Matter and forces in quantum field theory
An attempt at a philosophical elucidation

Jon-Ivar Skullerud

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Preface

This thesis arose from one primary motivation. I felt there was little sense in delving straight into theoretical calculations within e.g. particle physics without any overarching idea of what the theory was about and what would be the value of such work — I had little interest in doing something I might myself consider next to worthless for my thesis. But to judge what it could be worth working on it was necessary to take a step back and evaluate the theory as a whole. This feeling was further strengthened by the time I spent at CERN in the summer of 1989. It was an interesting stay and an exciting environment, but I found myself asking whether much of the activity might not be driven too much by prestige, and whether perhaps there was not so much scientific insight to be gained from the large accelerator experiments compared to the investments. It could be useful to conduct a general evaluation of where we stood and what was the aim of the experiments.

In addition, I have always (for as long as I have been interested in physics) been interested in the connections between philosophy and physics. After also having studied some philosophy in addition to physics, I believed it could be good to attempt to do some proper work in this area. It has been good for me — I have personally got a lot out of my work with this thesis. I have not managed to do as much as I had hoped — there is for example a half-finished section on particle species which did not make it in because I ran out of time, and there are several other questions I would have liked to discuss given more time. I have however got a greater interest in and understanding of both physics and philosophy. In particular got an idea of which areas of research within fundamental physics can be of interest — which was part of the aim of doing this work in the first place.

I would like to thank my supervisors Audun Øfsti and Kåre Olaussen, who have read through the manuscript and given me good advice along the way. Thank you also to everyone else who has provided opinions and encouragement. Finally, thank you to my father, who has given me access to his computers for writing the thesis, and also given me much support.

Trondheim, 6 May 1991
jon ivar skullerud

Preface to the revised edition

In this revised edition I have made some minor changes to the text in several places, and included more references. I have also corrected some typographical errors.

Trondheim, 13 July 1991
j.i.s.

Preface to the English translation

This thesis should be read as the opinions of a budding physicist in 1991. I have resisted any temptation to add anything save a small number of footnotes, and have also kept the style, including the idiosyncratic use of punctuation and quote marks, mostly intact. My opinions (and my writing style) have obviously evolved in the intervening years, but that will have to be for another day.

This translation has been a very long time in the making. Already in the first few years after it was written several people were asking me if I would translate it into English so that they could read it. I thought that would be a good idea, but it was never a priority among so many other things to do. Anyway, what would I do with it? The thought arose again after I put the original thesis on my web page in 1995, but again time and lack of any urgency meant nothing happened. Eventually, many years later, I started regularly reading the History and Philosophy of Physics eprints on arXiv [hist-ph], and concluded there would indeed be a potential repository where the thesis could reach a wider audience, justifying the effort that would go into a translation. Thus started a slow process, in my spare time, not being sure if I could justify this being part of my work or not.

Then, when I went on a one-semester sabbatical to Florence in autumn 2019 I decided this was when I was going to complete the translation, and I stuck to that. I wish to express my great appreciation to the Galileo Galilei Institute for Theoretical Physics for their hospitality during this time, and especially to the organisers of the mini-workshop "Beyond Standard Model: Historical-Critical Perspectives", which was the highlight of my stay at the GGI and gave me an additional spur to finish this work.

I wish to thank Máire O'Dwyer for her careful proofreading of the English translation. The Feynman diagrams were drawn using the *FeynGame* package.[1]

Firenze, 25 January 2020 / Dublin, 28 November 2020
j.i.s.

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[1] R. V. Harlander, S. Y. Klein and M. Lipp, Comput. Phys. Commun. **256**, 107465 (2020) [arXiv:2003.00896].

Contents

Chapter 1

Introduction

Physics and philosophy are not two independent disciplines. They share a common origin; both contribute significantly to our worldview, and in my opinion there remain several levels of mutual dependence between them — in particular in the areas where they impinge on each other: natural philosophy, fundamental physics and to some extent epistemology.[1] Not all these relations of mutual dependence can or should be made explicit, but an awareness of their existence is necessary for both disciplines. A philosophical interpretation of fundamental physical theories is a necessary part of such an awareness.

Up to the renaissance, religion and philosophy played a far greater rôle in the worldview of Western Europeans than the sciences — to the extent that it is possible to talk about a distinction between religion, philosophy and science.[2] The sciences, including physics, were subordinate to philosophy and religion: the framework within which physics worked was explicitly drawn up by philosophy. The most important characteristic of a good scientific theory was that it was in accord with the accepted philosophy and religion of the day. This has changed. As the sciences have become more independent of philosophy, they have played a more independent and dominant rôle in shaping the common worldview. It has almost got to the point that the most important criterion for whether a philosophy is good (acceptable to the public) is whether it accords with the accepted science of the day. This can be seen particularly clearly in the rôle classical (Newtonian) physics played in the 19th century. The view of everything as a result of deterministic forces pervaded not only the understanding of nature, but also of society and human life. Newton's physics was transformed into a philosophical axiom which very many (most people?) took as self-evident.

This is a specific example of a more general phenomenon: any worldview has a physical aspect, which consists of an understanding of the ruling paradigm of fundamental physics. This implies that this paradigm is tacitly assumed, taken for granted and taken to be unconditionally true among the general public. This will also form part of the basis for our experience of the world, and will thus also make its imprint on philosophy. Moreover, if philosophy has as one of its tasks to comment on our worldview and

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[1] Physics probably relies more on epistemology than vice-versa, but the dependence is not just one way: Kant's epistemology, for example, contained among much else a belief that Newton's physics (or at least its main features) was the final physical theory.

[2] Religion probably still dominates the worldview of most people on a worldwide basis, but this is much less the case in Western Europe.

investigate the conditions for our experience of the world, it will also have to comment on physics. We may say that even though it is accepted that ontology in the classical sense (as a study of how ‘being’, completely independently of us humans, must be) is not possible, *an* ontology (understanding of how the world fundamentally is) is still necessary, and may consist of an interpretation of fundamental theories of physics.

A new paradigm of fundamental physics will rarely if ever be completely understood immediately. It breaks with several previously tacit or presumed self-evident assumptions about the physical world, and will therefore tend to be considered ‘incomprehensible’. Such a situation is, however, untenable in the long run. As people become used to using the new conceptual framework, they will tend to become familiar with and build up a certain understanding of what it is about. This understanding will then (slowly) spread from professional circles to the general public.

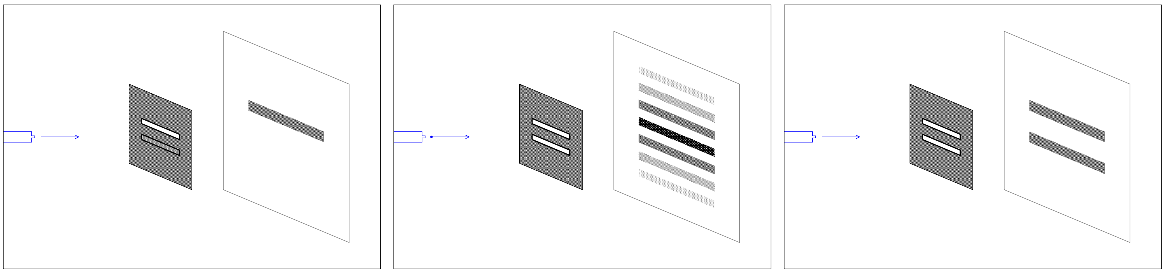
There are few physical theories that have been subject to as much philosophical debate as quantum mechanics. This debate has however often started from the premise that quantum mechanics is a curiosity, far from our ordinary understanding of reality and remaining for ever the sole domain of experts. My starting point is different, namely that quantum mechanics, and not least quantum field theory, tells us about fundamental features of physical reality, and that essential features of quantum mechanics will eventually form part of the common worldview. There is therefore a need for a philosophical interpretation which treats the theory as it stands as fully comprehensible — a *quantum ontology*, which considers how quantum mechanics and quantum field theory will fit into a general worldview. It will take some time before we reach a ‘fully mature’ understanding (when it comes to classical mechanics, this may be represented by Kant, 100 years after Newton). However, the understanding does not mature by itself, but is a product of the interpretations we make. It is such a sketch of an understanding or interpretation I wish to contribute to, within the limits allowed by this dissertation.

Another aspect of the relation between physics, philosophy and common sense is that none of these, including physics, come without prerequisites. Just as philosophy fools itself if it considers itself independent of any historical context, physics will fool itself if it considers itself independent of any metaphysical assumptions. All our statements about the world, both in daily life and in physics, presuppose that something is taken for granted. These preconditions can be of various kinds, from conditions for the possibility of talking about an objective reality (or coming to agreement about matters regarding the world), via an understanding of what characterises a particular science, to the complex web of theories that are assumed when carrying out and interpreting an experiment. Acknowledging these preconditions is crucial to the self-understanding of physics, and may also contribute to guidelines for what kind of further research may be fertile. An understanding of and explanation of these preconditions and their rôle is a philosophical problem.

I believe quantum mechanics gives a good illustration of the mutual interdependence between physics and philosophy. That philosophy is dependent on physics is made evident by several ideas that had been assumed to be necessary features of the world, such as deterministic causality and the possibility of precisely determining all properties of things, which are rejected in quantum mechanics. What had been considered *a priori* truths turn out only to be valid within classical physics. Quantum mechanics has therefore forced us to reevaluate elements of natural philosophy (and possibly also other parts of philosophy — there has been a good deal of work done on revising logic in the light of quantum mechanics). The same point is also illustrated by the fact that much of the opposition to quantum mechanics was of a philosophical nature, and was voiced by people who wished to defend the classical worldview.

That physics is dependent on philosophy is of course also illustrated by all the philosophical debates around quantum mechanics. Almost from the outset, the 'fathers' of quantum mechanics, like Bohr, Heisenberg and Schrödinger, pointed out the need for a philosophical interpretation of quantum mechanics. The connection with philosophy appears in particular in the rôle played by the subject in the theory or its interpretation. As an example, I will look at the 'particle–wave-dualism', as it appears in the double-slit experiment and the view of it within the Copenhagen interpretation.

The experiment is illustrated in figure 1.1. Single electrons (or other particles) from a source are sent through two slits to a screen which is marked when hit by particles.



a) Only one slit is open.

b) Both slits are open.

c) Both slits are open and which slit the particles pass through is registered.

Figure 1.1: The double-slit experiment.

If only the lower slit is open, a pattern as in fig. 1.1 a) will eventually appear — the particles have hit with some spread around one point at the continuation of the line between the source and the slit — like classical particles would have done. If both slits are open, something strange happens: the pattern formed on the screen is as in fig. 1.1 b) — a pattern of stripes. This is what one would have expected in classical physics if a wave had passed through the slits. But a wave is something extended, which should pass through both slits at the same time. If we now look at how the electrons pass through the slits (by placing detectors there), we find that they only pass through one slit at a time — but at the same time we obtain a pattern on the screen as in fig. 1.1 c) — as if it was classical particles passing through the slits. Depending on how the experiment has been constructed and what we observe, the electrons behave as particles or as waves, if we insist on using classical language.

The Copenhagen interpretation (in all its variants) says that the description of the electron as wave and as particle are equally valid.[3] Quantum mechanics is free of contradictions because the two descriptions are *complementary* rather than contradictory:

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[3] — if one is to use such classical concepts at all. I believe this is unnecessary, and that attempts to describe quantum mechanical systems in terms of classical concepts (which are not necessarily better understood than the quantum mechanical ones) hinder the understanding of quantum mechanics on its own terms. In particular, the wave concept is widely misused. In the early years of quantum mechanics, on the other hand, it was necessary to make use of 'known' concepts. Today we are better

they cannot be applied simultaneously where they would have given conflicting results. What decides which description should be used is the experiment or what is observed. The quantum mechanical phenomenon 'in itself' is not fully determined: only when it is observed (or placed in the context of an experiment) is it something definite. Here it is important that the experimental apparatus according to the Copenhagen interpretation must be described classically — i.e., there are no indeterminacies there. Our classical world of things is in other words characterised by definiteness and ordinary causality, while the 'quantum world' is characterised by indeterminacy, complementary descriptions and non-deterministic behaviour, and depends on our actions to become something definite.

The primary question raised by the Copenhagen interpretation is about the conditions for observation of physical systems — which is a philosophical question. It turns out that the character of the physical system depends on both *that* and *how* it is observed. More generally, the question arises of what an observation is as such; this is at the bottom of all the debates about measurement in quantum mechanics (which I will not go into any further). The 'naive' view of observation in classical physics (the observation has no bearing on what is observed) can no longer be sustained; instead physics becomes dependent on a well-developed epistemology.

Another reason why I feel a study like the one I will conduct here is necessary is that very little has so far been written about what might be called the implicit ontology of quantum field theory — the worldview implied by accepting quantum field theory as a fundamental theory of physics. What has been written has largely been limited to popularisations and discussions about specific problems. I know of only two wide-ranging expositions: Werner Heisenberg's 'Physics and Philosophy' [20] and Fritjof Capra's 'Tao of Physics' [23]. Heisenberg's book gives a brilliant, probing analysis of the philosophical issues arising out of quantum mechanics (including quantum field theory), informed by his variant of the Copenhagen interpretation. Capra's book is more directly aimed at advocating a particular interpretation or presenting one particular view, which is interesting, but would in any case benefit from being confronted with other possible views. Some articles discussing philosophical aspects of quantum field theory (including its implicit ontology) are collected in [18, 19].

The dissertation is aimed at both philosophers with an interest in, but not a detailed knowledge of, physics, and at physicists with an interest in philosophy. It therefore has a different style to what you might find in e.g. a journal of philosophy of science, where the readers may be expected to have a good knowledge of both. It is however not a 'popular' exposition, and demands a fair amount of the reader. I have tried to avoid excessive use of physics and philosophy jargon, but have not been able to get rid of all such 'weeds' — I hope this is not too annoying. It should in any case be possible to follow the main lines of the arguments; in particular, I will emphasise that this does not depend on having understood the mathematical details in chapter 2. However, I do assume some elementary knowledge of vector arithmetic, calculus (knowing the meaning of differentiation and integration) and complex numbers. The required knowledge of physics is strictly speaking limited (I believe) to not much more than knowing what energy and momentum refer to, but it is an advantage to also have a reasonably clear

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off formulating both quantum mechanics itself and the Copenhagen interpretation in purely quantum mechanical terms.

idea of classical fields (e.g., electric and magnetic fields). I have also used particle symbols in a number of places. A superficial knowledge of the history of philosophy should be sufficient to follow the philosophical arguments, if you can look past the jargon.

I have chosen to divide this dissertation into 4 chapters. Chapter 2 has a dual function. Firstly, it presents quantum field theory from both a historical and a systematic point of view. Secondly, the historical presentation may serve to give an insight into the process of active physical research, which is of interest for discussions of physical research in general.

In chap. 3 I wish to sketch a framework of ideas in epistemology and natural philosophy which may form the basis of a philosophical discussion of fundamental theories of physics. An important point is that this framework should accord with what I find to be scientific practice: the physicist should recognise himself or herself in the description of physics. There are of course many views, also among physicists, of what physics is, but I assume (or hope) that my description of aims, methods and preconditions can be broadly accepted.

Chapter 4 contains the most important part of the dissertation. The chapter is divided in three. First there are some 'preliminaries', where I primarily assert what quantum field theory is not, and say something about why this is so: why classical ideas of matter would eventually become untenable. Subsequently, I outline different possible interpretations of quantum field theory, centred around four 'paradigms'. The conceptual framework of the theory is thus also illuminated from different angles. Finally, I address some critical issues within the theory, including the question of how our world may be reconstructed from quantum field theory.

The parameters of the dissertation have not allowed me to discuss thoroughly all the philosophical issues related to quantum field theory. I have concentrated on 'ontological' issues — trying to say something about what the theory says about the external world — rather than issues relating to philosophy of science, which look at the theory as a human activity. The questions of renormalisation and of the validity of the approximations used in the theory are mostly just mentioned in passing, but this should not be taken as an indication that they are uninteresting. I had hoped to include a section on particle mixing — how the distinction between different particle species becomes blurred in quantum field theory — but time did not allow this. Some of the issues I would have addressed are discussed by Heisenberg [21], Redhead [38] and Weingard [41], as well as in several articles in [18]. The Higgs mechanism would also have deserved a proper analysis, but is not discussed here.

I have avoided many of the typical topics of 'quantum philosophy', such as causality vs determinism, quantum logic, the EPR paradox and Bell's theorem, the measurement problem etc. These questions have been thoroughly debated by others, and I do not expect to contribute anything significant here. I will not be able to completely avoid these issues, and will to some extent express a particular view without having justified this any further, or merely address the issues implicitly. This does not mean that I ignore that these are real issues (although I consider some of the discussions to be about non-issues); only that I do not consider a detailed discussion necessary or appropriate in this context.

In chap. 5 I try to look into the future, and in particular consider the positive heuristics of the theory: which possibilities it contains for future research. I have not had the time to make a detailed analysis of the situation (and in any case, such predictions are notoriously unreliable), but hope it can help form a basis for a more proper evaluation of potentially fertile areas of research: in which directions may we expect progress. In this chapter I will also take a closer look at physics as a human activity.

The parameters of the dissertation do not allow the extensive literature survey that would have been desirable — and the selection of literature is perhaps also somewhat ‘random’ and determined largely by what was to hand. Hence there is a clear risk that I have missed significant points and possible previous debates on the topic, and I may have repeated things that have been said before. Some articles which explicitly address philosophical aspects of quantum field theory [19, 39] are included in the bibliography, although I had not read them myself at the time of writing.

I hope that this can be a small contribution to a debate I consider necessary.

Chapter 2

What is quantum field theory?

2.1 Introduction

This chapter is divided into two parts: a historical and a systematic part. This is done because I have wanted to present the theory in a (more or less) logical order, as it appears today, to provide the best possible starting point for the subsequent discussion. Since the logical and the historical order can differ considerably, and since the concepts have often evolved quite a lot, I found it most appropriate to avoid confusion by not mixing the two up. The disadvantage is that the history is somewhat abbreviated, but I hope this is balanced by greater clarity later on.

I will also repeat myself to some extent, and the distinction between history and systematics will not be strictly observed. In particular, non-abelian gauge theories will be presented in their entirety in the historical section. I found this most natural both because the logical and the historical developments (at least as I see them) follow each other closely in this case, and because a systematic presentation of the theory cannot add much to what is required to present the historical development — unless you want to delve into abstract group theory.

The main point of this chapter is to provide a background for the reflections I will make in chapters 4 and 5. The main emphasis is therefore on the conceptual aspects of the theory, and I will attempt as far as possible to avoid using the mathematical formalism. Space does not allow me to go into detail, neither about theoretical contents, nor about history or debates among physicists regarding the status of the theories. For anyone who wants to delve further into these matters, I have included some books (including textbooks at different levels and with different approaches) in the references. I should in particular mention the book by Abraham Pais [2] on the history of particle physics, which in addition to being written with great insight and giving a near-encyclopaedic overview, contains almost everything that would be required of additional references in this area. I may also mention Max Jammer's *The Philosophy of Quantum Mechanics* [16], which similarly gives a near-encyclopaedic overview of the debates within nonrelativistic quantum mechanics.

Attempting to present the physical contents of the theory without becoming too mathematical is a difficult balance — especially if (at this stage) I am to try to take a 'neutral' stance in regard to the various interpretations. Any (not purely mathematical) concept I employ will necessarily have its connotations, implying a certain metaphysical 'bias'. I could have presented many basic concepts in the theory without using any mathematics, but this would have tied me to one specific interpretation. This issue also arises where there are several (equivalent) mathematical formulations of the same theory: different formulations make it easier to see different aspects of the theory. As long as I make use of physical concepts, and do not explicitly and consistently explain the equivalence between different formulations, the presentation will thus have a bias. The most obvious expression of this is probably my having put Feynman's path integral formalism on its own, right at the end of the systematic presentation.[1]

It would have been tempting to start the historical presentation with the debates between Newton and Huygens on the nature of light (particles or waves), since this is the question quantum field theory (quantum electrodynamics) solves quite brilliantly by removing the dichotomy. Feynman writes that Newton was right: light is particles; and his formulation and visualisation of the theory does on the face of it lend most support to this point of view. However, if you look behind the diagrams, you see that the particles must be some strange entities which are quite far removed from Newton's ideas and principles, and Feynman also points this out.[2] I will discuss this in more depth in section 4.2.1.

I could also have started with Faraday's and Maxwell's investigations of electromagnetism, which gave us a completely new understanding of what light is, and in retrospect must be said to have started the process leading to the demise of newtonian physics. This is also the origin of the concept of fields — it could have been interesting to follow the evolution of this concept, first in classical mechanics from Faraday's description of field lines, via Maxwell's mechanical model of the aether, to Einstein's special theory of relativity, and then how it is taken over and developed further in quantum mechanics. I will however not go any further into this part of the prehistory.[3] The reader who wants to acquaint herself further with this topic may read the histories by Whittaker or Meyer [3, 4].

2.2 Historical overview

2.2.1 The quantum mechanical revolution (1900–27)

Quantum field theory may be said to have started with Einstein's remark in his 1917 article on emission and absorption of radiation: 'The properties of elementary processes make the task of formulating a genuinely quantised theory of radiation appear inevitable.'[4] In this article he had, using Planck's law of radiation, Bohr's quantum postulates and thermodynamic considerations, computed coefficients for the emission and absorption of radiation by matter — the so-called Einstein's A- and B-coefficients.

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[1] Since writing this dissertation, I have worked for more than 20 years as a practising particle physicist using path integral methods, and these now form the cornerstone of my view of the theory. This is likely to have modified my views and would deserve a followup or postscript.

[2] For example, they may go in all possible directions without this being caused directly by any external force. In fact, they take all possible paths, including forwards and backwards in time — at the same time, if one may say so.

[3] I will, however, look at it in a quasi-historical perspective, with the benefit of hindsight, in section 4.1.

[4] A.Einstein: *Phys. Zeitschr.* **18**, 121 (1917).

The theory he had in mind, which could explain these coefficients from fundamental principles of quantum mechanics (though not in the way Einstein had in mind), would be formulated by Dirac in 1927: quantum electrodynamics.

But now I have jumped straight into a story which started with Planck's 1900 article on thermal radiation.[5] Planck did not understand what he did with his quantum postulate: originally, his radiation law was a pure interpolation with no theoretical basis, and the quantum postulate was introduced purely as a justification for this law. Initially, it was thus only applicable to a single, relatively peripheral problem in physics (black-body radiation, or thermal radiation from a cavity)[6] — and he tried long, unsuccessfully, to incorporate it into classical physics. Max Planck, who is considered to be the founder of quantum physics, and after whom its fundamental constant is named, never accepted quantum mechanics.

It was Einstein who first understood that Planck's work constituted a revolution in physics. He soon understood that Planck's *ad hoc* assumption that the atoms in the cavity wall only emitted and absorbed radiation in quanta, implied that the radiation (or light) must be considered as consisting of particles (photons, symbolised by γ), each with an energy $h\nu$, where ν is the frequency of the radiation. He used this to carry out detailed investigations of the interaction between radiation and matter, in studies of the photoelectric effect and black-body radiation.[7] Through this work, the famous (or infamous) wave-particle duality of light was demonstrated for the first time.

It was also Einstein who showed that quantum physics had applications beyond issues related to radiation. In an article from 1907[8] he showed that the energy quantum hypothesis, applied to molecular vibrations, could explain deviations from the predictions of classical physics regarding the heat capacity of solids, something which had previously been a mystery. As a result, the quantum postulate could be considered physically relevant, not just as an anomaly, but as a more general theory.

The last area where quantum theory had an early impact, was the study of the structure of atoms. It had been known for quite a while that different elements have their characteristic spectra: only radiation with certain frequencies is emitted or absorbed, and certain rules for these frequencies had been worked out for simple atoms. In addition, Rutherford made discoveries in 1911 which could be explained by thinking of the atom as a mini-'solar system' where the electrons orbit the nucleus as planets around the sun.[9] Both these observations posed problems for classical physics. Firstly, the emission spectrum would be expected to be continuous; and secondly, an electron orbiting a nucleus would emit radiation, and hence lose energy and spiral towards the nucleus. Bohr attempted to solve these problems with his 1913 model of the atom,[10] where he postulated that the electrons could only move in certain orbits with discrete energy values (*stationary states*), where they did not radiate anything. Transitions from one state with energy E_1 to another one with a lower energy E_2 occurred by the atom emitting a photon with frequency $\nu = (E_1 - E_2)/h$. Conversely, the atom could be

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[5] M.Planck: *Verh. Deutsche Phys. Ges.* **2**, 237 (1900); *Ann. Physik* **4**, 553 (1901).

[6] That it is a peripheral issue in physics does not imply that it is of little practical importance: the whole issue of the greenhouse effect and global warming is closely connected with this.

[7] A.Einstein: *Ann. Physik* **17**, 132 (1905).

[8] A.Einstein: *Ann. Physik* **22**, 180 (1907).

[9] E.Rutherford: *Phil. Mag.* **12**, 143 (1911).

[10] N.Bohr: *Phil. Mag.* **26**, 1 (1913).

brought into a higher energy state by absorption of a photon. The energy levels were chosen such that the radiation would satisfy the known rules. The discrete energy level postulate was directly confirmed in an experiment by Franck and Hertz in 1914.[11]

Based on this model, a series of further investigations of atomic structure was carried out, in particular by Bohr, Sommerfeld and their collaborators. The result was a set of 'quantum postulates' or quantisation rules, which explained how to find the correct quantum description of a problem after first having formulated it classically. A great help was that the quantum description always approached the classical one in the limit of large quantum numbers, and it was hence possible to consider the objects of quantum physics as analogous to the classical ones. Bohr formulated this as the *correspondence principle* in 1923.[12] However, the quantum postulates were for the most part unrelated to one another, and quantum physics was thus more a set of rules for calculation than a unified theory. In the words of Abraham Pais, 'Quantum physics was not in a crisis. Quantum physics *was* a crisis.' [2, p217] There was a need for a 'rational quantum mechanics'. The big breakthrough would happen in the years 1924–27, originally from two different starting points.

In 1923, Louis de Broglie[13] managed to show that Bohr's quantum postulates could be explained by considering the electron as a wave with wavelength $\lambda = h/p$, where $p = mv$ is the momentum of the electron. This line of thought was continued by Schrödinger,[14] who considered the electron as an extended charge with wave characteristics, and constructed a non-relativistic equation for this wave — yielding correct results for the energy states of the hydrogen atom. At the same time, Heisenberg[15] carried out a study of the harmonic oscillator (an oscillating or vibrating system with only one frequency), where he sought to describe the system purely in terms of relations between 'directly' observable quantities. The result of this was that the values of the observable quantities, which in the classical theory had been ordinary numbers, now became elements of matrices — and the theory was called *matrix mechanics*. Dirac and Jordan[16] showed that the two forms of quantum mechanics were equivalent, and developed a theory for transforming betweeen different representations of quantum mechanics. This transformation theory would thus form a unified theoretical basis for all of quantum mechanics.

Some important elements of the new physics which was developed during these years should be mentioned:

1. Quantum statistics. Quantum statistics was developed just before the great breakthrough in quantum mechanics, and was only fully integrated with the rest of the theory with the advent of quantum field theory. It is however essential for calculating processes and quantum mechanical systems with more than one particle, it is closely related to symmetries of the systems, and it tells us much about the concept of a quantum mechanical state. Two different statistics were developed: they share the

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[11] J.Franck and G.Hertz: *Verh. Deutsche Phys. Ges.* **16**, 457 (1914).

[12] N.Bohr: *Zeitschr. Physik* **13**, 117 (1923).

[13] L.de Broglie: *Comptes Rendus* **177**, 507, 548 (1923).

[14] E.Schrödinger: *Ann. Physik* **79**, 361,489 (1926); **80**, 437 (1926); **81**, 109 (1926).

[15] W.Heisenberg: *Zeitschr. Physik* **33**, 879 (1925); M.Born and P.Jordan: *Zeitschr. Physik* **34**, 858 (1925).

[16] P.A.M.Dirac: *Proc. Roy. Soc.* **A 109**, 642 (1925); P.Jordan: *Zeitschr. Physik* **40**, 809 (1926).

feature that they are based on the particles being absolutely identical (as opposed to classical statistical mechanics, where one may imagine 'marking' each particle). They are distinguished by how many particles can be in the same state at the same time. In *Bose–Einstein statistics*[17] (which is valid for photons and other *bosons*, there are no limits on this. *Fermi–Dirac statistics*,[18] which holds for electrons and other *fermions*, requires that no more than one particle can be in each state. This is known as the *Pauli exclusion principle*, formulated first by Pauli in 1925.[19] A connection between the two statistics was established with *Wigner's sum rule*, which states that where a system of particles may be considered an indivisible unit, it behaves as a boson if it consists of an even number of fermions, and as a fermion if it consists of an odd number.

2. The statistical interpretation. With the emergence of the new quantum mechanics it became evident that it was not possible to predict the exact outcome of an atomic process. For example, in matrix mechanics the question of the precise time of a transition between two energy states had become meaningless. It was also not possible to say exactly which stationary state an electron would end up in after an excitation, even though it was possible to compute the intensity of the spectral lines. Nor was it possible to predict the result of individual scattering processes. Max Born therefore proposed[20] that the matrix elements and wave functions referred to the distribution of the results of a series of identically prepared experiments. This interpretation was soon accepted by most physicists, and is today considered one of the basic principles of quantum mechanics.

3. The indeterminacy relation. In March 1927, Heisenberg published his indeterminacy relations,[21] which show that in quantum mechanics there is a theoretical limit to how precisely several physical quantities may be measured simultaneously. It is for example impossible, as a matter of principle, to simultaneously give precise values for the position and the momentum of a particle. This result emerges both from the mathematical formalism of quantum mechanics, and from considerations of the impact of the measuring apparatus on the system to be measured: an impact that cannot be made arbitrarily small. This inherent indeterminacy is one of the things distinguishing quantum mechanics most clearly from classical physics, and is often considered the first principle of quantum mechanics. It also led Bohr to formulate his complementarity principle.[22]

All of this happened in the course of a few years, in an intellectual climate with few precedents in the history of physics. A large amount of the work was done by a group of very young physicists (Pauli, Jordan, Heisenberg, Dirac, Wigner, Fermi and others were all born between 1900 and 1902), under the supervision and influence of Niels Bohr and Max Born in particular. In this environment, with Bohr as the most central character, the still-dominant interpretation of quantum mechanics — the so-called Copenhagen interpretation — was also developed. This interpretation represented a break with the

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[17] S.Bose: *Zeitschr. Physik* **26**, 178 (1924); A.Einstein: *Sitz. Ber. Preuss. Ak. Wiss.* 1924, p. 261.

[18] E.Fermi: *Rend. Acc. Lincei* **3**, 145 (1926), *Zeitschr. Physik* **36**, 902 (1926); P.A.M.Dirac: *Proc. Roy. Soc.* **A 112**, 661 (1926).

[19] W.Pauli: *Zeitschr. Physik* **31**, 765 (1925).

[20] M.Born: *Zeitschr. Physik* **37**, 863 (1926).

[21] W.Heisenberg: *Zeitschr. Physik* **43**, 172 (1927).

[22] N.Bohr: *Nature* **121**, 580 (1928).

realism of classical physics: that things are as they are, independently of whether we observe them — and also with the associated determinism, which had been widespread in the 19th century. This was poorly received by many physicists, especially in the older generation, also among those who had played central roles in the development of quantum physics: Planck, Einstein, Schrödinger, de Broglie. Einstein's words, 'God does not play dice', have become famous. The debate between the two 'camps' reached its climax at the Solvay conference in 1927, with Einstein and Bohr in the lead roles. This can also be considered the starting point for all later philosophical discussions of quantum physics, as depicted for example in [16].

2.2.2 Quantum electrodynamics

Since a proper theoretical foundation for quantum mechanics now existed, it was time to return to the question that Planck had started with: the interaction between radiation and matter. It was now possible to conduct an analysis of radiation phenomena taking into account the quantum nature of *both* radiation and matter. The task was then to attempt to use the theory that had been developed for the study of matter, to also quantise the radiation field and hence to explain Planck's quantum postulate.

