or formalized their interpretation, which prove that certain sets of assumptions lead to contradictions. They all purport to be in the position to exclude certain interpretations which are, to say the least, closely connected with the particle concept.

So far it is a point of debate what exactly has been shown and how the different results relate to one another. The clarification of these questions is pivotal for an enquiry of the ontology of QFT since the particle interpretation is, besides the field interpretation, the most widespread one. In the following subsections I will analyze the relation between two of the above-mentioned no-go theorems, namely the one resulting from Michael Redhead's interpretation of the Reeh-Schlieder theorem and a no-go theorem by David Malament. Two reasons render the ensuing analysis particularly fruitful. Firstly, we have a firm mathematical ground to start from and, secondly, the thorough comparison will force us to have a very close look at the exact presuppositions and the legitimacy of the conclusions drawn by either author. In the light of these two points it is almost of secondary importance what the analyis will finally tell us about the relation of the theorems.

6.3.1 The Clash of Causality and Localizability

The Consequences of the Reeh-Schlieder Theorem

The Reeh-Schlieder theorem[11] (1961) is a central analyticity result from algebraic QFT (AQFT), the axiomatic reformulation of QFT which was introduced in chapter 3. From a physical point of view the Reeh-Schlieder theorem is based on vacuum correlations. Although the theorem stems from an analysis of the vacuum state, the 0-particle state, it can easily be extended to other N-particle states with $N \neq 0$.[12] This already demonstrates the scope of its importance. In short the upshot of the Reeh-Schlieder theorem is that local measurements can never decide whether we observe an N-particle state. We begin with a technical statement of the theorem. With Ω being the vacuum state and $R(O)$ the von Neumann algebra as introduced in 3 the following result can be derived on the basis of the axioms of AQFT (see appendix B):

> *Reeh-Schlieder Theorem:* For *any* bounded open region O in space-time the set $\{A\Omega : A \in R(O)\}$ is dense in Hilbert space $\mathcal{H}$.

The definition of *dense* as well as of other technical concepts can be found in the physics glossary. For a rough-and-ready explanation one can say that one set lies dense in another set if its elements are so finely distributed over the whole second set that for any given element in this second set and any given distance one can find an element in the first set which lies closer to this element in the second set than expressed by the given distance. The set $\{A\Omega : A \in R(O)\}$ is said to be *generated* from the vacuum state Ω by the von Neumann algebra $R(O)$ of local observables associated with O because it is the set which you get when all the operators A in $R(O)$ are applied to the vacuum state. Recall that an operator is a mathematical entity which "can be thought of as an animal that eats vectors and spits

[11] Although Reeh and Schlieder (1961) is the original source later accounts render an easier access. For references confer the titles which are cited in the following footnotes.

[12] See Haag (1996), p. 102.

out other vectors"[13] . With these explanations the content of the Reeh-Schlieder theorem can be expressed as follows: choosing suitable elements of $R(O)$ and acting with them on Ω any vector in $\mathcal{H}$ can be approximated arbitrarily closely.

The statement of the Reeh-Schlieder theorem is different and much stronger than the well-known fact that the Hilbert space $\mathcal{H}$ can be spanned by eigenstates of the number operator which can be build up from the vacuum state by application of suitable creation operators. It can be shown that local algebras $R(O)$ - about which the Reeh-Schlieder theorem talks - never contain pure creation (or annihilation) operators. The strength of the Reeh-Schlieder theorem becomes clearer when one considers that O can be a small neighborhood of a point in space-time. What the Reeh-Schlieder theorem now asserts is that acting on the vacuum state Ω with elements of $R(O)$ we can approximate as closely as we like any state in $\mathcal{H}$, in particular one that is very different from the vacuum in some space-like separated region O'. The Reeh-Schlieder theorem is thus clearly exploiting long distance correlations of the vacuum.

Even though the Reeh-Schlieder theorem is an astonishing result it is not immediately obvious what the conceptual consequences actually are. To this end we need the following

> *Corollary of the Reeh-Schlieder theorem:* Ω is a separating vector for $R(O)$, i. e. two elements $A_1, A_2 \in R(O)$ which yield the same result when acting on Ω must be one and the same operator, or in short $A\Omega = 0 \Rightarrow A = 0$, where $A \equiv (A_1 - A_2)$.

The use of this corollary yields an interesting interpretive result. Again, the assumptions are the standard axioms of AQFT. It will be shown that:

> Local measurements can never decide whether we observe an N-particle state.[14]

[13] See p. 251 in Salmon et al. (1992).

[14] Cf. Redhead (1995a).

Let us call this statement 'Redhead's claim' because it was he who expressed this conclusion more explicitly than anybody else, at least to my knowledge. The underlying mathematical result is the fact that a projection operator P_Ψ which corresponds to an N-particle state Ψ can never be an element of a local algebra $R(O)$. Since the proof of 'Redhead's claim' is very instructive and comparatively easy I will restate it here.

Proof

Given the Reeh-Schlieder theorem and its above-mentioned corollary the proof is a straightforward reductio ad absurdum. Consider an arbitrary N-particle state Ψ (with $N \neq 0$). Since Ψ is orthogonal to the 0-particle state Ω the corresponding projector P_Ψ satisfies $P_\Psi \Omega = 0$. Let us now ask whether Ψ is an element of a local algebra $R(O)$ corresponding to a bounded region O. If this were the case then one could decide by a local measurement, restricted to the region O, whether we have an N-particle state Ψ or not, or, to be more cautious, whether we will find such a state or not when we perform such a measurement. Let us assume now as a trial that P_Ψ is an element of a local algebra $R(O)$. In this case our corollary is applicable so that $P_\Psi \Omega = 0$ would imply $P_\Psi = 0$. This, however, contradicts our assumption that P_Ψ is the projection operator corresponding to the N-particle state Ψ, which cannot be $\mathbf{0}$ unless Ψ itself is 0. We are forced, therefore, to drop our assumption that P_Ψ is an element of a local algebra $R(O)$.
q. e. d.

The exact meaning and range of Redhead's claim will become clearer when we compare it with the ensuing no-go theorem by David Malament. The comparison itself will follow the exposition of the two results to be compared and makes up the core of this section. We will conclude the section with some critical remarks about the legitimacy of the respective interpretations.

Malament's No-go Theorem

Malament's no-go theorem Malament (1996) is another consequence of analyticity which rests on a lemma of Borchers Borchers (1967). In short it says that a quantum theory of a fixed number of particles satisfying in particular the very weak locality condition of statistical independence of measurements in space-like related spatial sets predicts a zero probability for finding a particle in any spatial set.

Malament's no-go theorem rests on four conditions. We assume the existence of projection operators P_Δ on Hilbert space $\mathcal{H}$ representing the proposition that a particle detector would respond if a position measurement were performed in the spatial set Δ. Δ is taken to be a bounded open subset of a spacelike hyperplane in Minkowski space-time M. Furthermore we will assume that there is a strongly continuous, unitary representation $U(\mathbf{a}), \mathbf{a} \in M$ (in $\mathcal{H}$) of the translation subgroup of the Poincaré group in M. Malament's conditions now are the following:

(i) **Translation Covariance Condition:**

$$P_{\Delta+\mathbf{a}} = U(\mathbf{a})P_\Delta U(-\mathbf{a}) \tag{6.1}$$

for all $\mathbf{a}$ in M and all spatial sets Δ. $\Delta + \mathbf{a}$ denotes the set Δ after a translation by $\mathbf{a}$.

(ii) **Energy Condition:** The spectrum of the Hamiltonian operator $H(\mathbf{a})$ is bounded below (see glossary) provided that $H(\mathbf{a})$ satisfies $U(t\mathbf{a}) = e^{-itH(\mathbf{a})}$ for all unit vectors $\mathbf{a}$ in M which are future directed and timelike.

(iii) **Localizability Condition:** If Δ_1 and Δ_2 are disjoint spatial sets in the same hyperplane,

$$P_{\Delta_1}P_{\Delta_2} = P_{\Delta_2}P_{\Delta_1} = \mathbf{0}. \tag{6.2}$$

(iv) **Locality Condition:** If Δ_1 and Δ_2 are spatial sets (not necessarily in the same hyperplane) that are space-like related,

$$P_{\Delta_1}P_{\Delta_2} = P_{\Delta_2}P_{\Delta_1}. \tag{6.3}$$

What do these conditions mean? Condition (iii) is the essential ingredient of the particle concept: A particle - in contrast to a field - cannot be found in two disjoint spatial sets at the same time. P_{Δ_1} and P_{Δ_2} must therefore be orthogonal. The condition is very weak since it does not set any finite limit to the travelling speed of a particle. Condition (iv) is the relativistic part of Malament's assumptions: Measurements in Δ_1 must be statistically independent from measurements in the space-like related Δ_2. P_{Δ_1} and P_{Δ_2} must commute therefore. This condition again is very weak since it does not require for P_{Δ_1} and P_{Δ_2} to be orthogonal which would rule out that the particle can travel at superluminal speed.

How does Malament's no-go theorem work? Using a lemma of Borchers and each of the four conditions above Malament derives that

$$P_\Delta = 0 \qquad \text{for any spatial set } \Delta. \tag{6.4}$$

This means that the probability for finding a particle anywhere in space is 0 no matter how large Δ is. Since that is an unacceptable conclusion Malament's proof has the weight of a no-go theorem provided that we acccept his four conditions as natural assumptions for a particle interpretation.

What exactly does this say about the possibility of a particle interpretation? A relativistic quantum theory of a fixed number of particles, satisfying in particular the localizability and the locality condition, has to assume a world devoid of particles (more precisely: a world in which particles can never be detected) in order not to contradict itself. Malament's no-go theorem thus shows that there is no middle ground between QM and QFT, i. e. no theory with a fixed number of particles (like in QM) and which is relativistic (like QFT) without running into the localizability problem of the no-go theorem. One is forced towards QFT (without a fixed number of particles). A particle interpretation of QFT is not directly ruled out though!

6.3.2 Locating the Origin of Non-Localizability

A Comparative Study

Although both Redhead's interpretation of the Reeh-Schlieder theorem as well as Malament's no-go theorem are concerned with the non-localizability of relativistic N-particle states they seem to be two different results on a related matter. This is not to say that there is any contradiction between the two. It only seems that we have two more results which enrich our knowledge about the possibilities and restrictions for an ontological interpretation of QFT.

I wish to show that there is, in fact, just one result. Even though Redhead and Malament draw two different conclusions and use two different theorems for their considerations I shall demonstrate that the mathematical machinery employed is the only difference from an interpretive point of view. The assumptions made as well as the result one gets under these circumstances are exactely the same with respect to the question of localizability of relativistic N-particle states. In order to prove this claim I will compare Redhead's and Malament's work part by part using one common mathematical language. Since Malament's no-go theorem is already very clearly and explicitly structured I shall use his theorem as the standard for comparison.

Redhead starts from the Reeh-Schlieder theorem with its very general assumptions and content. It is only at the end of his considerations that Redhead gets more specific with respect to the question of the localizability of relativistic N-particle states. Malament, in contrast to this, addresses the question from the very start. Accordingly, his assumptions, in particular his four conditions, are more specific from the outset of his argumentation. In order to see this we will start from the end where the parallels can be seen most easily. To this end we will compare the two final results which have direct impact on the leading question of particle localization. In the second step we will examine whether the assumptions of the two results are identical so that one can legitimately say that we have effectively just one result from an interpretive standpoint.

The Proofs On the one hand Malament shows that, given his assumptions,

$$P_\Delta = 0 \qquad \text{for any spatial set } \Delta, \tag{6.5}$$

where P_Δ is the projection operator onto the set Δ which can be any subset of a spacelike hyperplane of Minkowski space-time. This means that the result applies to every possible inertial observer, i. e. for any given inertial observer and any given time we get $P_\Delta = 0$ no matter where and how large Δ is chosen.

Redhead, on the other hand, concludes that local measurements can never decide whether we observe an N-particle state[15]. In Redhead's consideration of the Reeh-Schlieder theorem there is no explicit reference to subsets of spacelike hyperplanes, however. His conlusion, therefore, seems to be more general in that respect already since it applies, due to the Reeh-Schlieder theorem, to any bounded open set in space-time. But let us consider whether there are any implicit restrictions to these space-time sets in the context of localizability. We are in this case concerned with position measurements which should be as general as possible as long as the area where the measurement takes place stays finite. Nevertheless, how ever general the position measurements we consider are, each single measurement has to take place at some time in some observers frame of reference. Or, to put the same thing in other words, the 'bounded open set in space-time' we consider has to be a bounded open subset of a spacelike hyperplane, just as in Malament's no-go theorem. So we passed the first check in the comparison of Redhead's interpretation of the Reeh-Schlieder theorem and Malament's no-go theorem with the result that they refer to the same set of measurement regions.

Now let us compare what Malament and Redhead actually say about position measurements in those space-time regions we discussed above. Malament on the one hand concludes that "there cannot be a relativistic quantum mechanics of (localizable) particles".[16] He derives his conclusion by showing that $P_\Delta = 0$ for any spatial set, given his assumptions. Since

[15] See section 6.3.1.

[16] See title of his paper Malament (1996).

this result is a striking contradiction to all experimental facts Malament can claim to have a no-go theorem provided that one accepts his assumptions.

Redhead on the other hand concludes, given his assumptions in turn, that "it is not a local question to ask "are we in an N-particle state?"".[17] Formally he shows that P_Ψ can never be an element of a local algebra, where Ψ is an N-particle state. He proves this claim indirectly by showing that P_Ψ would have to be $\mathbf{0}$ if it were an element of a local algebra.

We can immediately see that there is at least a certain superficial similarity between Malament's and Redhead's results. In both cases some kind of localizability is assumed and shown to lead to contradictions by deriving that a certain class of projection operators, which are directly linked to localizability, would have to vanish in that case. Since, for different reasons, it is not acceptable for these projection operators to be zero we can exclude the possiblity of localizability for certain states under certain conditions.

In order to see whether there is more than just this superficial similarity between Malament's and Redhead's results we have to compare the respective classes of projection operators

$$P_\Delta,\ \Delta \text{ bounded open set in spacelike hyperplane} \quad (Malament)$$

and

$$P_\Psi \in R(O),\ O \text{ bounded open set} \quad (\textit{Redhead})$$

more closely. Whereas P_Δ is explicitly linked to localizability[18] this is true for P_Ψ only in an implicit way via the assumption that it is an element of a local algebra $R(O)$.

Let us compare P_Δ and P_Ψ for the same bounded open region Δ of space-time, i. e. P_Δ and $P_\Psi \in R(\Delta)$. Surely P_Δ should be an element of $R(\Delta)$ since it refers to measurements in space-time region Δ. As we have seen, however, P_Δ can only be the trivial element $\mathbf{0}$ since it vanishes under those assumptions we stated above.

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[17]See Redhead (1995a), p. 127.

[18]The assumption of localizability is complete together with the localizability condition which we will discuss in the next paragraph.

We can thus take Malament's result

$$\underbrace{\begin{array}{l} P_\Delta,\ \Delta\text{: arbitrary spatial bounded open set} \\ \text{Conditions for translation covariance, energy, localizability and locality} \\ \text{(“Mal.-assumptions”) are fulfilled.} \\ \xRightarrow{\text{(Borchers' th.)}} P_\Delta = 0 \text{ in contradiction to experiments} \end{array}}$$
$$\Longrightarrow \text{Mal.-assumptions can not all be maintained.} \tag{6.6}$$

and reformulate it as follows:

$$\underbrace{\begin{array}{l} P_\Delta \in R(\Delta),\ \Delta\text{: arbitrary spatial bounded open set} \\ +\ \text{localizability assumption} \\ \xRightarrow{\text{(Borchers' th.)}} P_\Delta = 0 \text{ in contradiction to experiments} \end{array}}$$
$$\begin{array}{l} \Longrightarrow \text{Localizability assumption cannot be maintained for relativistic} \\ \qquad \text{N-particle states. (Impossible since localizability is an indispen-} \\ \qquad \text{sible ingredient of the particle concept)} \\ \qquad \underline{\text{or}} \\ \qquad P_\Delta \notin R(\Delta) \end{array} \tag{6.7}$$

where "+"denotes the logical conjunction of propositions. Redhead's result can now be formulated in an absolutely similar fashion as

$$\underbrace{\begin{array}{l} P_\Psi \in R(\Delta),\ \Delta\text{: arbitrary spatial bounded open set,} \\ \qquad\qquad \Psi\text{: N-particle state} \qquad\qquad (*) \\ \xRightarrow{\text{(Reeh-Schl. th.)}} P_\Psi = 0 \text{ in contradiction to } (*) \end{array}}$$
$$\Longrightarrow P_\Psi \notin R(\Delta). \tag{6.8}$$

Since in both cases we are dealing with N-particle states (implicitly in Malament's case, explicitly in Redhead's case) propositions about P_Δ and P_Ψ amount to the same thing: the impossibility to measure N-particle states when they are assumed to be localized.

Evaluation

The results about non-localizability which have been explored in this section may appear to be not very astonishing in the light of the following facts about ordinary QM: Quantum mechanical wave functions (in position representation) are usually smeared out over all $\mathbb{R}^3$, so that everywhere in space there is a non-vanishing probability for finding a particle. This is even the case arbitrarily close after a sharp position measurement due to the instantaneous spreading of wave packets over all space. Note, however, that ordinary QM is non-relativistic. A conflict with SRT would thus not be very surprising although it is not yet clear whether the above-mentioned quantum mechanical phenomena can actually be exploited to allow for superluminal signalling. QFT, on the other side, has been designed to be in accordance with special relativity theory (SRT). The local behaviour of phenomena is one of the leading principles upon which the theory was built. This makes non-localizability within the formalism of QFT a much severer problem for a particle interpretation.

Only very recently Malament's reasoning has come under attack in Fleming and Butterfield (1999) and Busch (1999). Both argue to the effect that there are alternatives to Malament's conclusion. The main line of thought in both criticisms is that Malament's 'mathematical result' might just as well be interpreted as evidence that the assumed concept of a sharp localization operator is flawed and has to be modified either by allowing for unsharp localization Busch (1999) or for so-called "hyperplane dependent localization" Fleming and Butterfield (1999). I fully agree to the extent to which the conclusiveness of Malament's interpretation is concerned. However, one problem is that the proposed alternatives are not sufficiently worked out to allow for a final evaluation. The discussion in subsection 10.4 has a direct bearing on this issue. The threads will come together in chapter 12.2.1.

In his article "A dissolution of the problem of locality" Saunders (1995) Saunders draws a different conclusion from Malament's (as well as from similar) results. Rather than granting Malament's four conditions and deriving a problem for a particle interpretation Saunders takes Malament's proof as further evidence that one can not hold on to all four conditions. According to Saunders it is the localizability condition which might not be a natural and necessary requirement on second thought.

A short word on terminology: Saunders calls Malament's localizability condition "weak-placing condition" since it does not, as Saunders "strong -placing condition" does, entail microcausality which Malament postulates separately in his locality condition. Saunders "strong -placing condition" reads as follows:

$$\Delta_1, \Delta_2 \text{ spacelike related } \Rightarrow P_{\Delta_1} P_{\Delta_2} = P_{\Delta_2} P_{\Delta_1} = \mathbf{0}.$$

Stressing that "relativity requires the language of events, not of things" Saunders argues that the localizability condition loses its plausibility when it is applied to events: It is not sensible to postulate that the same event can not occur at two disjoint spatial sets at the same time. One can only require for the same *kind* of event not to occur at both places.

For Saunders the particle interpretation as such is not at stake in Malament's argument. The question is rather whether QFT speaks about things in any physical sense. Saunders considers Malament's result to give a negative answer to this question.

One thing seems to be clear by now. Since Malament's 'mathematical result' appears to allow for various different conclusions it can not be taken as conclusive evidence against the tenability of a particle interpretation of QFT. Since I could show that Redhead's interpretation of the Reeh-Schlieder theorem is equivalent to Malament's theorem the same conclusion applies to Redhead's results as well.