The idea of *field quantisation* (often called second quantisation) can be said to have been originated by Jordan, and was first expressed in a paper by Born, Heisenberg and Jordan in 1925. A concrete formulation of the idea came in 1927, with Dirac's first paper on quantum electrodynamics.[23] Treating the field as a system of harmonic oscillators, it was possible to obtain discrete (quantised) energy states of the field, and these states (*field quanta*) behaved just like photons (massless particles with Bose–Einstein statistics). In this paper he also showed how the photons were *created* and *destroyed*. He carried out a consistent (but still non-relativistic) quantisation of the radiation field, and obtained the correct values for the emission and absorption coefficients. This theory was essentially a *perturbation theory*, ie., one first calculated the effects of processes involving one photon, then added contributions from processes with two photons (which should be less probable and hence give smaller contributions), etc.

Dirac's work was followed up by further work on a relativistic formulation of the theory. Certain problems emerged with obtaining a consistent quantisation of all the field components — Dirac could ignore this problem because it is not necessary to treat all the components equally in a non-relativistic theory. Heisenberg and Pauli[24] solved this problem by exploiting a freedom in the choice of fields — *gauge invariance* — which follows from Maxwell's equations. This could be used to eliminate the 'unphysical' field components and end up with a theory which was relativistically invariant although it did not look so. Other (equivalent) solutions were also proposed, but these were conceptually more difficult, and were not used in the 1930s. They would, however, form the basis for the later, explicitly relativistic theory.

It was shown that field quantisation of the kind carried out by Dirac could be used to describe bosonic systems in general. That raised the question of whether fermions also could be considered in a similar manner. This was shown by Jordan and Wigner in

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[23] P.A.M.Dirac: *Proc. Roy. Soc.* **A 114**, 243 (1927), reproduced in [26].

[24] W.Heisenberg and W.Pauli: *Zeitschr. Physik* **59**, 160 (1929).

1928.[25] As in the bosonic case, variable particle numbers could be taken into account, suggesting that not only photons, but also electrons, were field quanta which could be created and destroyed.

The same year, Dirac developed his relativistic equation for the electron,[26] which gave the correct results for the structure of the hydrogen atom, and which also explained the spin and magnetic properties of the electron, which it had previously been necessary to introduce as *ad hoc* assumptions. Combining the Dirac equation and quantum electrodynamics, it was also possible to calculate scattering processes to lowest order, with results in very good accordance with observed values. The first success was the Klein–Nishina formula [27] for Compton scattering ($e^-\gamma \to e^-\gamma$). Later on, Jordan–Wigner quantisation was employed for the Dirac equation, and a number of processes were calculated on this basis: pair creation ($\gamma\gamma \to e^-e^+$), pair annihilation ($e^-e^+ \to \gamma\gamma$), bremsstrahlung ($e^- \to e^-\gamma$ in an electrostatic field), Bhabha scattering ($e^-e^+ \to e^-e^+$) etc. A very important theoretical result from this period is the study by Paul in 1940,[28] where he showed that all particles with spin 1/2 (such as the electron) *must* obey Fermi–Dirac statistics, while all particles with integer spin (like the photon) *must* obey Bose–Einstein statistics. This conclusion relies fundamentally on relativistic considerations (the strong requirements of causality in relativity), and requires that everything is formulated in a relativistically invariant manner.

So then it seemed everything should be OK. But the new, relativistic quantum theory turned out — despite its successes — to be a disaster. There were in particular 3 or 4 issues that caused despair:

1. The positron. Dirac's relativistic equation for the electron was, as we have seen, an amazing success, as it could be used to derive all the important properties of the electron, without any additional assumptions. But it also contained a paradox: it predicted twice as many quantum states as expected. The 'superfluous' states corresponded to the negative-energy solutions of $E^2 = p^2c^2 + m^2c^4$. These solutions could not be simply rejected as unphysical: there was no mechanism which could prevent transitions between positive and negative energies. Instead, Dirac proposed that the negative energies could correspond to particles with positive energy and positive charge: all the states were originally occupied, and an electron left behind a positively charged 'hole' when it jumped to a higher state. The holes were thus identified with protons, which were the then known positively charged particles.

This theory was a complete disaster. Oppenheimer showed that it led to spontaneous decay of the hydrogen atom, giving a lifetime of 10^{-10} seconds for ordinary matter. There was also no way of explaining the mass difference. Dirac had to postulate the existence of a new, so far undiscovered particle — an outrageous idea at that time. With the recently discovered neutron, one knew of only 4 particles — and would rather not have any more. Luckily, Anderson discovered the positron by accident in 1932,[29] and the disaster turned to triumph.

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[25] P.Jordan and E.P.Wigner: *Zeitschr. Physik* **47**, 631 (1928), reproduced in [26].

[26] P.A.M.Dirac: *Proc. Roy. Soc.* **A 117**, 610 (1928).

[27] O.Klein and Y.Nishina: *Zeitschr. Physik* **52**, 853 (1929).

[28] W.Pauli: *Phys. Rev.* **58**, 716 (1940), reproduced in [26].

[29] C.D.Anderson: *Science* **76**, 238 (1932).

2. The self-energy of the electron. In classical electrodynamics, the electron has an internal electrostatic energy, which is infinite when considered as a point particle, and equal to the mass when considered as a hard sphere with radius $a = e^2/4\pi\epsilon_0 mc^2$ (the classical electron radius). In quantum mechanics and relativity, the particles are treated as points, and the infinite self-energy appears. But in addition there is an electromagnetic effect, which is purely quantum mechanical — and this turned out at first to behave even worse than the classical self-energy: it gave not just an infinite shift in the energy levels, but also an infinite relative shift, which would give an infinite shift of the observed spectral lines.[30]

But this was before the positron theory, and before the Dirac field was quantised. When this was included, and a consistent procedure was developed to subtract quantities which are nonzero in the vacuum, it turned out that there were indeed still infinities (divergent integrals), but they were 'nicer' (the divergence was weaker) than in both classical theory and the first calculation of the self-energy. On the other hand, all correspondence with the classical theory was lost and with it, apparently, any possibility of obtaining meaningful results by separating out the infinities — which appeared in all attempts at higher order calculations.

3. Vacuum polarisation. The process $\gamma \to e^-e^+ \to \gamma$, or an electromagnetic field inducing the creation of an electron–positron pair, with an associated charge distribution, must be included in the Dirac theory. If the induced charge and current is calculated, it turns out to be infinite. These charges in turn produce an electromagnetic field, and we get a new quantum effect: an (infinite) polarisation of the vacuum. This gave both the vacuum and the photon a self-energy, which of course could not have anything to do with the mass, as was the case for the electron. It was suggested that this polarisation might be *renormalised*[31] by e.g. absorbing the infinities in the charge of the electron — and Weisskopf observed that 'a constant polarisability is in no way observable.'[32] But as to *how* the process of eliminating the infinities was to be carried out, there was no answer.

Weisskopf showed[33] that all self-energies are at most logarithmically divergent (i.e., they only just diverge) — a result that would become important when a theory of renormalisation was developed. But this was still some time away. And in some cases (in particular for bremsstrahlung) there were also divergences for very low (photon) energies — the self-energy and vacuum polarisation diverge at extremely high energies. Because of these problems it was concluded that a consistent theory was still not available, and the theoretical research became quite dormant. Dirac distanced himself from quantum electrodynamics — the theory he himself had created — from 1936 on, and devoted the rest of his life until his death in 1984 to trying to develop an alternative electrodynamics. This was an extreme, but not completely untypical, expression of the prevailing mood. On top of this came the war.

Many of the underlying problems were solved by Japanese physicists during the war, but these results did not become known in the west until the end of the 1940s, by

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[30] J.R.Oppenheimer: *Phys. Rev.* **35**, 461 (1930).

[31] R.Serber: *Phys. Rev.* **49**, 545 (1936).

[32] V.F.Weisskopf: *Kgl. Danske Vid. Selsk. Math.-fys. Medd.* **14**, nr.6 (1936), reproduced in [26].

[33] V.F.Weisskopf: *Phys. Rev.* **56**, 72 (1939), reproduced in [26].

which time (in particular) US physicists also had made great progress in the same area. Much of the renewed effort was due to new experimental results: in 1947, Lamb and Retherford[34] had discovered, with the help of microwave technology, a small shift of lines in the hydrogen spectrum — the so-called Lamb shift. This was presented at the big Shelter Island conference the same year, and soon after, Bethe[35] was able to explain the results as a consequence of radiative corrections.

Bethe's calculation gave the correct result, but was not relativistically invariant, and could not be used as a more general procedure. In general the renormalisation, where the infinities were absorbed into a mass or charge term, appeared arbitrary, but it turned out that the outcome was unique if explicit Lorentz and gauge invariance was maintained throughout all stages of the calculation. Hence, the development of theories exhibiting such invariance became an essential aim.

Such theories were developed primarily along two lines. The first (Tomonaga, Schwinger)[36] took field theory as its starting point, and introduced a new formulation of quantum mechanics, where the interaction was separated from the remainder (non-interacting part) of the system. The second method, developed by Feynman,[37] was less general, but more intuitive and easily applicable. It started from the scattering problem, and considered the interaction as an action at a distance with a finite propagation velocity. The result was a description of quantum electrodynamics where the motion of the electron in time and space is fundamental. A particular feature of this formulation was that the positron may be interpreted as an electron moving backwards in time! Dyson[38] showed that the two formulations were equivalent: Feynman's 'rules' may be produced by integrating Tomonaga's and Schwinger's theory.

As a consequence of this breakthrough, there was fresh interest in formulating quantum field theory in such a way that it could 'stand on its own legs' — with strict relativistic invariance and gauge invariance built into the foundations of the theory. Until then, quantum mechanics had been almost exclusively constructed from the non-relativistic Hamiltonian formulation of classical mechanics; now many people sought to develop, from quantum mechanical principles, a theory in line with classical Lagrangian theory, which has a more invariant formulation. Such theories could clearly also be applied to problems other than electrodynamics, and this was now attempted.

2.2.3 Strong and weak interactions

At the first Solvay conference, in 1911, Marie Curie remarked that 'radioactive phenomena form a world of their own', without any connection with other physical phenomena. 'It looks as if [they] have their origin in a deeper area of the atom.'[39] This was before she got to know about Rutherford's discovery of the atomic nucleus earlier the same year. In the following years, the perceptiveness of her observation was confirmed: α

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[34] W.E.Lamb and R.C.Retherford: *Phys. Rev.* **72**, 241 (1947), reproduced in [26].

[35] H.A.Bethe: *Phys. Rev.* **72**, 339 (1947), reproduced in [26].

[36] S.Tomonaga: *Progr. Theor. Phys.* **1**, 27 (1946), reproduced in [26]; J.Schwinger: *Phys. Rev.* **74**, 1439 (1948).

[37] R.P.Feynman: *Phys. Rev.* **76**, 749, 769 (1949) [34], reproduced in [26].

[38] F.J.Dyson: *Phys. Rev.* **75**, 486 (1949), reproduced in [26].

[39] *Théorie du rayonnement et les quanta*, p. 385, eds. P.Langevin and M.de Broglie, Gauthier–Villars, Paris 1912.

(helium nuclei), β (electrons) and γ (photons) radiation all turned out to originate in the nucleus, and it also slowly became evident that completely new forces were needed to explain these phenomena.

Initially there was full agreement that the nucleus must be made up of the two particles that were known up to then: the proton (hydrogen nucleus) and electron, and electromagnetic forces should be sufficient to keep this system bound. However, this view soon met with difficulties. Rutherford discovered deviations from Coulomb's law in scattering of α particles off hydrogen at very small distances. The β particles turned out to be emitted from the atom with a continuous energy spectrum, in apparent contradiction to the requirements of energy conservation and the same process being at work in each case. The tight binding of protons and electrons was forbidden according to Bohr's quantum postulates, and also according to the new quantum mechanics under development. Also, many nuclei (^{1}4N being the best known and most studied) had the wrong spin and statistics compared with the theoretical expectations. (If ^{14}N consists of 14 protons and 7 electrons, it should according to Wigner's sum rule have half-integer spin and behave as a fermion — but it has spin 1 and behaves as a boson.) The most common response to all these problems was that the known laws of physics break down at distances of the order of the nuclear radius; quantum mechanics is no longer valid (just as classical physics breaks down when Planck's constant no longer can be considered small); the electron (and perhaps also the proton) completely loses its identity inside the nucleus — and Bohr also believed that energy is not strictly conserved.

By 1931 it had become clear that Coulomb's law would have to be modified, or new forces introduced, at small distances; and a qualitative account of radioactivity based on non-relativistic quantum mechanics had been obtained. There was however still no proper theory. The β spectrum and the spin–statistics problem was still a mystery. We have seen that Bohr advocated the view that physics as we know it, including conservation of energy, breaks down. Pauli[40] had postulated the existence of an electrically neutral spin 1/2 particle with a very small (≈ 0) mass (first called the neutron, but later renamed by Fermi to the *neutrino* ν) to save energy conservation and solve these problems — and became more and more sarcastic towards Bohr. There were no conclusive arguments on either side. Then, the following year, things again started to happen.

In February 1932, Chadwick discovered the neutron.[41] He, and other collaborators of Rutherford, had for 12 years been looking for a strongly bound system of a proton and an electron — and now he believed he have found it. However, in the course of the following year, evidence emerged for the neutron being a true elementary particle, with spin 1/2. This would at least explain the spin and statistics paradox, but β radiation would be a greater mystery than ever, unless one was prepared to still 'hide' some electrons inside the nucleus. So the situation was new, but the old fronts more or less remained in a stalemate.

In the same year, Heisenberg presented the first proper theory of nuclear forces.[42] Heisenberg took the side of Bohr against his good friend Pauli, believing in a composite neutron, but he wanted to push all the problems onto the neutron and hence forget

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[40] W.Pauli: *Phys. Rev.* **38**, 579 (1931).

[41] J.Chadwick: *Nature* **129**, 312 (1932).

[42] W.Heisenberg: *Zeitschr. Physik* **77**, 1 (1932); **78**, 156 (1932); **80**, 587 (1933).

them in the description of nuclear forces. In this way, the old view could help him: by considering a proton–neutron system in analogy with a H_2 molecule (two protons and one electron), he could see that the proton and the neutron could be 'exchanged' by interchanging the electron, and the interaction between them could be described by this exchange. This was the first step on the way to the insight that the strong forces do not distinguish between protons and neutrons (charge independence), and that they may be considered two states of the same particle, the nucleon. It is in fact possible to 'mix' (or superposition) the two arbitrarily wihtout this affecting the strong nuclear forces. This symmetry is called *isospin.*

In 1934, Fermi[43] sorted out the dispute between Bohr and Pauli, in favour of Pauli. He did this by invoking quantum field theory: a β decay was the result of an interaction between the nucleons and electron and neutrino fields, so that the neutron changes into a proton (Heisenberg's idea!), and at the same time an electron and a neutrino (or, according to modern conventions: an antineutrino) are created. (At the same time, other, similar, processes were also explained or predicted, e.g., $e^- \to n\nu$ (electron capture); $p \to ne^+\nu$ (β^+ radiation); $\nu n \to e^- p$.) Hence there was no longer any need to hide electrons in the nucleus: they were only created in the decay process. And the neutron turned out to be a true elementary particle with spin 1/2, on a par with the proton.[44] And, last but not least, it was seen that β decay (and weak interactions in general) cannot even be understood qualitatively without quantum field theory. Fermi was in fact the first person to amply field quantisation of spin 1/2 fields (the Jordan–Wigner method) — only later in the same year did Heisenberg do the same in his positron theory (quantum electrodynamics).

Fermi's theory was of course not complete, but it is a correct description at low energies. Over the next few years, Dirac wavefunctions were also employed for the nucleons, making it possible to write the interaction in a relativistically invariant form, and a more general form for the interaction was also soon developed. All of this followed almost automatically, and provided fertile soil for both calculations and experiments. But it was not known what happened at high energies.[45] And the theory did not work at all as an explanation for the binding of the nucleus: the coupling between the fields was far to weak, and it was difficult to obtain charge independence. Only slowly was it realised that there are two kinds of nuclear forces: the strong, responsible for binding the nuclei, and the weak, responsible for β decay and similar processes.

It was Hideki Yukawa who in November the very same year[46] proposed a model of the forces between the nucleons which could account for the main features of the strong interaction. It was based on the following analogy with electromagnetism. Electromagnetic interactions may be viewed as exchange of photons between charged particles. This should also be the case for the nuclear forces. The electromagnetic force has a long (infinite) range, and this is related to the fact that the photon has zero rest mass. The nuclear forces, on the other hand, are very short ranged. They should therefore be mediated by a massive (as yet undiscovered) particle, with a mass $m \approx \hbar/lc$, where l is the range of the nuclear force. This particle was (eventually) called the *meson.* On the

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[43] E.Fermi: *Ric. Scient.* **4**, 491 (1934); *Nouvo Cim.* **11**, 1 (1934); *Zeitschr. Physik* **88**, 161 (1934).

[44] It was later discovered that neither is elementary.

[45] This only became clear in the 1960s and 1970s, with experimental verification in 1983. I will come back to this in section 2.2.4.

[46] H.Yukawa: *Proc. Phys. Mat. Soc. Japan* **17**, 48 (1935).

basis of this, Yukawa developed a field theory in analogy with electromagnetism.

Towards the end of the 1930s, much good theoretical work was done with different variants of meson theories, especially after the discovery, in 1937, of what was thought to be the meson. As it turned out, the particle discovered in 1937 was not the meson, but a heavier version of the electron: the muon μ. In 1947, the 'real' meson — the π meson (pion) — was discovered, and people then realised why the previous calculations in the meson theory had given strange or wrong results. Now it seemed to work a lot better.

But it did not. Quantum field theory, which had just enjoyed great triumphs in electrodynamics, was a complete failure when applied to meson theory. No calculations gave any sensible result: the theory was not useful for anything. It did not help that it could be shown that the theory fitting the pion that was discovered was renormalisable: it was still all wrong. The explanation is simple: any process with n photons in quantum electrodynamics has a probability proportional to α^{2n}, where $\alpha \approx 1/137$ is the fine structure constant, which is a measure of how strongly the electromagnetic field couples to matter. A perturbative expansion (see p. 14) works because α is so small. The equivalent coupling constant for the nuclear forces, on the other hand, was found to be ≈ 15. A perturbative expansion in powers of this number is clearly meaningless.

Particle physics in the 1950s and early 1960s was chaos. New accelerators and new detectors were built, and hordes of new particles and 'resonances' (structures with a lifetime too short to be called particles) were discovered: K-mesons, Λ, Σ and Ξ particles, Δ and ρ resonances, etc., etc. — dashing hopes that everything was now sorted and the 'real' elementary particles had been found. There was almost enough to do trying to find the correct quantum numbers for the new particles and perhaps bring them into some kind of system. They were divided into three main groups: *mesons*, which are strongly interacting bosons; *baryons*, which are strongly interacting fermions (such as nucleons); and *leptons*, which are fermions which do not interact strongly (the electrons, the muon, and the neutrinos). Mesons and baryons are in turn grouped together and called *hadrons*. The quantum field theory of the strong interactions was, as we have already seen, a disaster, and theorists were limited to formulating phenomenological laws, and trying to find relations and rules which were as independent as possible of the dynamical details of the interaction.

At this point, symmetries and conservation laws turned out to be invaluable. It was possible to obtain many results relating the probabilities of various processes using for example isospin invariance or spin and parity considerations. Several new quantum numbers and abstract symmetries were employed to describe 'allowed' and 'forbidden' processes. Several of these symmetries only hold for processes involving strong interactions, but since these are much faster than weak and electromagnetic processes, this yields quite a lot of information. One may also find 'selection rules' (rules for which changes in quantum numbers are allowed) for the weak and electromagnetic processes.

There were several new methods and research programmes which attempted to go further than this. Of those, axiomatic field theory and S-matrix theory were probably the most extensive and general ones. Axiomatic field theory was, as the name suggests, a programme for investigating (and making explicit) the (previously implicit) principles on which quantum field theory rests, and finding out how much may be derived (strictly mathematically) from the smallest number of principles. Some relations which were first discovered experimentally or derived from plausible assumptions were later proved within the framework of axiomatic field theory. Beyond this, the programme did not contribute many results.

The S matrix programme was, in its most comprehensive version, an attempt to get rid of almost all of field theory. It had been initiated by Heisenberg[47] as an attempt to find out what could be 'saved' when quantum mechanics (in his view) broke down at distances less than 1 fm (10^{-15}m). The S matrix describes the probabilities of transitions between 'asymptotic' states (i.e, states long before and long after the interaction itself), and the concept is hence completely independent of whether it is possible to describe what happens during the interaction itself. Heisenberg eventually turned to other interests (a united field theory of all matter), but supervised several of those who subsequently worked on S matrix theory. The study of the S matrix gained renewed interest when it turned out to be possible, by imposing several generic conditions, to deduce a number of scattering data (such as relations between scattering and frequency). This led some people to suggest that all relevant physical properties of processes, and the entire spectrum of particles and resonances, could be explained by imposing conditions on the S matrix — the so-called *bootstrap* programme. Others were less 'starry-eyed', but considered the study of the analytical properties of the S matrix to be a fertile area of theoretical work. Several results were obtained, but these became more and more mathematical and less physical. Today, this S matrix programme must be considered to be dead (something which does not necessarily have any impact on the S matrix interpretation of quantum mechanics, and even less so on the usefulness of the S matrix in quantum mechanics in general).

Back to weak interactions. Until the end of the 1940s, the Fermi theory had been a theory of β decay, and that was it. As the amount of experimental data increased and the pion was discovered, it turned out to be possible to construct analogous theories for other processes: $p\mu \to n\nu$ (muon capture) and $\mu^\pm \to e^\pm\nu\bar{\nu}$ (muon decay), with approximately the same coupling constant. Pion decay could also be described in this way: $\pi^+ \to \bar{n}p \to \mu^+\nu$, and the ratio of the probabilities for this process and $\pi^+ \to e^+\nu$ was found to agree with the predictions. Similar models could also be constructed for K mesons. It thus became clear that far from being some special phenomenon, the weak interaction is a universal force.

In 1956, one of the old, well-established symmetries was toppled: it was discovered that weak processes are not symmetric under spatial reflections (parity)[48] — in fact, they are maximally unsymmetric, and this is the case for all weak processes. This came as a great surprise to theoreticians, but did not lead to despair: on the contrary, it led to a flourishing of theories of the weak interactions which aimed to incorporate broken parity, new theories of the neutrinoes and universal Fermi theory. This effort came to fruition in 1957–58. For some years, the belief was then that all processes were symmetric under the combination (CP) of reflection and exchange of particles and antiparticles. This hope was also dashed: in 1964, it was discovered that this symmetry is also broken[49] — but only very weakly, and only in very special systems. This symmetry violation is considerably more difficult than the previous one to incorporate into the theory in a

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[47] W.Heisenberg: *Zeitschr. Physik* **120**, 513, 673 (1943).

[48] T.D.Lee and C.N.Yang: *Phys. Rev.* **104**, 254 (1956); C.S.Wu et al.: *Phys. Rev.* **105**, 1413 (1957).

[49] J.W.Cronin et al.: *Phys. Rev. Lett.* **13**, 138 (1964).

‘natural’ way.

The increasing amount of data on the new particles made it possible to start constructing a kind of ‘periodic system’ of them, which might lead to the discovery of new symmetries which could yield more information on the probabilities of various processes. This effort was closely analogous with the idea of isospin, and was meant as an extension of this. In this context, the idea of abstract symmetry groups became a powerful tool. Group theory had been introduced in quantum mechanics by Wigner and Weyl in the 1920s, and had been used to describe spatial symmetries such as rotations, Lorentz transformations and reflections, but now the groups started as it were to live their own lives. In 1961, Gell-Mann, Ne’eman, Speiser and Tarski[50] managed to place the 8 most important baryons in a diagram (The Eightfold Way), and the 8 most important mesons in another diagram — as representations of the abstract symmetry group SU(3).

In 1964, Gell-Mann and Zweig[51] showed that these diagrams and the associated (approximate) conservation laws emerge naturally if one assumes that the hadrons are all built up of smaller particles, each with a charge of $-1/3$ or $+2/3$ of the elementary (electron) charge. These particles were called *quarks*, in a nod to a line from James Joyce’s Finnegan’s Wake: *Three quarks for Muster Mark!* — there were three different kinds of quarks: u(up), d(down) and s(strange), and three quarks were required to make a baryon. The quarks were also the simplest (nontrivial) representation of SU(3). Mesons consist of a quark and an antiquark.

This model ‘explained’ both the particle spectrum and some properties of the weak interaction, and must as such be considered a success. However, a question arose: are quarks real — or are they only convenient mathematical and theoretical constructs? After all, it is the hadrons that are observed in every reaction, and furthermore, the quarks appear quite exotic. Should we not instead consider all hadrons as equal and elementary, but subject to symmetry laws? This position would be in line with the S matrix and bootstrap programme, but was much more widely shared. Eventually, however, the quark model won out, although a free quark has still never been observed.

2.2.4 Renewed confidence in quantum field theory

One of the many failed attempts to construct a proper theory of strong interactions was made by Yang and Mills in 1954.[52] Their starting point was a relation which Weyl had noted between the electromagnetic interaction and freedom to choose the phase of the quantum mechanical wave functions (gauge symmetry). By extending this concept of gauge symmetry to also include symmetry between different particles (isospin symmetry), they hoped to be able to generate a useful meson field theory of the strong interactions. The results of this first non-abelian gauge theory, as it was called, were not very encouraging.

The theory did include quanta with the same charge as the π mesons, which were assumed to mediate the strong interaction. It also included non-linear terms, i.e., the field could interact with itself, and field quanta could be created and destroyed without

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[50] M.Gell-Mann: *The eightfold way*, Caltech Report CTSL–20 (1961), reproduced in [27]; Y.Ne’eman: *Nucl. Phys.* **26**, 222 (1961), reproduced in [27]; D.Speiser and J.Tarski: *J. Math. Phys.* **4**, 588 (1963).

[51] M.Gell-Mann: *Phys. Lett.* **8**, 214 (1964), reproduced in [27]; G.Zweig: CERN preprint 8182/Th401, 8419/Th412 (1964).

[52] C.N.Yang and L.R.Mills: *Phys. Rev.* **96**, 191 (1954).

any matter in the vicinity. This was a completely new phenomenon, but not a great suprise. However, the quanta turned out to be massless, and it was not possible to give them a mass without violating the gauge symmetry on which the theory was based. Accordingly, it was not possible to construct a theory of mesons, which definitely were massive particles — the theory was thus without (what was believed to be) reality, and was therefore abandoned.

This failed attempt would however form the basis for the theories that did emerge, both for strong and weak interactions. When it came to the weak interaction, the development of a new theory had two aims. Firstly, to obtain a renormalisable theory — Fermi theory was obviously useless at high energies, and Heisenberg had shown that a perturbative expansion was impossible in this theory. This problem might be solved by introducing new, massive, bosons $W^{\pm}$, which could mediate the weak force in the same way as the photon mediates the electromagnetic one. The second aim was to obtain a theory which could unify weak and electromagnetic interactions. This could be done by placing the W bosons, the photon, and possibly a 'new', massive, neutral boson, called Z^0, together in some symmetry group (and subsequently wonder about the origin of the mass differences).

The problem of particle masses was (partially) solved in the early 1960s, with the introduction of the concept of *spontaneous symmetry breaking*. The essential point here is that the system as a whole has a symmetry which the ground state does not have. An example of this is that the energy (energy density) E depends on the field Φ as indicated in fig. 2.1. The system is completely symmetric with regard to 'rotations' of the field components Φ_1 and Φ_2 (this is a kind of gauge transformation), and the ground state is therefore degenerate: all states on the dashed circle have the same energy, which is the lowest achievable. Any of these may therefore serve as the vacuum. But when we *define* the vacuum as one of these states, the symmetry is broken. When we then express the fields as deviations from their values in the vacuum, we get one massive and

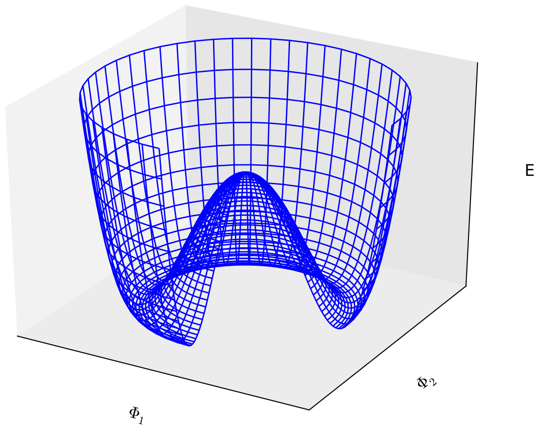

Figure 2.1: A typical Higgs potential

one massless field. The massive field can be useful; the massless one (called a *Goldstone boson*) is a nuisance — we have never seen such a creature.

If we now follow Yang and Mills, and let the gauge symmetry be local, so that the fields may be 'rotated' differently at each point in space and time, we will need to introduce gauge fields (and interactions) to compensate for this. These fields are originally massless, as in the original Yang–Mills model. But when the symmetry is broken, two things happen. Firstly, part of the coupling to the Φ fields, specifically the coupling to the value of the field in the vacuum, appears as a mass term for the gauge fields. Secondly, a local gauge transformation may be used to ensure that the Goldstone boson disappears. By 'mixing' fields, and by also 'mixing' 'extrinsic' properties (interactions) and 'intrinsic' properties (mass), the desired result was hence obtained: massive interaction quanta (gauge bosons). This is called the *Higgs mechanism*[53], after P.W. Higgs,[54] and the remaining component of the Φ field is called the *Higgs boson.*

At this point, Weinberg and Salam (independently) got the idea to try to unify the weak and electromagnetic interactions in a symmetry group ($\mathrm{SU}(2)\times\mathrm{U}(1)$) which had been proposed by Glashow, in a Yang–Mills type theory using the Higgs mechanism.[55] This worked. It started with massless leptons and 4 massless gauge fields, and ended with the three massive bosons $\mathrm{W}^{\pm}$ and Z^0 plus the photon — and the electron had gained mass through its coupling to the Higgs field. Z^0 and the photon are both 'mixtures' (linear combinations) of two of the original fields. Broken parity is incorporated into the theory. The Fermi theory was recovered in the limit of low energies.

The issue of renormalisability still remained. But in 1971, 't Hooft showed that *all* Yang–Mills type theories, with or without spontaneous symmetry breaking, are renormalisable.[56] Suddenly quantum field theory was back in fashion. And in 1973, the first prediction of the Weinberg–Salam theory was confirmed: neutral currents (processes involving exchange of Z^0 bosons) were observed in ν_μ–e^-scattering at CERN.

The Weinberg–Salam theory was a good basis on which to proceed; the next question was to include the quarks (hadrons) in the theory. In order to include all possible transitions, the 'fundamental' fields from the point of view of the weak interaction would have to be combinations of fields corresponding to the 'physical' d and s quarks. In addition, it was necessary to postulate the existence of a 'new' quark, called charm (c), which would serve two purposes. Firstly, and most importantly, it would ensure that neutral currents where s $\leftrightarrow$ d could not occur (the GIM mechanism).[57] Such processes had never been observed, but would be relatively common if the charm quark did *not* exist. Secondly, it would ensure renormalisability. It was shown that the theory is only renormalisable if the sum of the charges of all the fermions is 0. This could be arranged if one assumes that all quarks appear in three *'colours'* (red, green, blue), and that a fourth quark exists.

The concept of colour is the starting point for the new theory of strong interactions: *quantum chromodynamics* (QCD). The origin of the model was a concern that the baryon states that came out of the quark model (with SU(3) and spin) were incompatible with

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[53] Added in translation: or, more properly, the Brout–Englert–Higgs mechanism.

[54] P.W.Higgs: *Phys. Rev. Lett.* **12**, 132 (1964); *Phys. Rev.* **145**, 1156 (1966).

[55] S.L.Glashow: *Nucl. Phys.* **22**, 579 (1961); S.Weinberg: *Phys. Rev. Lett.* **14**, 1264 (1967); A.Salam: 8th Nobel Symposium, ed. N.Svartholm, Stockholm 1968.

[56] G.'t Hooft: *Nucl. Phys.* **35**, 167 (1971).

[57] S.L.Glashow, J.Iliopoulos and L.Maiani: *Phys. Rev.* **D2**, 1285 (1970).

the assumption that quarks are fermions which obey the Pauli principle. This problem could be solved by giving the quarks an additional quantum number — colour — and postulating that all hadrons are colourless, so that the three quarks in a baryon have different colours. Furthermore, the colour quantum number was associated with a new symmetry group $\mathrm{SU}(3)_{\mathrm{c}}$.[58] When a Yang–Mills theory (without symmetry breaking) is then constructed from this group, the result is QCD.

The interactions in QCD are mediated by 8 massless, electrically neutral *gluons.* Because the theory is non-abelian, the gluon fields have self-interactions: they are themselves coloured. This has several consequences. The first one, discovered in 1973, is called *asymptotic freedom*: if the quarks are very close to each other, or (equivalently) have very high energies, they will not notice each other — they behave approximately like free particles. This effect can only occur in a non-abelian theory, where the gluons can be 'dissociated' into gluons as well as into fermions (quark–antiquark pairs). In quantum electrodynamics, the effect is the opposite. Asymptotic freedom can explain experimental results which suggested that highly energetic leptons scatter off free point particles inside the hadrons. It also makes *perturbative QCD* possible: at very high energies we have a theory of the strong interactions which can be calculated using conventional methods.

The other consequence of the self-interaction is to be found at the other end of the energy scale: *confinement.* At large distances or small energies, the gluons will multiply into so many gluons of all possible colours to such an extent that it constitutes a huge force which will keep captive any quark which tries to 'run away': an 'anti-screening' effect. Only colourless states can have any hope of escaping. A free quark can never exist!

This provides an explanation both for why quarks always stick together in colourless states, and for the great problems the strong interactions had presented. Until the early 1970s, all experiments had occurred at relatively low energies, where confinement is relevant, and perturbative methods break down. The meson fields are now considered a residual interaction which can occur over larger distances than the 'free' gluons can reach. The correct theory of all these phenomena is now believed to be nonperturbative QCD.

The great breakthrough for the new theories came in the second half of 1974, when charm was discovered. The context was measurements of the reaction rate of processes $e^+e^- \to$ hadrons, where suddently a huge, narrow peak was discovered at 3.1 GeV. This 'resonance' was called J/ψ, and was eventually identified as a $\mathrm{c\bar{c}}$ bound state. Not only did this confirm the model with four quarks and three colours: it also turned out that QCD could be used to *calculate* $\mathrm{c\bar{c}}$ states! The reason is that the charm quark is heavy enough that it is bound at very small distances, so that perturbative QCD may be used, and the large mass also means that non-relativistic theory may be employed. With the help of qualified guesswork the problem could then be made to look like the hydrogen atom. After this, the combination of the Weinberg–Salam theory and QCD was called the *Standard Model.*

The particle spectrum received a new and unexpected menber in 1975, when a heavy lepton, called τ, was discovered. This disturbed the balance between leptons and quarks which the Standard Model relies on, a balance which was restored in 1977 with evidence

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[58] M.Y.Han and Y.Nambu: *Phys. Rev.* **139B**, 1006 (1965).

of a fifth quark (b: beauty or bottom). The sixth quark — t for truth or top – was finally discovered in 1995, but its existence was never in doubt. This new set of particles provided one important benefit: CP violation could be introduced in a natural manner by way of mixing between three quark 'families' (u,d), (c,s) and (t,b) — a mechanism which had already been proposed by Kobayashi and Maskawa in 1972.[59] According to the most recent data from CERN when this was written (1990), this is the end of the matter in this respect: there are no more than three families.[60]

Further experimental evidence for quantum chromodynamics was provided in the late 1970s and early 1980s with the observation of 'jets': concentrated showers of hadrons which could be traced back to a single outgoing quark (or one gluon), in very high energy reactions. The angular distributions of these showers were in good agreement with QCD predictions.

The 'final'[61] confirmation of the Weinberg–Salam theory came in 1983, when first the W bosons and later on the Z boson were discovered at CERN, with exactly the predicted masses. The only missing piece in the puzzle (after the discovery of the top quark) was the Higgs boson. However, in this case there were no clues as to what its mass should be (although some limits could be inferred), and it was not even known if there was one, several or even no Higgs: other, more complicated ways of introducing spontaneous symmetry braking can be devised. Only one thing was clear: the discovery of the Higgs boson would lead to a Nobel Prize.[62]

The successful unification of the weak and electromagnetic forces led many people to attempt to also unify the electroweak and strong forces in a single theory. The first attempts at such a 'Grand Unified Theory' (GUT) appeared already in 1974. All these theories predict that the proton should be unstable and decay, but no proton decay has ever been observed. So far, apart from much interesting speculation, such theories have yielded few if any useful results. The same is the case for attempts to integrate gravity into the theories — but that is a different story.

2.3 Physical principles of quantum field theory

Quantum field theory is a relativistic, quantum mechanical many-particle theory. It starts from the basic quantum mechanics concepts of operator and state, and the field theory concepts of field and Lagrange density, and is furthermore characterised by an extensive emphasis on symmetries and invariances which is common to field theory and quantum mechanics. Using this conceptual framework the theory treats systems of elementary excitations ('disturbances' in energy density, charge density, momentum density, etc.), and describes how these excitations appear and disappear, or relate to each other in other ways. If the elementary excitations are identified with elementary

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[59] M.Kobayashi and T.Maskawa: *Progr. Theor. Phys.* **49**, 652 (1973).

[60] This conclusion has been confirmed by subsequent experiments. Any additional families would have to involve physics beyond the Standard Model.

[61] This was originally written in 1990, long before the discovery of the Higgs boson in 2012, which may equally be called the final confirmation of the theory. This paragraph has been rewritten to take this discovery into account.

[62] The 1990 text stated that the person who discovers the particle would get the Nobel Prize, but this has not happened — probably because the experiments are too large to justify awarding the prize to one or two individuals.

particles, quantum field theory becomes the theory of the elementary particles and their interactions. This is how it will be considered here.[63]

2.3.1 Fields and Lagrangian density. Symmetries in classical physics

In classical physics, a *field* is defined as a quantity that has a specific value (or several, in the case of vector and tensor fields) at every point in space and time. Mathematically, it can thus be defined as a function of the coordinates in 4-dimensional space–time: $\Phi = \Phi(x) = \Phi(\vec{r}, t)$. In quantum mechanics this will, as we shall see, be modified because of the indeterminacy principle, but the fundamental feature remains, that the field exists everywhere: it is somehow defined everywhere in space–time, and is not localised in one region. In classical physics, each field represents one physical phenomenon — for example, electricity, magnetism, gravity, sound. A characteristic feature of quantum field theory is that each field represents one type of particle. How this happens will hopefully shortly become clear.

A *Lagrangian density* $\mathcal{L} = \mathcal{L}(\Phi, \partial\Phi/\partial x_\mu)$ is constructed as a function of the field and its derivatives; like the field, it is defined everywhere. Once the Lagrangian density is given, all the dynamical properties of the field are also given, and in classical physics this completely determines the behaviour of the field (when the boundary conditions are known). This comes about by requiring that the *action*, which is the integral of the Lagrange density over all of 4-dimensional space–time, have a minimum (or a stationary point) for the actual values of the field. In other words, those values for the field and its derivatives are chosen which minimise the action (or, to be precise: lead to a stationary value for the action with respect to variations of the field values). In mathematical language: $\delta S = \delta \int \mathcal{L} d^4x = 0$. This principle, which was first formulated by William Rowan Hamilton, can be formulated completely independently of which coordinate system one might choose to use, and may represent the most invariant (general) form that a physical principle can possibly take. The theory is *local*, i.e., the behaviour of the fields at one point is only determined by the values of the fields in the vicinity. This is ensured by $\mathcal{L}(x)$ only depending on the values of the fields and their derivatives at the point x.

If the physical system under consideration has a particular symmetry, the Lagrangian describing the system must also have the same symmetry. For example, if the behaviour of the system is unchanged if it is rotated, then such a rotation must leave the Lagrangian unchanged. This symmetry can also be described by the action remaining the same after certain kinds of coordinate and field changes. It can be shown that for any such symmetry there exists a corresponding conserved quantity, i.e., a quantity that does not change with time. It is thus possible to find out quite a lot about the system by studying its symmetries. If the system in addition has a symmetric initial state, we know that the system will always remain in a symmetric state.

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[63] There also exist non-relativistic quantum field theories, which find their applications primarily in condensed matter theory. The status of these theories vis-à-vis relativistic quantum field theory and ordinary, non-relativistic quantum mechanics is not entirely clear to me, and I will not discuss them here. Methods from quantum field theory are also extensively used in statistical physics, both classical and quantum, but this version of 'quantum field theory' is definitely completely incommensurate in its ontological (philosophical) status.

The symmetry principles may be accorded a somewhat different status from the 'ordinary' laws of nature. They determine to a certain extent what form the laws of nature can or must take, or in other words what kinds of laws are possible, or what must be demanded of a law of nature. One may for example associate the symmetries with the concept of a reproducible experiment, and specifically with the possibility of repeating an experiment under different conditions (for example in different locations or with different orientations of the apparatus) and still claim it to be the same experiment. They may also be directly related to the concept of a law of nature: is it possible to say that the *laws of nature* are different in different directions? Even if we should be wary of saying that the symmetry principles are *a priori* conditions for all science — apparently obvious symmetry principles have turned out not to be satisfied — then at least a certain amount of symmetry is required. Wigner has discussed these questions more thoroughly in several articles in [28]. Such questions are also related to the more philosophical issues of absolute space, absolute time, etc. The status of the symmetry principles in cosmology is more problematic, since there we cannot necessarily assume that all times, places and directions are equivalent, but to a certain extent we will want to explain *why* this is so.

The most important symmetries and conservation laws in classical physics are:

1. Spatial translation. It is (we now think) an obvious requirement of a physical theory that the laws shall be the same wherever we are. If the laws in a different part of the universe would differ from ours, then both sets of laws must be special cases of a more general law, which is valid everywhere. Moreover, we have no reason to believe that the universe exhibits irregularities in space which cannot in principle be moved or smoothed out. This is formulated as the system being invariant with respect to a translation in space, ie., the physics is unchanged if all spatial coordinates are shifted by a constant: $\vec{r} \to \vec{r} + \vec{a}$, where $\vec{a}$ is a constant vector. The conserved quantity corresponding to this symmetry is momentum: the fundamental physical principle that all places in the universe are equivalent (which followed from the break with aristotelian physics, which was based on the notion of absolute space and a distinction between terrestrial and celestial dynamics) corresponds to the fundamental law of *conservation of momentum* (first formulated — incorrectly — by Descartes).

2. Time translation. One of the tasks of physics is to find laws which are valid at all times. If we find that the laws of physics change with time, we are forced to search for the laws that govern this change — and these laws must of course be time independent. It must also in principle be conceivable for any situation to be repeated at any later time: there is no absolute point in time that we can use to set our time coordinates. The Big Bang theory challenges this principle, since it postulates that the entire universe emerged from a singularity 13 billion years ago. At that point, all laws of physics, and the concepts of space and time, may break down. At the same time, this theory is based on the principle that the laws themselves do not change. One might say that this is a case of a boundary condition which is not symmetric, while the laws are. However, when the system is the entire universe, it may be difficult to distinguish what are laws and what is a result of boundary conditions.

If we ignore this particular problem (which in any case does not play a significant role at 'normal' scales), we can assert that all properties of a system are unchanged if we 'move' the system forward or backward in time by a period t_0, i.e., if we change our time coordinate such that $t \to t + t_0$. This first basic principle of physics (which has been recognised as long as some kind of physics has existed) corresponds to the most fundamental law of physics: *energy conservation* (first formulated, in an incomplete version, by Leibniz). After Einstein's demonstration of the equivalence between mass and energy, the ancient principle of the constancy of matter has also been absorbed into this law.

3. Rotation. A third symmetry principle we assume in our physical considerations is that the universe looks (more or less) the same in all directions, and that the laws of physics do not distinguish between directions. Therefore, if we rotate our coordinate system by a fixed angle about some axis relative to the physical system, this should not make any difference. This symmetry corresponds to the law of *conservation of angular momentum*, i.e., the sum of the angular momenta $\vec{L} = \vec{r} \times \vec{p}$ of all particles in the system is conserved.[64]

In practice, parts of the system are often taken as given, or as fixed. This can be used to define fixed positions and directions in space, and neither momentum nor angular momentum is defined for the rest of the system. For example, when studying the behaviour of the electrons in a diatomic molecule, the positions of the nuclei are usually taken to be fixed, and the line between them defines a direction in space. In that case, we do not have full rotational symmetry, but there is still rotational symmetry about this line (axis). On the other hand, in a system with a single centre (as an atom or a solar system), or a system where all particles or subsystems are on the same footing, we will have full rotational symmetry. This information can be used to find out quite a lot about the functional form any mathematical description of this system must take, beyond the conservation laws. In quantum mechanics, this is even more prominent, both because there are more (abstract) symmetries which may be exploited, and because the quantum mechanical concepts of operators and states are very well suited to describing symmetry transformations: for example, symmetric states may be created from asymmetric ones.

4. Relativistic invariance. The principle of relativity — that two systems in uniform, rectilinear motion relative to each other are equivalent, that the laws of physics are the same for all such *inertial frames*, and that there is no way of determining whether a system is at rest — was first formulated by Galileo, and is incorporated in Newtonian physics. With the special theory of relativity, and the principle that the speed of light is the same in all inertial frames, relativistic (Lorentz) invariance becomes an explicit requirement that models may or may not take into account. (It is not necessary to take it into account for systems where all velocities are small.) This requirement puts strict demands on the types of quantities that are allowed: for example, the requirement that the Lagrangian density must be a Lorentz scalare already tells us much about what

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[64] This holds in classicle particle mechanics. We can also define an angular momentum density $\vec{\ell} = \vec{r} \times \vec{p}$ for fields, where $\vec{p}$ is now the momentum density, and the total angular momentum is the integral of this over all space. Conservation of angular momentum is hence just as fundamental in field theory. In addition, in quantum mechanics there is an internal angular momentum — *spin* — which does not have a classical analogue.

kinds of fields are allowed.

Relativity treats space and time in a unified manner, arising from the insight that it is not possible to introduce an absolute distinction between time and space, i.e., a distinction that is valid for all inertial frames. The 4-dimensional space–time is hence often just called *space*, which consists of *events*, or points $x = (t, \vec{r}) = (t, x_1, x_2, x_3)$. Even though the four coordinates take different values in different frames, the distance or *interval*

$$\Delta x^2 \overset{\text{def}}{=} c^2 \Delta t^2 - \Delta \vec{r}^2 = c^2(t_2 - t_1)^2 - (\vec{r_2} - \vec{r_1})^2$$

between two points is always the same. For $\Delta x^2 = 0$ this follows directly from the principle that the speed of light is a universal constant. If $\Delta x^2 < 0$, i.e., $\Delta \vec{r}^2 > c^2 \Delta t^2$, we say that the separation between the two points is *space-like*. In this case, the two points are completely separate: a signal from one of them cannot reach the other one. We can also talk about space-like (3-dimensional) 'planes', which are such that the separation between all the points on the 'plane' is space-like. Such a plane will be space-like in all inertial frames. An example of a space-like plane is the set of all points in space at a given time. If $\Delta x^2 > 0$, the separation is *time-like*. The *lightcone* of a certain point consists of all the points with separation 0 from this point, or in other words the points that may be reached with a light signal from this point. We can then say that separations 'within' the lightcone are time-like, while separations 'outside' are space-like.

A physical quantity A characterised by four numbers $(A_0, A_1, A_2, A_3) = (A_0, \vec{A})$ such that $A^2 \equiv A_0^2 - \vec{A}^2$ is the same in all inertial frames is called a *4-vector*. These play a huge role in relativity, not least because they may be used to construct Lorentz invariant quantities. Examples of 4-vectors are the position $x = (ct, \vec{r})$ and momentum $p = (E, c\vec{p})$ of a particle. Many fields, such as the electromagnetic and other gauge fields, are described by 4-vectors.

2.3.2 States and operators in quantum mechanics

Quantum mechanics is characterised (and differs from classical mechanics and 'common sense') first and foremost by what we may call the *indeterminacy principle*. This may be formulated in several different ways, and is encoded in several of the basic principles of quantum mechanics. In brief, it says that it is not possible to assign definite values to all physical quantities associated with a system everywhere and at the same time. The most famous formulation of this principle is Heisenberg's relation, which gives a limit to the accuracy with which two physical quantities can be measured simultaneously. Before I look more closely at this fundamental relation, I will explain how the indeterminacy principle is encoded in the concept of a state in quantum mechanics.

The *state* (the state function or the state vector) comprises the most complete description of a system that is possible.[65] Once the total state of a system is determined, everything that is possible to determine about the system has been determined. The state is denoted Ψ or $|\,\Psi\rangle$. The set of all possible states a system can have is called the *state space*.

The states obey the *superposition principle*: the sum (or a linear combination) of two states is also a state. This is where the indeterminacy principle enters. If Ψ_1 denotes a

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[65] I will leave 'hidden variables' interpretations of quantum mechanics out of this discussion.

state where a particular physical quantity in the system has the value a_1, and Ψ_2 one where it has the value a_2, then both values will occur when the system is in the state $\Psi_1 + \Psi_2$. On the other hand, no other values of this quantity will occur — the two values will not be 'mixed'.

I can illustrate this with an example that shows how quantum mechanics in this respect runs counter to common sense. Let us imagine that our system is a ball that may change colour, in such a way that it is always single-coloured. Each colour it can take represents a state of the system (i.e., the ball). Let Ψ_1 denote the state that the ball is red, while Ψ_2 denotes that it is blue. If our ball is a quantum mechanical system, then $\Psi_1 + \Psi_2$ is an allowed state. This state will not denote the ball being purple, but rather that it is *both* red and blue. Also, it does not denote for example half the ball being blue and half of it red: recall that the ball always remains single-coloured. $\Psi_1 + \Psi_2$ denotes a state where the ball is monochrome red and blue all over! That we can say something like this clearly requires that we do not look to see what colour the ball is — it is hard to imagine seeing something monochromatic red and blue. We can however not rule out this state having other strange characteristics which will allow us to conclude that the ball has in fact been monochromatic red and blue while we did not look at it.

In the case above, since we knew much about the states Ψ_1 and Ψ_2, it was natural to express the third state in terms of these two. We say that we *decompose* Ψ is Ψ_1 and Ψ_2 — Ψ contains a component of Ψ_1 and a component of Ψ_2. This is completely analogous to how we decompose (or add) vectors: the states can be considered as vectors (but not in our usual space — the state space often has an infinite number of 'dimensions'). To continue with the analogy, we can say that only the 'direction' of the state is relevant, and not the 'magnitude': no physical properties change if we multiply the state by an arbitrary (complex) number.

Starting with Ψ_1 and Ψ_2, we can construct all possible states of the ball with different 'amounts' of red and blue — all states that contain only red and blue depend on (may be expressed in terms of or decomposed into) Ψ_1 and Ψ_2. We can however never obtain any state containing any amount of yellow — all states of the ball containing any yellow are *independent* of Ψ_1 and Ψ_2. If we on the other hand have a state Ψ_3 containing some yellow (possibly in addition to some red and blue), then we can decompose all states containing only red, yellow and blue into Ψ_1, Ψ_2 and Ψ_3. Ψ_3 can then be taken to define a third 'dimension' in state space relative to Ψ_1 and Ψ_2.

Instead of decomposing all red and blue states into Ψ_1 and Ψ_2, we could have decomposed them into for example Ψ_1 and $\Psi_2' = \frac{1}{2}\Psi_1 + \Psi_2$ (if we for some reason had much information about that state). Our Ψ would then be written $\Psi = \frac{1}{2}\Psi_1 + \Psi_2'$, and it would look as if it contains less of the red state Ψ_1 than in the previous picture. This appears like an ambiguity in the description. We may however get an unambiguous expression for how much two states Ψ and Φ contain of each other by looking at their *product* (scalar product) $\langle \Phi \,|\, \Psi \rangle$, which is a (complex) number. If the product of two states is zero, they are said to be *orthogonal* to each other, and hence contain nothing of each other. (This is completely analogous to the scalar product in vector algebra.) The product of a state with itself gives the 'length' of the state; physical states all have the same length (usually 1).

A set of states $|\, n \rangle$ which are mutually orthogonal, have length 1, and are such that all possible states may be decomposed into states from this set,

$$| \Psi\rangle = \sum_n \alpha_n \,|\, n\rangle \qquad \text{where} \qquad \langle m \,|\, n\rangle = \delta_{mn} = \begin{cases} 1 & ; m = n \\ 0 & ; m \neq n \end{cases}$$

is called a *basis* (a set of basis states), and this decomposition is called a *representation* of the state. There are always several possible choices for such basis states: there is no preferred representation. Which representation is chosen usually depends on which properties of the system one is most interested in.

It is important to note that the state is something that characterises the system as a whole, and not its individual parts. In some cases — when considering a system consisting of independent (non-interacting)[66] parts — the state may be divided into substates, each of which can be ascribed to the separate parts. Very many systems may also be conveniently described as approximations to such systems of independent parts. From a strictly quantum mechanical perspective this is a purely mathematical technique, without any preferred physical content — in particular since the state may always be represented in other ways which do not involve such a separation. Strictly speaking, two subsystems cannot be considered to have any kind of independence if they are interacting, or if they are in some other kind of non-separable (entangled) state.[67] This is most clearly exhibited by properties of the individual subsystems being indeterminate. But usually this is of course an impractical approach.

Since the state is supposed to characterise all properties of the system, it should be expected that in a system of many particles, not only the energy, momentum, relative location, etc, of the particles, but also their number and kind, should be determined by the state. In a non-relativistic theory this can in general be ignored, and the particles can be taken as given — except for photons, which are massless and hence can be created in large numbers also at low energies.[68] In a relativistic theory (quantum field theory), on the other hand, the high energies involved imply that all particles can be created or disappear, and (the free) particles must be considered as features of the state of the system.

So far, I have treated the state as a purely abstract entity — and the state 'in itself' is a completely abstract and almost empty concept. The state 'in itself' contains no *direct* reference to physical quantities, nor to points in space and time. (Since the state characterises the whole system, it cannot itself be anywhere, neither in space nor in time.) Such a reference can only be provided by choosing a particular *representation* of the state, where the basis states are linked to certain physical quantities or properties.

In quantum mechanics, any property is associated with an *operator*. An operator can be defined as a linear function of states in state space, which returns states. We

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[66] Independent and non-interacting are not the same thing: as we shall see, two subsystems may not be independent even if they do not interact.

[67] Non-separable or entangled states may easily be constructed from separable states. If $\Psi_n(1)$ and $\Psi_n(2)$ are states of subsystems 1 and 2 separately, the 'tensor product' (which is a state, not a scalar) $\Psi_n(1)\Psi_m(2)$ with varying m and n will denote separable states of the combined system of 1 and 2. Linear combinations of these states, which according to the superposition principle are possible states of the combined system, will however be entangled. Consider for example the state $\Psi_a(1)\Psi_b(2) + \Psi_c(1)\Psi_d(2)$.

[68] This 'problem' may be avoided by treating the photons, or radiation, not as particles, but as classical fields. But this is not a quantum mechanical treatment of the radiation, and quantum phenomena such as the photoelectric effect cannot be described this way.

write $F\Psi = \Psi'$, where Ψ and Ψ' are states, and F is the operator. We say that the operator acts on the state Ψ, and that Ψ' is the effect of the operator. (But this is not something that 'happens to' Ψ at some point in time, it is merely the *definition* of the operator.) That it is linear means that the effect of an operator on the sum of two states equals the sum of the effect on each of the states:

$$F(\alpha\Psi_1 + \beta\Psi_2) = \alpha F\Psi_1 + \beta F\Psi_2$$

This is what makes the superposition principle relevant, since it implies that addition of states may be connected with addition of properties.

If $F\Psi = f\Psi$, where f is a number, Ψ is called an *eigenstate* of F, with *eigenvalue* f. In this case, the property F has the unique value f in this state. This will not be the case in general, and then the operator cannot be said to be defined *within* the state, since $F\Psi$ contains states which are orthogonal to Ψ. But for any operator it is possible to find at least some eigenstates. Finding eigenvalues and eigenstates is indeed one of the main topics of quantum mechanics.

In the general case, we may define the *expectation value* $\langle F\rangle$ and *matrix elements* F_{ab} of the operator F as

$$\langle F\rangle_\Psi = \langle\Psi\rangle F\Psi\,, \qquad F_{ab} = \langle\Psi_a\rangle F\Psi_b\,.$$

If Ψ is an eigenstate of F, then the expectation value of F in Ψ is equal to the eigenvalue. In any given representation, an operator will be completely determined by the matrix elements of the operator between the basis states: if all these are known, then the action of the operator on any state is given.

A *measurable quantity* (often called an *observable*), such as energy, charge, position, etc., is represented by a real operator, i.e., $\langle\Phi\rangle F\Psi = \langle F\Phi\rangle\Psi = \langle\Phi|F|\Psi\rangle$ for all Φ, Ψ. The eigenvalues (and expectation values) of such operators will always be real.

When we measure a quantity, we will never obtain anything but an eigenvalue of the corresponding operator — even if the system is in a state that is *not* an eigenstate of that operator. This can be related to the decomposition of the state into eigenstates of the operator (i.e., it can always be written as a linear combination of such states), where the operator acts on these separately, returning the eigenvalue for each eigenstate. In states which are not eigenstates, we can therefore *not* predict the outcome of each individual measurement, since the quantity does not have any specific value in this state — it is *in principle undetermined*. This, and the fact that measurements in general cannot return all possible values, is something that distinguishes quantum mechanics clearly from classical physics. The latter is what is often denoted by many quantities being *quantised* (and violates the principle that 'nature does not make any leaps').[69]

Since observables are related to real operators, all possible measurement results will be real numbers. The eigenstates of observables also have the properties required of basis states. That is, if F represents an observable, then every state can be written as

$$|\,\Psi\rangle = \sum_n \alpha_n\,|\,f_n\rangle \qquad \text{with} \qquad F\,|\,f_n\rangle = f_n\,|\,f_n\rangle\,,$$

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[69] I will here not go into the discussion about what actually happens during a measurement. Fortunately, this is not crucial to the remainder of this presentation.

where[70]

$$\langle f_n \rangle f_m = \delta_{nm} \, .$$

If Ψ is a physical state, we have

$$\sum_n |\alpha_n|^2 = 1 \quad \text{and} \quad \langle F \rangle_\Psi = \sum_n f_n |\alpha_n|^2 \, .$$

Upon measurement, F can take any of the values $f_1, f_2, \ldots$, while $|\alpha_n|^2$ gives the probability of each of these results. We can easily see that this obeys all criteria for probabilities, and the coefficients α_n are often called *probability amplitudes.* This association of the expansion coeffcients with the distribution of results in a large number of identically prepared experiments, is Born's statistical interpretation of quantum mechanics.

As we have just seen, we can use the eigenstates of observables to construct representations of the states. One such representation — the position representation — is obtained by expanding the state in eigenstates $\vec{r'}\rangle$ of the position vector $\vec{r}$ of a particle (assuming here that the system consists of a single particle). In such an eigenstate, the particle will with certainty be at the position $\vec{r'}$. A general state can then be written as[71]

$$|\,\Psi\rangle = \int \psi(\vec{r}) \, |\, \vec{r}\rangle d^3 r$$

where $\psi(\vec{r}) = \langle \vec{r} \,|\, \Psi \rangle$ is Schrödinger's wave function, which characterises the state in this representation. $|\psi(\vec{r})|^2$ gives the probability of the particle being found at the position $\vec{r}$ as result of a measurement.

Another commonly used representation of the state is the *energy representation.* A quantum mechanical problem is often considered solved once the energy eigenvalues (and other characteristics of the energy eigenstates) are found. This is related to the energy being a conserved quantity, so that if a system at some point in time is in a particular energy eigenstate, it will remain in this state forever (or: a state which is an eigenstate of the energy at one time, will also be an eigenstate of the energy at any other time). Examples of energy eigenstates are stationary states in atoms, and particles with a given momentum in quantum field theory.

The fact that a given quantity cannot be given a definite value in an arbitrary state, also implies that *two* quantities cannot always be given definite values (or be measured precisely) at the same time or in the same state: an eigenstate of one is not necessarily an eigenstate of the other. On the contrary, there are quantities that do not have *any* common eigenstates. These can therefore *never* be given precises values simultaneously. Other quantities may have some common eigenstates, and may therefore in some, but

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[70] In general, we do not necessarily have $f_n \neq f_m$ for $n \neq m$. In that case, the expansion is not quite unique. It is possible to choose linear combinations of eigenstates with the same eigenvalue, satisfying the same requirements. In such cases it will however be possible to find another observable G, which shares eigenstates with F, but where states with the same eigenvalue of F may not have the same eigenvalue for G. If we then use the states which are eigenstates of *both* F and G (and, if necessary, other operators with the same properties), the expansion will be unique. For any system one may determine how many operators are required to obtain a unique expansion. This number can be computed on the basis of the number of classical degrees of freedom in the system, and its 'internal degrees of freedom' (spin, colour, etc.).

[71] The position can take a continuous set of values, and hence we get an integral rather than a sum. In other words: not all observables are quantised.

not all cases be given precise values simultaneously. I will call all such sets of quantities *incommensurable.* If two quantities always can be simultaneously given precise values, i.e., if all eigenstates $|n\rangle$ are common, it follows that

$$\begin{aligned} FG\,|\,\Psi\rangle &= \sum_n FG\alpha_n\,|\,n\rangle = \sum_n \alpha_n F g_n\,|\,n\rangle \\ &= \sum_n \alpha_n f_n g_n\,|\,n\rangle = \sum_n \alpha_n GF\,|\,n\rangle \\ &= GF\,|\,\Psi\rangle \end{aligned}$$

for all states $|\,\Psi\rangle$. This is a necessary and sufficient condition for the quantities being compatible. This implies that

$$[F, G] \overset{\text{def}}{=} FG - GF = 0\,.$$

The operator $[F, G]$ is called the *commutator* of F and G. If it is not equal to zero, the two quantities are incompatible.

We may often express the commutator of two operators in terms of known operators, with no reference to any choice of representation. Such commutation relations form the most general starting point for describing a system: most of the physics of the system may be expressed in terms of commutation relations. For example, the dynamics of quantum mechanical systems may be expressed as commutation relations between known quantities and their derivatives. We may also say that a system is given by the commutation relations between the operators characterising the system. They define the ‘shape’ of state space, i.e., which kinds of states are allowed or forbidden. It is often also possible to derive information about possible eigenvalues more or less directly from the commutation relations.[72]

The expression for the commutator [F,G] can tell us about the distribution of eigenvalues of G in a state with a given distribution of eigenvalues of F. This gives us *indeterminacy relations* — lower limits for how precisely it is possible to simultaneously determine the values of incompatible quantities. The general form is that if

$$[F, G] = i\hbar K \quad \text{where } K \text{ is a real operator,}$$

then

$$\Delta F \Delta G \geq \frac{\hbar}{2} |\langle K \rangle|$$

where ΔF (ΔG) is the spread (indeterminacy) in the eigenvalues of F (G) in the given state.[73] For the momentum and position of the same particle, $[x, p] = -i\hbar$ and we obtain

$$\Delta x \Delta p \geq \frac{\hbar}{2}$$

This is the original Heisenberg indeterminacy relation.

In quantum field theory we no longer talk about the positions of the particles as operators, as is the case in ‘traditional’ quantum mechanics. Since the number of particles

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[72] Textbooks in quantum mechanics often describe how this may be done for angular momentum operators.

[73] More precisely: $\Delta F = \sqrt{\langle (F - \langle F \rangle)^2 \rangle}$.

can vary, it is difficult to make such a quantity well-defined. Moreover, it would violate the requirement of relativistic invariance, since time would have to be a parameter: if any talk of the position of a particle as a measurable quantity (or of measurable quantities in general) is to be meaningful, we must assume that we are talking of the position (or energy or angular momentum etc) *at some time t*. A measurement will necessarily have to take place at some specific time (or, rather, over a particular period of time). This approach is however obviously not satisfactory in a relativistic theory, where time and space coordinates should be treated on an equal footing.[74]

This problem is solved by also making the spatial coordinates into parameters. A *quantum field* is just like a classical field, except that the 'values' at each point are not numbers, but operators; i.e., the system is characterised by a set of *field operators* which are defined everywhere in space–time. The operators need not be real — most of the fields are indeed complex. The Lagrangian density and the field equations now describe relations between operators. On top of this, there are commutation relations between the fields, which give rise to typical quantum mechanical indeterminacies or fluctuations.