6.4 Further Problems for a Particle Interpretation of QFT

Problems Arising From the Standard Formalism of QFT

The standard definition for the vacuum state $|0\rangle$ is that it is the energy ground state, i. e. the eigenstate of the energy operator with the lowest eigenvalue. Now recall the notable result in ordinary non-relativistic QM that the ground state energy of e. g. the harmonic oscillator is *not* zero in contrast to its analogue in classical mechanics. The same is true for the vacuum state in QFT. The relativistic vacuum of QFT displays even more striking features. The expectation values for various quantities do not vanish for the vacuum state. The label "$|0\rangle$" does not indicate that the energy is zero in the vacuum state. It rather stems from the interpretation that there are no particles present in the vacuum state: an N-particle state can be built up from the vacuum state by the N-fold application of a creation operator (see pages 40 ff. of section 3.2).

Non-vanishing vacuum expectation values prompt the question what it is that has these values or gives rise to them if the vacuum is taken to be the state with no particles present. Since the vacuum state $|0\rangle$ is closely linked to N-particle states where N is not zero, properties of the vacuum state have a great impact on the particle interpretation as a whole. If particles were the basic objects about which QFT speaks how can it be that there are physical phenomena even if nothing is there according to this very ontology?

An even greater but related challenge for a particle interpretation of QFT is the Unruh effect which is the topic of the following subsection.

"Nothing" can be a lot for a Fast Observer: The Unruh Effect

The Unruh effect is a surprising result which seems to show that the concept of a particle is observer dependent. The Unruh effect (1976) is the striking phenomenon that a uniformly accelerated observer in a Minkowski vacuum (the standard vacuum $|0\rangle$) will detect a thermal bath of particles, the so-called Rindler quanta.[19] To be more specific, an accelerating observer in flat space-time feels himself immersed in a thermal bath of particles at temperature

$$\mathrm{kT} = \mathrm{a}/2\pi \quad (\hbar \equiv 1),$$

(a: acceleration of the observer) when the quantum field is in its vacuum state as determined by inertial observers.

Whereas the number of particles in the Minkowski vacuum is 0, an accelerated observer suddenly detects a thermal bath of particles. A mere change of the frame of reference thus leads to a change of the number of particles. Since basic features of a theory should be invariant under transformations of the referential frame the Unruh effect constitutes a severe challenge to the concept of particles as basic objects of QFT.

A Lesson from QFT in Curved Space-Time

Studies of QFT in curved space-time[20] show that the particle concept hinges on Poincaré symmetry. This result indicates that the existence of a particle number operator might be a contingent property of the flat Minkowski spacetime.

In flat space-time Poincaré symmetry is used to pick out a preferred representation of the canonical commutation relations which is equivalent to picking out a preferred vacuum state. This leads to a well-known definition of the notion of a particle. Neither the existence of global families of inertial observers nor the Poincaré tranformations which relate between these families can be generalized to curved space-time, however.

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[19]See Unruh (1976) and Unruh and Wald (1984) for details. Teller discusses the Unruh effect on pages 110-113 of his book Teller (1995). He tries to show that it is not a fundamental problem for a particle interpretation.

[20]In 'QFT in curved space-time' one treats gravitation classically (as in General Relativity Theory) and the matter fields propagating in this classical spacetime as quantum fields. QFT in curved space-time should have a limited range of validity and certainly should break down - and be replaced by a quantum theory of gravitation coupled to matter - when the spacetime curvature approaches Planck scales. See the authoritative monograph Wald (1994) for a detailed introduction to QFT in curved space-time.

QFT in curved space-time can actually teach us something about standard QFT (in flat space-time). Since QFT in flat space-time is a special case of QFT in curved space-time QFT in curved space-time can help us to see what is contingent in QFT in flat space-time.

6.5 Results

On the one side, the adoption of a particle interpretation of QFT would make the importance of particle experiments and the predominance of speaking in terms of particles comprehensible. It could explain why charge only exists in discrete amounts which is a typical feature of particles and not continuously which is characteristic for field quantity

On the other side, we saw that there are various problems for a particle interpretation. Some results indicate that particle states cannot be localized in any finite region of space-time no matter how large it is. Other results show that the particle number might not be an objective feature.

Nevertheless, it turned out that most arguments need to be seen in relative terms. At this stage of research it can only be recorded that there are various potential threats for the tenability of a particle interpretation. However, before one can take these arguments as conclusive evidence against a particle interpretation of QFT alternative explanations have to ruled out at first. A more comprehensive and detailed evaluation of possible arguments against a particle interpretation will be carried through in subsection 12.2.1 of the conclusion when we have a better background for this discussion.

Chapter 7

Field Interpretations of QFT

Many textbooks on QFT include in their introduction some remarks about the term 'quantum *field* theory' and the entities about which it is a theory. Some textbooks stress that QFT is just as much a particle theory as it is a field theory. Others stress that it is even more a particle than a field theory and that the term 'quantum *field* theory' is somewhat misleading. Still other textbooks say that the term is fully justified since the incorporation of relativity theory into quantum physics leads to the inevitable field character.

One thing one can learn from this is that there is obviously no agreement among physicists and that the situation is by no means clear. Another thing one can learn is that these two possibilities, particles or fields, are the standard options for the kinds of entities to which QFT refers. Accordingly, particle and field ontology are the first two approaches which are under investigation in this study. I considered the particle ontology first because it is the most immediate option for that theory which is the theoretical basis for electrons, quarks and protons after all. Nevertheless, the field interpretation of QFT is arguably the kind of ontology to which most physicists would subscribe if pressed for a decision. In this chapter I will investigate how well-founded and viable this choice actually is.

7.1 The Field Concept

Classical Newtonian mechanics is formulated as a theory about bodies and forces with pure "action at a distance". It is only stated which force bodies exert on each other. Nothing is said about how these effects are mediated since it is assumed that there is an instantaneous interaction between two massive bodies. It turned out that the electromagnetic interaction between charged bodies cannot be described within this framework. A mediating field, the electromagnetic field, had to be introduced which accounts for the local transmission of electromagnetic forces.

The systematic and efficient formulation of the theory of electromagnetism with Maxwell's equations at its core revealed another famous feature. There is a limiting velocity for the transmission of signals, namely the velocity of light. In classical electromagnetism the existence of a limiting velocity for the transmission of signals simply emerged from this theory which rests on observed electromagnetic phenomena. It was Einstein who established this feature as a requirement for any physical theory. Hence the term 'Einstein causality' which was introduced in section 3.4 already. Before decscribing how this principle was put to use in the formation of QFT I will say a little more about the notion of a field in general.

While the introduction of fields as mediators for the transmission of forces is a good starting point for getting an intuitive idea, the standard definition of a field is somewhat different. A field is generally defined as a system with an infinite number of degrees of freedom for which certain field equations must hold. A comparison of the specification of a field to the one of a point particle makes it clear what this definition means. A point particle can be described by its position $\mathbf{x}(t)$ which changes as the time t progresses. In a three-dimensional space there are three degrees of freedom for the motion of a point particle corresponding to the three coordinates x_1 - x_3 of the particle's position. In the case of a field the description is more complex. The field is represented by the specification of a field value ϕ for each point $\mathbf{x}$ in space where this specification can change as the time t progresses. A field is therefore specified by $\phi(\mathbf{x}, t)$, i. e. a (time-dependent) mapping from each point of space to a field value.

As I indicated already the formal specification $\phi(\mathbf{x}, t)$ is not enough for something to be a field. Certain field equation need to be fulfilled. Without giving any further details I wish to point out just one extreme case why the formal specification $\phi(\mathbf{x}, t)$ cannot be sufficient. Consider $\phi(\mathbf{x}, t)$ where $\phi(\mathbf{x}, t) = 0 \, \forall \mathbf{x} \neq \tilde{\mathbf{x}}$ with $\tilde{\mathbf{x}}$ being a particular point in space. In this case $\phi(\mathbf{x}, t)$ would just describe an ordinary point particle instead of a proper field.

One further information about fields should be supplied in order to make it understandable how one can come across the idea to think of fields as being *the* basic entities in the world. The intuitive notion of a field is that it is something transient and fundamentally different from matter. However, in physics it is perfectly normal to ascribe energy and even momentum to a pure field where no particles are present. This surprising feature shows how gradual the distinction between fields and matter can be.

7.2 Fields as Basic Entities of QFT

There are two lines of argumentation which are often taken to show that an ontology of fields is the appropriate construal of the most fundamental entities to which QFT refers. The first argumentation rests on the fact that so-called *field operators* are at the base of the mathematical formalism of QFT. The other line of argumentation is indirect. Since various arguments seem to exclude a particle interpretation, the only alternative, namely a field interpretation, must be the right conception.

7.2.1 The Role of Field Operators in QFT

It is well known that the basic variables describing the kinematical behaviour of a particle, position and momentum, are of a peculiar nature in QM. In the early days of quantum theory they were called quantum numbers (‘q-numbers’) as opposed to classical numbers (‘c-numbers’). The peculiarity of q numbers is the fact that they do not cummute in general, a fact whose details are condensed in the canonical commutation relations (CCRs). This peculiarity is in fact so characteristic that these relations are a sufficient information about the behaviour of a quantum particle. Everything can be derived by specifying these relations.

In mathematical terminology the reason for the general non-commutation of q-numbers is that they are operators and not ordinary numbers. The order in which operators act on something does matter in general. In order to denote this difference operators get a hat. The transition from classical to quantum mechanics can thus be described as

$$\mathbf{x}(t) \to \hat{\mathbf{x}}(t)$$

and correspondingly for the momentum, where certain CCRs hold for their components.

Without going into the details let me just state that in a similar fashion the transition from a classical field theory (like electromagnetism) to quantum field theory can be characterized by the transition

$$\phi(\mathbf{x}, t) \to \hat{\phi}(\mathbf{x}, t)$$

for the field and a corresponding transition for its conjugate field for both of which a certain specification of CCRs holds. In difference to a classical field $\phi(\mathbf{x}, t)$ the basic fields $\hat{\phi}(\mathbf{x}, t)$ of QFT are called *operator-valued fields* since to each point of space and time an operator is attached.

As one could see there is a formal analogy between classical and quantum fields. In both cases field values are attached to space-time points where these values are real-valued in the case of classical fields and operator-valued in the case of quantum fields. In technical terms the analogy reads as one between the mappings

$$\mathbf{x} \mapsto \phi(\mathbf{x}, t), \;\; \mathbf{x} \in \mathbb{R}^3$$

and

$$\mathbf{x} \mapsto \hat{\phi}(\mathbf{x}, t), \;\; \mathbf{x} \in \mathbb{R}^3.$$

This formal analogy between classical and quantum fields is one reason why QFT is taken to be a field theory. However, it has to be examined now whether this formal analogy actually justifies this conclusion.

In his paper “What the quantum field is not” Teller (1990) which became a central chapter of his later book *An Interpretive Introduction to Quantum Field Theory* Teller (1995) Teller puts considerable emphasis on a critique of this conclusion. He comes to the conclusion that ‘quantum fields’ lack an essential feature of all classical field theories so that the expression ‘quantum field’ is only justified on a “perverse reading” of the notion of a field. His reason for this conclusion is that in the case of quantum fields - in contrast to all classical fields - there are no definite physical values whatsoever assigned to space-time points. Instead, the assigned quantum field operators represent the whole spectrum of possible values. They have, therefore, rather the status of observables (Teller: “determinables”) or general solutions. Something physical emerges only when the state of the system or when initial and boundary conditions are supplied.

I think Teller’s criticism of the standard gloss about operator-valued quantum fields has one justified and one unjustified aspect. The justified aspect is that quantum fields actually differ considerably from classical fields since the field values which are attached to space-time points have no direct physical significance in the case of the quantum field. However, and here I disagree with Teller, this fact is not due to the operator-valuedness of quantum fields as such. It was not to be expected anyway that one would only encounter definite values for physical quantities in QFT. QFT is, like QM, an inherently probabilistic theory, after all.

Nevertheless, even taking the probabilistic character of QFT into account there still is the problem that we need quantum fields as well as state vectors in order to fix probabilistic properties. But I do not think that one can therefore conclude that quantum fields are not physically significant at all. It seems to me that physical significance of field quantities cannot be judged along classical distinctions. I think that there is more physical information encoded in quantum fields than Teller ascertains. But I agree with Teller that the field character of QFT is by no means as obvious as it first seems. The formal analogy between classical and quantum fields as such is not a fully convincing argument for a field interpretation of QFT. If a field interpretation should actually yield the appropriate ontology for QFT than it seems that those objects which are called "quantum fields" are not already the fundamental entities one is looking for, at least not alone.[1] And counting state vectors as basic entities as well spoils the idea of a field interpretation throughout since state vectors cannot be seen as fields in the sense of a mapping from space-time points to field values.

7.2.2 Indirect Evidence for Fields

The indirect evidence for a field interpretation consists in the reasoning that all arguments against a particle interpretation are tantamount to arguments in favour of a field interpretation. Examples concern peculiar features of the vacuum, non-localizability and non-local correlations.

However, just as in the case of a direct argumentation for a field interpretation as presented in the last section, the available indirect arguments do not equip us with an explicit idea about what these fields are. What are the fundamental entities in a field interpretation of QFT? Are they the properties ascribed to space-time points or the space-time points themselves? Or is it rather space-time as a whole or one big quantum field? All of these options turn out to be either inconsistent or too counter-intuitive or too weak in their explanatory force. In section 12.2 of my conclusion I will argue for a relative legitimacy of a field interpretation.

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[1] Teller's own proposal is an ontology of QFT in terms of *field quanta*. Teller argues that the "Fock space representation" or "occupation number representation" suggests this conception with objects (quanta) which can be counted or aggregated but which cannot be numbered. The number of objects is given by the degree of excitation of a certain mode of the underlying field. Particle labels like the ones in the Schrödinger many-particle formalism do not occur any more. I think that it is questionable whether it is legitimate to draw such far-reaching ontological conclusions from one particular representation. In addition to that the Fock space representation cannot be appropriate in general since it is only valid for free particles.

Part IV

Revisionary Ontologies

Chapter 8

Process Ontology

8.1 The Strands of Process Ontology

Independently of the discussions on conceptual problems of QFT process ontology has been thought about in philosophy for hundreds of years. It is still not clear what a process ontology looks like in detail and where and how it can help to overcome unsolved problems. The philosophical discussion has got new impulses in recent years: J. Seibt and others argued for a radical revision of the very foundations of ontological theories. Instead of ontologies which are based on the 'myth of substance' Seibt proposes a process-ontological approach. Seibt's process ontology presents itself primarily as a rejection of some deeply rooted presuppositions of ontological thinking so far. Seibt labels this bundle of presuppositions 'substance ontology', thereby including a large variety of ontologies, e. g. ontologies based on tropes as well. The fact that even trope ontologies are subsumed under the term 'substance ontology' already indicates that the traditional and well-known categorical dualism of 'substance' and 'attribute' does not lie at the heart of Seibt's citicism. It is rather the dualism of universals versus particulars that she considers to be at the core of substance ontology.[1]

[1]Schurz' article Schurz (1995) on 'A quantum mechanical argument for the existence of concrete universals' is an interesting example of what it means and how it can help

The central idea of the process ontology according to J. Seibt is to view non-countable rather than countable entities as the most fundamental ones. A countable concrete particular entity (e. g. a particular table) is then taken as a minimally homoeomerous non-countable entity. A 'homoeomerous' (homoeo-merous = like-parted, Seibt (1997) p. 167) entity is one which has in all its parts the same intrinsic properties as the whole down to some minimal parts. The minimal part of a homoeomerous entity is called 'minimally homoeomerous'. The term 'homoeomerous' has in some respects the same meaning as the popular expression 'self-similar' (selbstähnlich) which is used to describe the scale-invariance of fractals.

I will start my investigation from the fundamental theories of modern physics and explore physical motivations for a process ontology as well as some consequences for the interpretation of the formalism.

8.2 Why Process Ontology in QM and QFT?

The most convincing philosophical arguments for a *process* ontology are arguments against a *substance* ontology. This fact is reflected in considerations about the adoption of a process ontology for specific scientific theories: With respect to QM and QFT the strongest motivation for thinking about a process ontology are severe foundational problems which might stem partly from an unquestioned substance ontological background upon which most interpretations are based. There are a couple of problems in QM and QFT which have always defied a satisfactory solution suggesting that a loosening of certain deeply rooted ontological beliefs and restraints might be unavoidable in the end.

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in physics to soften the dichotomy of universals and particulars: Schurz demonstrates that the problems with identical particles (see section 3.1) appear in a very different light when particles are seen as concrete universals rather than particulars. Particles of one sort are all identical even though they are not numerically identical. Universals like 'electron' are repeatedly instantiated and the number of electrons is the cardinality of this instantiation. The problem of the distinguishability of electrons dissolves since it makes no sense to speak of different individual electrons any more.

We have already discussed one complex concerning difficulties with microparticles as individual objects. The next paragraph on “Consequences of a Process Ontology for the Interpretation of QM and QFT” will show how process ontology sheds a different light on old problems. At the same time it will help to clarify what a weakening of the dichotomy of universals and particulars means in concrete cases and how this might help to tackle problems.

The second complex of problems has not been discussed so far since it is not obvious that these problems are connected primarily with ontology: Microparticles or systems of microparticles are described by the quantum mechanical state function whose best-known representation is Schrödinger’s wavefunction in coordinate space. Derscribing systems with state functions is a very powerful and general method. Even though it has been equally successful in predicting and explaining physical phenomena, however, the exact connection between the state function and the system which it is meant to describe poses some unsolved conceptual problems. To be more precise the problem consists in the assignment of properties to quantum mechanical objects. There is just one easy case: If the state of a quantum system is an eigenstate of the observable (e. g. energy, spin etc.) to be measured the outcome of the measurement will with certainty be the corresponding eigenvalue. In this and only in this case there is no problem in saying that the system possesses this value of the observable as a well-defined physical property.[2] If the quantum system is not in an eigenstate of the relevant observable there are, with respect to that observable, severe difficulties to ascribe any property to the system before as well as after the measurement.[3] A special case of these general difficulties appears in investigations on incompatible properties or observables[4] respectively. Examples of such pairs are position and momentum or different spin com-

[2]This is what David Albert calls the ‘Eigenstate-Eigenvalue Rule.’ See for example his recent publication Albert and Loewer (1996).

[3]See Mittelstaedt (1998) for a detailed discussion.

[4]I will not go into any subtleties about the relation and difference of ‘observable’, ‘operator’ and ‘matrix’.

ponents (e. g. in x- and z-direction). Two observables A and B are said to be "noncommuting" when their commutator

$$[A, B] := AB - BA \tag{8.1}$$

does not vanish. The corresponding physical interpretation simply states that it is not possible to perform joint measurements of noncommuting observables. The consequences are even stronger than that, however: It is not even possible to assign values of both observables to one object at the same time not to speak of their measurement.

Such strong statements seem to stand in contrast to Heisenberg's uncertainty relations which allow measurements of noncommuting observables to a certain degree of accuracy at least. In order to overcome this gap simultaneous measurements of noncommuting observables have been explored extensively in the last decades.[5] This led to the concept of 'unsharp observables' which can be measured simultaneously and whose unsharp values can be assigned to the quantum system while this is impossible for the sharp counterparts of these observables.

On the one hand the concept of unsharp observables enables us to describe many physical situations a lot more realistically than with the older too narrow and too rigorous schemata of QM.[6] On the other hand we get new conceptual problems: To speak of unsharp observables and unsharp values suggests the idea that a quantum system *possesses unsharp properties*. It has to be stressed that the claim to be considered is not just that certain properties can be measured only in an unsharp fashion when measured simultaneously. The claim goes further to the point that the system actually incorporates unsharp properties.

The considered problems all hinge on the assumption that we can only understand physical quantities and measurements in terms of basically invariant object systems which in some way possess properties that can change in time. If this assumption were dropped things would appear in a very different light. In some sense the problems mentioned above could

[5] Busch (1982) is one of the first sources where these issues are investigated intensively.

[6] Cf. Busch et al. (1995) for many elaborate examples.

not even be stated any more. Since the situation is so desperate otherwise it is this vague hope which constitutes one motivation for a physicist to think about process ontology. In addition to this hope for a radically new solution for old problems the mathematical formalism of QM smoothly fits to the view to have properties without definitely assigning them to any underlying substances.