An important requirement for the field operators is *microcausality*: if no signal can travel between two points, ie if the interval between them is space-like, the fields at these points cannot depend on each other in any way — the fields must be separated, and all measurable quantities that can be constructed from the field operators at the two points must be compatible. A measurement at one point cannot have any impact on a measurement at the other point (unless the system was initially prepared in a state where the values at the two points are correlated). In mathematical language,

$$(x-y)^2 < 0 \Rightarrow [A(x), B(y)] = 0\,,$$

where $(x-y)^2$ is the relativistic interval between the points x and y, and $A(x), B(y)$ are measurable (real) quantities constructed from the field operators.

Only one of the fields has a classical analogue: the electromagnetic field. Every field corresponds to a particular type of particle, and from the field operators we may construct operators for energy-momentum density, charge density, etc, for this particle species. Particles appear as states with well-defined values of mass, charge and other quantum numbers. There is however no reference to the position of an individual particle. This is, as we will see, as it should be.

2.3.3 Transformations and symmetries

A *transformation* (of the most general kind) in quantum mechanics is a change in representation,

$$|\,\Psi\rangle = \sum_n \alpha_n\,|\,f_n\rangle = \sum_m \beta_m\,|\,g_m\rangle\,.$$

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[74] One possible way out would be to make both the time and space coordinates of a particle depend on a proper time parameter. This is the starting point for Feynman's path integral formalism, which I shall look at in section 2.3.3.

The transformation can be characterised by a transformation matrix S_{mn},[75] which relates the expansion coefficients to each other,

$$\beta_m = \sum_n S_{mn}\alpha_n \quad \text{with} \quad S_{mn} = \langle g_m \,|\, f_n \rangle \,.$$

A very important class of transformations is *coordinate transformations*, where we consider the system in a coordinate system which is rotated, shifted or transformed in some other way relative to the original coordinates. The classical symmetry transformations are examples of these. They are a subset of a larger group of transformations where the operators that form the basis of the representations have the same eigenvalue spectrum. Hence, coordinate transformations in quantum field theory can also be included, even though the space coordinates are not operators: the real operators constructed from the field operators $\Phi(x')$ have the same eigenvalues as those constructed from $\Phi(x)$. All such transformations may be viewed in two ways:

1. *Passive:* The state (system) is unchanged, but is viewed from a different perspective. We may express the operator G, which forms a basis for the new representation, in terms of F, which forms a basis for the old one. For example, $F = x, \qquad G = x + a$ — translation. The expression (matrix element) of all operators is changed to $A'_{mn} = \sum_{k,l} S_{mk}A_{kl}(S^{-1})_{kn}$.

2. *Active:* We transform the state, e.g. $\psi(x) \to \psi(x + a)$. In this case, the transformation matrix may be considered an operator in state space,

   $$S\Psi = S\sum_n \alpha_n \,|\, n\rangle = \Psi' = \sum_n \beta_n \,|\, n\rangle \,.$$

   This operator is also well-defined independently of the representation. An arbitrary operator will in general not have the same effect on the transformed state as on the original one, but we can define a *transformed operator* $A' = SAS^{-1}$ which has the same matrix elements. The transformed operator is the same as the original one if it commutes with the transformation operator, $[A, S] = 0$.

We often consider a group of similar transformations (e.g., the group of all possible space translations) together. We may then express the transformation in terms of one or more parameters α, e.g. $S(\alpha) : x \to x + \alpha$. The combination of two such transformations will then be another transformation of the same kind: $S(\alpha)S(\beta) = S(\gamma)$. The parameters may take a discrete or a continuous set of values. In the latter case we may always write

$$S(\alpha) = e^{i\alpha G/\hbar}$$

where G is a real operator which is called the *generator* of the transformation.

One transformation that often has an exceptional status is time evolution. Here, the bases of the two representations are formed by operators for the same quantities at different times.[76] This is a continuous transformation which is generated by the energy

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[75] This matrix is *unitary*, which means that the inverse transformation $(S^{-1})_{mn} = S^*_{nm} = (S^\dagger)_{mn}$.

[76] This may be made relativistically invariant by considering field operators on spacelike hypersurfaces (foliations) rather than at one point in time.

operator (the Hamiltonian) H (the transformation operator is now often called U^{-1} instead of S),

$$U(t,t_0) = e^{-i(t-t_0)H/\hbar}$$

As before, this may be pictured in two ways. If we choose the 'active' picture — that the operators remain the same (we measure the same quantities), but the states change — we arrive at the *Schrödinger equation*[77]

$$i\hbar \frac{d\Psi(t)}{dt} = H\Psi(t)\,.$$

The 'passive' picture — we are dealing with the same state, but the operators change with time — gives rise to *Heisenberg's equation of motion*,[78]

$$i\hbar \frac{dA}{dt} = [A,H]\,.$$

This has an important corollary: any quantity that commutes with the Hamiltonian is conserved (does not change with time). This may also be easily derived from the Schrödinger equation. Depending on your point of view, the Schrödinger equation or Heisenberg's equation of motion may be considered the equations of motion for the system.

If the transformed system is physically the same as the untransformed one, we call S a *symmetry transformation.* It is not always clear what is meant by 'physically the same'; usually we require that the equations of motion look the same, so that the same boundary conditions will lead to the same evolution. In field theory this may be straightforwardly expressed by the Lagrangian or the action being the same. We see that the quantum mechanical equations of motion are the same if the expression for H is the same and hence $[S,H]=0$. Since H is derived from $\mathcal{L}$, this does not introduce anything new, but it shows more clearly the relation between symmetries and conserved quantitites. If

$$S(\alpha) = e^{i\alpha G/\hbar} \quad \text{and} \quad [S(\alpha),H] = 0 \quad \text{for all } \alpha\,,$$

we also have $[G,H]=0$ – and G is conserved.

If we compare with what we know about classical symmetries, we find that space translations are generated by the total momentum, while rotations are generated by the angular momentum. In fact, a general consideration of rotation transformations will show that we have to take into account not only the classical orbital angular momentum, but also the spin, which has no classical analogy.

Another important class of transformations is *gauge transformations*, where the fields are changed without changing the coordinates. The simplest gauge transformation is the global

$$\Phi(x) \to e^{i\chi}\Phi(x)\,,$$

where Φ is a charged field. This transformation turns out to be related to charge conservation. If we now allow the parameter χ to depend on x (a *local* gauge transformation),

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[77] $\Psi(t) = U(t,t_0)\Psi(t_0) = e^{-i(t-t_0)H/\hbar}\Psi(t_0) \Rightarrow d\Psi(t)/dt = (-iH/\hbar)e^{-i(t-t_0)H/\hbar}\Psi(t_0) = (-iH/\hbar)\Psi(t)$ $\Rightarrow i\hbar d\Psi(t)/dt = H\Psi(t)$

[78] $A(t) = U^{-1}(t,t_0)A(t_0)U(t,t_0) = e^{i(t-t_0)H/\hbar}A(t_0)e^{-i(t-t_0)H/\hbar} \Rightarrow$ $dA(t)/dt = (iH/\hbar)e^{i(t-t_0)H/\hbar}A(t_0)e^{-i(t-t_0)H/\hbar} - e^{i(t-t_0)H/\hbar}A(t_0)e^{-i(t-t_0)H/\hbar}(iH/\hbar)$ $= (i/\hbar)(HA(t) - A(t)H) \Rightarrow i\hbar dA(t)/dt = [A(t),H]$

it turns out that if the Lagrangian is to be unaffected by the transformation, we are forced to introduce an additional field A_μ, which couples to Φ and transforms together with Ψ. The equations of motion of this field and its interactions with the charges turn out to be identical to those of the electromagnetic field. If we postulate that $\mathcal{L}$ is invariant under the local gauge transformation above, then all of electromagnetism follows!

We may also construct more complicated gauge transformations of the kind

$$\Phi_\alpha(x) \to \sum_\beta a_{\alpha\beta}(x)\Phi_\beta(x)\,,$$

where the coefficients $a_{\alpha\beta}$ should satisfy certain requirements, and where the different field indices may well represent different kinds of particles. A similar mechanism to the one above leads to non-abelian gauge theories (non-abelian refers to the mathematical properties of the coefficients $a_{\alpha\beta}$), which form the basis of theories of the strong and weak interactions.

The most important discrete transformations are *reflection* (parity transformation, represented by P), *time reversion* (T) and *particle–antiparticle exchange* or *charge conjugation* (C). The first of these also has a classical description and use (it was first introduced by Kant), but becomes really important only in quantum mechanics. When a system is reflected twice, it is obvious that we end up with the same system as we started with. Hence, $P^2 = 1$, and P has eigenvalues ± 1.[79] Furthermore, if P is a symmetry transformation (i.e., there is no difference between left and right in this system), then P is conserved — a symmetric state can never turn into an antisymmetric state, and vice-versa. We can therefore classify states (and particles, in quantum field theory!) as symmetric or antisymmetric under reflection. Moreover, because of the superposition principle, any state can be written as the sum of a symmetric and an antisymmetric state, which will evolve separately. We see that it is possible to find out quite a lot about which kinds of processes are possible or impossible by assuming that there is no difference between left and right.

Time reversal has a somewhat special status. It is easy to imagine how a system can be reflected, or how we can exchange particles and antiparticles, but it is more difficult to imagine what is meant by reversing time.[80] This operation is however well-defined in quantum field theory, and can be used to classify states and processes. It is difficult — but not impossible — to test time reversal symmetry experimentally.

To describe charge conjugation, it is necessary to employ the apparatus of quantum field theory, but there it has a status completely equivalent to the two other discrete transformations. All three are very similar in that $P^2 = T^2 = C^2 = 1$. It was a big surprise when it was discovered that none of them are exact symmetries: they are all violated in weak interactions (as described on page 21). However, this does not violate any principle of quantum field theory. On the other hand, it has been proven that in any Lorentz invariant, local quantum field theory obeying the principle of microcausality,

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[79] The operator P is real, and $\psi(-x) = \pm\psi(x)$ if ψ is an eigenstate of P.

[80] This problem is encountered in Feynman's path integral formulation, where particles can go backwards in time. The question of the arrow of time — the difference between past and future — does of course have a number of other aspects, both physical and philosophical, than those that are relevant in particle physics. Stephen Hawking [25] has a popular exposition of these questions.

their combination must be an absolute symmetry. This *CPT theorem* is one of the few real results from axiomatic field theory. No violations of this symmetry have so far been observed.

Identical particles

In quantum mechanics, we often consider systems consisting of a number of identical particles (particles without any individuating characteristics, e.g. electrons in an atom). In such a system, it is possible to define an operation where all coordinates or quantum numbers of two (or more) particles are exchanged, or (equivalently) two particles are exchanged. If the particles (which we may call 'particle 1' and 'particle 2') really are identical, it will not be possible to distinguish the state $\Psi(1,2)$ 'before' and $\Psi(2,1)$ 'after' this operation — for example, all operators must have the same expectation value in both states. In that case, $\Psi(1,2)$ must be a constant times $\Psi(2,1)$, and since we obviously must get the same state back when we repeat the operation, this implies that $\Psi(2,1) = \pm\Psi(1,2)$.[81]

Particles where $\Psi(2,1) = -\Psi(1,2)$ are called *fermions*, while particles where $\Psi(2,1) = \Psi(1,2)$ are called *bosons*. This can be generalised to systems with more than two particles: the state of a system will always be symmetric under exchange of two identical bosons, and antisymmetric under exchange of two identical fermions. We see that there are constraints on the state that arise exclusively out of the fact that the particles are identical.

If the particles do not interact, we may determine (measure) all quantum numbers for all the particles simultaneously. For fermions we find that two particles can never have the same set of quantum numbers, since this would give $\Psi(1,2) = \Psi(2,1) = -\Psi(1,2)$, which is impossible for a physical state. This is the *Pauli exclusion principle*: two fermions can never occupy the same (single-particle) state at the same time.

This is a necessary, but not sufficient condition for a fermion. To see this, it is sufficient to note that if particle 1 is in the single-particle state Ψ_a (has quantum numbers a), while particle 2 is in state Ψ_b, the total state can be written as $\Psi(1,2) = \Psi_a(1)\Psi_b(2)$. This state does not satisfy the symmetry requirements for either fermions or bosons.

On the other hand, the states

$$\begin{aligned}\Psi_-(1,2) &= \frac{1}{\sqrt{2}}(\Psi_a(1)\Psi_b(2) - \Psi_b(1)\Psi_a(2))\\ \Psi_+(1,2) &= \frac{1}{\sqrt{2}}(\Psi_a(1)\Psi_b(2) + \Psi_b(1)\Psi_a(2))\end{aligned}$$

satisfy the requirements for fermions and bosons respectively. If particles 1 and 2 are fermions, Ψ_- is an allowed state for the system consisting of the two particles, while Ψ_+ is an allowed state if the two particles are bosons. But this means that the particles do not take on their quantum numbers independently: they are non-interacting (at least not interacting in the usual sense), but not independent. The states cannot be separated into one part that only concerns one of the particles and another part that only concerns

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[81] This has obvious parallels to space reflection. Consider the position representation of two identical particles without any 'internal quantum numbers'. Instead of using the coordinates $\vec{r}_1, \vec{r}_2$, one may describe the system using $\vec{R} = \frac{1}{2}(\vec{r}_1 + \vec{r}_2)$ and $\vec{r} = \vec{r}_2 - \vec{r}_1$. Particle exchange is then equivalent to $\vec{r} \to -\vec{r}$.

the other; a change in the state of one will also be a change in the state of the other. This gives rise to observable effects: the expectation value of a quantity A in these states will contain an ‘interference term’

$$\mp \mathrm{Re}(\Psi_a\Psi_b, A\Psi_b\Psi_a)\,,$$

which is a manifestation of the system ‘being’ in both states $\Psi_a\Psi_b$ and $\Psi_b\Psi_a$. If A is the product of two quantities, each pertaining to one of the particles, $A = A_1(1)A_2(2)$ (e.g., the spin of particle 1 in the z direction and the spin of particle 2 in a different direction), then $\langle A\rangle$ expresses a correlation between the values of A_1 for particle 1 and A_2 for particle 2. This correlation will also contain such a ‘strange’ term. The positions of the particles is also correlated in this way, with the result that *bosons like each other, while fermions detest each other*: the probability of finding two fermions close to each other is small, while it is considerably larger than ‘expected’ for bosons.

We may also note that this is the case regardless of how far apart the two particles are — the symmetry of the state is independent of distances (although the size of the correlation term decreases with distance). This means that we are in fact correlated with something in the Andromeda galaxy (or behind the Moon, if we want to be somewhat more down-to-earth). This and similar phenomena are part of the essence of Bell’s theorem, which states that local realistic theories are incompatible with quantum mechanics.

An important result in quantum statistics is Wigner’s ‘summation formula’, which states that where a collection of several fermions can be considered an indivisible unit (as e.g. in an atomic nucleus), it behaves like a boson if it consists of an even number of fermions, and like a fermion if it consists of an odd number. This can be seen directly by noting that exchange of two units each consisting of an even number of fermions corresponds to an even number of fermion exchanges, which gives an even number of sign changes, and hence no net change in the state. Conversely, for units consisting of an odd number, we get an overall minus sign. Alternatively we may use the fact (which originally was an empirical discovery) that all particles with a half-integer spin are fermions, while all particles with integer spin are bosons. Using the rules for addition of angular momentum, we find that aggregates of an even number of particles with half-integer spin have even ‘internal angular momentum’ (which in this context may be taken to be the spin of the aggregate), while an odd number gives a half-integer ‘internal angular momentum’. (The orbital angular momentum is always integer, so it actually makes no difference to this argument.)

In quantum field theory, all these results follow directly from the basic principles, without any further assumptions. The field operator Φ can be written as a (linear) combination[82] of a set of operators $a(p)$, $a^\dagger(p)$ — one for each possible value of a parameter $\vec{p}$. When an energy–momentum density and an energy operator H are constructed from the Lagrangian density, and the operators are required to satisfy the Heisenberg equation of motion,

$$i\hbar\frac{\partial\Phi}{\partial t} = [\Phi, H]$$

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[82] The field is normally expanded in Fourier modes, although expansions in other basis functions could also be considered.

(or other, equivalent quantisation conditions), this can be reformulated in terms of commutation relations between the a and $a^\dagger$ operators, so that they appear as *annihilation operators* and *creation operators* respectively, as follows.

With a definition of the vacuum $|\,0\rangle$ and the physical operators for total energy, H, and total momentum, $\vec{P}$, so that $H\,|\,0\rangle = 0, \vec{P}\,|\,0\rangle = 0$, $a^\dagger(p)\,|\,0\rangle$ will become eigenstates of H and $\vec{P}$ with eigenvalues $E(\vec{p}) = \sqrt{\vec{p}^2c^2 + m^2c^4}$ and $\vec{p}$ respectively. The total energy and momentum will in general be written as

$$H = \int d^3p E(\vec{p})\, a^\dagger(p)a(p)\,, \quad \vec{P} = \int d^3p\, \vec{p}\, a^\dagger(p)a(p)\,.$$

This may be taken to define a *number operator* $n(p) = a^\dagger(p)a(p)$ which represents the number of particles with momentum $\vec{p}$ and energy $E(\vec{p})$, where the state $|mip\rangle = a^\dagger(p)$ is a particle: $a^\dagger(p)$ creates a particle with a definite energy and momentum. We also find that $a(p)\,|\,p\rangle = |\,0\rangle$: $a(p)$ destroys a particle. We may also define a *total number operator*

$$N = \int d^3p\; a^\dagger(p)a(p)\,,$$

which has integer eigenvalues. An eigenstate of N with eigenvalue n is then n particles. These particles need not have definite energy and momentum, but can be combinations of states with different energies and momenta.

This formalism makes it impossible to maintain any form of individuality for the particles. Considering the states as particles (or superpositions of particles) is only one possible representation. States that are superpositions of states with different particle numbers are not only allowed, but may also be physically relevant. For example, the eigenstates of electric and magnetic fields $\vec{E}$ and $\vec{B}$ have indeterminate particle numbers — electromagnetic field strength and photon number are incompatible quantities. And in cases where there is a definite particle number, it is only in certain limits that they can be individually identified, for example by their spatial separation. The state does not give the individual particle any special status or 'personality', and above all the formalism ensures that particles of the same kind are completely identical – they all emerge from the same field. The states are states of the fields, and are not assigned to individual particles, but at most to a particle number.

The distinction between fermions and bosons appears in how the fields are quantised. The requirements of microcausality and the existence of a lowest energy level imply that for a field with integer spin (scalar, vector or tensor field) we must (essentially) have[83]

$$[a(p), a(p')] = [a^\dagger(p), a^\dagger(p')] = 0\,,$$

while for fields with half-integer spin (spinor fields) we must have

$$\{a(p), a(p')\} = \{a^\dagger(p), a^\dagger(p')\} = 0 \qquad \text{where} \qquad \{a, b\} \overset{def}{=} ab + ba$$

The former gives rise to Bose–Einstein statistics (bosons), while the latter gives rise to Fermi–Dirac statistics (fermions). In particular we see that the Pauli principle is

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[83] Additional indices on the creation operators referring to e.g. spin orientation or polarisation give additional δ_{mn}-type prefactors.

satisfied: if we try to create a state consisting of two particles with the same energy and momentum, we get

$$(a^\dagger(p))^2\,|\,\Psi\rangle = \frac{1}{2}\{a^\dagger(p), a^\dagger(p)\}\,|\,\Psi\rangle = 0$$

This *spin–statistics theorem* has been proved on general grounds within the framework of axiomatic field theory.

Charged particles (or particles that have an antiparticle) are represented by a field Φ that is not real. It has an associated conjugate field $\Phi^\dagger$ and two sets of creation and annihilation operators: $a, a^\dagger$ annihilate and create particles, while $b, b^\dagger$ annihilate and create antiparticles (particles with opposite charge). The field Φ can be written in terms of the operators a and $b^\dagger$, and will hence destroy a particle or create an antiparticle. $\Phi^\dagger$ contains b and $a^\dagger$ operators, and will therefore create a particle or destroy an antiparticle.

Interactions

If two subsystems do not interact, the energy of the total system can be written as a sum of two terms, each of which only depends on one of the subsystems, and the subsystems will evolve independently. The interaction is written as a term that depends on both subsystems, and which cannot be separated. The simplest example is perhaps the interaction between two massive bodies in classical (Newtonian) theory,

$$E = \frac{1}{2}m_1 v_1^2 + \frac{1}{2}m_2 v_2^2 - G\frac{m_1 m_2}{|\vec{r}_1 - \vec{r}_2|}\,.$$

Here we can see where the idea of fields comes from: this may alternatively be viewed as body 1 establishing a field around it, which is proportional to the mass m_1 and inversely proportional to the distance from the body. The second body will then have an additional energy due to a coupling to this field, which depends on the mass of the body and the strength of the field. If we allow the field to spread out with a finite speed from one body to the other, we see that the energy will also depend on whether the field has yet reached the other body. We may also allow the field to have its own energy, which depends only on the field strength.

This is the situation in classical, dualist theories — the typical (and only?) example is classical electrodynamics. Here, both the charged particles and the field have their own intrinsic motion and their own energy; the coupling between them is added to this, and gives rise to mutual modifications.

All of this can be rewritten in terms of a Lagrange theory, where the interactions appear as additions to the ‘free’ Lagrangians and Lagrangian densities. In a non-dualist field theory the particles are viewed merely as ‘lumps’ of fields; each field can be considered a subsystem; and the interaction is manifested through a local additional term in the Lagrangian density,

$$\mathcal{L}(\Phi_1, \Phi_2) = \mathcal{L}_1(\Phi_1) + \mathcal{L}_2(\Phi_2) + \mathcal{L}_i(\Phi_1, \Phi_2)$$

In my treatment of particles in sec. 2.3.3 I ignored their interaction. It turns out that interactions influence both the stability of particles and to what extent it makes sense to talk about particles. The particles in sec. 2.3.3 are states of the system of free fields, and move freely. When the fields or particles interact, the picture becomes less clear.

Heisenberg's equation of motion (or whatever we use as our quantisation condition) looks different, and the commutation relations are changed. It can be difficult to recognise the operators, and the energy eigenstates are not necessarily eigenstates of the number operators — in short, the states have different properties. Hence, the particles lose even more of their identity. And obviously the time evolution is different (otherwise there would be no point in talking about an interaction).

The situation is however not quite as hopeless as it might seem. It is possible to choose a representation of the total state of the system — called the *interaction picture* — such that the (expression for) the states had been time-independent *if the interaction were zero*, and the field commutation relations are the same as for the free fields, whose properties we know. This is in other words a third way of viewing the time evolution transformation, in addition to the Heisenberg and Schrödinger pictures described in section 2.3.3. In this way we can start from the solutions of a known problem when solving the more complicated interaction problem.

The interaction problem can be divided into two main categories:

1. *Bound states.* Here we want to find stable states with a definite energy (which is lower than the energy of free particles), with a limited and constant spatial extent (i.e. the region where the average energy density is significantly different from zero is finite and constant). Examples of such states are atoms (bound states of a nucleus and one or more electrons) and hadrons (bound states of quarks and gluons). There is nothing in the conceptual framework of quantum field theory which should make it impossible in principle to compute this; it is however a fact that nobody has succeeded in developing rigorous methods to tackle these problems.[84] What is normally done is to transform the problem to a non-relativistic potential problem with a definite particle number, which may be solved using established methods. Quantum field theory may subsequently be employed to calculate relativistic corrections, which are hopefully small. The range of validity of such an approach cannot be known with certainty.

   The corrections to a known (approximate) solution are computed using the interaction picture. The known, bound system is now considered as a 'free' (known) subsystem, and the correction terms are the 'interaction'. If the correction terms are small, perturbative methods can be used.

2. *Scattering problems.* I am using the term scattering in its widest sense: the interaction is significantly different from zero only in a finite time interval; outside this interval the subsystems can be considered as free (and independent). This is in particular the case where several particles approach each other, react, and the products of the reaction subsequently go off in different directions and become separated in space. Quantum field theory has been shown to be particularly well suited to solving such problems.

   In the interaction picture we can treat the system as if the fields were free. We also know that the states long before and long after the interaction (the asymptotic

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[84] *Note added in translation:* This is evidently not the case, but when I wrote this, I was only vaguely aware of Bethe–Salpeter equations (whose rigour in practical applications can be disputed as they rely on approximations or truncations), and even less aware of lattice gauge theory, which has since been my main area of research.

states) are free particles, and these can be taken as the starting point of the calculation. Furthermore, we are rarely interested in the details of the interaction, but only in the probability of transitions between different asymptotic states. These probabilities are encoded in the *S matrix*, which is the asymptotic form of the time evolution operator in the interaction picture. With

$$\Psi(t) = U(t, t_0)\Psi(t_0)\,,$$

we have

$$S \stackrel{\text{def}}{=} \lim_{t\to\infty, t_0\to-\infty} U(t, t_0)\,.$$

We can write down an explicit expression for the S-matrix in terms of the interaction term $\mathcal{L}_i$ in the Lagrangian density,

$$S = e^{(i/\hbar)\int \mathcal{L}_i(x)d^4x}$$

It is very difficult to solve this operator equation exactly. If $\mathcal{L}_i$ may be assumed to be small, the exponential may be expanded in a power series,

$$e^x = 1 + x + x^2/2! + x^3/3! + \dots\,, \text{ i.e.,}$$

$$S = 1 + (i/\hbar)\int \mathcal{L}_i(x)d^4x + \frac{1}{2}(i/\hbar)^2 \int \mathcal{L}_i(x_1)d^4x_1 \int \mathcal{L}_i(x_2)d^4x_2 + \dots\,,$$

and assume that the higher order terms give only small contributions to the S-matrix.[85]

As a result, the processes can be viewed as composed of 'elementary interactions' (elementary processes) given by $\mathcal{L}_i$, which may occur (or do occur) anywhere and at any time, and may occur one or more times. Processes consisting of more elementary processes are less likely than those consisting of fewer. The total S matrix element for a transition between two given states is found by adding up the contribution from all possible (elementary or composite) processes that take the system from one state to the other. The transition probability is (proportional to) the absolute square of the S matrix element.

At this point it can be appropriate to say something about the form the interactions may take. Relativistic invariance requires that all interaction terms which include fermion (spin-1/2) fields must be of the form[86]

$$\mathcal{L}_i(x) \sim \Psi_a^\dagger(x)\Phi(x)\Psi_b(x)\,,$$

where Ψ_a and Ψ_b are fermion fields (the letter Ψ is used for historical reasons) and Φ is a boson field. If we now define the total fermion number as the total number of particles minus the total number of antifermions, we find that *the total fermion number*

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[85] To be precise, the integrands are also required to be time-ordered in the power series.

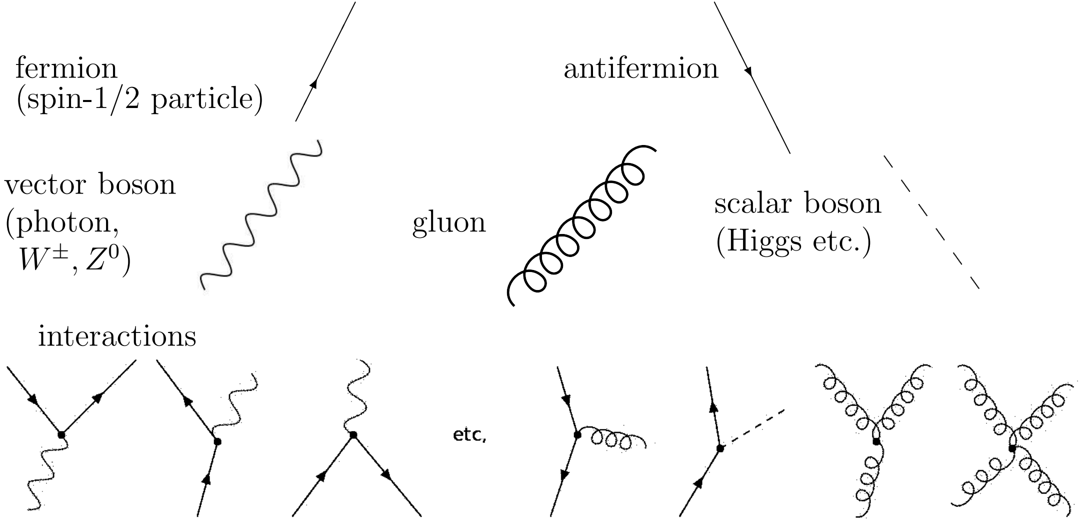
[86] Relativistic invariance also allows terms like $(\Psi_a^\dagger(x)\Psi_b(x))(\Psi_c^\dagger(x)\Psi_d(x))$. These interactions (which Fermi used in his description of weak interactions) also conserve the fermion number. This theory is however not renormalisable, and such terms are therefore excluded.

is conserved: Ψ_b must *either* destroy a particle *or* create an antiparticle, and *at the same time* $\Psi_a^\dagger$ must *either* create a particle *or* destroy an antiparticle. At the same time, a boson is either created (emitted) or destroyed (absorbed); the boson appears as a 'mediator' of the process.

In quantum electrodynamics these are the only possible interactions. In non-abelian gauge theories there are also 'self-interactions' where the boson (gauge) fields couple to each other, in terms of the kind $\Phi_1\Phi_2\Phi_3$ and $\Phi_1\Phi_2\Phi_3\Phi_4$ (the fields may be the same or different).

Feynman has invented a method to represent the elementary processes in terms of simple diagrams, where each element of the diagram is related to a factor in the S-matrix element. This also gives us a visualisation of the processes and simple rules for the calculation. The diagrams are space–time illustrations with a time axis (which is usually vertical) and a 'space axis' (which is supposed to represent all three space coordinates, and is usually drawn horizontally). The particle states are drawn as lines which are supposed to represent the 'world line' of the particle, i.e., its position in space as a function of time.

We have the following simple diagram elements:



Because of energy and momentum conservation, none of the elementary interactions can take place on its own — at least two such interactions are required to have a physical process.[87] Some simple physical processes are illustrated in figure 2.2.

A problem that appears with interactions is to define what a free particle is. Any particle can at any time interact with itself — i.e., we may have processes where one particle comes in and one particle, of the same type and with the same energy and momentum, comes out. An electron will for example from time to time emit a photon, only to shortly after absorb it again (i.e., we go from a 'pure' electron state to an electron–photon state and back). In the same way a neutrino will from time to time be 'dissociated' into an electron and a W-boson, while a photon will be 'dissociated' into a fermion–antifermion pair. There is no way of seeing from a particle whether the system has 'visited' one or more such states, or how often this has happened: the particles have no memory. On the other hand, it has definite consequences for the propagation and

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[87] *Note added in translation:* This is not entirely true. $2 \to 2$ particle scattering processes mediated by quartic gauge or scalar interactions are possible.