One further motivation for a process ontology arises from an interesting feature of QFT which will be the background for the case study in the following section as well. In QFT we have an important piece of formalism which is interpreted as a description of the creation and destruction of particles.[7] This fact is often seen as a characteristic difference between QFT and classical QM. In our context one could say that classical QM is, in this respect, closer to the concept of a conservation of substance than QFT where we have the possibility of transitions between states with different numbers of substances. These transitions are described by creation and destruction operators which act on the respective states. Maybe a description in terms of processes is more suitable to the otherwise strange idea of a creation of substances. The next section will explore further aspects of the creation and destruction of particles with respect to the 'substance versus process ontology-debate'.

8.3 A 'Case Study': Consequences of the Ontological Hypotheses for the Interpretation of Feynman Diagrams

So far there is no worked-out process ontology for QFT and it seems difficult to achieve this aim (see the last section on "Remaining Problems"). In the meantime we can only use general outlines of such a conception. In order to investigate the consequences of the approach with processes as basic objects of QFT, I want to focus on just one of the problems I

[7]See pages 40 ff. for some aspects of the mathematical background which led to this interpretation.

mentioned in chapter 3: the 'creation and destruction of particles' as they appear in either naive or preliminary descriptions of Feynman diagrams because of the occurence of creation and destruction operators in certain mathematical terms which stand behind Feynman diagrams. The purpose of the case study is to uncover how the chosen ontological approach can effect the interpretation of the formalism of QFT. As a representative part of formalism I shall look at the treatment of scattering processes in perturbation theory and especially at the visualisation of S-matrix elements by Feynman diagrams. The procedure of the case study is to examine how the interpretation of Feynman diagrams changes when we go over from the conventional substance ontology to a process ontology.

Even though a major part of chapter 8 deals with Feynman diagrams they are - for our purposes - not interesting in themselves but merely in order to illustrate some consequences of a process ontology. I speak of *a* process ontology because instead of any characteristics of a detailed conception of process ontology I shall only use very general features which result primarily from a loosening of constraints of substance ontology. The case study should not be misunderstood as giving arguments either for or against process ontology. The sole purpose is to explore some effects of a process ontology for QFT which cannot be seen immediately.

The following list of arguments against a realistic interpretation of Feynman diagrams is the first step of the case study. The interpretation of Feynman diagrams is called "realistic" or "literal" when it is asssumed that the diagrams correspond to something in the outer physical world in a one-to-one fashion. This first set of arguments constitutes the conventional view on Feynman diagrams which is grounded on the equally conventional and therefore usually unquestioned substance ontology. In the second step of the case study this list will serve as the background for a counter argumentation within a process ontology.

Substance ontology and arguments against a realistic interpretation of Feynman diagrams

a) Arguments concerning the origin of Feynman diagrams as parts of a sum

(i) Feynman diagrams have been invented for the sole purpose of classifying and calculating a sum of very complex terms which is otherwise extremely hard to handle systematically. No ontological obligations (i. e. statements about which objects exist) are connected with this procedure.

One simple example is the scattering process of two electrons whose states may be specified by their respective 4-momenta p and q. If before scattering the state of the two electrons is $\mid p, q\rangle$ the probability of finding the two-electron-state $\mid p', q'\rangle$ after the scattering between the electrons has taken place is given by

$$\mathrm{prob}^{S}_{|p,q\rangle}(\mid p', q'\rangle) = \left|\langle p', q' \mid S \mid p, q\rangle\right|^2 = \left|\sum_{i=0}^{\infty}\langle p', q' \mid S^i \mid p, q\rangle\right|^2,$$

where S is the so-called S-Matrix which describes all the possibilities of the scattering process in terms of incoming and outgoing states. $\langle p', q' \mid S \mid p, q\rangle$ is one element of the S-Matrix with respect to the complete orthonormal set $\{\mid p, q\rangle\}$ of basis vectors and the summation over i indicates an expansion of the S-Matrix.[8]

[8]In perturbation theory we use the so-called 'interaction picture' in which the equation of motion for the time-dependent state vector of the object system is governed by the interaction part of the Hamiltonian. Solving this equation of motion for an initial condition iteratively leads, in the limit $t \to \infty$, to an expansion of the S-Matrix by comparison with its definition. The contribution in each order of the expansion index i consists of a sum of multiple integrals where i determines the number of integrations. For details see, for example, Mandl and Shaw (1984) p. 98-102 (ch. 6.2).

Feynman diagrams are now used to calculate an S-Matrix element in successive orders which in turn are given by the expansion index i. To each value of i, i. e. to each order, corresponds a certain number (one or more) of Feynman diagrams. Each Feynman diagram *looks like* the sketch of a scattering process which is ever more complicated - i. e. contains more vertices - the higher i is. This can, for example, lead to diagrams which look like sketches of multiple internal scattering processes. It is common talk amongst particle physicists to call higher order diagrams or processes respectively 'corrections' to the 'main processes' which are given by the lowest non-vanishing order.

The advantage of using Feynman diagrams (instead of direct calculation of the above sum) lies in the fact that there are some simple graphic rules which are sufficient to determine all diagrams that have to be taken into account for each order whereas in a direct calculation it happens very easily that some relevant terms are missed out. The usage of Feynman diagrams is graphically represented in figure 8.1 (page 110).

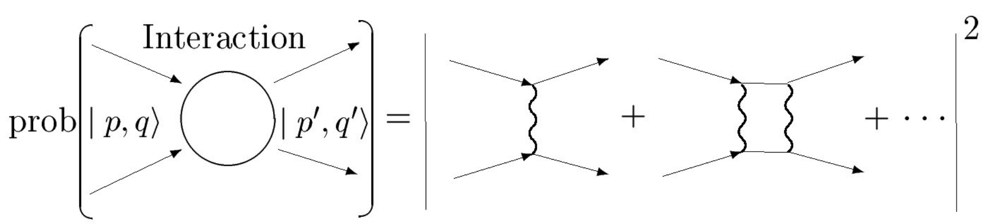

Figure 8.1: Illustration of the connection between Feynman diagrams (here only of the lowest order) and the probability for a certain scattering process.

(ii) The division into Feynman diagrams has a purely conventional character which results from the 'artificial' construction of interaction Hamiltonians in perturbation theory.

(iii) A realistic interpretation of an infinite series of Feynman diagrams (which is used to calculate the probability of an overall scattering process) commits - at least in a particle view - to the assumption of an infinite amount of particles that contribute a single scattering process.

(iv) Only the sum over all relevant Feynman diagrams of all orders leads to an observable quantity. Therefore the individual diagrams have no physical significance (cf Schrader-Frechette (1977)).

(v) To suppose that a scattering process is built up by the superposition of independent subprocesses which are given by the relevant Feynman diagrams produces false probabilities: The transition probability for a scattering process is not the sum of the probabilities of the individual processes that are depicted in the Feynman diagrams which are associated with this transition, as in equation (8.3). The reason for this is that the transition *amplitude* for a scattering process is given by the sum of the 'transition amplitudes' of the alleged subprocesses, as in equation (8.2) (cf Weingard (1982), p. 239).

$$
\begin{aligned}
&\mathrm{prob}^{S}_{|p,q\rangle}(|\, p', q'\rangle) \\
&= \left|\langle p', q' \mid S \mid p, q\rangle\right|^2 \;=\; \left|\sum_{i=0}^{\infty}\langle p', q' \mid S^i \mid p, q\rangle\right|^2 \qquad (8.2)\\
&\qquad\qquad\qquad\qquad\qquad\neq \sum_{i=0}^{\infty}\left|\langle p', q' \mid S^i \mid p, q\rangle\right|^2, \qquad (8.3)
\end{aligned}
$$

where terms in the first sum with two different indices are called 'interference terms.' Exactly these terms constitute the difference to the second sum.

b) Arguments concerning single Feynman diagrams

(vi) Feynman diagrams consist of sharp trajectories which are excluded because of the Heisenberg uncertainty relations for position and momentum.

(vii) If Feynman diagrams were visualisations of real processes the number and kinds of virtual particles in these processes would be sharp which is not possible (cf Weingard (1982), p. 240).

(viii) A Feynman propagator between two points x and x' with space-like separation would describe a particle traveling with a speed greater than the velocity of light (cf Mandl and Shaw (1984), p. 56 and Källén (1958), p. 256).

(ix) Single second order diagrams of covariant perturbation theory are actually combinations of two time-ordered diagrams. These combinations are necessary in order to get covariance since the division into time-ordered processes with $t > t'$ and $t' > t$ is not Lorentz-invariant if $(x - x')$ is a space-like separation (cf Mandl and Shaw (1984), p. 55 and Weingard (1982), p. 240).

The last nine arguments are supposed to show that we must not interpret individual Feynman diagrams as representing any real scattering processes in the physical world. Some of these arguments are explained in more sophisticated textbooks on physics. It is never stated, however, that some of them are grounded on implicit presuppositions - namely the substance-ontological presuppositions mentioned above - and some arguments are problematic for other reasons. We will therefore explore these two things in the next section.

Process ontology and counterarguments to the arguments against a realistic interpretation of Feynman diagrams

The following set of arguments in our case study are counterarguments to the first set of arguments against a realistic interpretation of Feynman diagrams. While the first set of arguments was mainly grounded in a substance ontology the second set contains arguments against these arguments which can partly only be raised from the point of view of a process ontology. In particular, we will have to examine whether the first set of arguments can still be maintained when we have no substance-like bearers of properties any more.

(i') The point of discussion here is whether a realistic interpretation of Feynman diagrams is possible not whether it is necessary. The origin of a certain piece of theory or formalism is of minor importance to its interpretation.

(ii') The counterargument again runs like the first one: Even if there were mathematical or practical reasons for a specific construction or representation originally these facts cannot be used against a further ontological interpretation.

(iii') Argument (iii) is only relevant in a substance ontology where something is conserved. In a process ontology 'particles' (or the like) themselves are seen as composed of processes! A superposition of an infinite amount of processes is not problematic since there is nothing like a conservation of processses.

(iv') Argument (iv) can be boiled down to the point that there is no direct empirical evidence of the processes depicted in Feynman diagrams. If this was a good argument it could be used to rule out many other entities as well, like quarks and electromagnetic field strength.

(v') Subprocesses need not be independent. There is no reason why the relevant subprocesses should not influence each other when taking place together. In this case the interference terms describe the mutual influence.

(vi') Arguments (vi) - (viii) are again only relevant in a substance ontology. In a process ontology there is no object traveling from x to x'.

(vii') “

(viii') "

(ix') There is no need to take every part of the mathematical formalism ontologically seriously even in a process ontology. This is the counterpart to the first two arguments in this list: We are only examining which parts of the formalism *could* be given a direct ontological meaning in a process ontology.

8.4 Evaluation of the 'Case Study'

The case study revealed that the interpretation of Feynman diagrams depends crucially on the ontological hypotheses which form the background of the interpretation. Nine arguments against a realistic interpretation of Feynman diagrams were discussed. All these arguments could be shown to rest on a substance-ontological background because to each argument we could find a counterargument when a process-ontological background is assumed. We can therefore record that a realistic interpretation of Feynman diagrams is excluded in a substance ontology while it seems possible in a process ontology.

We have thus found one point where the decision between substance and process ontology makes a difference to the interpretation of the formalism of QFT, namely of Feynman diagrams. This only shows, however, that these alternative ontological assumptions do have concrete interpretive consequences. At this stage of the argumentation, our result is neither an argument for nor against a process ontology. This would only be the case if we had independent reasons to prefer (or to disapprove of) a realistic interpretation of Feynman diagrams.

Although the case study constitutes no direct reason against a substance ontology or for a process ontology it could hopefully help to show the significance of this question for the interpretation of physics. At the same time it turned out, at least as far as our case study is concerned, that the difference between substance and process ontology lies only in the interpretation and not in any empirical consequences. There remains a lot of detailed work to be done, however, in order to examine how much a process ontology would contribute to the solution for instance of the problems I have sketched in section 3.1.

8.5 Remaining Problems

The most outstanding deficiency of current conceptions of a process ontology is the lack of a satisfactory positive description and definition of the assumed basic processes. For mathematically minded physicists there is the immediate question for a mathematical definition and a concise description of the mathematical structure of the set of processes. A first idea would be to understand a process as the triple of two events and a unitary time evolution operator. A good starting point could be to explore where conventional conceptions of processes differ from the kind of processes which a process ontology postulates. An interesting subquestion to the first one is the connection of process ontology to recent theories of the structure of space-time (e. g. geometro-dynamical models).[9]

The second set of remaining problems is concerned with explanations for phenomena which are natural for a substance ontologist while they call for a lot of effort on the side of the process ontologist. Whereas the substance ontologist has a hard time explaining how change in time is possible even though the things which change supposedly keep their identity, the process ontologist has the opposite problem: Why do we have the strong impression that many things are more or less static if everything is composed of processes? On top of that the process ontologist has to explain why many conservation laws seem to be fulfilled by nature as it appears to us. One old explanation is to assume counterprocesses which exactely balance other processes with the overall effect of the appearance that nothing happens.

The last point to be mentioned here is the question whether the adop-

[9] David Finkelstein made some interesting proposals in his older papers Finkelstein (1973), Finkelstein (1974) and Finkelstein (1979) as well as in his recent book Finkelstein (1996).

tion of a process ontology leads to any changes of scientific theories and the connected formalism. If the answer is 'yes' this could show a way to experiments which actually do make an observable difference between substance and process ontology.

Chapter 9

Trope Ontology

The last candidate for an ontology of QFT to be considered in this study is trope ontology. The fact that the trope-ontological approach to QFT comes after the event- and the process-ontological approaches in the 'revisionary-ontologies-section' is not to indicate that trope ontology would be the most radical revisionary ontology. The reason is rather that it is the latest revisionary ontology which has been proposed for quantum physics.[1]

It is hard to appreciate trope ontology without knowing the context in which it originated. Taken in isolation trope ontology might easily appear either trivial or inconceivable. In order to prepare the right setting for it I will hence describe this context. It should become clear why many analytical ontologists find trope ontology so appealing.

[1] *With respect to QM* probably the first serious argumentation showing the fruitfulness of trope ontology for the solution of some problems in the conceptual foundations can be found in Simons (1994). Special emphasis is given there to the so-called "problem of the identity of indiscernibles" in connection with many-particle systems in QM.

With respect to QFT I was the first, to my knowledge, to argue for a trope-ontological account of (the algebraic formulation of) QFT in a number of talks and one publication in 1999.

9.1 Introduction - The Ontological Status of Properties

The punchline of trope ontology is to take properties as particulars and not as universals. In the trope-ontological scheme of the world these so-called *tropes* are then taken as the simple and basic items of which everything is composed. 'Trope ontology' is a 20th century term for a philosophical position which in its content can arguably be traced back to ancient philosophy.[2] Partly because of its somewhat mysterious name trope ontology appears to be very exotic and in a sense it certainly is. Since it diverges considerably from everyday ontological thinking it is commonly classified as a revisionary ontology. Despite this classification it is a very popular position nowadays. Looking at some problems in ontology one can sometimes have the impression that one is almost automatically driven towards the trope-ontological position. Many problems vanish most easily once this point of view is adopted. In fact, trope ontology gives such a convenient solution to some problems that Johanna Seibt recently stressed the "comfortable conservativeness of the approach" which, by the way, she considers to be not without costs.[3]

Trope ontology cannot be understood sufficiently without realizing the stalemate in which it offered a diplomatic solution. I am talking about the so-called *problem of universals* which seems to be as old as philosophy itself. The key problem is to understand what it means that two distinct things 'have the same property', e. g. they are both blue or have the same charge. On the one hand one could have the idea that this property is another entity on its own. But how is it to be conceived that such an abstract entity has an effect on those two things? On the other hand one cannot deny that

[2]There are various famous philosophers who are sometimes considered to have been trope ontologists. In some cases this evaluation refers to the explicit content of their respective philosophies, in other cases only to the effective picture which emerges when different statements are taken together to form one consistent whole. Some examples are John Locke, Edmund Husserl and Rudolf Carnap.

[3]Seibt (2000), paragraph 4.

they 'have something in common' although they are completely distinct. The traditional positions within this debate are realism about universals and nominalism.[4]

Realism about universals claims that a property is something which is repeatable in many different individuals. Each such case is called an *instantiation* of the universal. In its best-known version realism about universals takes a universal to be an *abstract* entity, i. e. one which is neither in space nor in time. Plato is most famous for this so-called *universalia ante res*–position.

The very opposite position to realism about universals is called *nominalism*. A nominalist denies that there actually are any properties in the world. He not only denies the existence of properties separate from *concrete* things, i. e. entities which are at least localizable in time. This point of view would still be compatible with realism about universals in its version of *universalia in rebus* (e. g. Aristotle). The nominalist claims that properties are merely our construction. Nothing in the world corresponds to them. We only have the impression that there are properties that are distinct from concrete individuals which "have" these properties in the sense that the *same* property occurs in different concrete individuals. In order to account for this impression different versions of nominalism have been put forward. The simplest one is *class nominalism* which assumes that everything falls into *natural classes* where the naturalness is taken to be a primitive ontological ingredient which cannot be analysed any further. To say that a has property F is understood by the class nominalist to mean that a is a member of the natural class of things which, conventionally speaking, all have property F.

The immediate reaction to class nominalism is to question the primitiveness of natural classes. One should think that it is the very property, say F, that was meant to be avoided which makes the natural class a coherent class. On the one hand there is something right about this objection.

[4]Besides the excellent comprehensive and concise study by Armstrong (see footnote 5 on page 120) chapters 1 and 2 in Loux (1998) give a very readable introduction to the problem as well as to various approaches to its solution.

On the other hand a caution is appropriate here. Most if not all ontological conceptions have to take more than one kind of entity as basic or primitive. Usually one starts by assuming one (or more) kind(s) of entities and after some reflection it turns out that there is at least one more uninvited kind of entity which has to be ackowledged. Often this additional kind of entity causes at least some unease. Whether one is willing to accept the respective situation depends primarily on how convincing it seems to stop asking at a certain point. After all there always is a point where one has to start so that this fact is not problematic in itself.

There are various strong arguments against nominalism. In order to give a feeling for the kinds of problems that nominalism faces let us consider only one simple form of nominalism and discuss one specific problem. Nominalists have serious trouble to account for more complex statements involving relations and higher order predicates. Let us see why by investigating one special case. According to class nominalism a universal (or type) is to be identified with the class of particulars (or tokens) that correspond to it. Redness is identified with the class of all objects which are red. Let us now have a look at the following statement with a three-place relation from David Armstrong's latest book[5] on the problem of universals.

Redness is more like orange than it is like yellow.[6] $(\star)$

Since nobody would doubt that this is a perfectly sensible statement the class nominalist has to make sense of it too. He has to analyse it by using classes and unrepeatable particular things instead of universals. This means that he could translate the above sentence to something like "For each element in the class of red things it holds that it is more similar to each element in the class of orange things than it is to each element in the

[5] Armstrong (1989) is a crystal-clear and comprehensive introduction to various arguments for and against a large variety of different positions towards the problem of universals. Despite its subtitle "An Opinionated Introduction" Armstrong presents a balanced exposition which does not try to force a particular final evaluation upon the reader. Nevertheless Armstrong leaves no doubt about his own position in favour of realism about universals.

[6] Armstrong (1989), p. 34.

class of yellow things." But what have we got now? Although the last statement is true for a few things it is blatantly wrong in all other cases. A red flower is *not* more like an orange curtain than it is like a yellow flower. As a remedy one could think of comparing the whole classes by saying that "The class of red things is more similar to the class of orange things than it is to the class of yellow things." This again is wrong, however, or at least one can easily imagine a state of affairs of the world which renders this statement as wrong while at the same time "Redness is more like orange than it is like yellow" is true. Just imagine a world in which red and yellow only occur as colours of the vegetation and orange only for pieces of furniture.