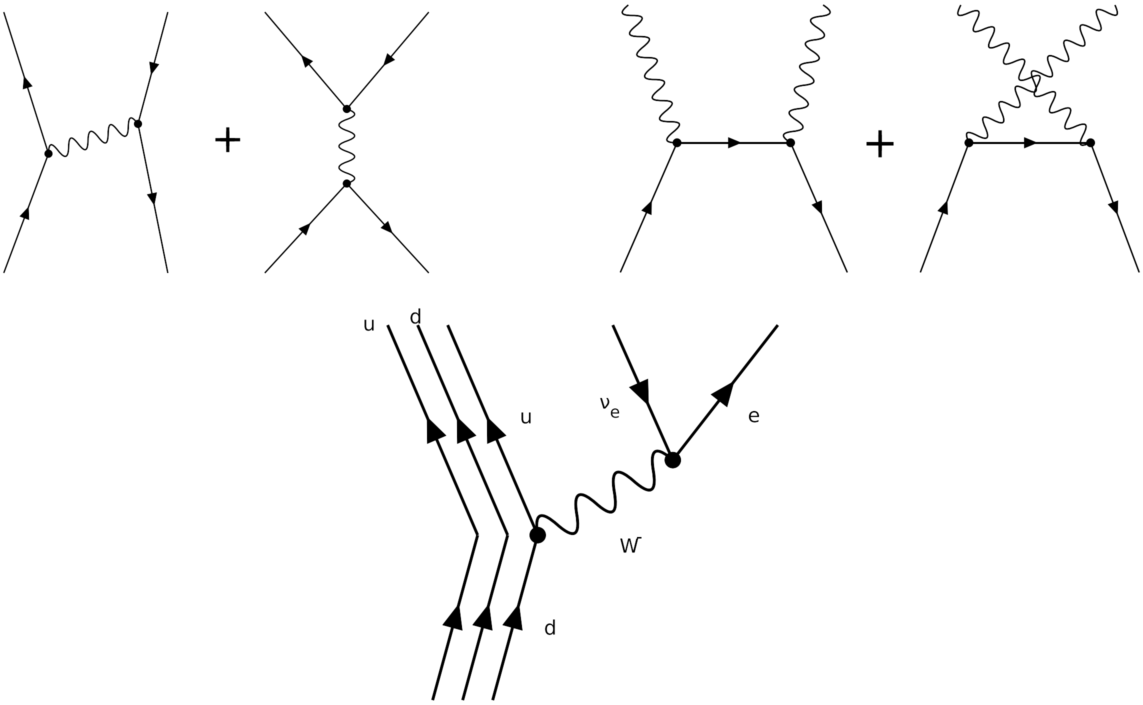


Figure 2.2: Some simple processes. Top left: Bhabha scattering ($e^+e^- \to e^+e^-$). Top right: pair annihilation ($e^+e^- \to \gamma\gamma$). Bottom: β decay ($n \to p^+e^-\bar{\nu}_e$).

properties of the particles. To obtain the properties of the electron we can observe, we must add up the contributions from all possible self-interaction processes, as in figure 2.3, and replace the mass of the 'bare' electron with the mass of the 'dressed' electron in

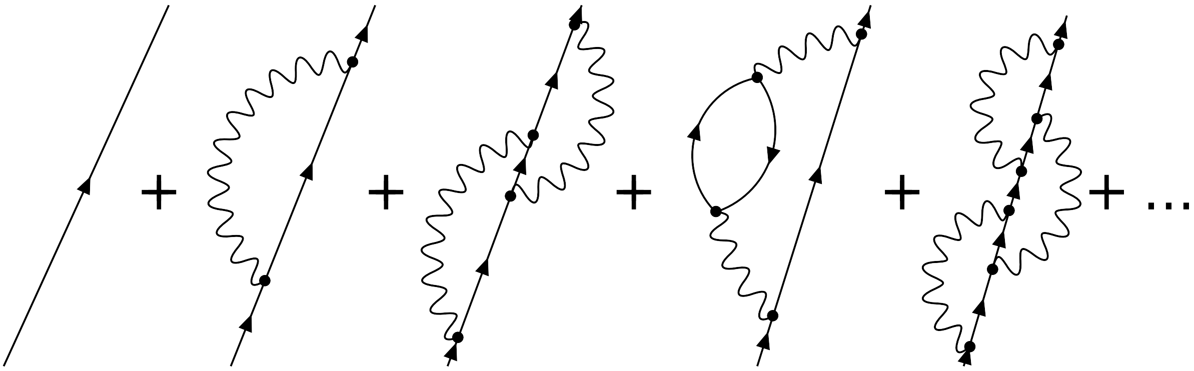


Figure 2.3: The self-interaction of the electron.

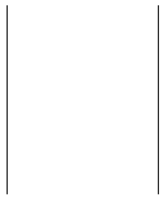
the figure. Similarly, the elementary charge is changed by 'dressing' the photon. This is called *renormalisation*. We find that the observed charge and particle masses are different from the quantities appearing in the Lagrangian, which would have been the charges and masses of the particles in the absence of interactions (in which case we would not have any possibility of observing them either). This difference is in fact infinite!

The path integral formalism

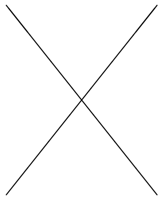
This overview would not be complete if it did not mention Feynman's path integral formalism. Strictly speaking, this formalism does not belong conceptually to quantum *field* theory,[88] and I have therefore postponed it until now, but it is mathematically equivalent. I will be brief; Feynman himself has an presentation of the theory intended for the uninitiated in [10]. His articles [33, 34] where the formalism was first presented are also readable for an 'ordinary' physicist.

The formalism takes as its fundamental starting point the particles and their paths in time and space, and notes that in quantum mechanics it is in principle impossible to know the path of a particle in detail. Hence, according to Feynman, to compute the probability of a particle going from one point to another, we must add up the probability amplitudes for all the possible ways this can happen — i.e., all possible paths for the particle. The probability is then obtained by taking the absolute square of this sum. Furthermore, all paths are equally probable, but they have different phases: the amplitude for each path is $e^{iS/\hbar}$, where S is obtained from the classical Lagrangian. This is the situation when the particle is alone in the world. moves through empty space and has no interactions. The resulting amplitude $K(1,2)$ for going from point 1 to point 2, called the *propagator*, will be dominated by the contributions from paths close to the classical path, and can be considered a 'primitive' element of the theory.

If we are dealing with two identical particles, which still do not interact, we have to take into account that we cannot know which one of the two we observe when each has gone from one point to another. Hence we have two possibilities (the lines now represent the integral of all possible paths from one point to the other):



and



For bosons we must add up the amplitudes for these two processes, while for fermions they must be subtracted. In this way we obtain the effect that bosons like each other, while fermions detest each other. For example we see that the probability of two fermions with the same spin ending up at the same point is zero, while for bosons it is larger than 'expected'.

When there are interactions in the system we must also take into account all the possible ways the interactions can occur. In relativistic theory in the Feynman picture, all interactions happen by emission and absorption (creation and annihilation) of bosons mediating the interaction.[89] These emissions and absorptions can occur anywhere in

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[88] *Note added in translation:* At the time when I wrote this, I had only been introduced to variants of canonical quantisation of quantum fields, and not to the functional integral formalism, which forms the basis for modern treatment of quantum field theory, and is the field theoretical extension of Feynman's path integrals.

[89] It is also possible to include potential scattering in this formalism, but the potentials are static and do therefore not strictly speaking belong in a relativistic theory.

space and time, and in any order, and we must therefore add up the amplitudes for all these possibilities. The result is exactly the same as in the power series expansion of the S-matrix, and the diagrammatic representations of the processes are of course intended by Feynman to represent the motion of the particles in time and space.

For charged particles we will also have to include not only paths where the particle moves forward in time, but also ones where they go backward in time. Such paths can be observed as antiparticles.

This is mathematically well-defined and unproblematic,[90] and has clear advantages in that we do not have to treat separately some processes which are impossible to distinguish experimentally, and which are only distinguished by the relative time ordering of spatially separated emissions or absorptions — a concept which is not relativistically invariant. This can be illustrated by two examples, as shown figure 2.4.

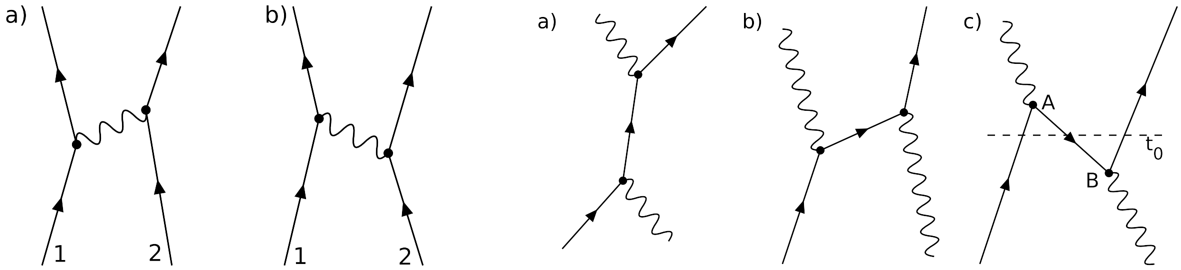

Figure 2.4: Left: Møller scattering (e^-–e^-). Right: Compton scattering (e^-–γ).

In the first example (Møller scattering) it is not necessary to treat the cases a) and b) separately, i.e., it is not necessary to worry about which electron emits the virtual photon and which one absorbs it. The formalism does not distinguish between emission and absorption, and we could just as well say that in case b) it is electron 1 that emits a photon, which travels backwards in time and is absorbed by electron 2 (it is not possible to distinguish between a photon moving forward in time and one moving backward in time — the photon is its own antiparticle). Indeed, by way of a suitable Lorentz transformation diagram b) can be transformed into a) (virtual photons do not have to move at the speed of light), so the two can be treated as one.[91]

In example 2 (Compton scattering), diagrams b) and c) can be treated as one, while diagram a) must be treated separately. Thus we see that it is not the order of emission and absorption in time that matters, but rather the order along the worldline of the electron. Diagram c) can be interpreted (in a traditional fashion) as one photon creating an electron–positron pair at B, whereupon the positron travels to A and annihilates the electron there — or (in the Feynman picture) as the electron travelling to A, emitting a photon, turning and running backwards in time to absorb the photon at B, whereupon it turns around again and behaves ‘properly’.[92]

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[90] The path is parametrised in terms of a ‘proper time parameter: $(x, y, z, t) = (x, y, z, t)(\tau)$, where t does not have to grow monotonically with τ.

[91] On the other hand, fermionic statistics requires that the diagram where electron 1 and 2 are interchanged in the final state must be subtracted.

[92] If you went in at time t_0 and observed, you would see three particles: two electrons and a positron. That would, however, be a different process. It is essential to integrate over all possible interaction points.

Chapter 3

Physics and philosophy

3.1 Basic concepts of ordinary life

3.1.1 Things, space and time

The starting point for our experience of and thinking about the world, and for all our activities, is found in our ordinary life. The primary conceptual framework of ordinary life is absolutely necessary — not in the sense that it cannot be revised (although it is probably the most robust of all conceptual frameworks), nor in the sense that we have to use it (explicitly) in all contexts — but in the sense that in order to live and function socially we need some minimal set of assumptions and concepts, which are encoded (explicitly or implicitly) in the primary conceptual framework of ordinary life. Since our understanding of the world is ultimately based on ordinary life, this is also where we find the original starting point for a more refined understanding, as expressed for example in physics. In my opinion, a correct understanding of basic concepts of physics must therefore be based on showing their relation to our everyday understanding of reality.

The most important elements of our (human) everyday understanding of reality are the (macroscopic) *things*. By a thing, I provisionally mean something independent, limited, which we can touch and see, and thereby immediately grasp as one entity. Starting from this, we find that almost all our daily tasks and conversations relate in some way or other to concrete things. The things form the starting point for our orientation in and understanding and recognition of the world. In this context it is not at all without interest to remark that we are also things — admittedly of a special kind compared to may others, but still things. This is reflected in the fact that what we usually recognise as things are and must necessarily be of the same order of magnitude as ourselves — with dimensions from about 1 cm to about 10 m. For us to see something as a thing, it must be such that we could treat it directly as a single entity, both physically (we should be able to, at least hypothetically, move it) and psychologically (we must perceive the whole thing). Also entities with larger or smaller dimensions can be considered things to the extent that they can be observed and (in our imagination, at least) handled indirectly, but this is only possible within certain limits. If the entities become too large or too small, the observation and/or the handling of them will be too unlike the daily observation and handling of things, so that the parallel is no longer valid. Entities larger than a planet can hardly be thought of as being handled in any sensible way, and can therefore not be considered things. I will come back to the limit for how small a 'thing' can be; for now, I can estimate it to be around the size of a macromolecule.

I will claim that the things, with their objective existence, form the basis for us being able to talk meaningfully and unambiguously about affairs in the world — indeed, they form the basis for us having any idea of a world in the first place. Two questions then arise: how do they do this, and which conditions must the things satisfy in order to form such a basis?

When we talk about, or in some other way relate cognitively to matters in the world, it is necessary that we have *something* to relate to: that we are not considering nothing or something that we have no idea about. Moreover, we must be able to recognise or identify it as a *something*, and (if we are to have meaningful relations with other people) describe it to other people in such a way that they also know what we are talking about, and hence are also able to identify it. And, since we are talking about matters in the world, it must also in some way or other be unambiguously located in the world. If it is to have any value to us in our ordinary life, it must also have a definite, unambiguous relation to our everyday experiences and our everyday activities.[1] But how can this happen? How can we even say that something is located unambiguously and objectively in such a way that we and others can relate to it; that the world and matters in the world are such and such, and not only appear like this to us?

A description of something gives us no guarantee that what we describe exists in the world, and much less where or how we should search to find it. The location can therefore not happen by way of a description. And a location is always relative to something — how can we then locate something unambiguously? We could locate it relative to ourselves, but we would still not have any measure or rule for the location — it will be arbitrary and without any possibility of recognition.

Let us imagine that I locate all phenomena in the world on a spherical shell around myself. (I cannot have any idea of *distance*, since this requires me to be able to move *among* the phenomena — i.e., that they are located relative to each other, and not to me.) I will not be able to turn my head or move around — that would mean that the whole world would move, and I could not say that the phenomenon that is located in direction α now is the same as the one that was in direction β a little while ago. This becomes particularly acute if I close my eyes for a moment: how could I for example say that the red that was straight ahead of me just then is the same as the red that is to my right now? It can even be difficult to find criteria for calling both red — to do this, I would have to be able to compare them objectively, and to decide how different they can be and still be said to have the same colour.

We also have no guarantee that other people's world (defined by location relative to them) is the same as ours — it is even questionable whether we could form an idea of other subjects who could have a world. The world would equal my world, which I could not in any sensible way distinguish from my own subjective sensory impressions.

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[1] We can of course tell tales, stories or fables about things and phenomena we have not put in any relation to our ordinary world, and have no difficulty in identifying the elements and understanding the meaning of such stories, but they do not tell us anything directly (only analogously) about our world. This is not an attempt to devalue such stories, fables and myths — but this is not what we are talking about here.

I would have to say with Wittgenstein: 'I am my world.'[2]

We therefore need something that can operate as a fixed, unambiguous and person-independent framework for the world. At the same time, this framework has to be related to us in some way, since otherwise we would not be talking about matters in our world. The things constitute such a framework: when we locate something in space and time, this is the same as locating it relative to the things in the world. And the things exist objectively — something which is is manifested by us all agreeing that they are there. By way of the things, we can at least agree on a common relative framework for the universe — when two people are in the same place, i.e., near the same things (which is usually the case when talking with each other), they can agree by referring to the things they see around themselves, and locate everything else relative to this. Alternatively, they can refer to named things whose location is already taken for granted, also relative to their 'immediate' surroundings.[3]

We see that there are some conditions that must be satisfied for this to work. Firstly, the things must by and large be at rest relative to each other, otherwise they could not in any way form a fixed framework for the world, and we would hence have no criteria for how to reidentify or recognise something as the *same* thing as opposed to a 'doppelgänger'. This is required if it is to make sense to talk about the things as individual things, and not only as collections of general properties. That in turn is required in order to talk about them as being present in the world — we have no other way of definitely determining whether something exists in the world than to show it: *There it is, as an individual phenomenon* — we cannot *point* at something other than as an individual phenomenon. But then we must in some cases also be able to say that two things are (numerically) different things even though they have identical appearance and properties. The things must also be relatively stable — they cannot be destroyed by the tiniest disturbance or after a very short time (by our measure). Secondly, we must ourselves (at least) be able to move relatively freely among these things, ortherwise we could not have any ideas about what existed in other places than our own.

The things are also essential in making it possible to talk about and make sense of the idea of extension: because of the stability of things, we can use certain things as measuring rods for extension in general. It is essential that these measuring rods are things with 'normal' dimensions to enable us to have any kind of control over them. Firstly, either the measuring rod or the item that is to be measured must be moved so that they are brought into contact with each other. Secondly, we must be able to read off the measurement, which means that we must have an overview over the entire measuring rod. One might object that we also measure events on completely different scales, with measuring rods on those scales, and that the unit of length (metre) for a while was defined according to a subatomic scale. However, these measurements presuppose the normal measuring rods that are things, in the sense that a measurement can only be considered to be completed and understood when it is 'translated' to normal scales. This is the case physically: the final observation must take place at 'our' level — or at least, it presupposes the possibility of such a 'normal' observation.[4] It is also the case

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[2] *Tractatus* 5.63

[3] This argument is given a thorough exposition by P.F. Strawson in *Individuals* [14].

[4] We may have measuring instruments that make observations at the everyday scale redundant, but they are always built on theories where such an observation enters in some place when the theory is to be validated.

mentally: we ‘scale’ the measurements up or down to form an image of them, and this image is alway an analogy to an ordinary measurement with a ruler.

As regards duration, this concept clearly requires the existence of change. Whether it is the things themselves, some feature of the things, something beyond or between them or a relation between them that changes, what forms the basis for a precise concept of duration must be a fairly clearly delineated transition from one state to another: the duration is the interval between these transitions. It is equally clear that the transition must be viewed against something (relatively) permanent — for example the general pattern of things. And if we are to establish a measure of duration, this requires processes that can be taken to be regular. The frequencies of these ‘clocks’ must be of the same order of magnitude as typical times for human activity — i.e., from about a second to a few days.[5]

3.1.2 Activity and change

We all know and see that change occurs — it makes no sense to deny this. Change is also a requirement for life: all processes of life (including thought) are changes. The fact that we are alive implies that we (as things) are changing. And for us to be alive, we must be able to handle and treat the things (at least some of them) for our purposes. This would not be possible if all things were eternal and unchangeable. It would also at least be hard to notice anything that does not undergo any change — it becomes an irrelevant background.

This means that the things, and not only phenomena beyond and between them, must have the possibility of undergoing change and even destruction. But how can these two cases, change and destruction, be distinguished? In other words: how can we say that a thing is still not just a thing, but also the *same* thing, when it has undergone change? Why do we not say that the thing has been destroyed and another thing has appeared — and in which case could we say just that? We must be able to distinguish between these two cases if we are to relate to things in the first place: the things being relatively constant does not prevent us from perturbing them, or the things themselves from changing slightly on their own accord.

It is also important that we distinguish between the changes that we cause with our activities, and those that occur independently of us, without any contribution from us. The first type of changes are part of what makes us acquainted with the things in the first place — our handling of the things acquaint us with them and their specific features, and distinguish between ourselves (as things) and the things we handle. At the same time, by handling the things we grasp which aspects of them are changeable and which are conserved, and we come to appreciate their independence of us at the same time as we appreciate our independence of the things. But as long as I do not have any conception of the second type of change, the world is still centred around me, and has no objective existence.[6] I may distinguish between myself and the world, but the world depends on me and relates first and foremost to me (the sun follows me in the sky). To see the world and its changes as fully objective, I must have the idea of changes that

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[5] The primary clock is the day (e.g., sunset to sunset), and then the oscillations of pendulums, burning candles, sand flowing in hour glasses, etc. Of these, only the day can be defined without any explicit dependence on things.

[6] Piaget writes about how small children experience the world in this way.

occur because the things are the way they are, independently of what I do with them. The things must be able to change themselves, according to their nature, so to speak.

For us to be in a position to say that the thing is the same thing even when it is changes, i.e., that the thing changes, there must be something about the thing that is not changed — something that we can identify as the *essence* of the thing. This is not only what we can call its essential properties, but the whole web of relations and possible changes that make the thing what it is to us. It is part of the essence of the thing to undergo a certain type of change if it is exposed to certain kinds of external influences — e.g., a thing made out of china will break if we drop it on the floor, while a balloon expands when we blow into it. There are also changes that usually happen without any specific trigger — like a plant growing — and changes that do *not* happen according to the nature of the thing — like a billiard ball beginning to grow. All of this makes the thing what it is , and something we can recognise and relate to as having an independent existence. To the extent that we consider the thing with its essential features, we can think of it as a *substance*: something (relatively) independent and (relatively) constant. This substance can then be in several different *states* — a balloon can for example be filled with air or other gases to a greater or lesser extent — without changing its essence or substantive character.[7] A change in the system of a thing (or a system or entity) can be labelled an *accidental* change, as opposed to creation and destruction, which are *substantive* changes.

To summarise: We recognise our world (and hence are able to relate to it) primarily by recognising (and relating to) the things, with their (largely) unchanged mutual relations. We recognise the things in turn by noticing that (what we perceive as) their essence is unchanged and that they are located at (more or less) the same place relative to the other things. (If a thing has moved, we must have a reasonable explanation for how this has happened if we are to maintain that it is the same thing.)

3.2 Matter and forces, physics and natural philosophy

This is sufficient for us to live in and relate to the world unreflectively. That the things are only relatively stable does not matter much for our ability to relate to them as substances: we are also only relatively stable. However, a world that is to such a large extent ‘accidental’ or ‘coincidental’ will be alien to us; we cannot feel safe towards it — there may always be surprises in store, which will mostly be unpleasant. Granted, many things may be explained by pointing out that this is how it *is.* For example, we reject many questions from children or fools of the kind

> ‘Hvoffer har en buko ingen vinger?
> Hvoffer si’r den bu og ikke vov?
> Hvoffer sitter neglen paa min finger?

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[7] This distinction (between substance and state) is also useful beyond where we can talk about subtance in the usual sense. In physics, the idea of a substance is usually replaced by the concept of a *system*, which is a collection of entities (particles, fields, etc.), possibly including boundary conditions. This system may be in different states, and can to a certain extent be considered a substance.

> Hvis den satt paa nesen, var det sjov.'[8]

But still: much of what happens is accidental, and we could still ask the 'childish' questions about why things are as they are — or why there are so many different things. The world is still alien. To feel at home in nature, it is necessary that we *understand* it — that we can grasp its essence.[9]

Religion — in particular 'primitive' religion — can be one kind of attempt to understand the world: the essence of the world becomes more or less human, and hence less alien to us. And even if we cannot assume that nature has a humanoid essence, for us to feel at home in it, it must consist of structures we can conceive, not of horrific monsters (the terrible unknown). It must be possible to understand what happens on the basis of these structures, and we must therefore extend our concepts beyond the concepts of ordinary things so that they may encompass such structures.

Another side of the same problem is that the world must necessarily be conceived and experienced as one world. If the world, consisting of a countless collection of things that constantly change or every so often are obliterated (or new things are created), plus any number of non-thing phenomena, is to be understandable and possible to relate to in practice, i.e., not just a chaos, all things must have something in common. Moreover, when a thing is not eternal, but has once appeared and will once disappear, it cannot be considered completely independent, but must be considered a manifestation of a more underlying substance. We must imagine that there is something that does *not* undergo substantive change, and that such changes are accidental changes of this something. The thing for example also depends for its existence on 'lucky coincidences' having created it once upon a time. The things (with their essential features) thus become merely relative substances compared to the more fundamental substance, which in the final instance must be the substrate of everything in the world (also non-thing phenomena such as sounds, flames, mountains, lightning, water, etc.).[10]

We might imagine that this more fundamental substance resides either *in* the thing itself and in other phenomoena — as something that all things and phenomena are made out of, regardless of what kind of phenomena they are — or *beyond* (or rather *behind*)

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[8] Why has a cow no wings?// Why does it say moo and not woof?// Why is the nail on my finger?// If it was on the nose, it would be fun. From *Spørge-Jørgen*, a Danish children's book from 1944.

[9] Feeling at home in nature has (at least) three elements: understanding, control and adaptation. The purpose of basic sciences is, as I will argue regarding physics, to provide understanding. There has however often also been a large focus on control, which is reflected in the demand that science should have applications, and that it should first and foremost provide predictions, and satisfy the nomological–deductive 'explanation scheme'. There are also strong political and economic forces acting in support of this, although this is not the only reason for the focus on control. This is however an attitude which is far from that of the basic researcher. The point about predictions there is to satisfy the requirement that the theory should agree with reality, and that it should be testable. Predictions are far from being the main aim; the main aim is to reach an explanation or understanding that makes us see that what happens follows, as one might say, from the 'nature' of the things (or entities). This is as much the case for natural sciences as for the humanities, although the methods and the character of the understanding may be very different. Control is important, but belongs to the technical disciplines, not the theoretical. I will discuss this further in section 3.5. As regards adaptation, this is most important for behaviour, ethics and ecology, which I will not discuss here.

[10] Here we may see a shift in the concept of substance, from denoting a web of properties, possible relations and changes which together make up the essence of an independently existing thing, to mean either the essence of the whole world, or something that is absolutely conserved in time. The first is how Aristotle uses the concept; we find the other two meanings in Spinoza and Kant.

the things, as an eternal pattern or origin (which may for example express the essence of the things). The latter is however of very little help in understanding nature as we experience it. Not only is this pattern incapable of undergoing substantive changes; it cannot even undergo accidental change — and we can hardly see our world of things as a state of this. The world as a structure in space and time will rather become more incomprehensible, and there is no explanation either of how creation and destruction of things is possible, or why there are several things of the same kind. We do not even have any grounds for saying that what we experience as one world is the same world, since the respective positioning of the things in space and time hardly can be part of the eternal pattern. We are therefore left to seek the fundamental substance in the phenomena themselves. This first (or last) substance is what is called *matter*.[11]

We see that matter appears as the first principle for the unity and order of the world: by way of it we can explain that it is the same world we find ourselves in at all times and places, and that this world is not just a chaos of wildly changeable phenomena and unrelated things. In a sense, matter becomes the essence of the world.

In this way, we can understand that the world is one, but changes are for the most part as incomprehensible and uncertain as ever, even though we have the security that something is conserved. To be able to understand how change happens, we must in addition to the passive principle (matter) have an active principle which engenders the changes. I will call this principle the *ultimate force*[12] — and it must be *comprehensible*,[13] in the same way as matter is.

Both physics and natural philosophy have as their task to find the fundamental principles (active and passive) for the world we have around us — to say something about what is common, what does not change, what does change and why it does — i.e., to say something about (ultimate) matter and ultimate force. Indeed, the two disciplines were for a long time identical (Newton called his main work ‘Mathematical principles of natural philosophy‘) — but one may still find a slight distinction from the outset.

Philosophy aims to argue completely *a priori*, i.e., without taking account of what we at the present time may happen to have observed or experienced, or what the world happens to look like right now. It wants to say something about matter or ultimate force which must be valid regardless of what we might experience later. A natural philosopher will preferably argue purely logically, and hence produce necessary truths — or, at least: truths with a far more general validity than what may be obtained on the basis of current experience.

However, this rarely leads anywhere. One problem is to find a starting point which leads to anything other than tautologies — to find this, one must assume that certain facts about the world are known and certain. Another at least equally important problem is that there will always be certain hidden assumptions in any chain of reasoning, assumptions which will depend on our current experience. This will make it impossible to pursue a strictly logical chain of reasoning. It is however possible to produce arguments that others will subsequently have to take into account — like Parmenides

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[11] *Note added in translation:* In the original, I used the word *urstoff* as well as *materie*, but there is no good English translation of *urstoff* (the nearest would be original or ultimate stuff), so I have left it out.

[12] *Urkraften* in Scandinavian.

[13] Comprehensible as a ‘natural concept’: something it is possible to become acquainted with.

setting the agenda for Greek philosophy by denying the possibility of change. This may of course be fruitful, and may indirectly yield greater insights.

A more ‘appropriate’ task for natural philosophy might be to investigate the preconditions for our current knowledge of the world, and hence which assumptions about the structure of the world lie implicit in our current knowledge. The question is thus: What must we assume about the world if our current knowledge is mainly correct? or: What must we assume if we are to exist and have experience of the world, given how we today understand ourselves and our world? This is no guarantee against future surprises, but it will be easier to explain the surprises, and therefore understand the world better. It will also be easier to see which parts of the old knowledge are still valid.[14]

Physics seeks the concrete — the concrete (ultimate) matter and force, and the laws for how they interact. The physicist always talks about concrete quantities or *entities* in the world. By an *entity* I mean a something that appears in the world, and which we hence can imagine to be identifiable in some way or other — it has (at least) a kind of ‘quasi-individual status’. An entity is not necessarily a substance, but it must be capable of being in different states. For example, “the” matter (singular definite) is an entity.[15]

To the physicist, ultimate matter must therefore necessarily be a potential subject of experience, while the philosopher may take it to be a principle beyond our potential experience. This contrast may be illustrated by taking Thales (who said ‘All is water’, i.e., that the ultimate matter is water) to be (the first known European) representative of physics, while his student Anaximander (who said that ultimate matter is ‘the indefinite’) was a typical representative of philosophy. But since the two disciplines have such similar aims, it is no wonder that the main paradigms of fundamental physics tend to have a counterpart in philosophy, and vice-versa. And when physics is pursued to its foundations, it becomes natural philosophy.

More specifically, the research programme of fundamental physics (the area of physics that has as its aim to explore the most basic laws and principles of the world) can be sketched as follows. You start by postulating one or more specific properties, which are taken to be common to everything material, i.e., everything in the world we see around us, to be the essence of matter. Subsequently, you explore the dynamical principle(s) that can give rise to the changes in or transitions between the different appearances of this ultimate matter. All other properties and phenomena should then be considered to be derived from these.[16]

However, what may be claimed to be the essence of matter is not arbitrary. It must be something that is or is perceived as common to everything that is around us and that we call material. This will be properties or functions that we almost automatically ascribe to matter, and if a physical theory does not postulate these as the essence of

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[14] This is also how my reflections here are to be understood.

[15] I am deliberately using an imprecise word, since entities can be of many different kinds, and need not have any similarity to things, for example. If I used a word such as object, it would be too strongly associated with pure individuals. *Note added in translation:* The Norwegian word used was *greie*, which would never be used in formal language; however, this was in the absence of any more appropriate word such as entity.

[16] This is of course an idealised and oversimplified description. The process often happens the other way around.

matter, it must at least explain where these common features come from.

- Stuff, or matter, is conserved in time. This is a direct consequence of how matter was defined — as that which is never created or destroyed. Regardless of how much we destroy something, the matter will remain. If it makes sense to talk about quantity of matter, this quantity will be conserved.

- Everything we call material takes up space. This is the case for things, earth (solids), water (liquids), air (gases) and fire (plasma). An important difference between these four states of aggregation or states of matter (as we now call them) is their hardness or impenetrability: while we cannot penetrate a (solid) thing without destroying it to a greater or lesser extent, air presents virtually no resistance against being pushed aside. Ultimate matter must therefore in some way occupy space (at least as one of its secondary properties), while it must on the other side be fairly 'flexible'. Matter must at least *refer to* space or *be placed in* space, since we can *point at* matter.

- Matter has an *individuating* function. Two separate things may be distinct because they contain different bits of matter. This was important to Aristotle, since matter could ensure that several things that are (qualitatively) identical could still exist independently of each other, in contrast to the Platonic forms. We may for example have two completely identical chairs, which are both independent things — although they are qualitatively identical, they are not the same chair: they are not numerically identical. Hence it also makes sense, if we were later on to spot a chair of the same kind, to ask *which* (if any) of the two original chairs we are dealing with.

  The last question obviously only makes sense, or can at least only have a positive answer, if the chair (or our thing or entity) has not been destroyed in the meantime. But even then we may ask if the stuff it is made of is (numerically) the same.[17] Since matter is what remains and is conserved through all destruction and all changes, it follows that matter itself can never be destroyed; it only enters (as numerically the same matter) into new things.[18] We can thus talk about how the individual (particular) bits of matter pass through the things: a bit of matter will always be particular (it is always *that* particular bit of matter), and it therfore has its own (numerical) identity. This identity is then assumed to be conserved in time.

- Matter is *separable* and *movable*. Given the right tools we can always divide up and separate a piece of matter, ending up with two different pieces of matter. These may then (if we are able to 'hold on to' them) be treated separately, as completely independent bits, even if they might be identical, or originally very

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[17] That something over time is the same thing and that it consists of the same matter are not equivalent: a thing may undergo a complete replacement of all its matter, and remain the same thing. For example, the atoms in a human being are replaced over an average of seven years, but the form (structure) is conserved. Thus we may distinguish between *material* and *thingy* numerical identity over time. The two are of course connected to a certain extent: a certain continuity is required — all the matter cannot be replaced instantaneously.

[18] This was Aristotle's explanation for how creation and destruction are possible.

tightly bound. And even if we are not able to hold on to them completely, we may make them move — or matter can move 'by itself'. This may be called the *mechanical* character of matter.

- Since ultimate matter is the stuff that appears in all possible forms, it must also have the ability to somehow take on all these forms — what Aristotle calls *potentiality.* How this happens 'from the stuff's point of view' is however an open question.

These properties of matter are not independent, but are closely intertwined. This can be clearly seen by for example considering the necessary conditions for numerical identity to be a meaningful concept.

A clear condition for two entities being considered to each have a separate numerical identity is that they in fact are (or may be) separate. If the entities can only be understood as parts of a larger whole, if it is not possible to consider each entity as independent, then the concept of (numerical) identity cannot be applied. This does not mean that it must be possible in practice to separate the entities — it may well be that it is (in principle) impossible to construct a tool to carry out this separation — but it must be possible to *imagine* them as separate without losing their essence. In daily life the separation is effected by *placement in space*: when two entities are in different places, they are effectively separated and hence numerically different. This condition can thus be related to the material characteristic of being in space. In daily life a material entity will always be characterised by a specific placement in space, while this is not necessarily the case in experimental science, as quantum mechanics demonstrates.