Let us now investigate problems which realism about universals faces. In order to make things as easy as legitimately possible and in order to be fair let us consider the most extreme version of realism about universals, the universalia ante res-version. Here we have no specific problem with relations or higher-order predicates.[7] Instead, the universalia ante res-version faces the "problem of instantiation". How are we to explain that universals from a realm of abstract things outside of space and time play a role in our concrete world? How is the transgression from Plato's heaven of universals to our spatio-temporal world to be conceived? In short, one can say that whereas nominalism has the problem to understand the world solely in terms of concrete particular things, extreme realism about universals has the problem to explain how abstract universals can have any relevance for concrete particular things.

[7]Note that realism about universals still has a problem with our sentence ($\star$). However, this has nothing to do with relations or higher order predicates in general. The problem lies specifically in the similarity relation between universals. An infinite regress is threatening if this similarity could not be analysed any further. One would be faced with an infinite number of similarity relations, similarity relations of similarity relations and so on.

9.2 Trope Ontology as a Solution to the Problem of Universals

At this stage *trope ontolgy* enters the game with a compromise: Don't worry about acknowledging properties like red or yellow, but let them be particulars and not universals. It is acceptable to say that this flower is red, as long as its redness is taken to be something which occurs just once in this particular flower. We have this particular red of this particular flower and another particular red of a particular book and so on. Since this conception of properties differs considerably from our everyday-use as well as from the traditional understanding the difference is indicated by employing a new term: Properties taken as non-repeatable particulars are called *tropes*. (It is best not to think about this expression.)

How is trope ontology to solve our red-orange-yellow-problem in sentence ($\star$)? Since ($\star$) is meant to be a general statement about red, orange and yellow, the trope ontologist has to think about an analysis catching on the one hand the generality of the statement while using on the other hand only properties as particulars, i. e. tropes. One decisive feature of trope ontology now comes into play. Nominalistic moves like analysing properties in terms of natural classes of particulars awake to new life in the context of trope ontology. While the classical nominalist cannot carry his program through when it comes to explaining more complex statements the very same ideas survive in a trope-ontological environment. In order to see how this is possible consider the combination of trope ontology and class nominalism. The trope ontologist using natural classes will analyse sentence ($\star$) by saying that (each element of) the class of red tropes is more like (each element of) the class of orange tropes than it is like (each element of) the class of yellow tropes. The above argumentation against this analysis of ($\star$) in terms of classes of particulars is no longer valid. Even if we lived in a world where all the vegetation is red or yellow and all pieces of furniture are orange the class of red tropes is still more like the class of orange tropes than it is like the class of yellow tropes. In the context of trope ontology we are no longer forced to take a whole red thing into the class of red things but only its red trope which is a proper part of the whole red thing.

In a similar fashion the trope ontologist is able to analyse all kinds of complex statements which the realist about universals can explain and the classical nominalist cannot. David Armstrong classifies this third alternative as 'moderate nominalism'.[8] Trope ontology is moderate since it includes properties and relations into its ontological scheme. It is still closer to nominalism, however, than to realism about universals because only particulars are admitted since power properties are taken as particulars and not as universals. We thus almost have a middle ground between nominalism and realism about universals and this fact makes trope ontology so strong in its range of explanatory power.

Summing up one can say that there are at least four reasons for adopting a trope-ontological conception of the world. First, the gap between universals and concrete particulars is bridged by admitting properties as basic entities in the ontological scheme. This is achieved by letting properties enter as particulars and not as repeatable universals. Second, a middle ground between nominalism and realism about universals is found in virtue of which the problems of either side can be avoided while their respective achievements are retained. Third, as properties are empirically more basic and accessible than everyday things it seems natural to put these entities at the bottom of the ontology and not those more complex things which can be seen to be made up by them. Forth and last, the trope ontological scheme is very economical because there is just one main class or category of basic entities, viz. tropes.[9] These four reasons for adopting a trope-ontological account of the world are far less controversial than another feature of trope ontology which will be discussed in the following section, namely the bundling of tropes in order to get an object which can exist by itself. This much debated feature of trope ontology is of particular im-

[8] Armstrong (1989), p. xi.

[9] It is instructive to compare how economical different ontological conceptions are. In general one can say that the number of entities which belong to one category rises quickly the fewer basic categories of entities are assumed. It does not seem to be just a matter of inverse proportion.

portance in the context of the present study since the ontological status of universals as such is not the relevant question but rather the constitution of physical objects.

9.3 The Bundle Theory of Tropes

In its classical form[10] trope ontology is conceived as a *bundle theory.* Everyday objects as well as objects in scientific theories like elementary particles, molecules and genes are considered to be bundles of tropes, or bundles of bundles of tropes. In order to illustrate the strength of this assertion I will again give an example which is not quite right but which is sufficiently correct for the current purpose. According to the bundle theory of tropes, this particular cup *is* the bundle of this green, this roundness, this consistency, this gloss, etc. It is *not* said that we first have some kind of 'bare cup' and and than we can add its colour trope, its shape trope and so forth. When we take away all its tropes nothing is left no matter whether this taking away is conceived of as an actual process or mere abstraction.

Simons stresses that tropes should not be thought of as proper parts of the whole bundle.[11] Simons agrees with some other authors that to think of tropes as "ways something can be" catches the nature of some natural kinds of tropes better than thinking of them as things which are at the same place as parts of an object. However, Simons has various cautions to add. One of them is that these ways would have to be particularized ways since a trope ontologist cannot accept ways which are considerd as universals. The other and more important caution is about the view not to think of tropes as things at all. Simons argues, and I agree to him, that tropes are in

[10]Keith Campbell is probably the best-known advocate of the "traditional" bundle theory of tropes. To my knowledge Campbell's *Abstract Particulars* Campbell (1990) is the latest monograph on trope ontology. Earlier trope ontologists are G. F. Stout in the twenties and thirties and D. C. Williams in the sixties.

[11]For the details of his emphasis that tropes are not proper parts of the whole bundle see Simons (1994), pp. 561-565, as well as his book *Parts. A Study in Ontology* Simons (1987).

the end meant to make up substantial objects. If tropes are not somehow real entities, i. e. things, even if they cannot exist independently like substances, then how can something real arise by bundling tropes together.

To put the bundle view of objects in classical terms, we have no split-up into underlying persisting *substratum* on the one side and changeable *attributes* on the other side. The advantage of abandoning this division lies in the impression that the discrimination of substratum and attributes is artificial and derives primarily from the misguiding structure of most western languages. Although it is convenient to speak of something permanent and its changing properties it is dubious what this something is. It seems that it is merely a product of mental abstraction from all properties which has no real counterpart outside of our mind. It is a "something I know not what" (Locke) which is hard to grasp. This makes it understandable why it is so appealing to dispose of it.

However, trope ontology in its bundle version faces some questions which might not be easy to answer. What makes a bundle of tropes a bundle? The individuating power of the substratum has to be at least substituted in trope ontology. The traditional answer of trope ontologists is to postulate the so-called *compresence relation*. In virtue of this relation among the tropes of a bundle these tropes exist together to make up one unified object.

Postulating the compresence relation is not unproblematic for at least four reasons. First, it lowers the economy of trope ontology since one category of basic items, i. e. tropes, is not enough any more. Second, what kind of entity is the compresence relation? Is it not a universal? This would be embarassing for the trope ontologist since the abandoning of universals is his credo. Third, one could argue that this postulation is a costly or even unfair move. It could be compared to Carnap's reaction on Quine's assertion that the analytic/synthetic distinction is one of the two dogmas of empiricism. Quine argued that sentences like 'All bachelors are unmarried.' are neither analytic nor synthetic which shows that the whole distinction is rather a dogma than a fact.[12] In response, Carnap added

[12] "Two dogmas of empiricism" Quine (1951).

so-called meaning postulates like

> For all x it holds that if x is a bachelor than x is not married.

to the ordinary logical rules like the tertium non datur.[13] Including these postulates in the semantical system sentences like

> All bachelors are unmarried.

become analytic sentences. The postulation of the compresence relation may seem somewhat similar. The substratum is thrown out of the ontology since only something like the attributes, here the tropes, are needed. And then, suddenly the compresence relation is added. One could ask: is not compresence actually the same as the old substratum?

Fourth and last, one could go the opposite way and object that the introduction of compresence is a mere verbal trick. The question why tropes are together in a bundle is answered with recourse to the 'being-together-relation'. There seem to be only two ways out for the trope ontologist who postulates the compresence relation. Either compresence must be given up in favour of something else or it must be explicated and justified in a convincing way.

Another question to the bundle theorist of tropes concerns the transtemporal identity of a bundle of tropes. What ensures the identity of a bundle at two different times? This problem together with the status and explication of the compresence relation place a heavy burden on the bundle view of tropes and are not completely settled yet for my taste.

9.4 Evaluation

There are two very different reactions to the classical version of trope ontology and its problems. According to Johanna Seibt trope ontology only safes the core of substance ontology by getting rid of the traditional di-

[13] Carnap (1952)

chotomy between substance and attribute.[14] Seibt argues that trope ontology soothed the ills of substance ontology without going down to the root of the problems which she considers to be the basic role of particulars. While Seibt sees no hope for trope ontology the reaction of some trope ontologists could be put as acting according to the motto 'attack is the best means of defense'. C. B. Martin Martin (1980) as well as, more recently, Peter Simons Simons (1994) explicitly retained a substratum-attribute view in surprising divergence from the classical stance of trope ontologists which is usually in direct opposition to that of substratum theorists.[15] Simons' conception of objects is a combination of the bundle theory of tropes and the classical split-up into substratum and attributes. According to his view objects consist generally of two bundles of tropes although various deviations are allowed. One bundle comprises the essential tropes and serves as a substitute for the substratum. The other bundle includes the non-essential tropes. Details of Simons' account will be given later.

[14]In Seibt (2000), paragraph 4, Seibt argues that trope ontology fails to give satisfactory answers to *the* three basic ontological problems, i. e. the problem of individuality, the problem of universals and the problem of persistence. Note, however, that Seibt does not consider these problems to be specific for trope ontology. According to her view, all ontological concepts fail in the face of these problems as long as they adhere to the so-called "substance-ontological paradigm". It has to be stressed that the range of this paradigm is extremely wide in Seibt's assessment.

[15]In effect, a substratum-attribute version of trope ontology can already be found in the philosophy of John Locke as Martin and Armstrong have pointed out. Some details of this assertion can be found e. g. in Armstrong (1989), p. 63f. Note that Armstrong uses the term "*substance*-attribute view" for exactly the same theory (or theories) which I call "*substratum*-attribute version". The difference stems from my usage of 'substances' as 'independent concrete particulars' (see glossary).

Part V

Proposal for a New Ontology of QFT

Chapter 10

Dispositional Trope Ontology

10.1 Introduction

The last section of part IV dealt with trope ontology in general without fundamental reference to physics. As in the case of process ontology it is primarily for philosophical reasons that trope ontology has been established and it is mostly discussed in this context. In this chapter I wish to propose a trope-ontological account of QFT building on this philosophical foundation. My starting point will be an elaboration on an argument by trope ontologist P. Simons. He argued Simons (1994) that his "nuclear theory of tropes" can be used for the solution of a conceptual problem in quantum mechanics, namely the problem of the individuality of 'identical particles'.

My own proposal differs from and goes beyond Simons' ideas in a number of aspects. Simons' trope ontological attitude has arisen out of philosophical considerations (at least I suppose so) and, in the last decade or so, he has been checking the applicability and appropriateness of his approach in various special sciences, with physics being one among them. I am proceeding just the other way round. I start from a particular theory of one particular science, namely QFT, which - as I have argued in part II - I consider to be ontologically more fundamental than any other theory of natural sciences. In a second step I am looking for an ontological construal of nature which best fits this theory (i. e. QFT). So one can say that whereas Simons starts off being biased philosophically but neutral regarding single sciences, I start off being biased regarding the priority of single sciences and neutral with respect to ontological conceptions. Of course Simons and my biases have their respective basis.

I go beyond Simons in two further aspects. First, I try to be more explicit in specifying which are the fundamental tropes in the case of quantum physics. Second, my aim is to give this specification with respect to QFT and not QM as Simons does.

I briefly recapitulize the main ideas of trope ontology. I introduced trope ontology as a diplomatic way to handle the 'problem of universals' which mediates between extreme nominalism and extreme realism about the ontological status of properties. The treatment of properties is the salient feature of trope ontology. Properties are acknowledged as entities which really exist outside of our mind and which are not merely mental constructions or even just words. In this sense trope ontology deviates from classical or extreme nominalism and makes a concession to realism about universals by accepting the reality of properties. However, the trope ontologist still shares a (if not *the*) basic scepticism of the nominalist aginst realism about universals. Both classical nominalists and trope ontologists deny that properties are universals. The trope ontologist keeps the nominalistic attitude that it is inconceivable that properties are entities which exist outside of space and time and which can be multiply exemplified or instantiated. Both classical nominalist and trope ontologist think that all there is are concrete particulars, i. e. entities which occur only once (particulars) and which are at least in time and often in space as well (concrete).

Neverthess, as I indicated there is point where the trope ontologist diverts from the classical nominalist. The trope ontologist counts properties as concrete particulars as well. Note however, that while tropes have concreteness and particularity in common with everyday objects like this keybord, they differ from them in that their existence is strongly dependent on the existence of other entities, namely of other tropes. Other more common examples for strongly dependent entities are boundaries or states since they are necessarily the boundaries or the states of something. Generally, tropes cannot exist by themselves but can only occur in clusters of tropes. A cluster of tropes which makes up an independently existing object is called a bundle. The tropes of a bundle are related to one another in a certain way called compresence relation.

10.2 Dispositional Tropes of 'Many-Particle Systems'

Reading the titles of and in this and the next section might come as a surprise since it is about particles and fields. It was to be expected that a revisionary ontology differs radically from the conventional particle and field interpretatoin of QFT. However, one has to realize that trope ontology does not rest on the claim that there are no particles and fields if the world is properly conceived. All that the trope ontologist claims is that particles and fields and all other objects in the usual everyday sense are not fundamental. It is possible to further analyse these 'substances' until one reaches tropes at the very bottom. I will try to show how it works and which problems are solved in the domain of quantum physics.

10.2.1 'Elementary Particles'

By the somewhat misleading term 'identical particles' physicists denote sets of elementary particles like electrons and photons whose permanent (or essential) properties are exactly the same. In the domain of QM rest-mass, charge and spin are permanent properties. The introduction of spin is due to the fact that it turned out that it is necessary to ascribe a further *internal degree of freedom* to make sense of certain behaviour of quantum mechanical particles in inhomogeneous electro-magnetic fields. The qualification *internal* is opposed to external degrees of freedom like the three degrees of freedom corresponding to the three dimensions of space. For a first approximation one can image spin to refer to the angular momentum of a spinning charged ball. Note, however, that conceptual problems are involved with a too figurative understanding of spin. For our purposes it suffices to just keep in mind that the spinning bevaviour is essential for a quantum particle and labels some kind of intrinsic property.

Specifying a certain combination of values (m, e, s) for these properties fixes a particular *kind* of elementary particle. For an electron it would be

$$(m, e, s)_{electron} = (0.000511\,\mathrm{GeV/c^2},\ -1,\ 1/2) \tag{10.1}$$

where eV is the typical energy unit of high energy physics and the numerator c^2 stems from Einstein's equation $E = mc^2$, so that $\mathrm{GeV/c^2}$ has the dimension of mass. Note that 'mass' refers to *rest mass*, i. e. the mass which is measured when the particle is at rest relative the observer. Due to the special theory of relativity the *effective mass* of a particle diverges from its rest mass when the particle is in relative motion to the observer.

In order to fix one particular specimen of a kind of elementary particles one has to specify more than its permanent properties, however. It seems obvious that one way to do this is by supplying its location or through space and time. We can then say that we have, for instance, one individual electron here and another one there. Both have the same essential properties, since they are both electrons, but they have different locations and therefore they are two individual electrons.

Of course, things are not quite that simple in quantum physics since generally a quantum object has no exact position. Instead, the quantum mechanical wave function gives us probabilities for finding the object in a given volume. I will call these properties specified by the wave function as the 'relational properties' of the quantum object since they tell us how this object relates to the continuum of space and time. For an everyday object like a house such relational properties would the specifications of where it stands, how high it is, how deep it is etc.

10.2.2 Individuality of Quantum Objects

So far everything is fine. But things get more intricate when we consider two 'identical particles', say electrons, which have been in mutual interaction in the past. Due to their interaction they get into the so-called quantum mechanical 'entanglement', whose mathematical counterpart in QM is a superposition of wave functions. A collection of identical particles of the same kind which is in such an entangled state is called a *many-particle system*.

As I explained in section 3.1, experimental results about the statistical bevaviour of quantum mechanical many-particle systems require a certain symmetrical structure of the wave function which describes the state of a many-particle system. With respect to their statistical behaviour in a many-particle system quantum mechanical particles fall into two groups. The first group of particles behaves according to Fermi-Dirac statistics and they are therefore called *fermions*. The second group of particles behaves according to Einstein-Bose statistics and they are called *bosons*. Pauli's famous theorem about the connection of *spin and statistics* tells us that all fermions have half integer spin and all bosons have integer spin. Examples for fermions are electrons, all the six types of quarks and protons. They all have spin 1/2. Examples for bosons are photons and gluons, each with spin 0. Common gloss has it that all *matter constituents* are fermions and all *force carriers* are bosons.

The behaviour of fermions according to Fermi-Dirac statistics requires that the wave function of a many-particle system of fermions is *antisymmetric*. As an example I take the wave function of a system of two fermions (e. g. electrons) from equation 3.1 on page 37:

$$\Psi(x_1, x_2) = \frac{1}{\sqrt{2}}\Big(\psi_\alpha(x_1)\psi_\beta(x_2) - \psi_\beta(x_1)\psi_\alpha(x_2)\Big), \tag{10.2}$$

where $\psi_\alpha(x_1)$ and $\psi_\beta(x_2)$ are energy eigenfunctions of one-particle Hamiltonians and α and β represent sets of quantum numbers characterizing one-particle states. An antisymmetric wave function of a system of fermions is a superposition of product wave functions, i. e. a sum of tensor products of one-particle states. The requirement that this wave function is antisymmetric means that it has to change its sign when the labels '1' and '2' are interchanged. Intuitively this change of labels refers to a swapping of two particles since the labels '1' and '2' stem from the two separate particles we started with before they became to be involved in an entangled compound state. Note that the antisymmetry requirement for many particle systems of fermions has the effect that the antisymmetric wave function automatically fulfills the well-known *Pauli exclusion principle*. When the two electrons described by equation 10.2 were to occupy the same state the wave function of the compound state would vanish. That means there is no possible compound state where both electrons are in the same state.

The explanations I gave in the last paragraph are standard explanations one can find in later chapters of any standard textbook on QM. I recapitulated them because they make up a necessary step which one has to go and I don't see a better first introduction. Nevertheless, as I will try to show now the last paragraph contained various misconceptions. Although these problems I am alluding to are well known it is very hard to avoid speaking and even thinking in somewhat misguiding terms.

Since x_1 and x_2 are variables of the "single particles" 1 and 2 it is natural to ask what the states of these "single particles" are. It turns out that it is impossible to give a satisfactory answer to this question if one holds on to the conception of individual particles. Each "single particle" is in the *same* state as a part of the compound system even though in the wave function of the compound system *different* one-particle wave functions are used. In the following I will describe a way to prove this claim.

In the *Quantum Theory of Measurement* (see appendix A) there is an important procedure which goes back von Neumann. Given is a compound state after an interaction of two subsystems which are now entangled. This means that the compound state is superposition although it is a pure state. The question now is 'what can be said about the two subsystems?'. In which state are they? In the standard case of the Quantum Theory of Measurement the two subsystems are a measurement apparatus and an object system to be measured. Nevertheless the same procedure to be explained applies two any two entangled quantum systems.