A condition for considering material entities as separate, and for talking about material numerical identity over time, is that there are conserved, extensive (additive) quantities associated with matter. That some (not necessarily mathematical) quantity must be associated with matter is obvious, since matter can move in space, and can therefore not be directly identified with space itself.[19] That this quantity is (these quantities are) conserved follows directly from the principle that matter is conserved. The additivity of the quantities is related to the separability of matter, but goes beyond the mere question of whether two entities that exist at the same time are separate. It is primarily related to the possibility of claiming that we are looking at *the same* matter before or after an act of destruction or substantive change. If we now imagine that two entities a and b somehow join together in a whole, there must be some sense in which the whole is *not* greater (or less) than the sum of its parts: the whole must contain a 'quantity of matter' that *equals* the sum of the 'quantities of matter' of the parts it is made up of. Hence it will also make sense, if one were subsequently to destroy the whole and separate off one piece, to ask if this piece contains *the same* matter as for example entity a. This is also gives meaning to any statement that some matter has disappeared out of a thing, and to questions about where this matter has gone. It is only possible to say that you have accounted for all the matter if the sum of the quantities of matter is the same.[20]

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[19] There is *something* that can be moved in space — even Descartes would have to admit to that. To solve this problem, he invoked or somehow assumed *two* spaces: matter and space.

[20] This is the basis for chemistry. Alternative (non-additive) 'formulae' for quantity of matter can be imagined, but they do not conserve identity.

Even if we have such an additive conservation of matter, it does still not make sense to talk about the same matter if during reactions (substantive changes), the stuff 'mixes' in such a way that it is in principle impossible to identify the stuff from the different reactants in the reaction product. It must therefore be possible to *imagine* the matter as identified and separated (with its extensive quantities) inside any finite-sized entity. One (but probably not the only) way to imagine this is that the material points are identified with persistent, well-defined worldlines, i.e., that two worldlines which at some point in time have a finite distance from each other, will maintain a finite distance at any other time. The worldlines may be countable (each worldline belongs to an atom or elementary particle) or may form a continuum (but with a certain density of worldlines per unit volume everywhere). The quantity of matter inside a volume is directly proportional to the flux of worldlines through the volume. Worldlines are not allowed to intersect, since this would make separation impossible (if it was not possible to introduce any additional, qualitative criteria for separation of worldlines), and worldlines cannot appear or disappear. One may extend the concept of space, so that two lines can be at the same point in space, but separated in another 'dimension' (state variable). The criteria for numerical identity being possible on the microlevel will still be quite restrictive — it is not a given that this concept makes sense.

Ultimate force has considerably fewer restrictions than ultimate matter, but it also cannot be the subject of arbitrary claims. It must at least be capable of acting on matter (and matter must be capable of acting as a source and point of influence for forces). If you have said something about matter, you have therefore also said something about forces. One should also be able to explain the origin of the forces that we see acting at the everyday level. These can roughly be classified into three kinds.

- The things act on each other by contact. The resistance that prevents a thing from penetrating another, and that enables a thing to push another, is a form of force. The same is the case for the friction or resistance that appears when two things rub against each other (as well as the resistance in air and water), and the force that makes brittle things break and soft things deform when they hit something harder. All this may be called *mechanical* forces.
- We also have external forces that change the state of matter without this having to occur by direct contact — *distance forces* of various kinds. The most important of these is gravity, but we can also consider phenomena such as light conditions, temperature, etc., which act as forces. Tensions (elastic forces such as in springs etc.) may perhaps also be included in this category — if they do not fit better in the next one.
- The changes that happen with the things 'on their own accord' must also be considered results of some kind of forces — *internal forces.* These include all kinds of natural growth etc., and generally anything that arises from the internal structure of things.

In our search for ultimate matter there are two competing interests. On the one hand, there is a programmatic obligation to try to find one overarching principle, i.e., one and only one ultimate form of matter. On the other hand, there are so many different kinds of substances (in the weaker sense of the word) that it seems very unrealistic to be able to explain all of this from only one or two principles (passive and active). A better procedure appears to be to attempt to *classify* all the different kinds of material manifestations we have in the world, to put the matter into some kind of order. This leads naturally to the idea of not one but several ultimate forms of matter, or (rather) elements. The two directions appear to be mutually exclusive, and they exhibit quite different thought processes. While an 'ultimate matter thinker' is set on explaining, and considers the theory of the (multiple) elements as quite *ad hoc*, an 'element thinker' is more intent on classifying, and may consider the principles of the ultimate matter thinker as quite dogmatic and unrealistic. Both are however necessary, since (to use a platitude) both the unity and the plurality of the world must be accounted for — they represent two different, but equally fundamental, knowledge interests. History also has several examples of the two directions being of mutual assistance — this is possible because they normally operate on somewhat different levels, or may even be associated with two different sciences, like physics and chemistry. A successful classification of elements often leads to the discovery of a new principle of unity, often in form of a new symmetry. And a unified scientific theory must always have some foundation to work on — a foundation that can only be obtained through classification. Hence, the classification of the elements made quantum mechanics possible, while the classification of the hadrons in the 1950s prepared the way for SU(3) and the quark model.

This conflict is stronger in philosophy, because we there (for the most part) operate at the same level (that is at least what we tend to think). Here it appears as the conflict between monist and pluralist directions.

3.3 The research programme of fundamental physics

As I said above, fundamental physics sees it as its task to explain all phenomena in the world from (preferably) one passive principle (matter) and one active principle (force) which exist and act in the world. Usually, to be realistic the task will be limited to trying to completely explain one kind of phenomenon or event at one particular level in the world. This kind of phenomenon or this level is then considered to be the fundamental, on which everything else depends, even if it is not at the moment possible to fully describe this dependence. (To view it differently would be to give up the claim to be considered a fundamental physicist, and request a transfer to a different science.) This procedure is fully consistent with what I sketched in the previous paragraph — postulating a property or a set of properties as the essence of matter, followed by exploring the behaviour of matter in light of this. The essence of matter is associated with those properties or quantities (entities) which are considered the most fundamental in the area of concern. Hence, in Newtonian physics the essence of matter will be to have mass, which is again associated with inertia and gravitation. If electromagnetism is taken to be the fundamental theory, the essence of matter will be charge, and the fundamental entities will be charged particles and fields.

Since physics is concrete, it cannot concern itself exclusively with general properties, essences and principles, even if it must take these into consideration (for instance in the form of symmetry considerations). All of this must (as previously stated) be associated with something that occurs in the world; as something concrete that has these properties or essences or is the carrier of these principles. I will call these concrete, primary quantities in physics *the entities of fundamental physics*. I will now say something about how these entities are defined and determined in physics, and furthermore about how theories are built around these entities.

- We always start from a part of our known conceptual framework when we construct a theory. Some of these concepts are taken to correspond to entities in the physical world, and between them there are relations that we have specified, and that are taken to correspond to essential relations, laws or forces in the world. This part of the theory can be denoted the *essential* part, and is the primary concern of theoretical and mathematical physics. The entities and their relations are here defined purely in terms of themselves: the definition is homogeneous. For example, an electron may be defined as a lepton — i.e., a quantum mechanical particle that satisfies the Dirac equation (with spin 1/2), and interacts weakly and electromagnetically, but not strongly — with a rest mass of 0.511 MeV and charge -1.

  But if we only have this part of the theory, our entities will be Platonic forms and our world merely a Platonic realm of ideas, without much of a connection to the sensory world. We will never be able to recover our entities in nature — firstly, because we know nothing about how or where to look for them, or how they should look to us; secondly, because the entities are defined purely in terms of themselves, without any disturbing influence from external factors, while such factors will always come into play in reality; and thirdly, because the entities still appear as universalia, and not as individual entities. To obtain such a connection, two further parts of the theory are required:

- Firstly, a *constructive* part which says where these entities appear in the construction of the world (to the extent that the world can be said to be a construction). For an electron, this could look something like this:

  > One or more electrons, together with an atomic nucleus, make up an atom, when they are bound together by electromagnetic forces in a quantum mechanical bound state which is electrically neutral. Several atoms may be bound with chemical bonds in a molecule, and a quantity of approximately 10^{23} atoms or molecules make up 22 litres of gas when there are no or only very weak bonds or interactions between them, while it makes up a few tens of grammes of a solid if there are stable bonds of different kinds between the atoms or molecules.

  We could imagine what a similar exposition would look like for a galaxy, for example.[21]

- Then, an *operational* part which gives rules for how we can get hold of the entities and register their properties. This is the part that makes experimental

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[21] It will be a bit more problematic for entities that only occur in fairly exotic situations, such as muons. Here we could say that they do not play much of a role in the construction of the world, but that they appear at the same level as the electrons.

> physics possible, and which thus makes physics something other or more than pure metaphysics. These rules must be heterogeneous, since they should connect our entities and the level of observations or instruments of observation. The rules can be very simple, of the kind 'If it is shining yellow, and you can bite it, it is gold', or very complicated, of the kind 'If you dig a 27 kilometre long ring, and erect some hundred tonnes of instruments of a particular kind (which have now luckily been erected), and following this you undertake certain operations with some machines, and then look at the screen on your computer, which is connected to the instruments, and see a pattern of dots or lines out from a centre there, this is an indication that in the ring, in the centre of the instrument, a Z^0 particle occurred, and its energy can be measured by adding up certain numbers that can also be obtained by the computer.'

What happens when a theory concerns levels of reality far from our everyday level, is often that these three elements (essential, constructive and operational) diverge more and more, and that the operational element tends to become very complicated — although all three are inextricably linked and mutually supportive. (It is for example difficult to justify a measurement if you do not have a theory for how the measuring apparatus works, and how it is related to the world being studied.) The essential element will also tend to be very abstract for a lay person, but what characterises a scientist with a good grip on her theory is that she has a good command of all these three elements and (more or less) immediately can see the connections both between the different elements and within each part of the theory.

There is a final element of a physical theory that must obviously be mentioned. When the operational element of the theory has been established, this also gives access to empirical data which may be used to establish more empirical laws for the behaviour of the entities (and obviously to test the validity of the already established laws). What kind of empirical laws may be established is however not arbitrary — it is clearly circumscribed by the essence of the entities or the theory. For example, a body in the theory of relativity cannot interact instantaneously with another body with which it is not in direct contact.

We may find (and will soon find) that any selection of the properties we are usually directly acquainted with (the everyday intuitive concepts) does not have the potential to be basic elements of our theory, since the laws we can formulate in terms of these concepts are not sufficient to describe or explain, on the basis of two fundamental and completely general principles (matter and force), the phenomena we observe. Hence we must try to obtain the basic properties from other parts of our conceptual framework — and the consequence is they become, in a sense, not something that can be experienced. One way of viewing this is that since we seek to make a theory about nature, and we cannot assume that this has any human-like characteristics, we must try to remove the 'anthropomorphic' elements that reside in our ordinary concepts. We can for example take a mathematical structure and give it a name (I am not claiming here that this is how concepts are formed). We may also find empirical connections between entities which are operationally defined in analogy with (what is in this context) well-known entities, but that these relations do not correspond to our essential definitions. Then we do not know what we are talking about before we have established a new concept of the essence of the entities the theories describe. This was the situation in the early years of quantum mechanics.

The positive heuristics of a theory, i.e., the opportunities for further fertile research, resides among other things in how rich the fundamental conceptual framework is in avenues for formulating new laws or relations. This is also (I believe) part of the reason for the success of mathematical formulations. Mathematics, in particular following the development of calculus, contains a near unlimited number of possibilities to formulate both essences and relations in a precise way, which are hard to find in any other 'language'.

If a theory can be formulated in several logically or mathematically equivalent, but conceptually different, ways, this is a strength rather than a weakness of the theory — even though it implies that the interpretation is ambiguous. This gives more opportunities for further development of the theory, by inserting new elements or replacing some of the elements (entities) with new, analogous ones — i.e., several possible directions. What in one formulation can be a fairly small and simple change can be a large and complex revision in the other formulation. In this context it is important to note that we never make use of concepts completely beyond the framework of concepts we already know and work with — in some sense we have to choose among our known concepts, or possibly in analogy with these.

Finally, I will illustrate these reflections with two examples of fundamental physical theories, at quite different levels. One is Anaximenes' theory of air as ultimate matter, the other is quantum field theory.

Anaximenes claimed that everything in the world is air in different forms. The essential, constructive and operational features of matter are in this case very evident: invisible, volatile, neutral — and sustaining life. It appears concretely in the world as, indeed, air, which is what we breathe (this can serve as an operational definition); what is usually found above the ground and water. Furthermore, earth, water and fire are condensed or rarefied forms of air. Despite the simple construction of this theory, we can see that it contains everything required of a fundamental physical theory.

The research programme could consist in a further investigation of the processes of condensation and rarefication. Do condensation and rarefication in themselves constitute the fundamental force, or is it gravity or heat? (Anaximenes believed heat was identical to rarefication of air.) Attempts to for example transform air into water and earth or vice-versa could be paramount. One problem for the programme could be how to explain the difference between for example iron and stone — forms of matter which appear to have the same hardness and density. An attempt at an explanation could be that they have small, but different variations in density, variations so small that we cannot see them directly. This is however where the programme would come to a halt as long as there were no means of investigating these variations. It would also be difficult to explain colours.

Looking back at this theory from our vantage point today, we can see that in spite of its naivety it contains several lasting insights. If we translate the theory to statements about the four states of matter (solid, liquid, gas and plasma), along with the phenomena heat and density, we will find that it chimes in well with modern statistical physics and thermodynamics: gas is considered the primary state of matter (i.e., it is at least the easiest in terms of calculations, which is not necessarily the same thing). When cooled or compressed (reduced volume, increased pressure), a gas will become liquid and then solid, while when heated or rarefied it will be ionised (turn into a plasma). In fact, heat may be seen as identical to the tendency to move to higher states of matter, while the states of matter on their part are expressions of the bonds in the system, and hence of its density. However, a long detour was required before these insights could be formulated in more precise language.

Without preempting the discussion in sec. 4.2 too much, we can affirm that quantum field theory is centred around the concept of *particle species*. The particle species can be divided into two main groups: fermions and bosons. The fermions are characterised among other things by a 'natural repulsion': two fermions of the same species can, if they exist, not be in the same state at the same time, and they hence have a natural aversion to being in the same place. Note that this is not due to any interaction (force) between them, but is part of what it means to be a fermion. In contrast, the bosons have a 'natural attraction': they can be in the same place over a finite time interval.

Each particle species is characterised by a set of quantum numbers which determine its behaviour and interactions. The most important quantum numbers are mass and spin, which determine the propagation of the particles (or the evolution of a system consisting of one particle species) when left to themselves, plus charge, colour, weak isospin and weak hypercharge, which determine how they interact (the shape of the interactions). In addition there are requirements for invariance and microcausality. This may be considered the essential part of the theory.

The constructive part of the theory (which I will consider in more detail in sec. 4.4) is centred on the concept of bound states. Up quarks, down quarks and gluons may enter into stable, spatially limited configurations which are colourless and have electric charge 0 or +1, mass approx. 1 GeV and spin 1/2: neutrons and protons. By way of residual interactions these may then form stable configurations with integer charge: atomic nuclei. An atomic nucleus may combine with photons and electrons to form electrically neutral, stable configurations: atoms. (The ensemble of bound, electrically neutral states formed from the same atomic nucleus is denoted as different states of the same atom.) Atoms may in turn be bound with electromagnetic residual forces, giving rise to molecules, crystals, liquids, etc.

The operational part of the theory is primarily based on the possibility of observing individual particles in particle detectors of various kinds. Most of these make use of the ionising power of charged particles and photons. That is, we make use of known theories of ionisation, as well as theories of phase transitions or drift of charged particles (electrons) in gases with an applied electric field. A large amount of work on construction and calibration on the basis of known theories and properties of for example cosmic radiation gives rise to the criterion for claiming that a particle has been observed: a correlated 'track' of for example small pulses of currents in wires. Further information about the particle — momentum, charge, mass (i.e., particle species) — may be obtained by looking at bending in a magnetic field, time spent traversing a certain distance, etc., while the energy is measured by stopping the particle completely (and possibly destroying it).

A contrarian may object that what is observed is interactions rather than the particle itself — and hence that the existence of the particle is merely inferred on a more or less flimsy basis. The particle may be considered merely a construct. In response, it may be asserted that the correlation of the data in the measuring instruments is *the criterion* for there being a particle there; this is what makes it possible to talk about observable particles. The individual particles, thus observed, form the (primary) empirical basis of the theory, in light of which the rest of the theory must be evaluated.

The masses of the different particle species, the values of the coupling constants, and various other data, make up purely empirical parts of the theory. There is also scope for introducing new interactions and particles and revising the form of the known interactions within certain limits. For example, the Higgs mechanism is very flexible; there may be a number of ways of grouping particle species; and one may 'invent' new interactions or symmetries with their corresponding new particle species. I will briefly consider possible research areas in chapter 5.

Certain anomalies are also known (even ignoring the question of whether renormalisation is valid). These are mostly associated with the relation to gravity. It is accepted that quantum field theory is valid for all phenomena except gravity, which is governed by Einstein's theory of general relativity. These two theories are mutually inconsistent, and it is an open question how deep this inconsistency is. Part of the problem is that quantum field theory takes space and time as given, while general relativity is concerned with modifications of the structure of space and time. This may suggest that the inconsistency is fundamental. At least, the attempts that so far have been made to unify the two have not borne fruit. It can therefore not be ruled out that this problem will force a fundamental revision of the theory in the future, just as new discoveries may of course also do.

3.4 Reduction, correspondence and complementarity

By *reductionism* I understand an attitude which says that *everything* (all phenomena, events, entities, properties) is to be explained by a small number of principles, properties or laws at a more 'fundamental' level, and claims that what occurs at this fundamental level is strictly speaking all that is real. Everything else is only combinations or modifications of this, and the concepts expressing these modifications are strictly speaking superfluous.

In fundamental physics we always seek the most general and overarching principles possible, from which as much as possible can be derived. The aim is what in physics circles today (somewhat irreverently) is called a 'Theory of Everything' (TOE). If one set of principles can be replaced by a more general set (with a wider range of applicability), this is always a big triumph. This is what I call a *reduction.* Here I am using the concept of reduction both about what can be considered reduction in the strict sense — when a theory (*reducendum*) may be formally explained or derived from another (*reducant*), which may be considered more fundamental — and about what might rather be termed a *scientific revolution*, when an old theory is replaced by a new one, which after it has broken through may be seen as more fundamental, and which can explain everything the old theory could.

A reduction has several purposes, and there are several requirements for considering it to be a success.

The main purpose is to give a deeper, more fundamental explanation and understanding of the world, and to be able to explain and understand more phenomena. Often the multitude of theories is reduced because the reducant is originally created to explain phenomena that are not encompassed by the reducendum. Hence we get closer to the aim of one fundamental principle on the basis of which the world may be understood.

It is considered a further success if the reduction contributes to explaining or predicting additional phenomena that were previously unknown or inexplicable (e.g., in statistical mechanics, as opposed to classical thermodynamics, it is possibly to give a proper treatment of energy fluctuations).

The new theory must of course explain everything that was explained in the old one — this is implicit in the concept of reduction. But this is not satisfactory on its own — if a theory (partly) replaces an old one, this introduces a new problem requiring a solution: how could the old theory work that well? Usually it cannot be directly deduced from the new one, since they operate on different logical levels. And even if parts of the theories can be shown to yield formally the same results, it may be pointed out that the general conceptual framework implies that the formalism represents completely different entities. The theories are thus logically incommensurable, and in light of the new theory the old one will become meaningless and incomprehensible.

Physicists usually do not consider this a problem, since they are normally more concerned with empirical evidence than logical niceties. For philosophers of science this appears more problematic. It appears you have a choice between two kinds of answer if you believe the new theory is correct. Either you may reject the old theory completely (as meaningless), or claim that today's science is talking about something completely different than previously (if you do not wish to merely give a purely sociological explanation for how people could believe in such nonsense) — or you may claim that the old theory still has a certain (limited) area of validity, where it is approximately correct. The former is preferred by many philosophers of science, but is not really satisfactory: the science and thinking of earlier ages is in effect made worthless and scientifically irrelevant, and our own science is at risk of becoming so too, in light of the development we must assume will happen. Moreover, even the theories that are most completely rejected may be shown to have a certain validity. Ptolemean astronomy gave correct prediction, and Aristotelian physics can function as a first (and often sufficient) explanation of everyday phenomena: stones fall down and fire rises up — that is that. If the second alternative is chosen, it is necessary to show that there is a *correspondence relation* between the two theories, to explain that the new one is generally valid, while the old one still has a certain validity.

The term correspondence relation may denote several different concepts used in describing the relation between an old and a new theory.[22]

Firstly, the correspondence principle can be seen as a methodical rule when working on a new theory: the concepts in the new theory correspond to the concepts occurring in the old one, and have an analogue or in part formally equivalent function. In particular, the methods for measurement or observation are approximately the same. This is

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[22] The positivist correspondence problem — regarding the relation between theoretical terms and observational data — is beyond the scope of this discussion.

necessary for us to be able to claim that this is a new theory within the same science, and not a completely new science. In addition it functions both as a means to soften opposition to the new theory, and as a source of ideas for new developments. This was Bohr's main use of the principle.

Secondly, it can be said to express the requirement that a new theory explain at least as much as the old one did. This is however also embedded in other methodological principles.

The third meaning of the term is more interesting and more controversial among philosophers and logicians. It implies that the old theory is implicit in the new one, typically as a limiting case, even if the two are formally incommensurate or contradictory. For example, we say that classical physics emerges from quantum mechanics when $\hbar \to 0$. Taken literally, this is meaningless. From a physicist's point of view it is on the other hand not very different from what we always do: make approximations where we ignore what may be considered irrelevant to the problem at hand. This leads to solutions which are known to be idealisations to some extent, but which are still a good approximation of reality — all theories imply an idealisation. In the same way we may for example for big systems consider all effects due to Heisenberg's indeterminacy relation to be so small that they are of no consequence. This gives a formal solution of the quantum mechanical problem which is identical to the classical solution (except in those cases where macroscopic quantum effects occur). Hence, classical mechanics may be considered an approximation to quantum mechanics within a certain region, and within this region the whole conceptual framework of classical physics may be used, as long as the limits of its validity are known. In showing this, we have also explained why classical mechanics worked as well as it did, by demonstrating a correspondence relation between it and quantum mechanics. This holds not only for the relation between these two theories, but for relations between overlapping physical theories in general, where one is considered more fundamental than the other.[23]

But, again: the theories are also often based on incompatible or incommensurable conceptual frameworks. The entities of one theory do not fit into the other one at all. This is not only the case where one theory is often said to contradict the other (like quantum mechanics and classical mechanics), but also in typical examples of reduction, like thermodynamics and statistical mechanics. Even in those cases where a thermodynamical quantity (like temperature) has a direct analogy in statistical mechanics, the two concepts have very different meanings and are logically incommensurable. Within certain areas the theories will overlap; here they (or their conceptual frameworks) will be considered *complementary*.[24]

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[23] A deeper analysis of the importance of correspondence relations in science may be found in Krajewski [15].

[24] This use of the concept of complementarity does not quite correspond to Bohr's ideas. His point is that there are pairs of entities, phenomena or quantities in the world where precise knowledge of one precludes knowledge of the other. Examples of this are the wave and particle aspects of light in quantum mechanics, or that detailed and complete knowledge of the physical and chemical construction of a body precludes knowledge of the same body as a living organism — since it would be dead in the course of the investigation. I would however claim that my concept of correspondence (which in part is based on Heisenberg's discussions in [20]) retains what is worth keeping of this. In particular, I would claim that the wave-particle complementarity is really an aspect of the complementarity between classical and quantum physics: waves and particles are classical concepts, which do not belong (at least not in their classical sense) in a quantum mechanics that stands on its own two feet.

Another thing must be noted here. As mentioned above, nearly all theories have a limited region of validity. This becomes clear from noting that a single theory rarely (never?) can stand completely on its own, and neither can a single science (like physics). The essential element of a physical theory may do so. The constructive and in particular the operational elements, on the other hand, require the occurence of phenomena which cannot be described in purely physical terms. As far as the operational element is concerned, this is obvious: for it to make any sense, we must assume ourselves as consciously acting (experimenting) beings.

The 'reverse requirement' in the constructive element is more subtle. The constructive element is the one that forms a bridge to our everyday world. This bridge usually has many spans, in particular when the theory is at a level far from our own. For a theory to work, it is not necessary for all these bridge spans to be fully constructed, but we must have some idea of where they lead. Without this the theory is close to worthless as a physical theory, since we would not know what we were talking about, and what we are talking about would in any case not be of any relevance as an explanation of the world. Democrit's atomism, for example, which says nothing about how many atoms of which sizes make up a body, nor does it give any indication as to how to find this out, is merely a metaphysical position.

Only once we have an idea of where we can find the connection between our fundamental theory and the other levels of reality may we start considering a reduction. And, to reiterate, a reduction is in general something quite different from a simple negation. The purpose of the reduction is to explain the concepts, phenomena or properties that are reduced; this is obviously not done by rejecting their validity. On the contrary: it is assumed that the concepts to be reduced are known and given and have their application in their own area. And if there is a science which covers this area, this science is still as valuable, and will rather have gained a further dimension and justification from the reduction — it constitutes a link between the more fundamental theory and a level of reality that (normally, at least) is closer to the everyday level.

A one-eyed reductionism ignores these points, and considers what occurs at the fundamental level as the only true reality, and the concepts that occur at the other levels as essentially superfluous, if not empty — and the theories about them are wrong (period). Only concepts directly (logically and mathematically) constructed from the primary, fundamental concepts can be accepted — they can be part of a kind of 'economy of thought'. This is the case for physical reductionism (everything is really matter or atoms in motion or quantum mechanical states), which is what I so far have implicitly referred to, and which cares only about the essential element of physical theories. This position (which may also be denoted 'ultra-realism') implies in effect that we cannot say anything about the world until we have the fundamental, all-encompassing theory — unless we dogmatically assert that we are already in possession of this theory.

This one-eyed rejection of everything except the fundamental level is also found in what I will call mental reductionism (that everything is really a construct from sensory impressions, feelings, thoughts or principles of association — i.e., mental quantities), which is concerned only with the operational element of the theories (if that). I will take a closer look at an important variant of mental reductionism in the next section. At the end of the day, a reductionist stance will not be in a position to explain anything. And the world, to the extent that it exists, becomes completely alien to us.

On the other hand, the opposite of reductionism, a relativism that does not recognise any fundamental relations, nor any common principles or criteria, will be just as unable to explain anything. All theories, worldviews, events, etc. will just be loose fragments with no value or mutual connections. This is really a case of being thrown into an alien, chaotic world.

When working on a physical theory it is entirely legitimate (and necessary) to consider everything else mere manifestations of what occurs in the theory — to consider the theory all-encompassing and all-explaining. The aim of physics is to explain everything in the world, and it cannot accept anything beyond itself, anything not linked to the concept of matter. Immaterial phenomena are physically impossible and oxymoronic. This does not present any difficulties as long as it is recognised that what happens at secondary levels, considered *at and from* these levels, has aspects that are alien to the primary level. There must be a formal link (correspondence) between the fundamental and secondary theories, but at the same time the independence and necessity of the different theories on their own levels must be recognised (complementarity).

I can illustrate this with some reflections on what can be seen and said by an observer from different levels. We often (usually?) illustrate our theories by imagining an observer at the level of the quantities we are working with. (Here we are still working within the area of physics.) This observer will see very different things from what we see — presumably primarily the entities we assume exist at this level. It is however also possible to make the observer a 'physicist' who carries out investigations at our level. This requires the observer to be able to consider itself as a 'thing', so that it can handle the entities at its level, but I will not worry much about this issue here.

A galactic observer will probably see galaxies, radio galaxies, quasars and similar entities. There are entities that *we* really consider more or less accidental collections of stars, interstellar plasma and dust. To the extent that we may imagine them as 'things', this is because we have scaled them down in our mind. Moreover, they consist almost exclusively of plasma ('fire'), which for the galactic observer will be the primary state of matter, but which for us can never form things. Solids, which our things mostly consist of, do not feature much in the world of the galactic observer. They will also barely notice the effects of the existence of things (in our sense) and humans. Our level risks becoming the most irrelevant one.

At the atomic level, the aggregate states of matter, which are so important to our perception of things, do not exist. The entities are also defined more in terms of their relations, and less as independent 'things'. At the subatomic level it is hard to find anything at all that deserves the label 'thing', as I will show in section 4.1. So what does one see at this level? A subatomic observer in our sense of the word is a contradiction in terms: an elementary particle must be blind — observation requires a method and a means of observation, and the particle cannot have these if this level is the lowest. A method would require the observer to have a flexible structure and be able to differentiate between the different parts of itself. How could for example an electron have any critera for saying that it was hit by a photon arriving from a certain direction with a certain energy? At most it could say that 'something happened'. A subatomic observer therefore requires an even lower level of reality, which we (so far) do not have the least knowledge of. If we still imagine such an observer, there is very little we can assume about what this observer can ‘see’.[25] We can however with great certainty claim that it would be a big stretch for it to ‘see’ (or construct the concept of) us.

3.5 Instrumentalism and positivism

According to positivism, all we have to go on when it comes to the world is the impressions that have come to us through the senses. All talk of a reality ‘behind’ or on top of this is rejected as meaningless — it is not possible to give an account of what is meant by such statements. All our statements about the world must hence be such that they can be traced back to statements about what can be sensed or (unconditionally) observed empirically. Those disciplines that try to go beyond this have no justification; the only discipline with any claim to validity is the one that deals with relations between observations (observable quantities), i.e., (natural) science.[26] The only valid task for philosophy is to investigate which statements have meaning and which are meaningless in light of the criterion above — i.e., to act as a kind of servant for science. In this way, positivism claims to represent a wholly scientific view: only scientific investigations have any real value.

When it comes to what is considered ‘primary content of experience’, there are varying views. Phenomenalism, represented primarily by Ernst Mach, accepted only simple sensory impressions, and considered everything else (included things) to be constructions and ‘economy of thought’. The logical positivists, such as Moritz Schlick and Rudolf Carnap, eventually found it difficult to maintain such a view, and introduced a revised requirement that all statements should be analysed in terms of statements about things, with a given method for verifying the statements.

Positivism implies an instrumental view of theoretical terms in science. The theoretical terms only have a value and a meaning in their relation to observational data — as a ‘stenographic’ description of relations between many observational data, as tools for predicting observations, or as logical constructs (generalisations from which observational statements can be deduced). The theoretical terms do not denote anything that can be ascribed any independent existence.[27]

I will characterise positivism (both the logical and the phenomenalist variants) as mental reductionism because it *treats* the world or science merely as a logical construct from our experiences, whether these experiences in the final instance be considered pure sensory data or experiences (concepts) of things. The starting point is that the primary experiences are given; the subsequent construction of the world is purely logical.[28] The value of theories is given purely by their logical relation to experience.

According to logical positivism, scientific explanation is nothing but presenting a general (universal) statement from which singular (observational) statements may be deduced. The general statement is then a scientific law, and this view of scientific

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[25] Henry Margenau has an interesting attempt to describe the world as it would look to a subatomic observer in [32].

[26] Ernst Mach talks about three sciences: psychology, which investigates the connections between our ideas; physics, which investigates the connections between our sensory perceptions; and psychophysics, which investigates the connections between sensory perceptions and ideas.

[27] Mach for example considered atoms to be merely practical counting variables.

[28] Inductive and/or deductive — here I use logic in the sense ‘rational science of thinking’.

explanation is called the *deductive-nomological model of explanation.* Scientific activity consists in attempting to subsume our (possible) observation under ever more general laws (with ever greater empirical content).

Positivism appeals to some scientists and others because a positivist or instrumentalist point of view apparently involves a liberation from all metaphysical preconditions. All that must be considered is the empirical data that are immediately given; there is no need to make any assumptions about the sources (if any) of these data. You are therefore free to construct scientific theories independently of any philosophical prejudices, dictated only by 'raw facts' — a 'pure' science should be possible.

A positivist or instrumentalist view of science will always be able to give a fully consistent 'interpretation' of any scientific theory. As long as there are unambiguous rules for deriving observable consequences of the theory (which, according to positivism, there must for it to be a theory), no problems with the interpretation of the mutual relations between the theoretical terms can ever occur (as could happen in realist interpretations), since the theoretical terms have no kind of mutual relations beyond what is determined by their relations to the observational data.