The state of one subsystem of a compound system, let us call it W_1, can be determined by means of the following requirement: For any observable A the expectation value for measurements on the subsystem, say S_1, in state W_1 must be identical to measurements of the observable $A_{1} \otimes \mathbf{1}_{2}$ on the compound system, let us call it $S_1 + S_2$ in state Ψ. $\mathbf{1}_2$ denotes the identity operator in the Hilbert space of the second subsystem. Explicitly this requirement reads as follows:

$$(\Psi, A_1 \otimes \mathbf{1}_2 \Psi) = \mathrm{tr}\{A_1 W_1\}, \tag{10.3}$$

where 'tr' denotes the trace operator, which gives a number when applied to another operator. Note that W_1 is a density operator acting on a Hilbert space and Ψ a vector in a Hilbert space. These are two ways to describe states. However, whereas Ψ could be written in the form of a density operator, W_1 could not be written in the form of a state vector since it is a mixed stated. That W_1 is a mixed state is a major result of the utilization of requirement 10.3. W_1 is called a *reduced state* due to the reduction of the degrees of freedom of the second subsystem which is entailed by the requirement 10.3. W_1 is explicitly given by

$$W_1 = \mathrm{tr}_2 P[\Psi]. \tag{10.4}$$

I skip further details[1] and state the relevant outcome for the case of the 2-electron system. It turns out that the reduced states for the two electrons is identical. With this result we have a serious threat for the individuality of the two electrons. Since they are both electrons they have the same permanent or essential properties. So far there is no problem. But as individuals we would expect the two electrons to be different in at least some relational time-dependent properties (position, momentum) which in quantum physics are given by the state. We saw, however, that the states of the two electrons are identical. There is no property whatsoever that would allow to make a difference between these two electrons. It arises the question whether there are two individual electrons at all. This way of reasoning is known in philosophy as the *Leibniz principle of the identity of indiscernibles.*[2] When we start off with two things and there is

[1] See for instance Mittelstaedt (1998).

[2] Stöckler (1999) contains an up-to-date description and evaluation of this conceptual problem stressing the connection between the questioned individuality of quantum mechanical particles and the Leibniz principle of the identity of indiscernibles.

no ‘legitimate’ property in which they are discernible the Leibniz principle of the identity of indiscernibles says that there actually is just one thing. Formalized it runs as follows: $\forall x_1 \forall x_2 \big[\forall F \big(F(x_1) \Leftrightarrow F(x_2)\big) \Rightarrow x_1 = x_2\big]$.

Can one agree with the conclusion that we actually have just one electron in our system? No, we cannot. We know that we started off with two electrons and we know that the compound system has, for instance, twice the charge of an electron. We cannot be talking about just one electron. On the other hand it seems to be excluded that we have two electrons as well. So we have reached a certain stalemate. Which alternative we choose we get into trouble.

10.2.3 Dispositions and Tropes

I believe that the stalemate reached regarding the individuality of ‘identical particles’ as subsystems of many-particle systems can be solved elegantly within a trope-ontological construal of particles. As I indicated in the introduction to this chapter I am very sympathetic with a worked-out theory by trope-ontologist P. Simons.[3] In his *nuclear theory of tropes* Simons tries to combine advantages of substratum and bundle theories while avoiding the respective disadvantages. Simons’ nuclear theory assumes that objects are composed of a bundle of essential tropes (’nucleus’) and additional non-essential tropes. Tropes can be defined as individual property instances or dependent concrete particulars. The nucleus accounts for the individual nature of a substance and therefore has a similar function as a substratum.

When identical particles form parts of a compound quantum system, they simply cease to be independent substances. Their nuclear trope bundles rearrange to one new nucleus and since they were both bundles they can easily restructure. Different kinds of identical particles lead to different constraints for this rearrangement, namely to either symmetric or antisymmetric wave functions, as I explained in section 10.2. The advantage over a

[3]Most important for the present cpntext is Simons (1994). Valuable additional information can be found in Simons (1987), Simons (1998a), Simons (1998b), and Simons (1999).

substratum theory consists in the fact that once the old nuclear bundles are broken up and rearranged in one new nuclear bundle the question about the identification of the old substances in the new substance disappears. In a substratum theory, however, this question cannot be suppressed and leads to the described problems with the individuality of identical particles. If the substratum is to fulfil its role as an individuating basis of an object it would be strange if it could pop in and out of existence as is required for a satisfactory account of ‘identical particles’ as ‘parts’ of many-particle systems.

Let me say the same again with other words. The investigation of quantum physics tells us that quantum objects can quickly win and loose their status of independent concrete particulars, short of being substances. Let two electrons interact and form one compound 2-electron system and you loose two substances, the electrons, but you win a new substance, namely the 2-electron system. Perform a position measurement on this 2-electron system and, in the case of a detection of an electron, the 2-electron system looses its status of a substance while the measured electron becomes a new substance and with it a second electron becomes a substance as well. Note that it is not legitimate to say or to think that one of the original electrons has been measured and regained its status of a substance.

Now consider the classical substratum theory of substances and the trope bundle theory of substances, i. e. a theory where substances are analysed as bundles of tropes. The question is which ontological conception can explain the quick popping into and out of existence of substances most naturally. I believe that the trope bundle theory of substances rates far better than a substratum theory in this respect. Since substances are construed as bundles it is easily conceivable that these bundles can quickly be rearranged. Bundles are broken up and loose their status of substances. A different collection of tropes is bundled together and there we have a new substance. From the point of view of trope ontology these restructurings are do not appear mysterious. This is only the case when substances are taken as fundamental entities which cannot be analysed any further.

Dispositions

Since Carnap's *Logical Construction of the World* the definition of dispositional predicates has been a point of philosophical debate and the discussion is still going on. The starting point for the debate is the problem whether dispositions can be analysed within the language of extensional logic, first and second order logic. If dispositional predicates like 'water-soluble' are defined as material implications of the form "x is water-soluble ≡ if x is put into water, it will dissolve" we get a problem. According to this definition all objects have this disposition as long as it is not tested since an implication is true when its antecedens is wrong. Later it turned out that definitions in terms of possible-world semantics a la D. Lewis are very succesful.

Besides non-probabilistic dispositions like 'water-soluble' there are probabilistic dispositions to get a certain desease with a certain probability when living uder certain conditions. One question about probabilistic dispositions is whether the probability is due to our ignorance of all details, so that it is inappropriate to assign such a probabilistic disposition as a real property to an object. Opposed to these merely epistemic probabilities are objective or real probabilities which can actually been ascribed as properties of objects.

Quantum physics is a case where we are dealing with objective properties. An ignorance interpretation of quantum probabilities can be excluded.[4] So-called *non-objectification theorems* show that the assumption of a merely epistemic understanding of quantum probabilities leads to conclusions which are in contrast to very well-established experimental results. When in the following I use 'prob' as an abbreviation for 'probability' I am refering to these quantum probabilities which I assume to be attributable to single quantum objects. I thus understand quantum probabilities as objective probabilistic dispositions of quantum objects.

[4]This is only true as long as we stick to the standard formalism of QM. In Bohm's alternative version of QM the situation is fundamentally different.

10.2.4 An Example

I will use the following notation to speak about my ideas more explicitly. $[\cdot, \cdot, \cdot, ...]$ denotes the compresence relation which accounts for the tropes of a bundle being a bundle and not just an arbitrary collection of tropes. The '·'s stand for tropes. Their order is of no significance. I use $[\cdot, \cdot, ...|\cdot, \cdot, ...]$ to make an explicit distinction between essential and not essential tropes. This second bracket-notation therefore introduces a certain order. Tropes before the | are essential tropes, tropes after the | are non-essential tropes, i. e. [e-tropes | n-tropes]. Again, among essential tropes and non-essential tropes the order is of no significance. I will use a lower index at the compresence bracket - $[\cdot, \cdot, \cdot, ...]_{\text{object}}$ - to indicate which object these tropes make up. Remember that the claim of trope ontology is not that there are no objects in the usual sense (independent concrete particulars). What trope ontology claims is that such objects are not fundamental. They can be analysed in terms of tropes.

In order to make my proposal clearer I will supply an explicit example of how a bundle of tropes for an e-electron system could look like:

$$\begin{aligned} & [\text{e-tropes} \mid \text{n-tropes}]_{\text{'2 el.-syst.'}} \\ = \;& [m = 2\mathrm{m}_{\mathrm{el}},\ e = -2,\ s = 1 \mid \mathrm{prob(pos.)}, \mathrm{prob(spin)},\ \cdot\,, ...]. \end{aligned} \tag{10.5}$$

where prob(pos.) and prob(spin) are just two examples of dispositional tropes with an informal denotation. Note that I assumed the preparation of a particular spin correlation by choosing $s = 1$ for the compound system.[5]

To make things more explicit prob(pos.), for instance, would be given by

$$\mathrm{prob}^{Q}_{\Psi}(V) = \int_V dq\, |\psi(q)|^2, \tag{10.6}$$

where ψ is the spatial part of the '2-electron'-wave function Ψ, Q denotes the position observable and V a volume V which is a (Borel) subset of

[5]Note further that there is no mass defect as in the case of an atom where the mass of a nucleus is less than the sum of the masses of its constituents in isolation. While the mass defect is due to the binding energy of the nucleons the standard assumption for a many-particle system is that the particles are not in interaction.

$\mathbb{R}^3$. The expression 10.6 is to be understood according to the standard interpretation, i. e. it is the probability for detecting a particle if a suitable measurement is performed in volume V. The probability given by 10.6 comprises probabilities

$$\mathrm{prob}^Q_\Psi(N,V)_{N\in\{1,2\},V\in\mathcal{B}(\mathbb{R}^3)} \tag{10.7}$$

for detecting $N = 1$ or $N = 2$ particles in a position measurement. This means that the probabilities for $N = 1$ or $N = 2$ together have to sum up to unity for a disjoint partition of volumes.

What I indicated with 'prob(spin)' and '$\cdot, ...$' in the trope bundle 10.5 are the further terms for spin measurements, momentum measurements etc. One thing that 'prob(spin)' specifies are spin correlations in an EPR-fashion. The trope bundle 10.5 is thus to be understood as comprising an infinite number of dispositional tropes.

The given expressions are just meant to give a general idea of how things would run. I suppose that the details are largely a matter of further investigation. In particular, over- as well under-specification has to be avoided. Besides that the distinction into essential and non-essential tropes might not always be as easy as in the case of one elementary particle.

10.3 From Many-Particle Systems to Fields

As I have set out in sections 3.3, 3.4 and 4.2 AQFT is a conceptionally 'clean' axiomatic reformulation of QFT which, as I have argued, I consider to have a high value for ontological considerations. AQFT rests on the observation that two 'quantum field theories' are physically equivalent when they generate the same algebras of local observables. It is thus reasonable to take the algebras themselves as a starting point. These results indicate that the algebras of observables are ontologically more significant than those entities which appear as fundamental in the standard formalism of QFT. AQFT shows that Algebras of observables are sufficient as basic entities of QFT. No fields or particles are needed on this fundamental level. As explained earlier in more advanced axiomatic reformulations of QFT the *assignment* of local algebras of observables to space-time regions entails *all* the physical information. No other entities are needed.

Since I take AQFT to be more significant than QFT in an ontological sense I am particularly interested in the connection between trope ontology and AQFT. I think the abstract formula for a dispositional trope bundle in the language of AQFT would read as follows:

$$[\,\mathrm{AQFT}\ \,] = [[\mathcal{O} \mapsto \mathcal{A}(\mathcal{O})]_{\mathcal{O}\in\mathcal{B}(\mathrm{M})}], \tag{10.8}$$

where $\mathcal{O} \mapsto \mathcal{A}(\mathcal{O})$ is the mapping of space-time regions to algebras of observables measureable in that region and $\mathcal{B}(\textsc{m})$ denotes the set of all Borel subsets of Minkowski space-time M. Since the encoded physical information is probabilistic, the tropes are dispositional.

The compactness of this formula for a trope bundle in comparison to equation 10.5 shows how natural the trope-ontological approach fits AQFT. It contains properties like the *asymptotic particle content* which is of particular interest for the high energy physicist. Besides that, probabilities for all kinds of measuremnts are encoded in the above mapping.

10.4 Reconciliation of Theory and Experience

Non-Localizability, Unsharp Properties and Trope Ontology

From a philosophical point of view the most thought provoking concept in this model is that of *almost localized operators/observables* corresponding, in this context, to almost localized positions of the respective particles. In our detector model 'almost localized in a certain region' implies that all the rest of space-time still plays a role even if this can almost be neglected. However, for the bearer of the unsharp property 'almost localized,' this has an enormous consequence. It needs to be present in all of space-time because a property cannot be assigned in a part of space-time where the bearer of this property is not present. One can see this in the following way: The bearer, or 'substratum', of properties is by definition itself without any further properties. It gives only unity and individuality to objects. The substratum can begin and end to exist but since it is itself without any properties it is either fully there or not at all. This is the reason why the idea of the attribution of an unsharp position has such far-reaching consequences for the goal of describing particles within QFT. The bearer of the property 'almost localized' has to be uniformly spread out in the whole universe. This is effectively tantamount to a field ontology, the very opposite of trying to understand QFT in terms of particles. Thus in the course of trying to save the particle concept by introducing approximate localizability the problem comes in through the back door again.

One way to handle this situation is to take the use of unsharp properties as a mathematical trick to smooth over the transition from theory to pretheoretical conceptions of nature and to dispense with ontological considerations altogether. Instead of that I wish to propose an alternative ontology for unsharp properties.

Obviously the very question of how an unsharp property can be attributed to the bearer of this property presupposes that properties always have to be attributed to something underlying, i. e. to a substratum. In the light of trope ontology, however, our problem vanishes. The unsharp property needs not be attributed to a substratum. A trope ontologist is therefore not forced to assume a particle to be equally present in all of space-time. Objects which are constituted by bundles of tropes are only as much present in a region of space-time as the respective properties are present. We thus have a way to maintain the view that QFT speaks about particles, leaving the question of individuality aside. The price, however, is that one has to drop a basic assumption of the usual account of particles, the assumption of a propertyless bearer of properties.

As a piece of descriptive metaphysics a trope ontological account of the emergence of particles in QFT is more appropriate than a substratum account: firstly because it makes much more sense of 'almost localizability' and secondly because it takes seriously that QFT effectively has only access to properties while the direct appearance of individual particles via particle labels in tensor products is purely conventional.

Finally I want to mention that there is a further logical alternative to understand an unsharp property, viz. that it is a sharp property which is only attributed in an unsharp fashion. This alternative sounds compelling but turns out to be hard to grasp on second thought. One should think that something either has a property A or it does not and if it seems that it has the property A only approximately then what one should really be saying is that it actually has a property other than A, say $A^\star$. In that case $A^\star$ is only very similar to A and it is hard to see or to understand $A^\star$ without mentioning or thinking of A.

10.5 Summing Up

I hope to have successfully argued that my proposal of a dispositional trope theory is particularly appropriate as an ontology of QFT. I have pointed out that a dispositional trope ontology suggests itself when looking at that formulation which is most significant in an ontological sense, namely AQFT.

Besides the immediate naturalness of a trope-ontological understanding of QFT in its algebraic formulation, two specific ontological problems could be solved. Both of these problems have the same structure: Although one should like to see a many-particle system as just one object or substance and although one would in general like to ascribe an unsharp localization to particles both manoeuvres are impossible as I have argued. I could show that the situation changes on a trope-ontological background. Now both wishes can be fulfilled due to a change in the ontological attitude.

A more detailed account of how dispositional trope ontology can foster a more natural understanding of QFT will be given in the following conclusion to the whole thesis.

Part VI

Conclusion

Chapter 11

The Interplay of Physics and Philosophy

I begin my conclusion with some remarks on the relation of physics and philosophy when ontological questions are under consideration. If only a fraction of my investigations have been convincing they should yield ample evidence for the theses I will lay out in this chapter. In short, I claim that neither philosophy alone nor physics alone are in a position to paint a coherent picture of the general structure of the physical world that takes all relevant knowledge into account which is available today. Note, however, that this claim is *not* meant to imply that physics and philosophy could not be pursued without taking notice of each other. All I want to argue for is that getting a comprehensive idea of the physical world on an up-to-date level of discoveries necessitates a cooperation between physics and philosophy.

Investigating the most general structures of what there is in the world two extreme ways can be chosen and often are chosen. One of them is deeply rooted in the tradition of philosophy from ancient and medieval times to modern rationalism and idealism until the twentieth century. Proponents of this way foster the idea that the structures of being qua being can be investigated by pure thinking in an a priori fashion. Some take a more modest stance and concede the necessity for at least some intuition or everyday experience. Nevertheless, defenders of the (quasi-) a priori tradition of ontology imagine their results to be immune against any specific scientific results.

Opposed to this first way of investigating the most general structures of being is a second one. Proponents of this second way to ontology claim that *only* specific sciences, in particular natural sciences, are in the position to say anything about the basic entities there are and their irreducible characteristics. They contend that purely philosophical considerations on ontology are fruitlessly speculative and ill-founded and have no value in the light of 'real scientific findings'. This pejorative stance towards ontology as a philosophical discipline has found emphatic support within some philosophical schools as well. Most notable are the British Empiricists in the seventeenth and eighteenth century and the Logical Positivists in the twentieth century.

I believe that there is some truth to be found in both ways but that they can profit from each other and even need each other eventually. Using a similar statement by Kant I think that with respect to ontological questions 'philosophy without sciences is empty and science without philosophy is blind'. I will try to give explanations for both sides of this claim.

Why does philosophy depend on sciences when ontological matters are treated? I think that philosophy can get substantial results about our everyday ontological thinking and can uncover some hidden assumptions of our way to conceive of the world. However, when it comes to more fundamental questions about the ontological structure of the world apart from our possibly changing ways to think about it in everyday terms, it seems to me that philosophy alone comes to an end. All philosophy can do here, I believe, is to lay out a matrix of ontological options. In some cases it will be possible to exclude some of these options for internal reasons. In general, however, things are not so easy. I have the impression that most ontological conceptions have their merits with respect to those aspects which gave rise to their establishment while they have their weak points in other respects. In a situation where each conception has its successes but carries the burden of anomalies or unsolved problems as well an evaluation of different aspects becomes pivotal.

How can physics profit from philosophical considerations about ontology? Probably the most important benefit for the physicist is not one that would help with his work. Nevertheless, I think ontological considerations can be helpful as heuristics when a theory is not completed yet as in the case of QFT due to the so far unsuccessful incorporation of gravitation.

Chapter 12

Evaluation and Comparison

12.1 General Remarks

The investigation in this thesis can be devided into two main parts. The first part consists of general ontological considerations and their foundations in philosophy as well as quantum physics. The second part contains investigations of some either important or promising ontological approaches to QFT. The considered approaches have emerged partly in physics and partly in philosophy. Likewise, the arguments for their evaluation came in some cases from philosophy and in other cases from physics.

Philosophical investigations about QFT form a relatively new area of philosophical research compared to similar studies in the philosophy of science and of course even more so with respect to general philosophy. Nevertheless, philosophical questions about QFT do have a tradition both in regard to methods and contents. As I have laid out in chapter 1 this two-fold anchorage in tradition applies to the history of general philosophy as well as to modern philosophy of science.

With respect to the history of general philosophy the most prominent forerunner to questions about the ontology of QFT happens to be the same regarding methods and contents, namely the history of atomism. As regards contents the debate about atomism is the historical forerunner of ontological considerations about QFT since the atomistic point of view rests on the assumption that all natural phenomena can be reduced to a set of basic indivisible building blocks, namely the atoms. (Note that what we denote as atoms today are of course no candidates for the atoms of atomism.) The same program of reduction has always been at the core of QFT and naturally this holds for attempts of ontological analyses of QFT as well. As we saw in chapters 9 and 10 on trope ontology 'reduction to a set of basic entities' must be understood in a very wide sense since some revisionary ontologies like trope ontology strain the limits of this notion of reduction. Nevertheless, I rate trope ontology to be within the limits of the reduction program.