The problem with a positivist or instrumentalist view is that it in no way reflects the way science is done. The positivist philosophy of science undermines itself, since it renders scientific activity pointless. Science only makes sense if it is taken for granted that it deals with real entities, and this is also the case for the constructs (theoretical terms).[29] There is no point in seeking explanations without an implicit assumption that these explanations reflect something real in the world. Researchers usually consider their work to be *discovery* of laws, not construction or *invention* of concepts which may summarise observations in a concise form. Granted, the concepts and laws we deal with are idealised constructions — but this very point, that we can consider our concepts to be idealisations compared to some real entities, is of utmost importance for our understanding of science. Because of this, it is also possible and appropriate to eventually 'factualise' the law to make it fit reality.

If our laws were only convenient descriptions, there would also be no point in maintaining a hypothesis if it fitted the observations less well than a previous hypothesis — which is something that can be justified if there is reason to believe that the new hypothesis better reflects essential features of reality. By maintaining the hypothesis despite the negative evidence, it may subsequently be developed into a successful theory. An example of this is the heliocentric view of the world, which was maintained by several people despite Copernicus' model giving incorrect predictions and all other experience going against it. Only when the model was developed by Kepler, Galileo and Newton could it be given the status of a theory. This would be a miracle if you had an instrumentalist starting point. It would also appear pointless to carry out experiments to create new phenomena to be explained (unless this is with the aim of exploiting these phenomena). Positivism, which presents itself as a radical view, could hence result in a rather reactionary practice.

Positivism (or the deductive-nomological model in general) is also unable to distinguish between a scientific theory and a phenomenological relation or correlation. Both

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[29] One issue is that no such thing as 'pure observational data' exists: all observations rely on certain theoretical or metaphysical presuppositions. Logical positivism has partly taken account of this by taking things as the starting point.

will have the same logical form, and they may even predict exactly the same phenomena. The theory will however be accepted as an explanation, while the phenomenological correlation will *not*. The difference is not at the logical level, but at the level of understanding. The theory explains the phenomena by fitting them into a comprehensible or coherent pattern, as consequences of principles and relations that appear as natural. A phenomenological relation or correlation is only a mathematical expression which does not appear as part of any larger pattern. How could the deductive-nomological model explain that Planck's law of radiation, when it was first proposed, was not a theory, but that it changed character completely once the quantum postulate was introduced? Nor does a theory need to give precise predictions or agree completely with observations. It is sufficiant that it is 'in principle correct' and provides a qualitative explanation of the phenomena; one may also choose to adapt the observational data to the theory rather than the other way around. For a phenomenological relation this would make no sense. Norwood Russell Hanson expresses the inadequacy of the deductive-nomological model as follows:

> 'Philosophers sometimes regard physics as a kind of mathematical photography and its laws as formal pictures of regularities. But the physicist often seeks not a general description of what he observes, but a general pattern of phenomena within which what he observes will appear intelligible.'[30]

Positivism aims to establish the correspondence between theories at the level of 'direct observation' alone — otherwise, the correspondence can only be considered a heuristic rule. This cannot, however, as pointed out previously, be considered an explanation of the correspondence between the theories. There is no explanation for how the theories 'build upon' each other, conceptually as well as empirically.

Instrumentalism could have worked as a philosophy of science if the purpose of science had been to control the world, or to give more precise predictions of what will happen. A quick glance at (for example) theoretical physics should be sufficient to convince anyone that this is not the case. The research operates (in principle) completely independently of whether the results will ever have any application, and experimental situations are constructed which have nothing to do with everyday reality. Basic researchers do not carry out their research for the purpose of being useful, but out of a pure interest in knowing what the world really is like.

Positivism may, however, have some positive (!) uses.

A theory that conflicts with accepted philosophical ideas may be more easily accepted if a positivist or instrumentalist view is taken, since this will make the theory immune to criticism in a consolidation phase. One does not make any claims about 'reality', but only describes how certain things are related. There are a number of examples of this in the history of science. We may mention Andreas Osiander's preface to Copernicus's *De revolutionibus orbium coelestium*, Newton's 'Hypotheses non fingo' (on the origin of action-at-a-distance forces), or Bohr's 'There is no quantum world' (against the classical realism of Einstein and like-minded people). All of these were intended as defences against criticism that was primarily philosophical, and did not imply that they did *not* take their theories to be statements about reality. But by pretending that one was only describing phenomena in the simplest way possible, the theory could be given space to

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[30] *Patterns of Discovery* [13], p.109

develop. Quantum mechanics is probably also in debt to positivism — the positivist climate in the 1920s and 1930s meant that quantum mechanics met with considerably less resistance than would otherwise have been the case.

It can also be useful to have a 'positivist spring clean' in science once in a while. If there is a suspicion that a theory is fundamentally flawed, it can be useful to peel off anything unnecessary and look only at what can be observed or measured. There are several examples of this leading to a theoretical breakthrough. Einstein's special theory of relativity had as one of its starting points an analysis of whether it is possible to determine empirically whether two phenomena are simultaneous, and Heisenberg's matrix mechanics started from an intention to study only directly observable quantities.[31]

Finally, as an example of how far the positivist critique of the status of 'constructs' and 'theoretical terms' is from the mentality of many practising physicists, I can quote Rutherford's response when Eddington once at a dinner remarked that electrons were very useful concepts, but that they did not need have any real existence:

> 'Not exist, not exist, — why I can see the little beggars there in front of me as plainly as I can see that spoon.'

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[31] It can be mentioned that Einstein in his earlier works was inspired by Ernst Mach, while Heisenberg in turn was inspired among others by Einstein.

Chapter 4

Critique of quantum field theory

4.1 Newtonian physics in the perspective of hindsight

> ‘The classical mechanistic world view was based on the notion of solid, indestructible particles moving in the void. Modern physics has brought about a radical revision of this picture. It has led not only to a completely new concept of “particles”, but has also transformed the classical concept of void in a profound way. This transformation took place in the so-called field theories. It began with Einstein’s idea of associating the gravitational field with the geometry of space, and became even more pronounced when quantum theory and relativity theory were combined to describe the force fields of subatomic particles. In these “quantum field theories” the distinction between particles and the space surrounding them loses its original sharpness and the void is recognized as a dynamic quantity of paramount importance.’ *Fritjof Capra*[1]

Newton was an atomist. But the physics he founded found itself torn between atomism and continuum theory. The idea of fields was always lurking in the background as a threat, even though it was not developed until the first half of the 19th century and brought to its conclusion within the framework of classical physics by Einstein.

In Newton’s physics the duality between matter and force is clearly expressed. Matter — the passive principle — was characterised by mass (inertia and weight) and extension, while the forces — the active principle — acted at a distance, and changed the velocities (or momenta) of the bodies by an amount depending on the distance between the interacting bodies. The paradigmatic example of such a force was gravity, which acted on all bodies — but other forces, such as magnetism, were also known, and Newton believed there would have to be additional, stronger forces which kept matter together in our macroscopic bodies (things). Impact forces could be considered a special case of forces acting at a distance. The world consisted of atoms (or at least matter particles) in motion, under mutual influence of action-at-a-distance forces. An important part of the research programme was to find the forces that were dominant at the atomic level, and hence perhaps derive the forces at the macroscopic level as ‘residual forces’. An example of this, and one of the most stunning successes of this programme, is when

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[1] *The Tao of Physics* [23], p.229

Boltzmann and others in the last half of the 19th century and the early 20th century could explain all of thermodynamics and all frictional forces (including hydrodynamics) in principle as a result of microscopic (atomic) collisions or other forces.

All of this looked very nice, and it is no wonder that Kant tried to derive the essence of this programme (including Newton's laws) purely *a priori.* But with hindsight we can point out several issues that Kant should have seen.

The first, and most obvious one, was a problem for Newton's physics already at its birth. Seventeenth-century physicists, brought up on Descartes' physics (derived purely *a priori*) — a continuum theory that only recognised contact forces (impulse, pressure and friction) — reacted with horror to the idea of action at a distance. Such forces were considered 'occult', and in no way explanatory. Although Newton officially refused to construct 'hypotheses' about the origin of action-at-a-distance forces, he could not avoid attempting some explanations. The three main types of explanation were as follows.

- Bodies act directly on each other at a distance. This hypothesis is philosophically the most unacceptable, but at the same time it involves the fewest assumptions on top of what can be observed, and many people eventually came to terms with this idea. This explanation may be more easily acceptable if God is introduced as mediating the forces between the bodies.

- There is a material substance — the *aether* — which fills all of space and mediates the forces. This hypothesis involves a number of additional assumptions, and leads to some paradoxes, but was accepted by many. Newton made use of this hypothesis to some extent. The reason for its popularity was that it gave an apparently intuitive explanation, and the distance forces could be reduced to mechanical forces.

- The points in space have mathematical properties that depend on the distribution of matter, and which determine how the forces act — or put differently: there is a field that is defined everywhere in space. Newton linked this to the idea of an absolute space (*God's sensorium*) — an idea which was however in latent conflict with Galileo's principle of relativity (which was encoded in Newton's first law). This was not the correct path to take, as was made clear by Einstein in his theory of relativity (derived almost *a priori*).

Kant should have been in possession of what was required to be able to 'predict' a relativistic field theory — it is almost strange that he did not do so, in particular since several central points in the theory of relativity are very close to Kant's arguments.

The connection between the possibility of talking about absolute simultaneity and the existence of (instantaneous) forces at a distance, which was Einstein's starting point, was Kant's main argument for his interaction category: one can only say that two phenomena are simultaneous if they have an unbroken interaction (continuous connection) with each other. As an example[2] he uses something that could have been taken straight out of a textbook in relativity: The light travelling between us and remote celestial bodies forms a mediate interaction which enables us to determine their simultaneity. (Kant knew very well that light had a finite velocity.)

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[2] *KdRV* [12], B280

It also appears that Kant believed the space between the interacting bodies could not be empty, since an empty space cannot be experienced. Therefore he would have to advocate either a field theory or an aether theory, where the field or the aether are considered to be real entities.[3] Then it will be natural to assume a finite velocity for the propagation of forces, based on the principle that a cause never achieves its full effect in an instant.

All of this leads not only to Einstein's theory of relativity, but also (and in particular) to a breakdown of the strong dualism between matter and forces. The forces are considered fully real, and may well be carriers of energy (or other measures of quantity of matter). In an aether theory, this is almost unavoidable. The idea of forces at a distance are also in latent conflict with the idea of extended bodies on several other points, as follows.

If distance forces (in some form) are acting between the atoms, and impact forces can be considered merely a special case of distance forces, then this implies that these forces are everything we notice. The forces become more primary than matter, which may be reduced to points: sources of and points of influence for forces. In any case it leads to the breakdown of the analogy between atoms and things already at this point. The traditional (Democritian) idea of atoms is as (infinitely) hard bodies — as a kind of 'super-things', completely independent of each other, which can never be destroyed — and with a clearly delineated extension. If distance forces constitute the general case, it will not be possible to distinguish clearly between the atom (its extension) and the surroundings — or it is not possible to distinguish clearly between the thing itself and its effects. And what kind of *thing* is that? The idea of a separate and bounded thing is linked to contact forces, to being able to say that *there* we are in contact with the thing. With distance forces, a clear delineation of the thing will always involve an arbitrary boundary.

We may expose this paradox even further by asking the questions of where in the atoms the forces come from, and what they act on — questions which were foreseen by Galileo (who refused to attempt to answer them, since they were metaphysical). Are they composed of the contributions from the smallest parts of matter (points), or do they come from a central point in the atom? And do they act on the smallest parts, or on the body as a whole? If attractive forces act on the smallest part, why does the body not then collapse to a point? And external forces should act differently on the different parts of the body, which could lead to the atoms being deformed or even crushed. To counteract this we would have to assume some kind of 'metaphysical' force inside the atoms, which ensures that they retain their extension regardless of what happens.

All this has no effect on the macroscopic functions of matter. In particular, the forces ensure that 'matter' is still extended — an 'intruding' particle or structure of particles will be more or less effectively kept at a distance. The remaining functions are taken over by the (point) particles. However, the debate between atomist and non-atomist conceptions becomes irrelevant when the atoms do not have to be extended.

There is a second point where the essence of matter had to change in the Newtonian programme: as more forces were discovered, matter would have to obtain more essential properties (attributes).

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[3] Kant's opinion on this is somewhat unclear. Some places he appears to advocate an aether theory; other places he rejects this idea as absurd.

Matter which is characterised only by extension and mass (for now, we can ignore the argument that extension cannot be an attribute of microscopic matter) will be insensitive towards all other forces than those that couple to these attributes, i.e., impact forces and gravity and similar forces. It was well known *both* that neither of these forces could explain stable, microscopic bonds — impact forces are always repulsive, while gravity is too weak — *and* that other forces existed, which coupled to other attributes. In particular it can be noted that if electricity is a fundamental force, then charge must be one of the attributes of matter. Moreover, charge differs from mass in that it occurs in two versions: positive and negative. Hence it cannot be reduced directly to one quantity of matter — we need (at least) two types of matter, positively and negatively charged. Neither can we immediately get rid of mass as an attribute. Thus we are for the time being left with (at least) to mutually irreducible ultimate forces and (at least) two attributes of matter.[4]

Kant pointed out[5] that the empirical criterion for being able to identify matter is its role as a source of forces. It is thus clear that all measures of source strength must be considered an attribute of matter. Hence, we should expect that if more forces are discovered, matter must also acquire more attributes. This yields a multitude of (apparently) independent, irreducible matters, or the matter acquires qualities — which appears odd considering what was originally required of matter.[6] In particular we may note that if we assume several matters (e.g., 'charge matter' and 'mass matter'), these will (partly) coincide in space — the same body will always have components of several matters. Matter becomes more and more *quality*, and less and less *extension.*

And even if it were once more possible to reduce all the different forces to one ultimate force, this will necessarily have a different character to the forces we started from. Hence we are left with both 'occult forces' and matter with 'occult qualities'. And the forces effect qualitative changes as much as spatial motion. This, if nothing else, is a break with the Newtonian programme.

This break also emerges in a different area, where furthermore the relation between theory of ultimate matter and theory of elements is illustrated.

Galileo and Newton's atomic theory was metaphysical. The scientific atomic theory was developed in chemistry, which contained both quantitative properties (e.g. mass), taken from Democritean theories, and qualitative properties (chemical properties), inherited from Aristotelian and Averroist theory. The interactions were to all intents and purposes qualitative. The results were around 90 different atoms and substances which physics could start working on during the 19th century.[7] We may also note that extension was in no way a relevant attribute of chemical matter.

If we now accept that the world exhibits a structure of different levels, and that matter at deeper levels has different attributes (properties) from those we experience at

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[4] It is possible that the observation that the force in both Newton's law of gravity and Coulomb's law behaved like $1/r^2$ inspired Kant to attempt to derive this dependence *a priori* — there were at least a number of attempts by different people to find a common origin of the two forces, without success.

[5] *KdrV*, B249–250. Kant's concept of substance corresponds more or less to what I call matter.

[6] Kant was of the opinion that qualities are of critical importance for experience, and that they can be treated within the framework of mathematical physics. But firstly, these qualities were taken to be sensory qualities, and secondly, they could in no way replace spatial extension. Moreover, it seems reasonable to assume that he thought of the qualities as states of the substance.

[7] The historical development is described by van Melsen [5].

the everyday level, it follows that these 'deeper' properties must be observed indirectly. We are forced to construct experiments in order to observe and define these properties and entities in the first place, not just to give them a precise value. This has the following consequences.

- Observation must necessarily be treated as a physical process. This brings up for discussion the entire set of questions related to what observation and sensory perception really are. It is not possible to claim that sensory perception is unproblematic, nor that it is the be-all and end-all of experience — there is a lot more to it.

- Observation becomes an *active* process to a much larger extent than before — we prepare the conditions that make it possible to 'see'. To observe a charge, we *have to* set up instruments such as conducting plates, wires, batteries etc. (This example is perhaps not the best, since we can get a shock if the charge is large enough!) This is in contrast to everyday life, where we do not need to do anything except turn our heads, i.e., arrange ourselves so that we can lay our eyes on something; and also in contrast to Galilean experiments, which serve to increase the precision or *select* what we want to see — something that could in principle have happened naturally.[8] The 'deeper' phenomena cannot be seen by us when they occur naturally — we can only see them (identify them) in an experiment.[9] There is therefore no reason why experimental setups that are necessary for observing one phenomenon, may in fact rule out the observation of another phenomenon at the same level or a different level. This is at the root of Bohr's principle of complementarity.

- Our observations become to a large extent theory-laden. The theories of the higher levels form the background for the observations at lower levels, since the existence of lower-level entities is inferred from experience and theories at higher levels, and since the experiments assume known theories. To make the latter point clear: in modern experimental physics it is essential that the measuring instruments are *calibrated* — i.e., parameters are adjusted so that the instruments give correct values in well-known experimental situations, and so that the sources of errors are known. This is obviously meaningless unless you have a theory that says something about expected experimental data and a theory of the behaviour of the measuring instruments.

  This theory dependence is much deeper than what can be claimed at the everyday level. It can be claimed also in that case that to 'see' always assumes a certain pre-established knowledge if we are to see *something* that we can identify, or if we are to know what to look for. This knowledge may however to a large extent be reduced to synthetic *a priori* requirements along Kantian lines, or to fundamental categories of everyday language — things that it does not make any sense to doubt (like things, space and time, as discussed in section 3.1.1).

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[8] Kant saw clearly the importance of an experiment being a far more active process than an ordinary observation: we force nature to answer *our* questions (see e.g. *KdrV*, Bxiii). This is however still within the framework of Galilean experiments, where what is measured is more or less directly observable.

[9] Bohr wanted to limit the word 'phenomenon' to only observations or events in a properly defined experimental setup.

This prefigures (in hindsight) many essential features of quantum mechanics (e.g. in the Copenhagen interpretation) as features that are implicit in Newtonian mechanics. The concrete appearance of quantum mechanics, including for instance the discovery of Planck's quantum of action (as a finite quantity), could of course not have been predicted, but nor does the argument require this. From an 18th century point of view, however, this involves too many logical steps into the unknown for us to expect that anyone — not even Immanuel Kant — could have carried it out without a misstep somewhere. It is pure hindsight — an argument that we can carry out now that we know what we can hang it onto.

However, there is one of the preceding points for which Kant may be criticised for not having raised: the question of observation and sensory perception as a physical process. This issue had been raised already by Democritus, and was later discussed by Descartes and Locke.[10] Democritus' reflections lead naturally to a very important conclusion: the atoms can in no way be regarded as things in our sense of the word. Let us follow this line of reasoning, which is valid within a much wider framework than Democritus' atomic theory.[11]

Democritus' atomic theory is one of the clearest examples of physical reductionism: everything is really only atoms in motion. Colours, smells, heat etc. do not exist in the things — they are phenomena that appear when the 'messenger atoms' collide with the 'soul atoms' in the sensory process. Democritus was aware of the problems of such an attitude — he lets the senses say to reason, 'Poor reason, do you hope to defeat us while from us you borrow your evidence? Your victory is your defeat.' The senses are the only basis we have for speaking about concrete things in the world, and they are based on a signal being transmitted from the thing to us. We form an image of the thing as a whole (including extension) by a large number of signals (or a continuum, to generalise compared to Democritus and quantum mechanics) that are emitted and absorbed by our sensory organs. So far, everyone should be able to agree. But what happens when the 'things' are so small that they can be compared with the signals — when they are atoms? Then we have no possibility of grasping them as separate entities, independent of the signals through which we observe them. Democritus drew the logical conclusion of this, and said that the atoms cannot be sensed (... but he ascribed extension/geometry and number to them, taking these to be concepts of pure reason...). We may also note that this argument does not depend on the signals being atomic, only on their being physical. Democritus' messenger atoms might well be the smallest of all the atoms.

If we add the pragmatic criterion for calling something a thing — that we can *handle* it as a single unit — the point is even clearer. The atoms (or the smallest constituents of matter) must be handled by their 'peers', which however are themselves the smallest, structureless constituents of matter. We can thus in no way handle the atoms with

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[10] The reflections of Democritus, Descartes and Locke were based on a fallacious distinction between 'primary' and 'secondary' qualities, and a belief that it is possible to eliminate the 'subjective' and be left with the primary qualities as properties of the things in themselves. This position was correctly criticised by Berkeley, a criticism accepted by Kant. However, it appears that Kant also (in my view) accepted too many of Berkeley's other conclusions regarding sensation. It is clear that sensation must also be considered a physical process in *Erscheinungswelt*, and if Kant had as his aim to clarify the preconditions for sensation being used as evidence, he should also have taken into account the physical limitations of sensation.

[11] Although his opinions on this point are mostly in agreement with quantum mechanics — see the next section for a portrayal of Feynman as a neo-Democritean.

tools that we hold fixed — the tools will be neither more nor less fixed than the atoms themselves! Hence it is nonsense to talk about the atoms as things that can be known or experienced independently of their relations to other 'things'. A matter–force dualism will not solve this problem, since there we may well be able to move the atom, but cannot at the same time know that we are doing this.

This was however something neither Kant nor anyone else at that time considered.

4.2 What are the entities of quantum field theory?

One of the most salient features of quantum field theory is that it all but abolishes the divide between matter (traditionally seen as *particles* in some sense or other) and forces (*fields* in classical physics). The divide was already partly erased with Einstein's demonstration of the equivalence between mass and energy, but is now abolished in a more subtle way: matter is also fields, while forces are also particles. Any attempt at an interpretation must take this into account, although the emphasis may be placed more on one or the other aspect. Here I will concentrate on four kinds of interpretation that can be taken as 'paradigms' — a number of other interpretations can be considered intermediate positions. I will call these four interpretations the Feynman interpretation, the aether interpretation, latence interpretations and the S matrix interpretation.

All these interpretations are variants of more or less 'moderate realism'. This means that I am avoiding both the 'reductionist ditches', ultra-realism and positivism. Both those versions of interpretations have however been present in the debate, so I should say some words about them. The ultra-realist interpretations of quantum mechanics are mostly variants of 'many-worlds' and 'universal wave function' interpretations: all problems with the theory are solved by incorporating the observer into the state function, which is seen as the only true reality. The problem is of course to what extent such an interpretation says anything at all, since 'true' reality becomes completely unobservable. Margenau's version of the latence interpretation, which I will consider in section 4.2.3, may be considered a more 'moderate' version of these interpretations. Positivism has played a large and in part constructive role in the history of quantum mechanics, both in the development of the theory and in getting it accepted. A positivist attitude to the theory does of course avoid all problems, as positivism always does, but is subject to the general criticism of positivism as I have explained in section 3.5.

An interpretation should, I believe, deal with both the essential, the constructive and the operational elements of the theory, although the essential element usually receives the greatest emphasis. This may be because it contains the 'ontology', and because it usually is in greatest need of interpretation to be understood. The operational and constructive elements are typically tacitly assumed. The operational element receives greater scrutiny in quantum mechanics, and both the Copenhagen school and positivism place most emphasis on it. This emphasis is here found in the S matrix interpretation. None of these interpretations have much to say about the constructive aspect; I will discuss this separately at a later stage.

Almost as a summary of what I have written so far, I will first say something about what *can not be* (are not) and what *can be* (are) attributes of matter in quantum field theory. It should be obvious from the previous section that extention and geometry cannot be attributes. (It is then of course an important task to explain why extension is an attribute of all macroscopic matter.) Nor can any of the sensory qualities (with one exception!) be attributes — this is Anaximander's point. Of attributes which without any problem (of any note) can be ascribed to matter, we can mention energy, momentum, charge and colour charge.[12] These are straightforward, additive quantities. (Colours obey the law of 'colour addition': blue + red + green = white.) Mass is a minor problem: whether or not it is considered a fundamental attribute depends on your point of view. Mass is not a directly additive quantity in relativity, but on the other hand it is a Lorentz invariant. More significant problems arise when considering *number* and *being*[13] as attributes of matter — different ways of solving these problems lead roughly to the four interpretations mentioned above. This is also related to the problem of identity, which I will discuss in section 4.3.2.

These are properties we can attempt to ascribe to matter, and to assign a value to. How this is to be done is an interesting enough topic in itself and concerns what we may call the static part of the theory. However, it becomes even more interesting when we also attempt to interpret the dynamical part — relating to the equations of motion or the time evolution of the system, which are often to a larger extent 'hidden' in mathematics.

The quantum mechanical equations express the time evolution of operators and states, and some of these quantities must enter as entities in any moderate realist interpretation. As shown in sections 2.3.2 and 2.3.3 there is quite a significant freedom of choice in how to express this: we may say that the system is in the same state all the time, but that this state is characterised by evolving quantities and properties, or that the state evolves — or both. We may also choose which properties to concentrate on. This freedom of choice can be considered an essential feature of quantum mechanics, but can be difficult to carry over into a philosophical interpretation; we are almost forced to consider one point of view as more fundamental than the others.

Another essential feature of the theory is that it deals with objective tendencies in some sense (at least if we choose a moderate realist interpretation). These objective tendencies are moreover associated with subsystems and properties that may be separated to a certain extent, but not completely. An example of this is that neither individual particles (particle states) nor particle species can be completely separated from each other, but are to some extent entangled. This entanglement will however not be greater than what would allow, under certain circumstances, a notion of separate subsystems. It is also not possible to uniquely identify what is a system and what is a state of the system; this is related to the flexibility of expression.

4.2.1 The Feynman interpretation

I will devote a considerable amount of space to this interpretation, both because it is quite a 'popular' interpretation of relativistic quantum mechanics, and because several

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[12] Charge, or electricity, which is a fundamental attribute of matter, can be sensed. Who had thought of that?

[13] Here I am considering being as an 'ontological category', not existence in a logical sense, which cannot be any property or attribute. If matter has being, it means that it has the same kind of 'full reality' as (or perhaps even more reality than) the things — that it exists completely independently, as something definite. This is in contrast to a view that there are several degrees of reality, and that matter has less reality than e.g. the things — a view advocated by Aristotle.

of the problems that occur in all the interpretations appear here. I do not imply that everything I present here was Feynman's own views — I call it the Feynman interpretation because it by and large follows the ideas of Feynman, but I have painted a bit of a 'caricature' to make the points clearer. Some of what Feynman himself has written is included in the references [10, 33, 34].

Feynman considered the *individual particles* to be primary, and believed that all systems in principle can be described by the motion and configuration of point particles in space and time. If we are to place this within the conceptual framework of quantum mechanics, we can say that he starts from a particular type of states, *viz* particle states. However, since the interpretation is tied to his own formulation of quantum mechanics, this does not do it full justice. He distinguishes between fundamental fermions, which can never be created or destroyed in an absolute sense, and which represent 'matter', and (gauge) bosons, which represent the 'forces' and which are emitted and absorbed by the fermions. The Feynman diagrams give a space–time representation of this.

So far, this looks like a good, realistic and perspicuous interpretation which does not depart too far from common sense, and the lines back to Democritus are quite clear. The elementary particles are, as Democritus' atoms, equipped with *being* and *position in space and time.* They obviously do not have any extension, so they cannot interact through impacts, as they do according to Democritus — therefore they instead interact by bosons being created and destroyed, and hence exchanged by fermions. This can be considered a 'minimal solution' to retain as much as possible of the perspicuous contact forces. It is also necessary to satisfy the requirement of locality in relativity.

Now these particles start behaving oddly, as Feynman says. They do not limit themselves to taking one particular path in space, as proper things do; on the contrary they may decide to take all possible paths. This means that the quantum mechanical indeterminacy principle is satisfied, at the same time as an apparently pressing problem is solved: it appears incredibly unlikely that a boson should 'hit' and be absorbed by another particle, but when the particles can encounter each other anywhere, this is not a problem.[14] It can also be considered a kind of 'reverse causality principle': why should the particles choose a particular path if they do not have a reason to do so? So this property, which appears quite strange and incomprehensible when you first encounter it, can be considered natural and logical once you become used to it.

Just how the principle of 'all possible paths' is to be understood is however not clear. Feynman emphasised (in line with the Copenhagen school of thought) that we cannot say that the particle *really* took one or the other path, although we do not know which one. This is equivalent to summing up the amplitudes rather than the probabilities. If we imagine that a particle only has two possible paths to take to any endpoint (as in the double-slit experiment), there may be points it can never reach — not because the paths leading to these points are themselves excluded, but because their contributions cancel out.

If we instead try to say that the particle takes all paths at the same time, we must be careful with what we mean by this. We can definitely not take it to mean that the particle 'splits' and that each part takes a separate path — the particle is always whole and intact. (We sum up amplitudes for *whole* particles.) The particle will moreover never

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[14] In fact, it is a problem. If there are more than 4 (3+1) space–time dimensions, the particles will not hit each other, even if they can take all possible paths.

be observed in several places at the same time, so when we observe it, it is always in a specific location. The path integral formalism expresses neither more nor less than the probabilities or possibilities of going from one place to the other, possibly with additional constraints for 'internal coordinates' such as spin. This does of course require that we are able to observe the particle unambiguously at these points (or, rather: prepare it at the first and observe it at the last).[15] One may also imagine that the particle 'sniffs out' the path in front of it, so that it 'knows' what is possible and impossible. This may appear to bring an element of teleology into the theory. A final possible way of viewing it is a latence interpretation, which we will look at later.

The particles taking 'all possible paths' obviously corresponds to the field aspect of matter. That there is no difference in principle between fermions and bosons in this respect is an expression of the matter–force equivalence. This equivalence is broken in two ways.

Firstly, bosons are emitted and absorbed, while fermions are not. I will look closer at this difference below. Secondly, for gauge bosons a distinction is made between 'real' and 'virtual' quanta, a distinction that is not made for fermions. For electrons, the same propagator is used throughout the process, while the propagator of a photon that is being exchanged differs from the expression used for an external photon: a plane wave.[16] This is related to the starting point: the movement of electrons from one place to the other, where the interaction is not viewed as a field, but as a direct (but delayed) interaction between the electrons. This interaction is represented by the photon propagator, which has a different character to the free field. This somehow problematic distinction can be made less problematic in two ways. Firstly, the integration over all possible interaction points can be carried out, resulting in Feynman diagrams in *momentum space* (the particles are characterised by their energies and momenta rather than their positions). Then we will find virtual electrons as well as virtual photons. Secondly, it can be argued that all light has been emitted from a source at some time, and will at some point in the future be absorbed, e.g. by a detector, so that the 'free' photons really represent an interaction between the source and/or the detector and the electrons that enter into the process. A third way out can be found in the S-matrix interpretation. The problem of how virtual quanta are to be considered is one of the central philosophical problems in quantum field theory, and will reappear several times (in various guises).[17]

In the 'ordinary' field theory formulation there is no difference between fermions and bosons in terms of their constancy — both fermions and bosons have variable particle numbers: particles may be created and destroyed. In the Feynman interpretation only bosons have this property. This realist, Democritean view of matter can be maintained by giving the particles the ability to move backwards in time. With a positron interpreted as an electron moving backwards in time, all pair creations and pair annihilations

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[15] Both an ultra-relativist and a positivist 'interpretation' will avoid these difficulties. The universal state function interpretation implies that the particle in fact *is* everywhere, also when we observe it — but when we observe it, this leads to us (or our consciousness) also being 'everywhere' — the consciousness branches into all the possible states, but we can only access one at a time. A positivist will of course say that it is meaningless to say anything about the particle except at those moments when it is observed.

[16] An electromagnetic plane wave can only have transverse polarisation, while virtual photons can also have both longitudinal and 'scalar' polarisations.

[17] More opinions about the problem of virtual quanta may be found in [18].

may be eliminated by interpreting them as the electron 'turning' in time. The worldline of an electron will hence always remain an unbroken, infinite line.

As pointed out in section 2.3.3 this is mathematically unproblematic — it is a way of parametrising all possible paths — and this point of view can have a number of advantages. We may however ask: what does it mean that 'the electron is moving backwards in time'? This appears on the face of it to be a contradiction in terms: motion means change of position with time, and hence requires a time in which the motion takes place. Motion backwards in time would then mean that time decreases with time, or that one at a later time finds oneself at an earlier time. It is not quite as paradoxical as that: the worldline of the particle is parametrised by its *proper time*, which is a precisely defined concept — and the CPT theorem (see section 2.3.3) tells us that motion with reversed proper time is equivalent to the motion of an antiparticle.