As regards methods the development of atomism can be seen as a forerunner of ontological investigations about QFT for one general and one more specific reason. The general reason is that the development of atomism displays an interplay of physics and philosophy (to the extent that one can speak of two separate disciplines at all) which has gotten closer over its history. I have pointed out in chapter 1 that from ancient times to the middle ages the focus shifted from atomistic speculations as an aim in itself to the search of pragmatic explanations of natural phenomena on the basis of atomistic theories. The more specific reason why the debate about atomism is a methodological forerunner of the ontological analysis of QFT is that in both cases, atomism and QFT, the program of reduction to a set of basic building blocks was a very fruitful heuristic. It is one of the spectacular successes of QFT to correctly predict the existence of previously unknown particles on the basis of systematical reduction schemes.

In my main study three general kinds of arguments (which can be either positive or negative) occured. The first kind of arguments are primarily philosophical. They refer to questions of consistency, simplicity, scope etc. The second kind of arguments are those which are mainly grounded in physical requirements, such as relativistic covariance or independence from the frame of reference. It turned out, however, that a third kind of arguments is predominant in the ontological analysis of QFT. These are arguments which cannot be construed as having separable philosophical and physical components. In these cases a physical argument can radically change its significance when different ontological approaches are considered. Arguments concerning non-localizability and unsharp properties are among the most important examples.

12.2 Comparison of Ontological Approaches to QFT

12.2.1 Particles Versus Fields

I begin my final evaluation and comparison of the considered ontological approaches with the seemingly clearest result. Various arguments were marshalled in chapter 6 which put a heavy pressure on a particle interpretation of QFT. It was demonstrated in chapter 3 already that the formalism of QFT allows for the "*creation and destruction of particles*". If particles are considered as the "substances of the world" (Armstrong) then the possibility of a creation and destruction of particles would spoil the whole conception. After all, as I have argued, the notion of substance is meant to ensure the very possibility of cognition in a changing world by reference to something stable and independent. Entities which simply pop into and out of existence do not fit this picture very well, to say the least.

One could argue that the expression "creation and destruction of particles" is just a figurative way of talking about a certain piece of formalism rather than an ontologically significant statement. However, the same stance would then have to be valid with respect to N-particle states as well and this would imply that N-particle states have nothing to do with N particles. This would mean that degrading "creation and destruction of particles" to mere figurative talk is like throwing out the baby with the bathwater. Nothing is gained for the particle interpretation on this way.

Some further problems for a particle interpretation of QFT were introduced and discussed in section 6.4 to the effect that the particle number is not an objective feature of a physical system. One of these problems is the possibility of a *superposition of particle states with different numbers of particles*. Although it first appears like an embarrassing fact for the particle interpretation it can probably be at least weakened by a proponent of this view. He can argue that the possibility of counter-intuitive superpositions (see Schrödinger's cat) is rather an odd trait of quantum physics than a peculiarity of the particle interpretation. In the light of my arguments in section 10.3 I would back this general line of reaction by pointing out that quantum physics is inherently dispositional.

Nevertheless, it is again not clear whether it would actually be a wise move by the particle ontologist to defend himself by reference to the dispositional character of the quantum world. As I have argued in chapter 10 I think that not all ontological approaches can handle the dispositional nature of quantum theory equally well. I will come back to this point when discussing my own proposal of a dispositional trope ontology.

I wish to add a general remark. The evaluation of arguments against the tenability of a particle interpretation of QFT displays a characteristical feature which we will encounter again in other discussions. There are some traits and problems of quantum theory which tend to pop up in disguise and notoriously cause trouble. Such issues are for instance the quantum measurement problem, the dispositional character of properties and the emergence of classical properties which are all closely related to one another. My point now is that reference to these problems must not in itself make up a good argument against a particular ontology. Since these problems are either yet unsolved in general or something we have simply not quite get accustomed to, no single ontology should get all the blame.

However, the extent to which a general quantum feature is a problem can depend on the context, in particular on the ontology one has adopted. One and the same feature can be completely against the spirit of one ontology whereas it can be incorporated rather naturally into another ontological scheme. I think that the possibility of a superposition of particle states with different numbers of particles is such a feature which is against the spririt of a particle interpretation.

I discussed some further results in section 6.4 which can all be seen as demonstrations for the non-objectivity of the particle number of a physical system. The best known of these results is the existence of *vacuum fluc-*

tuations, i. e. local deviations from the global particle number zero. The second result was the *Unruh effect* which shows that the particle number is not independent of the state of the observer. The third of these results comes from the study of *QFT in curved space-time* and indicates that the existence of a particle number operator is a contingent property of the flat Minkowski spacetime. At least the first two apparent problems for a particle interpretation can be challenged (and were challenged, e. g. by P. Teller) in the same way as the above argument regarding the superposition of particle states with different numbers of particles. Naturally, the corresponding counterargumentation can again be used as well.

Instead of elaborating on this discussion I will now leave the problems of the particle interpretation of QFT which are connected with the particle number in favour of a different problem which might be particularly devastating for the idea of a particle as basic entities, namely the problem of non-localizability.

Over a little more than the last two decades a number of results have been produced which purport to demonstrate an unavoidable *clash of causality and localizability* when quantum theory is considered in a relativistic setting. Most notable of these are theorems by Hegerfeldt, Malament and Redhead. It is immediately clear why so much notice has been given to these results in ensuing discussions. Provided that the general line of interpretation given by the above-mentioned authors is correct, then particles could not be localized in any finite region of space-time, no matter how large it is. While it is obvious that the notion of a point particle is just a mathematical idealization, the smearedness of particles over *all* of space-time seems to stretch the idea of a particle beyond its limits.

In section 6.3.2 I compared the theorems by Malament and Redhead in detail. It turned out that both theorems are equivalent although their appearances, their starting points, the formalism and mathematics used as well as the final conclusion drawn by the respective authors are quite different. Besides the in itself interesting fact of the equivalence of these results my comparative study effected a closer look at the respective assumptions and conclusions. Intuitive notions became explicit and could be given a second, more sceptical look.

As with the evaluation of arguments concerning the objectivity of the particle number, the evaluation of arguments concerning the non-localizability of particles does not have as straightforward an impact on the tenability of a particle interpretation as it first appears. Locating the origin of non-localizability is more delicate than one might expect. I think that the conclusion that non-localizability speaks against the tenability of a particle interpretation is *a* legitimate way of interpretation. However, it is not *the* one and only legitimate way. There are some other alternatives left.

I have considered other reactions to the problem of non-localizability which see its core not as a problem for a particle interpretation but rather as evidence the concept of sharp localization itself is flawed. When discusssing my own proposal for an ontology of QFT in subsection 12.2.3 I will argue for still another line of reaction to the problem of non-localizability. In short I will show that it depends on your ontological assumptions whether or not non-localizability is fatal for a particle interpretation.

On the other side it was pointed out that the particle interpretation of QFT is an option which one is not easily willing to surrender. After all, QFT rests on experiments with colliding particles. How can it be that the theory corresponding to these particle experiments tells us that there are no particles? Although this looks like a strange conclusion it is not absurd. It is perfectly possible that the impression that we have observed collisions of particles was deceiving. Like many other scientific observations the 'observation' of elementary particles is a highly interpretive business.

Whereas a particle interpretation of QFT is confronted with various direct arguments against its tenability a field interpretation has a very different kind of trouble. It is not even clear what to argue against. As I pointed out the first immediate reason why QFT is often considered as a field theory is the occurence of quantum fields in the formalism of QFT. However, this does not lead to a viable conception of fields as the basic entities of QFT. 'Quantum fields' cannot be taken as these basic entities because they yield something physically real only together with the state vector. This problem cannot be cured by taking the state vector as a field as well because it is a fundamentally different kind of quantity.

The other line of argumentation in favour of fields takes all arguments against a particle interpretation as evidence for a field interpretation which is tacitly taken to be the only alternative. However, this line of argument is even less apt to specify what these fields are. As I will explain later, I think there is a more promising way to handle arguments against a particle interpretation.

12.2.2 Processes Versus Tropes

Formulating my final judgement when comparing process and trope ontology is an easy task. Process ontology might be apt to solve a number of conceptual problems which bar an ontological understanding of QFT. But I think that it is simply not necessary to go through such a radical revision of our ontological schemes to tackle these problems. I believe that with respect to QFT a trope-ontological account has the same problem-solving potential with much lower 'revisionary expenses'. Whether or not internal philosophical considerations will in the end speak in favour of process ontology is a question I am not addressing here. As far as I know the arguments the race has not yet come to an end.

The idea of trope ontology is to analyse ordinary objects, like a chair or an electron, in terms of bundles of properties. However, and this is the main point, properties are taken as concrete particulars and not as universals which can be realized (or instantiated) many times. In order to express this difference to the standard view the trope ontologist denotes properties as *tropes*. Although tropes are now classified as concrete particulars there is an important difference to those objects which are commonly thought of first when speaking about concrete particulars. In contrast to these ordinary objects tropes cannot exist by themselves. Tropes are *dependent* concrete particulars which can only exist in bundles together with other tropes.

Despite of the figurative talk of 'bundles' tropes should not be conceived as proper parts of a bundle. It would obviously leed to contradictions to think of a charge trope as a proper part of the bundle of tropes which makes up an electron. Instead of being in a part-whole relation the tropes of a particular bundle stand in the so-called *compresence relation*. It seems best not to construe this relation as a further real entity besides the tropes of that bundle but rather as an internal relation which expresses how the tropes of a bundle necessitate each other.

I have argued that I consider a trope-ontological account of QFT to be superior to the other options. In order to justify that claim I have proposed a new ontological construal of QFT in terms of dispositional tropes. The contents and merits of my proposal will be summarized in the next subsection. Since a treatment of the notions of particles and fields is an integral constituent of my argumentation for a dispostional trope ontology the summing-up of my proposal contains my final evaluation of particle and field ontologies as well. The concluding subsection is therefore tantamount to a comparative judgement about the the ontological options considered in this thesis.

12.2.3 The Merits of Dispositional Trope Ontology

Trope ontology is a revisionary approach which claims that the ontologically most fundamental entities are not those objects which are commonly taken to be fundamental. In trope ontology it is claimed that tropes are the most basic. On the one hand this claim should not be read as the assertion that e. g. electrons do not really exist since only tropes have true existence. All that trope ontology claims is that objects like electrons can be further analysed. On the other hand the idea of an analysis of ordinary objects in terms of bundles of tropes is different and in a sense more radical than the idea that it is possible to further divide electrons and quarks, e. g. into superstrings.

The main idea behind trope ontology is the view that the standard conception of objects as such is misconceived. The stance of trope ontology is directed against a widespread and and mostly unrecognized construal of objects (or substances) into an invariable substratum on the one side and properties on the other side. As I have argued in a number of contexts it seems to me that it is this (mis-)conception of objects, to which particles and fields count, which is responsible for various problems which particle and field interpretations of QFT are confronted with. I will give two important examples.

As I have set out the study of many-particle systems of quantum mechanical 'identical particles' revealed a serious problem for the idea of individual particles and therefore for a particle ontology in general. My point is now that these problems stem from the conception of a substance, here a particle, as somehow composed of an underlying substratum and its properties. One would like to say that once identical particles come together (via mutual interaction) to form a 'many-particle' or compound system there are no individual electrons any more. The is just one substance, namely the whole system. As I have argued I consider this to be mere rhetoric as long as one holds on to the substratum/properties-view. This gloss cannot bar the question where the 'old' substrata of the single electrons have gone.

Within a trope-ontological scheme the same gloss of the 'many-particle system' being just one substance is more than rhetoric since it can be given a natural explanation. The bundles of the former single electrons have been 'restructured' to form one new trope bundle. In contrast to this explanation the corresponding explanation within the substratum view is far less convincing because the 'comprehensive' substrata of the former electrons are to rigid and 'block-like' to allow for such a restructuring.

Now I come to the second example of an issue where I have argued that the problems have their origin in the misconception of an object as composed of a substratum plus its properties. I am talking about the apparent non-localizability of particles and the notion of unsharp properties as a way to handle these problems. I have set out that within a substratum framework the introduction of unsharp properties does not solve anything. The basic problem is just pushed to a different place. In order to ascribe an unsharp localization to an object, the bearer of this property, i. e. the substratum, has to be present in the whole universe. Since the substratum is so block-like nothing is gained. The substratum has to be assumed as equally present in the whole space.

I have argued that a trope-ontological conception of objects sheds a very different light on unsharp localization. In a trope-ontological framework an unsharply localized object is just as much present in a certain region as the unsharp localization property tells. This would mean that the concept of unsharp localization unfolds its merits only when objects are construed as bundles of tropes but not when taken in the standard substratum view.

The last point of my proposal for an ontological understanding of QFT to be mentioned again here concerns the nature of tropes which I take as the fundamental entities. I have set out that since QFT is an inherently probabilistic theory this salient feature has be reflected in its ontology as well in terms of dispositional tropes. This is one of the two contexts for which I have introduced Algebraic QFT (or short AQFT) which is a conceptually 'clean' axiomatic reformulation of QFT. I have shown that a *dispositional trope ontology* is the most natural ontology for AQFT which almost immediately suggests itself. In AQFT all the physical information about a quantum object is encoded in a certain nesting of algebras of observables. AQFT can be seen as a theory purely in terms of dispositions. And since there is nothing else than these dispositions I have argued that it is best to conceive of them as tropes.

The punchline of my own proposal for an new ontology of QFT runs as follows. Both a particle and a field interpretation of QFT do have a certain legitimacy and neither can be refuted conclusively. However, I have argued that both particles and fields should not be taken as fundamental in an ontological sense. In the approach I propose *dispositional tropes* are the basic entities out of which everything is composed. Arguments against a particle and a field interpretation of QFT can thus at least be weakened although there is a price one has to pay: It is acceptable to speak and think of particles and fields provided one does not take them as being fundamental.

Personally, I suppose that questions concerning the ontology of QFT are doomed to the same fate as questions concerning the quantum measurement problem: If our questions should ever come to an end the final solution, I believe, will neither be beautiful nor will it be accompanied by an alleviating eureka. I rather expect that we might in the end, at least partly, simply get accustomed to different ways of thinking which dissolve rather than solve our problems.

Part VII

Glossaries

Physics Glossary

Algebra Linear space over field of complex numbers $\boldsymbol{C}$, provided with an associative and distributive (in general non-commutative) multiplication. Haag and Kastler (1964) p. 856; Horuzhy (1990), p. 5.

Bounded Below An operator A is said to be *bounded below* if there exists a number k such that $(\phi, A\phi) \geq$ k for all unit vectors ϕ in the domain of A.

Causal statistical independence Existence of certain product states. Buchholz and Yngvason (1994), p. 4.

C*-algebra Haag and Kastler (1964), p. 857.

(weak and strong) Einstein causality Busch (1999), p. 6538 is a modern account.

EPR See Redhead and Wagner (1998), p. 2; Wald (1986), p. 293.

Isotony property Set of observables increases with the size of the localization region. Buchholz (1998), p. 4.

Local commutativity 'Local commutativity' is here used synonymously to the term 'locality'. Both denote the commutation of operators/observables which refer to space-time regions which are spacelike separated from one another. The postulation of 'local commutativity' or 'locality' respectively is the central condition of AQFT. It states the *statistical* independence of measurements in spacelike related regions of space-time. See appendix B.

N-particle state An N-particle state (where N is a positive integer) is the eigenstate of the number operator corresponding to its eigenvalue N. The conventional but problematic gloss is that an N-particle state is a state where N particles are present See page 40.

Observable Equivalence class of observation procedures. Haag (1996), p.7 fn.

Primitive causality Equations of motion are hyperbolic. Buchholz and Yngvason (1994), p. 4; Horuzhy (1990), p. 14ff.

Operator The characteristic feature of operators which distinguishes them from ordinary numbers, which are scalar quantities, lies in the fact that two operators in a product can generally not be switched without changing the product. When Heisenberg recognized this peculiar behaviour of “quantum numbers” he did not know that there is a whole field in mathematics which is concerned with such entities, namely the theory of operators within functional analysis. Today functional analysis is an important prerequisite for any physicist working on the foundations of quantum physics.

Pure state A pure quantum state is a maximal set of information or properties respectively which can be ascribed to a quantum object. It is a characteristic feature of the quantum mechanical state that it can never contain answers to all possible experimental questions.

'Quasilocal' or 'global' observable Obtainable from local observables by limiting operations. Horuzhy p. 3 fn., Haag, p. 109, Redhead 95, p. 125.

Topological charge Refers to the topological structure of space-time. Horuzhy pp. ix f., 157f., Haag, p. 153 and ch. IV.3.

Unitary Equivalence Haag, p.1.

Vacuum correlations Fredenhagen 85, p. 461, Wald 86, p. 300

Vacuum state The vacuum state is the eigenstate of the energy operator with the lowest eigenvalue, i. e. the lowest possible energy. Note that it is characteristic of quantum physics that the lowest possible energy of a quantum system is not zero. The label 'vacuum state' stems from the fact that the vacuum state is also the eigenstate of the number operator corresponding to the eigenvalue 0. This fact explains the common but problematic gloss that the vacuum state is the state with no particles present. See section 6.4 for some surprising problems of this gloss.

W*-algebra W: alg. closed w. r. t. **w**eak limits, *: stable under taking adjoints Buchholz (1998), p. 4, f.n.

Weak additivity Spacetime is homogeneous, no phenomena like minimal length exist. Horuzhy, p. 13.

Wedge Image of the set $\{|x^0| < x^1\}$ under a Poincaré transformation. Fredenhagen 85, p. 461.

Suggestions for further reading. Further details can be found in Baumgärtel (1995), Bjorken and Drell (1967), Bogoljubov and Sirkov (1984), Mittelstaedt (1989), Reed and Simon (1980), Reed and Simon (1975), Ryder (1996), Weinberg (1995) and Weinberg (1996).

Philosophy Glossary

Concrete Concrete objects have at least a temporal location, as the summer of 1969, and mostly have a spatial location as well.

Dependent Something is dependent when it cannot exist of itself. For more details see section 5.3 and for the distinction of different senses of (in-)dependence see Simons (1998a), p.236.

Nominalism Denies the existence of universals.

Ontology Details can be found in section 2.

Particular See 'universal'.

Substance The expression 'substance' as used in this study indicates an *independent concrete particular*. This matches Aristotle's (primary) original use of 'substance' in the *Categories* for which a particular horse or a particular human being are prime examples. It deviates, however, from Aristotle's later use in the *Metaphysics* where substance or *ousia* is identified with the individual form of a concrete particular. Substance understood in this way only makes up a concrete particular together with matter which is not part of the substance in this second sense of substance. In the later philosophical tradition a third usage of substance was very important, namely substance as the 'factor of particularity' (Locke) in things as opposed to their properties. This third usage of 'substance' is synonymous to *substratum*. For more details see chapters 2, 5 and 9 in this thesis as well as Hoffmann and Rosenkrantz (1997), Loux (1998), chapter 3 and Simons (1998a).

Substratum In various ontological approaches a substratum is assumed which is responsible for the individuality of a concrete particular. Since one gets to the substratum of an object by abstracting from all the object's properties the substratum is sometimes called *bare particular* (Gustav Bergmann). If Aristotle's later identification of a substance with the form of an individual is taken to mean a universal form then *prime matter* would take the role of the individuating substratum. This interpretation of Aristotle is controversial, however. See section 5.2 for a different interpretation. Substratum theorists commonly take the individuating power of the substratum to be irreducible. For details see Armstrong (1989), p. 60 f, Loux (1998), chapter 3 and Simons (1998a), p. 237.

Trope A trope is an *individual property instance* or a *dependent concrete particular*. This is the same terminology as in Simons (1994). K. Cambell characterizes tropes as *abstract particulars* where 'abstract' (as opposed to concrete) is his usage means '(capable) incapable of independent existence' Campbell (1990).

Universal A universal/(opposite: particular) can/(cannot) be multiply instantiated or exemplified.

Part VIII

Appendices

Appendix A

The Quantum Theory of Measurement

The Quantum Theory of Measurement is based on the assumption that quantum mechanics can be applied not only to the object of the measurement but also to the measuring apparatus. The first such attempt goes back to John von Neumann von Neumann (1932) who tried to analyze the quantum mechanical measurement process. The two main constituents of the quantum mechanical measurement process as it is seen today are (i) premeasurement and (ii) objectification.

Premeasurement *Premeasurement* denotes the transition of the initial state $|\psi\rangle := |\varphi_S\rangle \otimes |\phi_M\rangle$ of the system S to be measured and the measuring apparatus M to the entangled compound-state $|\psi'\rangle := U|\psi\rangle$ after an interaction described by the unitary operator U for the time evolution of $S+M$. The expression "pre- measurement" is meant to emphasize the fact that for a complete measurement the objectification is still missing because the premeasurement does not lead to a definite result.

The evolution operator U should fulfill the *calibration postulate*: If S is already in an eigenstate of the observable to be measured then a measurement should with certainty lead to a corresponding result. In the case of a position measurement an evolution operator that satisfies this requirement is

$$U = e^{-\frac{i}{\hbar}\lambda Q_S \otimes P_M} \tag{A.1}$$

where Q_S is the position operator of S, P_M the momentum operator of M and λ a so-called *coupling constant*. A short and simplified (because the following $|q\rangle$ is not an element of the Hilbert space) calculation demonstrates the effect of U with $|q\rangle$ being an "eigenstate" of the position operator of S:

$$U\Big(|q\rangle \otimes |\phi_M\rangle\Big) = |q\rangle \otimes |\phi_{\lambda q}\rangle$$

where

$$\langle r|\phi_{\lambda q}\rangle \equiv \phi_M(r - \lambda q) \quad \Big(\phi_M = \phi_M(r)\Big), \tag{A.2}$$

since the momentum operator is the generator of a translation. One can see that U shifts the wave function of M by an amount proportional to the measured eigenvalue q, i.e. the position of S with λ as the factor of proportionality. If $|\varphi_S\rangle$ is not an eigenstate of Q_S, the general case, one gets a corresponding result after an expansion of $|\varphi_S\rangle$ with respect to $\{|q\rangle\}_{q\in\mathbb{R}}$:

$$|\psi'\rangle \equiv U\Big(|\varphi_S\rangle \otimes |\phi_M\rangle\Big) = \int_{\mathbb{R}} dq\, \varphi_S(q)|q\rangle \otimes |\phi_{\lambda q}\rangle. \tag{A.3}$$

The *shift operator* U was constructed for the purpose of fulfilling the calibration postulate.

Objectification A major problem in the Quantum Theory of Measurement is a theoretical explanation of how objective outcomes of quantum mechanical measurements are possible. All that can be described within quantum theory in Hilbert space is the transition from the initial states of the measured system S and the measurement apparatus M to the corresponding *mixed states* W_S and W_M after the measurement interaction when S and M are described separately. This fact constitutes a severe problem for the description of a real measurement since the mixed states W_S and W_M do not admit an ignorance interpretation, i.e. it is not allowed to assume that the system in question is in a certain state which is, however, not known to the observer.

In order to cope with this situation the working physicist uses the so-called *projection postulate*. According to this postulate after the measurement the system S is in a state which corresponds to the measured x-interval. It is obvious that the projection postulate is in conflict with the impossibility of an ignorance interpretation for the mixed states W_S and W_M.

Appendix B

Assumptions of AQFT

The basic structure upon which the assumptions or conditions of AQFT are imposed is the following:[1]

- $\{\mathcal{O}_i\}$ Bounded open regions in Minkowski space-time M.[2]
- **Local observables:** Hermitian elements in local (non-commutative) von Neumann-algebras $\mathcal{A}(\mathcal{O}_i)$, which are subsets of $\mathcal{B}(\mathcal{H})$, i. e. the set of all bounded operators acting on Hilbertspace $\mathcal{H}$.[3]
- **Physical states:** Positive, linear, normalized functionals ω on $\mathcal{A}$ which map elements A of local algebras to real numbers, i. e.

$$\omega : A \mapsto \omega(A),$$

[1]Apart from the works cited in footnote 13 see Redhead and Wagner (1998) and Buchholz (1994) for brief but nice expositions of the assumptions in AQFT.

[2]It is a matter of convenience and convention to consider only open regions. One could just as well take just closed regions (as some authors do). To consider both would be superfluous recognizing that the observables in an open region $\mathcal{O}_i$ will determine the observables of its closure $\overline{\mathcal{O}_i}$ as well.

[3]The exclusion of unbounded operators might worry since important observables like position and momentum are obviously unbounded. However, this constitutes no actual restriction to the generality. The reason is that an unbounded operator can be represented by the family of its spectral projections which are bounded operators. It has to be mentioned, however, that this escape leads to a certain ambiguity of the description. For details see e. g. Horuzhy (1990), p. 10.

where $\omega(A)$ is the expectation value of A in state ω.

Relativistic Axioms

(i) **Locality:**

$$\text{If } \mathcal{O}_1 \subset \mathcal{O}_2', \text{ then } \mathcal{A}(\mathcal{O}_1) \subset [\mathcal{A}(\mathcal{O}_2)]',$$

where $\mathcal{O}'$ denotes the set of all points which are spacelike separated from all points in $\mathcal{O}$ and $[\mathcal{A}(\mathcal{O})]'$ the set of all operators (in $\mathcal{A}$) which commute with all operators in $\mathcal{A}(\mathcal{O})$.

The assumption of locality (or 'spacelike commutativity' or 'Einstein causality' or 'microcausality') requires that observations in spacetime regions which are causally separated (in the sense of special relativity theory) must be statistically independent.

(ii) **Covariance:**

The Poincaré group $\mathcal{P}_+^\uparrow$ is represented by automorphisms on the net of local algebras, i. e. $\alpha_g[\mathcal{A}(O)] = \mathcal{A}[g(O)]$. The map $g \rightarrow \alpha_g(A)$ is assumed to be strongly continuous for any $A \in \mathcal{A}$ [$\leftarrow$ global algebra generated by all local algebras $\mathcal{A}(\mathcal{O})$]

Covariance: A transformation (active or passive) of all spacetime-coordinates (according to the formula of special relativity theory) must not change the physics. Specifically for local algebras: It makes no difference whether we take a local algebra w.r.t. a spacetime region which is translated in Minkowski space or whether we take the local algebra w.r.t. the original spacetime region and transform it by the corresponding automorphism on the net of local algebras.

(iii) **Diamond:**

$\mathcal{A}(\mathcal{O}) = \mathcal{A}[D(\mathcal{O})]$, $D(\mathcal{O})$: 'causal shadow' of $\mathcal{O}$.

General Physical Assumptions

The next set of assumptions are 'general physical assumptions' in the sense that they can be motivated and understood by themselves on purely physical grounds (but not related to relativity theory). We will see in the next paragraph why this is not the case with all of our assumptions.

(iv) **Isotony:**

$$\text{If } \mathcal{O}_1 \subseteq \mathcal{O}_2, \text{ then } \mathcal{A}(\mathcal{O}_1) \subseteq \mathcal{A}(\mathcal{O}_2).$$

Isotony: The set of local observables grows with the considered spacetime region, i. e. the more room we have (in spacetime) the more measurements are possible. This gives rise to the so-called net structure of local algebras. The net structure of local algebras, in turn, contains the physical information which distinguishes one qft from another (as the map from spacetime regions to local algebras depends on the considered qft) [Buchholz 98 (Current Trends...) p. 5]. As a consequence of the isotony condition the set-theoretic union of all local algebras has *-structure [Haag, Kastler, S. 849, fn13].

(v) **Spectrum:**

The spectrum of the translation subgroup of $\mathcal{P}$ is contained in the closed forward lightcone.

A more familiar and physically more intuitive formulation is to postulate that the spectra of the energy operator $H = \hat{p}_0$ (Hamiltonian) and the mass operator $m = (\hat{p}^2)^{1/2}$ are nonnegative.[4] [M.] The spec-

[4]From a mathematical point of view the spectrum condition makes it possible to use various theorems from the theory of analytic functions. A famous example of this connection, although not within AQFT, are Hegerfeldt's articles on the incompatibility of causality and particle localization, e. g. Hegerfeldt (1974), Hegerfeldt and Ruijsenaars (1980) Hegerfeldt (1985) and Hegerfeldt (1998). Hegerfeldt's main assumption is merely the positivity of the energy. Starting with this assumption Hegerfeldt derives his results, from a mathematical point of view, primarily by the use of the theory of analytic functions.

trum condition requires the energy of a physical system to be bounded from below, i. e. that there must be a lowest possible energy, in order to exclude a perpetuum mobile.

(vi) **Vakuum:**

> $\exists$ unique state Ω, invariant under all Poincaré transformations, i. e. $U(g)\Omega = \Omega \; \forall g \in \mathcal{P}$.

It is not necessary in all approaches to postulate the existence of a vacuum state. The most famous example where this postulate appears is the Wightman theory. In other approaches certain stability conditions are sufficient. The best way to handle the situation seems to be a question of ongoing research.[5]

Technical Assumptions

The last set of asumptions can be called 'technical assumptions' since they are closely connected to 'technical' (i. e. relating to the mathematical formalism) requirements which turn out to be necessary but which cannot be given a satisfactory justification in physical terms. These assumptions are physical assumptions only in the sense that are needed to get a formalism which is physically meaningful. The separate significance of these assumptions apart from features of the formalism as a whole is not yet fully understood. Hence it is possible that there will be some changes in the future to understood and justify the foundations of AQFT better.

Weak additivity is essentially the assumption that the space-time continuum is homogeneous, so that no subquantal phenomena like minimal legth are present. The *irreducibility* condition is a global condition requiring that the global algebra R is irreducible which means that it is a factor of type I_∞. Physically this condition states that the considered system has no superselection rules, i. e. the system can be described within one single coherent superselection sector.[6]

[5] Private communication with D. Buchholz.

[6] The existence of invariant subspaces of the global algebra is the very essence of superselection. *Superselection rules* are due to certain conserved physical quantities,

'Without Loss of Generality'-Assumptions

In order to make the derivation of theorems easier one often imposes further conditions on the set of bounded space-time regions. Such conditions are meant to render the study of the inherent structure of AQFT more lucid without diminishing the generality of the derived results. Obviously the choice of space-time regions to be studied should be such that all possible space-time regions can be covered or approximated and that this choice determines the whole net of local algebras. A common choice is to consider only the so- called *double cones* which are a subset of the *diamonds*.

like total electric charge. The eigenspaces of the corresponding operators are called *superselection sectors*.

Appendix C

Proof of Malament's No-Go Theorem

We begin by restating and explaining the central lemma which Malament employs.

> *Borchers' Lemma:* Let the spectrum of the generator H of the group of unitary time translation operators $U(t) = e^{-itH}$ be bounded below. For two projection operators P_1 and P_2 which satisfy
>
> $$P_1 P_2 = \mathbf{0} \tag{C.1}$$
>
> and
>
> $$[U(t)P_1U^*(t), P_2] = \mathbf{0} \quad \text{for } |t| < \epsilon, \epsilon > 0 \tag{C.2}$$
>
> it holds that
>
> $$U(t)P_1U^*(t)P_2 = \mathbf{0} \quad \text{identically in } t\text{, i. e. for all } t. \tag{C.3}$$

$U(t)P_1U^*(t)$ denotes the same proposition about a measurement result as P_1 only with respect to a later time t, let us therefore abbreviate $P_{1,t} \equiv U(t)P_1U^*(t)$. Borchers' lemma thus says that if P_1 and P_2 are orthogonal and if $P_{1,t}$ and P_2 commute for all sufficiently small $t < \epsilon$ then $P_{1,t}$ and P_2 are orthogonal for all times t. That analyticity is of vital importance in this lemma can be seen from the fact that a proposition (C.1) which holds for one particular value of t (viz. $t = 0$) can, when certain conditions (C.2) hold for a small range of values t, be extended to all values of t (note that $(U(t)P_1U^*(t) = P_{1,t} = P_1$ for $t = 0)$. Since $U(t)P_1U^*(t)P_2 = \mathbf{0}$ implies $P_2U(t)P_1U^*(t) = \mathbf{0}$ (take the c. c.) and thereby $[U(t)P_1U^*(t), P_2] = \mathbf{0}$ one can say equivalently that a proposition (C.2) which holds for a small range of values t can, when a certain condition (C.1) holds for one particular value of t (viz. $t = 0$), be extended to all values of t.

Using this lemma of Borchers and the conditions for translation covariance, energy, localizability and locality on page 85 Malament derives that

$$P_\Delta = 0 \qquad \text{for any spatial set } \Delta \tag{C.4}$$

with the interpretation that the probability for finding a particle anywhere in space is 0 no matter how large Δ is. Since this result is in contradiction to the fact "particle detectors" do click sometimes and since the above conditions are meant to capture the minimal traits for a relativistic quantum theory of particles Malament concludes that such a theory is not viable.

In the following pages Malament's proof of C.4 will be restated in three steps.

1.) Consider an arbitrary spatial set Δ and take any vector $\mathbf{a}$ which is parallel to Δ such that Δ and $\Delta + \mathbf{a}$ are disjoint (see figure C.1). Under these circumstances it holds that:

$$P_\Delta P_{\Delta+\mathbf{a}} = P_{\Delta+\mathbf{a}} P_\Delta = \mathbf{0}. \tag{C.5}$$

2.) Take any future directed timelike unit vector $\mathbf{a_1}$ and a sufficiently small $|t|$ such that Δ and $\Delta + \mathbf{a} + t\mathbf{a_1}$ are spacelike related. With the Locality Condition on page 85 it follows that

$$[P_\Delta, P_{\Delta+\mathbf{a}+t\mathbf{a_1}}] = \mathbf{0}, \tag{C.6}$$

and because of the Translation Covariance Condition we get

$$[P_\Delta, U(t\mathbf{a_1})P_\Delta U(-t\mathbf{a_1})] = \mathbf{0}. \tag{C.7}$$

With equations C.5 and C.7 and under the assumption of the Energy Condition on page 85 we are now in the position to apply the lemma of Borchers

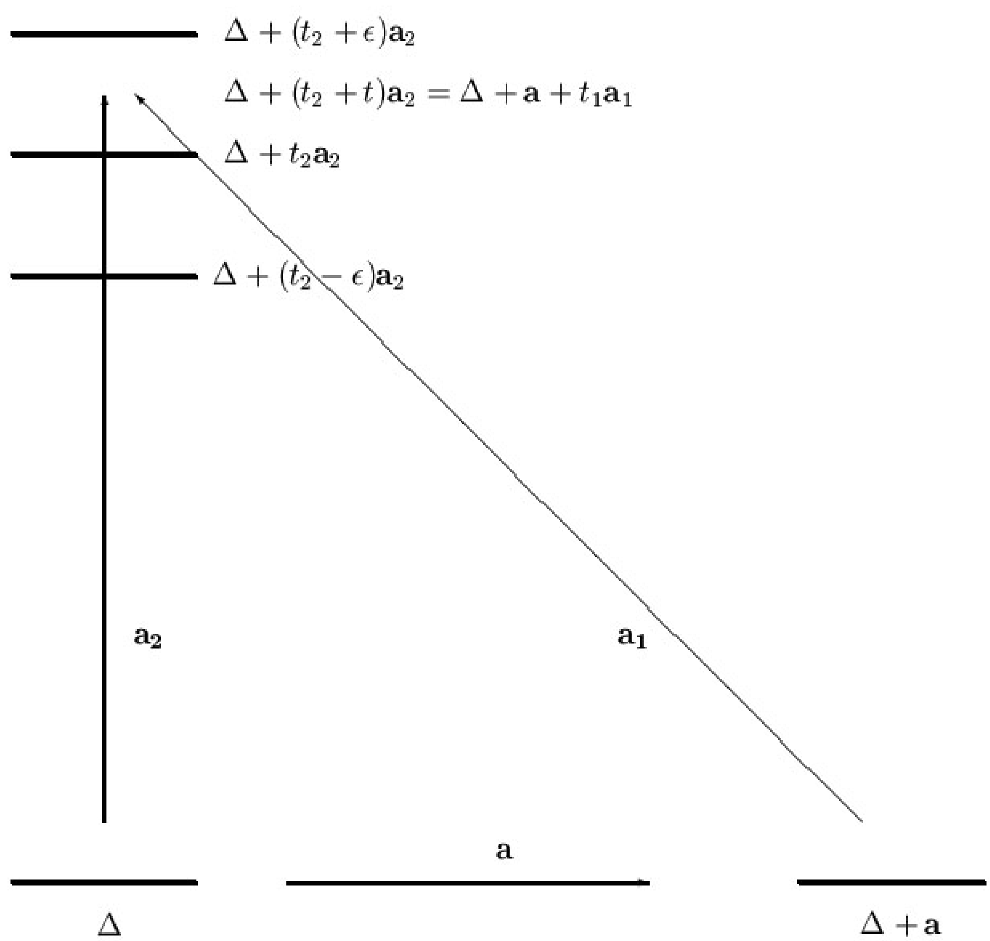

Figure C.1: Some visualized help for Malament's proof. The figure is taken from the original paper Malament (1996), p. 8.

for the first time to get

$$P_\Delta U(t\mathbf{a_1})P_\Delta U(-t\mathbf{a_1}) = U(t\mathbf{a_1})P_\Delta U(-t\mathbf{a_1})P_\Delta = \mathbf{0} \tag{C.8}$$

for all t! Using the Translation Covariance Condition once again, now "in the opposite direction", yields:

$$P_\Delta P_{\Delta+\mathbf{a}+t\mathbf{a_1}} = \mathbf{0}. \tag{C.9}$$

3.) Take any future directed timelike unit vector $\mathbf{a_2}$ and choose $t_2 > 0, \epsilon > 0$ such that $\Delta + (t_2 + t)\mathbf{a_2}$ and $\Delta + \mathbf{a}$ are timelike related for all t with $|t| < \epsilon$.

Apply the translation covariance condition once, the lemma by Borchers and apply the translation covariance condition once again in order to get:

$$P_\Delta U[(t+t_2)\mathbf{a_2}]P_\Delta U[-(t+t_2)\mathbf{a_2}) = \mathbf{0} \tag{C.10}$$

Taking $t = -t_2$ yields:

$$P_\Delta P_\Delta = \mathbf{0} \tag{C.11}$$

which, since P_Δ is a projection operator, implies:

$$P_\Delta = \mathbf{0}. \tag{C.12}$$

q. e. d.

Bibliography

Ackrill, J. L. (1981). *Aristotle the Philosopher.* Oxford University Press, Oxford.

Albert, D. and Loewer, B. (1996). Tails of Schrödinger's cat. In Clifton (1996), pages 81–92.

Armstrong, D. M. (1989). *Universals: An Opinionated Introduction.* Westview Press, Boulder.

Baez, J. C., Segal, I. E., and Zhou, Z. (1992). *Introduction to Algebraic and Constructive Quantum Field Theory.* Princeton University Press, Princeton, New Jersey, second edition.

Barrett, J. A. (1996). Empirical adequacy and the availability of reliable records in quantum mechanics. *Philosophy of Science*, 63:49–64.

Barrett, J. A. (1999). *The Quantum Mechanics of Minds and Worlds.* Oxford University Press, Oxford.

Baumgärtel, H. (1995). *Operatoralgebraic Methods in Quantum Field Theory.* Akademie-Verlag, Berlin.

Bell, J. S. (1964). On the Einstein-Podolsky-Rosen paradox. *Physics*, 1:195–200.

Bell, J. S. (1966). On the problem of hidden variables in quantum mechanics. *Reviews of Modern Physics*, 38:447–52.

Bell, J. S. (1982). On the impossible pilot wave. *Foundations of Physics*, 12:989–99.

Bell, J. S. (1987). *Speakable and Unspeakable in Quantum Mechanics*. Cambridge University Press.

Berezin, F. A. (1966). *The Method of Second Quantization*. Academic Press, New York.

Bjorken, J. D. and Drell, S. D. (1967). *Relativistische Quantenfeldtheorie*. B.I.-Wissenschaftsverlag, Mannheim.

Bogoljubov, N. N. and Sirkov, D. V. (1984). *Quantenfelder*. Physik-Verlag, Weinheim.

Borchers, H.-J. (1967). A remark on a theorem of B. Misra. *Communications in Mathematical Physics*, 4:315–323.

Brown, H. R. and Harré, R., editors (1988). *Philosophical Foundations of Quantum Field Theory*. Clarendon Press, Oxford.

Buchholz, D. (1994). On the manifestations of particles. In Sen, R. N. and Gersten, A., editors, *Mathematical Physics Towards the 21st Century (Based on the Beer-Sheva Workshop, 14-19 March, 1993) (hep-th/9511023)*.

Buchholz, D. (1998). Current trends in axiomatic qantum field theory. *Talk given at Ringberg Symposium on Quantum Field Theory, Ringberg Castle, June 1998 (hep-th/9811233)*.

Buchholz, D. and Yngvason, J. (1994). There are no causality problems for fermi's two atom system. *Physical Review Letters*, 73:613–616.

Busch, P. (1982). Indeterminacy relations and simultaneous measurements in quantum theory. *International Journal of Theoretical Physics*, 24:63–92.

Busch, P. (1999). Unsharp localization and causality in relativistic quantum theory. *Journal of Physics A: Mathematics General*, 32:6535.

Busch, P., Grabowski, M., and Lahti, P. (1995). *Operational Quantum Physics*. Springer, Berlin.

Campbell, K. (1990). *Abstract Particulars.* Blackwell, Oxford.

Cao, T. Y. (1997). *Conceptual Developments of 20th Century Field Theories.* Cambridge University Press, Cambridge.

Carnap, R. (1931). Überwindung der Metaphysik durch logische Analyse der Sprache. *Erkenntnis*, 2:219–241. (Engl. transl.: The elimination of metaphysics through logical analysis of language. In Ayer, A. J., editor, *Logical Positivsm*, Free Press, Glencoe, Ill. Allen & U., London 1959).

Carnap, R. (1950). Empiricism, semantics, and ontology. *Revue Internationale de la Philosophie (Brussels)*, 4(11):20–40. Reprinted in the second edition of Carnap (1956).

Carnap, R. (1952). Meaning postulates. *Philosophical Studies*, (3):65–73. Reprinted in the second edition of Carnap (1956).

Carnap, R. (1956). *Meaning and Necessity.* Chicago University Press, Chicago.

Clifton, R., editor (1996). *Perspectives on Quantum Reality: Non-Relativistic, Relativistic, and Field-Theoretic*, The University of Western Ontario Series in Philosophy of Science, Dordrecht, Boston, London. Kluwer Academic Publishers.

Cushing, J. T. (1986). The importance of Heisenberg's s-matrix program for the theoretical high-energy physics of the 1950's. *Centaurus*, 29:110–149.

Cushing, J. T. (1990). *Theory construction and selection in modern physics: the* S *Matrix.* Cambridge University Press, Cambridge.

Darrigol, O. (1986). The origin of quantized matter waves. *Historical Studies in the Physical and Biological Sciences*, 16:197–253.

Dijksterhuis, E. J. (1956). *Die Mechanisierung des Weltbildes.* Springer-Verlag, Berlin, Göttingen, Heidelberg. (German translation of the Dutch original from 1950 by Helga Habicht).

Dirac, P. A. M. (1927). The quantum theory of emission and absorption of radiation. *Proceedings of the Royal Society of London*, A 114:243–256.

Faye, J., Scheffler, U., and Urchs, M., editors (2000). *Facts, Things and Events*, volume 72. Poznañ Studies in the Philosophy of the Sciences and Humanities.

Finkelstein, D. R. (1973). A process conception of nature. In Mehra, J., editor, *The Physicist's Conception of Nature*, pages 709–713, Dordrecht. D. Reidel Publishing Company.

Finkelstein, D. R. (1974). Quantum physics and process metaphysics. In Enz and Mehra, J., editors, *Physical Reality and Mathematical Description*, pages 91–99, Dordrecht. D. Reidel Publishing Company.

Finkelstein, D. R. (1979). Process philosophy and quantum dynamics. In Hooker, C. A., editor, *Physical Theory as Logico-Operational Structure*, pages 1–18, Dordrecht. D. Reidel Publishing Company.

Finkelstein, D. R. (1996). *Quantum Reality: A Synthesis of the Ideas of Einstein and Heisenberg*. Springer, Berlin et al.

Fleming, G. N. (1965a). Covariant position operators, spin, amd locality. *Physical Review*, 137(1B):B188–B197.

Fleming, G. N. (1965b). Nonlocal properties of stable particles. *Physical Review*, 139(4B):B963–B968.

Fleming, G. N. (1988). Strange positions. In *Brown and Harré (1988)*, pages 93–115.

Fleming, G. N. and Butterfield, J. (1999). Strange positions. In Butterfield, J., editor, *From Physics to Philosophy*, pages 108–165. Cambridge University Press.

Frede, M. (1987). *Essays in Ancient Philosophy*. Clarendon Press, Oxford.

Frede, M. and Patzig, G. (1988). *Aristoteles ,Metaphysik Z' - Text Übersetzung und Kommentar*. C. H. Beck, München. Two volumes.

Friedrichs, K. O. (1953). *Mathematical Aspects of the Quantum Theory of Fields*. Intersciences Publishers, New York.

Haag, R. (1996). *Local Quantum Physics: Fields, Particles, Algebras*. Springer, Berlin, Heidelberg, New York, second edition.

Haag, R. and Kastler, D. (1964). An algebraic approach to quantum field theory. *Journal of Mathematical Physics*, 5:848–861.

Haag, R. and Swieca, J. A. (1962). When does a quantum field theory describe particles? *Communications in Mathematical Physics*, 1:308–320.

Hegerfeldt, G. C. (1974). Remark on causality and particle localization. *Physical Review D*, 10(10):3320–3321.

Hegerfeldt, G. C. (1985). Violation of causality in relativistic quantum theory? *Physical Review Letters*, 54(22):2395–2398.

Hegerfeldt, G. C. (1998). Causality, particle localization and positivity of the energy. In Bohm, A., Doebner, H.-D., and Kielanowski, P., editors, *Irreversibility and Causality in Quantum Theory - Semigroups and Rigged Hilbert Spaces*, Berlin, Heidelberg, New York. Springer.

Hegerfeldt, G. C. and Ruijsenaars, S. N. M. (1980). Remarks on causality, localization, and spreading of wave packets. *Physical Review D*, 22(2):377–384.

Heisenberg, W. (1943a). Die “beobachtbaren Grössen in der Theorie der Elementarteilchen. *Zeitschrift für Physik*, 120:513.

Heisenberg, W. (1943b). Die beobachtbaren Grössen in der Theorie der Elementarteilchen. II. *Zeitschrift für Physik*, 120:673.

Heisenberg, W. (1959). *Physik und Philosophie*. Ullstein, Frankfurt Berlin.

Hoffmann, J. and Rosenkrantz, G. S. (1997). *Substance - Its Nature and Existence*. The Problems of Philosophy. Routledge, London, New York.

Horuzhy, S. S. (1990). *Introduction to Algebraic Quantum Field Theory.* Kluwer Academic Publishers, Dordrecht, Boston, London, first edition. Original Russian Publication: 1986.

Jammer, M. (1974). *The Philosophy of Quantum Mechanics - The Interpretations of Quantum Mechanics in Historical Perspective.* John Wiley & Sons, New York et al.

Jauch, J. M. (1974). The quantum probability calculus. *Synthese*, 29:131–154.

Källén, A. O. G. (1958). *Quantenelektrodynamik*, volume V, part 1 of *Handbuch der Physik*, pages 169–364. Springer, Berlin, Göttingen, Heidelberg. (Engl. transl.: *Quantum Electrodynamics*, Springer, New York 1972).

Kuhlmann, M. (1999a). Quanta and tropes: Trope ontology as descriptive metaphysics of quantum field theory. In Meixner, U. and Simons, P. M., editors, *Preproceedings of the 22nd International Wittgenstein Symposion*, volume VII of *Contributions of the Austrian Ludwig Wittgenstein Society*.

Kuhlmann, M. (1999b). Was sagt das Vakuum über Teilchen aus? Neuere Ergebnisse aus der theoretischen Physik schaffen zusätzliche Probleme für den Teilchenbegriff. *Praxis der Naturwissenschaften – Physik*, 48(4):28–31.

Kuhlmann, M. (2000). Processes as objects of quantum field theory. In **?**, pages 365–388.

Kuhlmann, M., Lyre, H., and Wayne, A., editors (2000). *Ontological Aspects of Quantum Field Theory.* To be published.

Kuhlmann, M. and Stöckler, M. (2000). Quanten und Tropen - Philosophie und Physik auf der Suche nach den fundamentalen Bausteinen der Materie. *Impulse aus der Forschung*, (1).

Lasswitz, K. (1890). *Geschichte der Atomistik vom Mittelalter bis Newton*, volume 1: Die Erneuerung der Korpuskulartheorie. Hamburg, Leipzig.

Loux, M. J. (1991). *Primary Ousia - An Essay on Aristotle's Metaphysics Z and H.* Cornell University Press, Ithaca.

Loux, M. J. (1998). *Metaphysics - A Contemporary Introduction.* Routledge, London, New York.

Malament, D. (1996). In defense of dogma: Why there cannot be a relativistic quantum mechanics of (localizable) particles. In Clifton (1996), pages 1–10.

Mandl, F. and Shaw, G. (1984). *Quantum Field Theory.* John Wiley & Sons, Chichester et al.

Martin, C. B. (1980). Substance substantiated. *Australasian Journal of Philosophy*, 58:3–10.

Mittelstaedt, P. (1986). *Sprache und Realität in der modernen Physik*, volume 650 of *Hochschultaschenbücher.* B.I.-Wissenschaftsverlag, Mannheim, Wien, Zürich.

Mittelstaedt, P. (1989). *Philosophische Probleme der modernen Physik*, volume 50 of *Hochschultaschenbücher.* B.I.-Wissenschaftsverlag, Mannheim, Wien, Zürich, seventh edition.

Mittelstaedt, P. (1998). *The Interpretation of Quantum Mechanics and the Measurement Process.* Cambridge University Press, Cambridge.

Nortmann, U. (1997). *Allgemeinheit und Individualität: die Verschiedenartigkeit der Formen in ,,Metaphysik" Z.* Ferdinand Schöningh, Paderborn et. al.

Ozawa, M. (1984). Quantum measuring processes of continuous observables. *Journal of Mathematical Physics*, 25:79–87.

Pabst, B. (1994). *Atomtheorien des lateinischen Mittelalters.* Wissenschaftliche Buchgesellschaft, Darmstadt.

Peres, A. and Zurek, W. H. (1982). Is quantum theory universally valid? *American Journal of Physics*, 50:807–810.

Quine, W. V. O. (1948). On what there is. *Review of Metaphysics*. Reprinted in Quine (1961).

Quine, W. V. O. (1951). Two dogmas of empiricism. *Philosophical Review*. Reprinted in Quine (1961).

Quine, W. V. O. (1961). *From a Logical Point of View*. Harvard University Press, Cambridge, Massachusetts, second, revised edition.

Redhead, M. L. G. (1975). Symmetry in intertheory relations. *Synthese*, 32:77–112.

Redhead, M. L. G. (1980). Some philosophical aspects of particle physics. *Studies in History and Philosophy of Science*, 11:279–304.

Redhead, M. L. G. (1983). Quantum field theory for philosophers. In Asquith, P. D. and Nickles, T., editors, *PSA 1982: Proceedings of the 1982 Biennial Meeting of the Philosophy of Science Association, Vol. 2*, pages 57–99.

Redhead, M. L. G. (1987). *Incompleteness, Nonlocality and Realism*. Clarendon Press, Oxford.

Redhead, M. L. G. (1988). A philosopher looks at quantum field theory. In *Brown and Harré (1988)*, pages 9–23.

Redhead, M. L. G. (1995a). More ado about nothing. *Foundations of Physics*, 25:123–137.

Redhead, M. L. G. (1995b). The vacuum in relativistic quantum field theory. In D. Hull, M. F. and Burian, R. M., editors, *Proceedings of the 1994 Biennial Meeting of the Philosophy of Science Association ("PSA 1994")*, volume 2, pages 88–89, East Lansing (Michigan). Philosophy of Science Association.

Redhead, M. L. G. and Teller, P. (1991). Particles, particle labels, and quanta: the toll of unacknowledged metaphysics. *Foundations of Physics*, 21:43–62.

Redhead, M. L. G. and Wagner, F. (1998). Unified treatment of EPR and Bell arguments in Algebraic Quantum Field Theory. *Foundations of Physics Letters*, 11:111–125.

Reed, M. and Simon, B. (1975). *Methods of Modern Mathematical Physics - II: Fourier Analysis, Self-Adjointness*. Academic Press, New York et al.

Reed, M. and Simon, B. (1980). *Methods of Modern Mathematical Physics - I: Functional Analysis*. Academic Press, New York et al., revised and enlarged edition.

Reeh, H. and Schlieder, S. (1961). Bemerkungen zur Unitäräquivalenz von Lorentzinvarianten Feldern. *Nuovo Cimento*, 22:1051–1068.

Ryder, L. H. (1996). *Quantum Field Theory*. Cambridge University Press, Cambridge, second edition.

Salmon, M. H., Earman, J., Glymour, C., Lennox, J. G., Machamer, P., McGuire, J. E., Norton, J. D., Salmon, W. C., and Schaffner, K. F. (1992). *Introduction to Philosophy of Science: A Text by Members of the Department of the History and Philosophy of Science of the University of Pittsburgh*. Prentice Hall, Englewood Cliffs, New Jersey.

Sambursky, S. (1962). *The Physical World of Late Antiquity*. Princeton University Press, Princeton, New Jersey.

Saunders, S. (1988). The algebraic approach to quantum field theory. In *Brown and Harré (1988)*, pages 149–183.

Saunders, S. (1995). A dissolution of the problem of locality. In Hull, D., Forbes, M., and Burian, R. M., editors, *PSA 1994: Proceedings of the 1994 Biennial Meeting of the Philosophy of Science Association, Vol. 2*, pages 88–98.

Saunders, S. and Brown, H. R. (1991). *The Philosophy of Vacuum.* Clarendon Press, Orford.

Scheibe, E. (1991). Substances, physical systems, and quantum mechanics. In Schurz, G. and Dorn, G. J. W., editors, *Essays in Honour of PAUL WEINGARTNER on the Occasion of his 60th Birthday.*, Advances in Scientific Philosophy, pages 215–230, Amsterdam, Atlanta (GA). Editions Rodopi B. V.

Schrader-Frechette, K. (1977). Atomism in crisis: An analysis of the current high energy paradigm. *Philosophy of Science*, 44:409–440.

Schrödinger, E. (1954). *Nature and the Greeks.* Cambridge University Press, Cambridge. Shearman Lectures, delivered at University College, London, May 1948.

Schroer, B. (1963). Infrateilchen in der Quantenfeldtheorie. *Fortschr. Physik*, 173:1527.

Schurz, G. (1995). Ein quantenmechanisches Argument für die Existenz konkreter Universalien. In J. L. Brandl, A. H. and Simons, P. M., editors, *Metaphysik. Neue Zugänge zu alten Fragen*, volume 11 of *Conceptus Studien*, pages 97–120, St. Augustin. Academia Verlag.

Schweber, S. S. (1994). *QED and the Men Who Made It.* Princeton University Press, Princeton.

Seibt, J. (1995). Individuen als Prozesse. *Logos*, N. F. 2:352–384.

Seibt, J. (1997). Existence in time: From substance to process. In Jan Faye, U. S. and Urchs, M., editors, *Perspectives on Time*, Boston Studies in the Philosophy of Science, pages 143–182, Dordrecht. Kluwer Academic Publishers.

Seibt, J. (2000). The matrix of ontological thinking: Heuristic preliminaries for an ontology of QFT. In *Kuhlmann et al. (2000).*

Simons, P. M. (1987). *Parts. A Study in Ontology.* Clarendon Press, Oxford.

Simons, P. M. (1994). Particulars in particular clothing: Three trope theories of substance. *Philosophy and Phenomenological Research*, LIV(3):553–575.

Simons, P. M. (1998a). Farewell to substance: a differentiated leave-taking. *Ratio (new series)*, XI:235–252.

Simons, P. M. (1998b). Metaphysical systematics: A lesson from Whitehead. *Erkenntnis*, (48):377–393.

Simons, P. M. (1999). Against modesty: claims of revisionary metaphysics. In Meixner, U. and Simons, P. M., editors, *Proceedings of the 22nd International Wittgenstein Symposion*.

Stöckler, M. (1988). Individualität, Identität, Ununterscheidbarkeit (überlegungen zum Gegenstandsbegriff in der Quantenfeldtheorie). *Conceptus*, 57:5–29.

Stöckler, M. (1999). *Leibniz* und die Quantenfeldtheorie - Was man aus der mathematischen Struktur der Quantenfeldtheorie über die Natur der Quantenobjekte lernen kann. *Praxis der Naturwissenschaften – Physik*, 48(4):24–28.

Strawson, P. F. (1959). *Individuals - An Essay in Descriptive Metaphysics.* Routledge, London, New York.

Strawson, P. F. (1975). Semantics, logic and ontology. *Neue Hefte für Philosophie - Semantik und Ontologie*, 8:1–13.

Streater, R. F. (1988). Why should anyone want to axiomatize quantum field theory? In *Brown and Harré (1988)*, pages 137–148.

Teller, P. (1983). Quantum physics, the identity of indiscernibles and some unanswered questions. *Philosophy of Science*, 50:309–319.

Teller, P. (1990). What the quantum field is not. *Philosophical Topics*, 18:175–186.

Teller, P. (1995). *An Interpretive Introduction to Quantum Field Theory*. Princeton University Press.

t'Hooft, G. (1996). *In Search of the Ultimate Building Blocks*. Cambridge University Press, Cambridge.

Tugendhat, E. (1967). Die sprachanalytische Kritik der Ontologie. In Gadamer, H.-G., editor, *Das Problem der Sprache*, Achter deutscher Kongress für Philosophie, pages 483–493, München. Wilhelm Fink Verlag.

Unruh, W. G. (1976). Notes on black hole evaporation. *Physical Review D*, 14:870–92.

Unruh, W. G. and Wald, R. M. (1984). What happens when an accelerating observer detects a rindler particle? *Physical Review D*, 29:1047.

van Melsen, A. G. M. (1967). Atomism. In Edwards, P., editor, *The Encyclopedia of Philosophy*, volume 1, pages 193–198, NewYork. The Macmillan Company & The Free Press.

von Neumann, J. (1932). *Mathematische Grundlagen der Quantenmechanik*. Springer, Berlin.

Wald, R. M. (1986). Correlations and causality in quantum field theory. In Penrose, R. and Isham, C. J., editors, *Quantum Concepts in Space and Time*, pages 293–301, Oxford. Clarendon Press.

Wald, R. M. (1994). *Quantum Field Theory in Curved Spacetime and Black Hole Thermodynamics*. The University of Chicago Press, Chicago, London.

Weinberg, S. (1995). *The Quantum Theory of Fields – Foundations*, volume 1. Cambridge University Press, Cambridge.

Weinberg, S. (1996). *The Quantum Theory of Fields – Modern Applications*, volume 2. Cambridge University Press, Cambridge.

Weingard, R. (1982). Do virtual particles exist? In Asquith, P. D. and Nickles, T., editors, *PSA 1982 - Proceedings of the 1982 Biennial Meeting of the Philosophy of Science Association*, volume 1, pages 235–241, East Lansing, Michigan. Philosophy of Science Association.

Wightman, A. S. (1962). On the localizabilbity of quantum mechanical systems. *Reviews of Modern Physics*, 34(4):845.

Wigner, E. P. (1939). On unitary representations of the inhomoneneous Lorentz group. *Annals of Mathematics*, 40:149.

Acknowledgement

First of all I wish to thank Manfred Stöckler for an exceptionally commited and interested supervision. Further thanks go to Jeff Barrett and David Malament for various discussions and helpful suggestions during my research visits at UC Irvine and the University of Chicago in 1998 and to audiences at the Universities of Bremen, Chicago, Göttingen and Hamburg (Desy), in particular to Detlev Buchholz, Jeremy Butterfield, Klaus Fredenhagen and Miklos Rédei. Finally, I especially like to thank Christina Egger for her comprehensive inspiration in all stages of my work.