We thus have to find out what proper time means, and for that we must turn to relativity. Here the concept can be defined in two (equivalent) ways. Firstly, the (infinitesimal) proper time interval can be defined as the Lorentz invariant quantity formed from the difference between the temporal and spatial coordinates of a particle, $d\tau^2 = dt^2 - dr^2/c^2$. This quantity has an important function in the theory of relativity, e.g. in defining relativistic velocity and in a relativistic formulation of Lagrangian particle mechanics (not field theory) — which was the starting point for Feynman's formalism. The sign of $d\tau$ is however not determined by this definition; it can be fixed in a coordinate system that follows this particle. However, this presupposes and observer 'attached' to this particle, and this is only possible if the particle is a macroscopic system. For an observer to be attached to a Feynmanian electron is unthinkable.

It is tempting to make the electron (or particle) itself an observer, and hence to equip it with consciousness. Apart from being rather speculative, this will not be very satisfactory: we can of course not ask the electron about anything. The electron cannot in any case be an observer — apart from being blind, it can certainly not be equipped with measuring rods and clocks that would make it possible to conduct objective measurements. It can in fact not have anything like an objective concept of time, since it does not experience anything except possibly sporadic external changes. Nor can it have any memory that would be accessible, since this would violate both the indeterminacy principle in quantum mechanics and the principle of causality (that an effect cannot come before its cause). The only option is hence to make the electron a Leibnizian monad, with the possibility of introspection and monadic consciousness, but without 'windows'. Despite the speculative nature of this picture, it may be a possible key to an understanding of Feynman's system: a monadic particle can in no way be bound by external spatiotemporal coordinates, and will therefore be able to take all possible paths. It will only know its own, subjective 'proper time'. A 'pre-established harmony' will then ensure that this 'proper time' corresponds to the objective proper time — and perhaps also that the path integral works as required? These speculations are however very far from the spirit of Feynman.

It may get even more speculative if we ask what closed fermion loops represent. An electron moves forward in time, turns and goes back and not only meets, but 'swallows' itself. This appears to suggest an eternal, rhythmic process or circular time, if we still are to take 'motion backwards in time' literally. It is best, I think, to leave these speculations at this point. I will come back to some of these issues in connection with the problem of identity.[18]

Another issue with the Feynman interpretation arises (in particular) from weak interactions. In weak processes, particles of new kinds are formed — eg, muon decay gives a muon neutrino (ν_μ), an electron (e^-) and an electron antineutrino ($\bar{\nu_e}$). This happens through an exchange of a W boson between the muon and electron 'parts' of the system. To maintain the conservation of matter (fermions) and the path integral interpretation, one is forced to claim that μ^- and ν_μ are 'really' just two states of the same particle, and the same for $e^-$and ν_e, so that the antineutrino can be interpreted as an electron moving backwards in time. This means that the distinction between different particle species is effectively abolished, and it is a purely empirical question whether different types of fermions exist. It also becomes less and less clear what is really meant by a particle. Up to now we have been able to give the particles mass, charge and some other 'labels'; now this becomes difficult. We could try to characterise a particle by its propagator, but it depends on the particle's mass — which is not conserved. This can however be a strength as well as a weakness.

A final, serious problem with this interpretation is how to explain bound states. One issue is the purely calculational procedure — processes with an unlimited number of gauge boson exchanges must be included. This issue is however common to the whole theory, to the extent that it is applied perturbatively. There being an indeterminate number of photons in an atom does not for example represent any additional calculational problem. It does however represent a problem for the interpretation, if one wants to view photons as primary entities with the attribute of existence.

A more serious problem is that the formalism to a large extent precludes any consistent definition of a bound state. We can say that the formalism deals with *processes* rather than states; to the extent that states occur in the conceptual framework it is as instantaneous configurations of particles. The concept of a stationary state is hard to fit in. We can try to define it as two (or more particles) that at a certain time are close to each other still being close to each other after a long time has passed. Such a definition does however not capture the *stationary* aspect of the state, even if the time is taken to infinity. It is one thing that the particles should be in close proximity all the time, and that a stationary state is essentially time-independent. In addition, it at least looks like it assumes the possibility of measuring the position of the particles *in* a bound state. This is however impossible. In an atom any precise measurement of the position of an electron will involve such a strong interaction that the electron immediately escapes from the atom. When it comes to quarks in hadrons, it is even theoretically impossible to isolate them and treat them as individual particles (confinement). When they are sufficiently close together, bound in the hadron, they behave as if they were free (asymptotic freedom), and it should be possible to identify them. However, we do not know how many of them there are — in addition to the quarks that contribute to the 'net' quantum numbers of the hadron, there may be an arbitrary number of quark–antiquark pairs.

The conclusion is that it is in any case difficult to view bound states as something essentially stable in the Feynman intepretation. They must instead be considered as eternal processes where everything looks the same at the surface — like a Heraclitean river. It appears that this would contradict the Democritean basis of the interpretation.

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[18] Other problems arising from Feynman's 'time reversal' are discussed by Margenau [31].

There are however other states of physical interest that have indeterminate particle numbers, such as states with definite values for the electromagnetic field strengths.

Despite all these problems, the Feynman interpretation has an obvious advantage in its realism and perspicuity — even where it fails. It is also the interpretation which best maintains numerical identity on the microlevel, as we shall see — although at a considerable cost. It is also useful in terms of comparing classical physics and quantum field theory: employing the Feynman interpretation makes it clear just where the differences reside. At the same time we are reminded that in very many cases it is permitted to view the subatomic entities as particles, but we must then be aware that they are Feynmanian.

Furthermore, information about processes is usually expressed through Feynman diagrams, and the particle species and the diagrams are usually what you are first acquainted with — before you learn the specific concepts of field theory. Some qualitative features of Feynman's formalism or interpretation may be explained to a layperson without any use of technical terms. Feynman's own outstanding physical intuition and ability to present his material in an understandable way probably also play a role. He claimed himself not to understand quantum mechanics. In that case, we can say that his presentation of his lack of understanding have made many other people understand!

4.2.2 The aether interpretation

I am not aware that anyone has explicitly formulated and advocated this interpretation.[19] On the other hand, there appears to a widespread opinion that the aether is rehabilitated in quantum field theory, albeit in a very different form to the classical aether, and many qualitative descriptions of the concept of a quantum field are close to that of the aether interpretation.[20] The aether interpretation also presents several features which are interesting in themselves and make many essential aspects of the theory explicit. For these reasons, and in order to have a certain completeness in the system of interpretations, I have included it.

If the Feynman interpretation can be termed Democritean, the aether interpretation is best termed Heraclitean. Heraclitus claimed that *change* is the essential feature of the world. Everything is in a state of continuous flux; the world is like an 'ever-living fire, kindling itself and going out by regular measures'. Ultimate matter is fire, which is at the same time a process or a force: the fire looks 'stable' just because it always changes and is never the same; it lives by burning and transforming every new pieces of matter. 'Out of discord comes the fairest harmony,' said Heraclitus, and by this he meant that discord, conflict and activity are preconditions for the existence of anything. Nothing can be in a state of quiet, without change. In line with this, he sought the One in the many — the difference in the world is just what makes it one. Difference is a principle of unity — a measure of difference and change.

Now we can directly translate Heraclitus' concepts to quantum field theory. Fire can be identified with energy, force with fields or field operators; change consists in

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[19] Fritjof Capra [23] may come closest to it. However, he explicitly bases his arguments on the S matrix interpretation and S matrix theory, although he takes a considerably more 'realistic' point of view of the fields and particles. The result can be considered a blend of the two interpretations.

[20] See eg., Dyson's presentation in [35].

the creation and translation of particles in an eternal dance, while the Lagrangian (or action?) is an underlying measure that regulates everything.

To be somewhat clearer, the aether interpretation states that the *fields* (field operators) are the primary entities. The fields are present everywhere in space, not as static but as dynamic quantities. This can be related to the field concept originally being associated with and derived from the concept of force, which is an expression of changes in nature. Thus, the nature of the fields is change. The 'material' aspect of the fields is expressed primarily in energy, and secondarily in other conserved quantities. We may note that energy is also originally associated with dynamics: energy is what can be transformed into work.

In the world of phenomena the effects of the fields appear as movement, change and annihilation of particles in a 'cosmic dance'. This term is quite apt — a dance is a continuous motion, complicated but rule-bound. There is a *pattern* in (or behind) the movements which is just what makes it a dance and not chaos. In field theory this pattern resides in the fields and their inherent properties, and in particular in the Lagrangian constructed from the fields.

I use the concept of *aether* because the fields in quantum field theory have a material character which is deeper than just being energy carriers. To clarify the peculiarities of quantum field theory it may be useful to compare it with classical aether theory and classical field theory.

The classical aether is a very fine or rarefied material substance that permeates everything, that is present everywhere in the world, and through which all motion and all forces are mediated. The prototype of an aether is found in Anaximenes' *pneuma* (breath of life) or the Chinese *ch'i*. It is hence not exclusively a passive principle, but rather the condition for all motion and all life; it is (usually) taken to never be at rest, but always in motion. It is often thought that the aether can condense into material things, and dissolve again later.

In classical physics, the aether was primarily taken to be the material substance through which light is transmitted: light is aether waves. Furthermore, distance forces may be taken to be transmitted through the aether, as pressure or stress. The function of the aether is in other words still first and foremost dynamical, as a medium for transmission of motion and forces. The aether may also be taken to be an absolute reference system — all motion is ultimately related to the aether.

When the last function is included the aether has lost much of its original dynamical character, although there may still be flows in the aether. But even ignoring this, it is obvious that it is something material: it can be moved, and has attributes such as density and pressure, which apply only to matter. To the extent that matter is taken to emerge from aether, it is as condensation, i.e. quantitative, not qualitative, changes. In reality, classical aether theory can be considered an attempt to completely eliminate forces — the forces are reduced to pulsation and flow in the aether, and are subject (and subordinate) to the law of conservation of the quantity of aether.

A classical field is on the other hand primarily immaterial. It is originally not defined on its own terms, but through its effect on matter. The field expresses the dynamics of the system, and no more — it does not have any 'life of its own'. The field is there, or not, with greater or lesser strength, according to the distribution of matter, and it acts by changing the distribution of matter.

A Newtonian force field (like the gravitational field) can be considered a compact notation for the sum of the contributions from several (even infinitely many) material sources to the total force on a particle at a given position. What makes it a useful concept is that the field can be made independent of the particle that might be at this position — the field is the same, independently of the mass, charge, etc. of the particle. Hence we may say that the field is there independently of whether there is a particle there or not. However, no empirical consequences can be drawn from such a statement.

If we now do not have instantaneous forces at a distance, but finite propagation speeds, the field acquires a more real status. It transmits information about what happened yesterday which is of importance for what will happen tomorrow, and thus ensures a continuity between cause and effect. At the same time it is natural to make the field an energy carrier — e.g., the energy that must be transmitted between two particles in a collision. It also begins to acquire a 'life of its own' — we can write down equations describing the evolution of the field independently of the material sources.

It is however difficult to make the field more material than this. The field can not be imagined as an aether, where variations in field strength are condensations and rarefications: there is no law of conservation of 'field quantity' (total field strength). It is also very hard to view the material sources as merely regions of space where the field is particularly strong, as Einstein attempted, or as regions with a particularly high energy density.[21] Quite apart from any problems arising with the original definition of the field (from its effect on matter), the behaviour of the sources is not covered by the field equations.[22] For the theory to be Lorentz covariant, the sources must also be taken to be points, and they are hence not just regions with large field strengths, but singularities in the field. We see that from the attempt to create continuity, strong discontinuities arise, which need special treatment.

Classical aether theory attempts to reduce force to matter (flow or vibrations of the aether), and runs into problems with explaining how matter can be transformed, i.e. what force really is. The matter may well become dynamical (have motion as part of its nature), but not active. Hence, it is ultimately sterile. Classical field theory attempts to reduce matter to force (there is matter where the forces are strong), and runs into problems with explaining where the forces originate and what they act on, i.e. what matter really is. You get activity without this activity having anything to act on. Both models take being as something completely continuous, and run into problems with explaining the discontinuous aspect of matter. How anything can be delineated and stable remains a mystery.

Quantum field theory abolishes the matter–force dichotomy not by reducing one to the other, but by going to a higher level of abstraction. It operates at the outset with two levels: the fields, which are underlying, active quantities which are present everywhere, and the states, on which they act (literally). The condition for talking about the fields as active quantities, with a (possible) effect everywhere, is that they have something to act on. But matter, which the fields act on, is now not something that exists independently — on the contrary, it is created by the fields. Matter (particles)

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[21] For example, it makes no sense to say that *that* energy is moved in space, but it does make sense to talk about moving a piece of matter in space.

[22] This does not mean that it is in principle impossible to describe the sources field theoretically, but this must involve a certain revision of the field concept. Either it must include several fields acting reciprocally on each other, or certain non-linear structures in the field equations.

consists of manifestations of the fields, but these are not themselves fields. A particle state (a state that is a particle) is not identical with a region of space where the field strength or energy density is large.[23]

The aether interpretation emphasises that the fields contain creation and annihilation operators, and that these act 'continuously' in space and time, and that change is effected by them. We can thus talk of a continuous dematerialisation and rematerialisation — a 'dance' of particles appearing and disappearing. Taken to the extreme, we may say that all change in the state of the system consists in creation and annihilation of particles. In particular we may note that all interactions involve creation and annihilation, i.e. materialisation and dematerialisation.

Another important point, and the reason I have chosen to call this the aether interpretation, is that this 'energy dance' takes place everywhere in space, although the activity is greatest in the vicinity of physical particles. Suddenly, particles (quanta) may appear from 'nothing', only to disappear back into 'nothing'. Vacuum is not empty; on the contrary it is involved in a continuous process of materialisation and dematerialisation, which forms an essential part of the 'vacuum'. Vacuum is transformed from empty space, via a role as 'container' for the fields to a very living 'aether'.[24]

Self-interactions can be interpreted as there being around every physical particle a 'cloud' of virtual quanta, which contributes significantly to the properties of the particle. The mass of the particle receives significan contributions from this cloud, while the interaction properties may be said to be determined by the shape of the cloud. Renormalisation asserts that the particle can in no way be separated from the cloud surrounding it; it is not itself without all these virtual quanta. Capra says, 'A subatomic particle not only performs a dance of energy, it *is* also a dance of energy; a pulsating process of creation and annihilation.' [23, p. 271] The essential features of the particle are determined by the dynamical whole it forms part of. This view is quite distinct from the Feynman interpretation, where we can either 'imagine away' the virtual quanta or redefine the particle concept to include this 'cloud', leaving us with a fairly clearly delineated entity.

Quantum field theory differs from classical aether theory and classical field theory (and classical atomism) by the quantum field being *both* continuous *and* discontinuous. It is continuous because it is nicely defined everywhere[25] and discontinuous because it is quantised. The manifestations (materialisations) of the fields are always *quanta* — we never find half-particles (half-quanta).[26] The discontinuous aspect to a certain extent — but only to a certain extent — makes it easier to account for the particular (particle-like) features of matter. Matter as sources and points of influence for the forces is easy to grasp: all processes involve quanta. These quanta play roles both as matter and forces, according to your point of view.

The aether interpretation denies the existence of matter and forces at a fundamental

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[23] The particle state may however be in a state where the energy density is large in a certain region of space.

[24] Vacuum fluctuations are physically relevant, and among their consequences is that vacuum looks hot to an accelerated particle. The gravitational effect of the vacuum has problematic consequences for attempts to construct a theory of quantum gravity.

[25] The derivatives are well defined everywhere.

[26] In the aether interpretation is is probably more correct to use the term *quantum* than the term *particle*. A quantum can be considered an excitation of the field.

level. These two basic concepts of physics are both absorbed into the quantum field. The primary manifestations — the quanta — cannot be identified with either, although they have the potential to appear as both. Here we see a difference compared to the Feynman interpretation, where fermions can immediately be identified with matter, and gauge bosons with forces. In the aether interpretation the Fermi–Bose distinction does not play such a big role — all quanta can be considered equally perishable; all changes of state are creation and annihilation (at the fundamental level), while movement in space plays an essential role for Feynman. The distinction between fermions and bosons is not due to the permanence of the respective quanta, but what kinds of patterns they enter into. Similarly, the distinction between matter and forces appears at this level — we may talk about 'material patterns' (such as particles) and 'force patterns'. It may be added that the typical patterns are determined by the form of the Lagrangian — i.e., how the fields relate to each other.

In conclusion, we may say that the aether interpretation features three 'layers' or reality at the fundamental level:

- The fields, which are the most fundamental and underlying, and which are typically active quantitites.
- The quanta, which are the primary manifestations of the fields, and which are constantly created and destroyed.
- The pattern of creation and destruction, where we can glimpse the origin of some of the more well-known phenomena: stable particles and forces acting between them.

The aether interpretation definitely represents an unfamiliar way of thinking, at least for us Europeans.[27] This is a strength as well as a weakness. A strength, because it makes it possible to a larger extent to be unshackled from old thought patterns which are inadequate for understanding quantum field theory. A weakness, because it requires using metaphors to a large extent — we do not have access to the appropriate words, and cannot base ourselves to such an extent on logical rigour. In particular it is difficult to relate the interpretation to categories that are fundamental in our ordinary experience, like the distinction between substance and attribute or state. We usually think of being (in the ontological sense) as *subsistence*, and this is at the root of the Feynman interpretation, while in the aether interpretation being is primarily thought of as *activity*.[28]

It is a problem for the aether interpretation that the world as it appears to us to a large extent is dissolved, and it is easy to fall into an existential angst because nothing is solid in the world — the angst that physics was supposed to help remove — or else seek a more or less mystical insight into what lies behind. (This is a general problem in quantum field theory, but is particularly prominent in the aether interpretation.) This problem is exacerbated by its being hard to see that what we consider to be fixed points of reference or stable structures emerge naturally (although bound states are more natural here than in the Feynman interpretation — they are as natural as individual particles).

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[27] Capra emphasises strongly that this way of thought is much more widespread in other parts of the world. Heisenberg also hints at this.

[28] Would it perhaps have been easier if we had said 'The grass greens' instead of 'The grass is green'?

Granted, this is a common feature of all interpretations. It is more problematic that the operational part of the theory appears to be absent — but it should be possible to add it.

On the positive side, we may note that the interpretation is very faithful to the essential mathematical framework of the dynamics of quantum field theory, and thus gives meaning to most of the concepts or symbols. Hence, the essential part of the theory is well explained — in my opinion, the aether interpretation, correctly understood, represents the best and most complete understanding of quantum field theory as a fundamental theory of physics.

4.2.3 Latence interpretations

Latence interpretations are best characterised as intermediate interpretations, and various versions have been advocated as general interpretations of quantum mechanics. Versions denying that quantum mechanics says anything about the behavious of individual systems (Popper), as well as versions maintaining a form of realism within the Copenhagen framework (Heisenberg [20]) or Kantian transcendental philosophy (Strohmeyer [36][29]), have been proposed. Margenau's interpretation in [22, 30] also belongs to this group of interpretations. Some theories of multi-valued logic also have similarities to latence interpretations. Here I will not take sides among these various points of view. I will however primarily base my discussion on Heisenberg's and Margenau's views, as they cast light respectively on two important concepts in quantum mechanics and quantum field theory. Heisenberg's interpretation may serve as a gateway to understanding the concepts of quantum fields and operators, while Margenau's interpretation provides a good insight into the concept of quantum states.

The central point of latence interpretations is that quantum states express *potentialities* or *tendencies* in the system, and that these potentialities or probabilities in some way or other are real. When the system is in a certain state, some properties are *latent*. This means that we cannot say that the system *has* these properties, but neither can we say that the state is unconnected to the individual system. This can however still be viewed in several different ways.

Heisenberg's version.

In Heisenberg's view[30] 'the atoms and elementary particles are not as real [as the phenomena of everyday life]; they form a world of potentialities or possibilities rather than of things and facts' [20, p. 186]. The state thus describes propensities, tendencies or

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[29] Strohmeyer claims that transcendental philosophy can justify the concept of *potentiality*, but cannot provide the foundation for a science of objective probabilities.

[30] I must point out that this section does not cover Heisenberg's view in its entirety. For example, he believed that quantum mecchanics or quantum field theory is not complete, and that a contradiction between the concepts of quantum mechanics and relativity (the sharply defined lightcone in relativity vs. the indeterminacy relations) is what leads to the divergences of quantum electrodynamics. It is against this background we can view his work on S matrix theory and on a universal lengthscale. The former belongs naturally in the context of the S matrix interpretation, while the latter has lost some of its topicality in the light of newer theories, and belongs to a set of issues I will consider in relation to Planck scale physics in section 5.3. These issues are not necessarily related to the elements of Heisenberg's thinking I will discuss here.

potentialities in the system — possibilities which all *may* become real, but which *are* not so in the isolated system. When a measurement happens, i.e. when the system is brought into contact with a macroscopic system which must be described classically, a transition occurs from the *possible* to the *real* (from *potential* to *acta*) — the system acquires some property which previously was only present as a possibility. Heisenberg makes explicit use of Aristotle's terminology, but employs it in a new way to establish a 'quantum ontology'. Strohmeyer [36] presents his 'quantum ontology' as a kind of synthesis of Kant and Aristotle.

This transition from 'potential' to 'real' does not happen only during measurements, although it is most prominent there, since we 'force' the systems into the framework of classical ontology and logic. For example, an excited atom will naturally evolve via states containing the possiblity to be excited as well as non-excited, to the pure ground state. At the same time the surrounding electromagnetic field will have possibilites for different excitations.

This language can describe superpositions of states and measurements of incompatible quantities. A system may have several values of one and the same quantity as potentialities (latent values), but only one value can be real. Similarly, a particle can have potential position and potential momentum, but only one of these can be realised at one time. It is also possible to talk about greater and lesser degrees of actuality.

In quantum field theory we may also have latent or real particles: since the quantum field makes the particle number variable, the very existence of individual particles can be potential rather than real. In addition the field can have latent properties both as one or more particles, or as forces. These properties are to a large extent incompatible: for the field to have reality as force, the particle number must be indeterminate. The quantum field thus expresses the *potential* existence of the particles and the forces. If the particles are real, they may still be considered as more or less individual — i.e., they have a potential individuality which is only realised when the particles for all practical purposes can be treated as separated (i.e., when external forces play a much greater role than statistical interference).

Heisenberg introduces the idea of potential properties at yet another level (although he does not explicitly use the word potentiality in this case). He claims that the system or quantum field has the possibility to manifest itself not only as particles or forces, but also as different types of fields (particles or forces of different kinds). Examples of this can be a proton's potential existence as a neutron, or a neutrino's potential existence as an electron, which gives the neutrino electrical properties. The last 20 years of his life, Heisenberg devoted himself to an attempt to derive the entire particle spectrum as excitations of an underlying field which would represent all of matter — clearly inspired of Anaximander and Aristotle's view of matter, as what is itself devoid of properties, but has the possibility to take on all possible forms.

Heisenberg puts great emphasis on describing the relation between the everyday world of fully real things and the 'degrees' of reality that feature at the quantum level — that the potentialities of the quantum world are realised in the everyday world and in measurements. In this way it is also easier to understand the correspondence between quantum and classical physics. Heisenberg also emphasises the retention of an explicit symmetry between 'complementary' classical descriptions — pairs of mutually exclusive descriptions, where both tell us something essential about the phenomena — a symmetry which he considered essential in quantum mechanics. Examples of such ‘complementary’ descriptions can be the description of the fundamental as matter or forces, of matter as particles or waves, and of a particle using position or momentum.

A problem with the Heisenberg interpretation is how to deal with the transition from potentiality to reality. Is it at all possible to describe this transition *within* quantum mechanics? It is tempting to treat the measurement process as some kind of ‘magical’ operation which effects this transition. This is not very satisfactory — there is no proper answer to when (under which conditions) the transition occurs. This is at the root of the quantum mechanical measurement problem.

Margenau’s version

In certain respects, Margenau goes a notch further than Heisenberg in accepting the probabilities denoted by quantum states as ‘real’. To enable him to do this, he first establishes a distinction between *nature* or *historical reality*, which is the sum total of all individual events (including all sensory impressions), and (physical) *constructs* or *physical reality*, which is enduring and regular. The quantum mechanical state vector is an (abstract) construct, which serves a function in physical explanations, and hence has in principle the same status as other constructs. The state vector is part of physical reality, and the same is true of the probabilities it encodes. The individual observations, on the other hand, belong to historical reality — and at the subatomic level there is no direct (one-to-one) correspondence between physical and historical reality.

Among the constructs we may in turn distinguish between two important groupings: *systems* (such as crystals, magnetic fields, or atoms) and *quantities* (energies, wavelength, probability, etc.). The quantities can, as the word indicates, have numbers assigned, while the systems cannot. Assigning numbers to quantities can however be complicated, as in quantum mechanics. Combinations of a system and a set of quantities can make up a *state*.[31] The constructs of physical reality are subject to *causal* laws[32] — i.e., the changes in the quantities defining a state are determined solely by time-invariant laws. When the states are determined by probabilities, the laws of quantum mechanics are causal. It is not a problem that these quantities cannot be determined by a single measurement, but only by a (large) number of measurements of identically prepared systems — nothing prevents us from employing such constructs. ‘Observables’ such as the position and momentum of a particle are as much constructs as are probabilities — there is no reason why these should have any preferred status. If we insisted on defining the states in terms of these quantities, the theory would be acausal — but classical mechanics would also be acausal if we instisted on using colours and extensions as state variables.

Quantum mechanics is thus a causal discipline. The states evolve causally; the states express objective probabilities, which are part of physical reality. This does not change because the measurements always give definite results — according to Margenau the measurement results belong to historical not physical reality. There is a correspondence

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[31] The system, when it is also characterised by what kinds of states it can be in, may be called an *entity*.

[32] For Margenau, this is if not a necessary condition for physics, then at least a rule that should be followed.

between these, but it is not a one-to-one correspondence. The measurement in no way affects the state of the physical system (there is no ‘collapse of the wavefunction’).

We see that the entities of quantum mechanics are quantum particles and fields — characterised by quantum states (state vectors). Naturally, in quantum field theory it is the fields that must be considered entities — Feynmanian particles, for example, would yield an acausal theory, since they can move backwards in time.[33] If we however consider the states of the fields at any point in time, the theory is completely causal. If we call the states latences, we may furthermore employ the same ‘ladder’ of levels of latence as Heisenberg uses.

Margenau’s interpretation has the advantage that the relations between quantities, states and entities are made completely clear, and avoids the problems Heisenberg has in accounting for the transition from ‘potentiality’ to ‘reality’. The disadvantage is that he introduces a ‘duplication’ of the world that can be problematic. Where Heisenberg to a certain extent emphasises the correspondence between classical and quantum physics, Margenau places a greater emphasis on quantum mechanics as different from and independent of classical physics. The main emphasis is on the essential and the operational aspects; Heisenberg also considers the constructive aspect to be important.

The latence interpretations are not complete, although they have greater or lesser degrees of completeness. They are primarily suited to illuminate and clarify one (important) issue in quantum mechanics: how to understand *objective probabilities*. Discussions of the measurement problem arise easily out of latence interpretations — but the different versions give radically diverging answers. The interpretations have little to say about essential features of quantum field theory such as interactions and entanglement of systems.

4.2.4 The S matrix interpretation

The S matrix theory can, as previously described (page 21), be treated as an independent research programme, transcending the limits of and forming an alternative to quantum field theory. This was the aim of both Heisenberg and several of those who got involved with this theory in the 1950s and 1960s, and who continued to work on it in the 1970s. It can also be treated as an interpretation of ordinary quantum mechanics which does not necessarily break with quantum field theory; this is what I will now consider. The clearest exposition of the S matrix interpretation is due to H.P. Stapp [37], who considers it the best candidate for a pragmatic version of the Copenhagen interpretation. My discussion will be based mostly on his presentation, although I will allow myself some assessments of my own, which Stapp would probably not accept, to adapt the interpretation to quantum field theory. All quotes are, unless otherwise stated, taken from Stapp’s article [37].

The central concept in the S matrix interpretation is the *experiment*, consisting of *preparation* and *measurement*. In the interpretation of the experiments it distinguishes between the *observing* and the *observed* system, and the correlation between preparation and measurement can be described in terms of the evolution of the observed system. The observed system thus forms a link between preparation and measurement. However, the possibility of such a link, separated from the experimental apparatus, requires that

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[33] He discusses this in [31].

the processes of preparation and measurement are physically separated. Hence, in order to effectively be able to identify and 'isolate' the observed system, it is necessary to look at the asymptotic form of the correlation between preparation and measurements — the limit when the two are infinitely far apart. This asymptotic form is expressed through the S matrix.

The S matrix interpretation takes over and develops the Copenhagen school's emphasis on the influence of the experimental apparatus on what is to be measured,[34] and its insistence that the experimental apparatus must be described classically. Stapp delineates the latter point further to being an *operational* or *technical* description. We are thus *not* interested in a precise and detailed description of the apparatus, only in what can be termed relevant calibration and measurement data. A precise and detailed description would not be possible since this would prevent a use of classical concepts — since the classical conceptual framework does not correspond completely to the nature of the world. Furthermore, such a description would require making the observing system an observed system.

By almost *defining* the observed system by its relation to the observing system, the S matrix interpretation stresses that a thing or physical entity can never be understood completely in separation, but always in relation to other things or entities. The concept of a separate physical entity has a precise meaning only when this entity is infinitely far from the observational instruments; in other cases we can only talk about its separate, independent existence as a practical approach to reality. In general we can say that all entities are defined first and foremost in terms of their *relations* — the S matrix interpretation considers the essential feature of reality ('being') to be relation, as opposed to the Feynman interpretation, which views it as subsistence, and the aether interpretation, which considers it to be activity.

To elaborate on the last point, I may first mention the obvious fact that an entity that has no relation whatsoever to its surroundings can never be discovered by or have any effect on these surroundings, and can hence justifiably be said to not exist in this world (only in 'its own world'). The only criteria that the surrounding world has for deciding not only *whether* an entity exists, but also *what kind of* entity it is, are its (possible) relations to other entities, i.e. to its surroundings. It is thus not completely wrong to claim that an entity is defined by its relations rather than by its essence, or maybe even that its essence *is* its relations. Stapp writes, 'An elementary particle is not an independently existing entity. It is, in essence, a set of relations stretching out to other things.'

This point also goes beyond the obvious one that to observe something (an entity) we must be in some relation to it (directly or indirectly). It also emphasises that we never perceive something as existing completely independently; it always has a certain relation to its surroundings (in space and time). 'The idea of a table existing alone in the universe has an aura of unreality' — the table is located in a certain room among other things, and has its own history and a future. This is essential to our perception of the table. In other words, the world is perceived more as a network of relations than as a collection of things.

In line with this, an elementary particle is perceived not as something that *has*

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[34] Cf. Bohr's insistence that a *phenomenon* is defined only within the framework of an experimental setup.

relations, but as *being* itself a relation. Here what Stapp calls *macrocausality* plays an important role: energy and momentum can only be transmitted over large distances by way of physical particles. If there is a correlation between preparation and measurement that implies a transfer of energy and momentum over large distances, this means that we are dealing with physical particles, providing in turn an operational definition of these. An individual particle is thus not something we 'observe', but an objective relation between the preparing and the measuring systems. All other measurements of the observed system can then be calibrated against this simplest type of relation. The quantum mechanical measurement problem is thus considered to be solved. The same is the case for the problem of renormalisation. A 'bare' particle is simply an empty concept, since this implies considering the particle as completely isolated from its relation to its surroundings — an idealisation without any justification at this level. The *physical* particles occurring in the S matrix are always 'dressed', and those are the ones that are used for calibration, etc.

The S matrix interpretation strongly emphasises the non-separability or entanglement in quantum mechanics. This should be clear from what I have written above, but requires some further comments. The entanglement can be between preparing and measuring system, between observing and observed system, and between subsystems of the observed system. These all have in common that the systems or subsystems can only be considered to be separated in the asymptotic limit.

If preparation and measurement are entangled, it is not possible to define any observed system, and the treatment of the observed system requires that it is isolated during the process. If we for example intervene with a measurement during the process, this must be treated as two experiments, not one — the conditions for treating it as a single experiment (e.g. by use of one wavefunction which evolves continuously according to the Schrödinger equation) are violated. This is what happens when one intervenes in the double-slit experiment, or more generally, in any attempt to 'follow' the trajectory of a particle.

The entanglement of subsystems means that during part of the process it is not possible to describe the observed system in terms of separate subsystems, even if all preparation and measurement is translated to properties of such systems. This does not necessarily imply that the observed system cannot be described at all during these time intervals, so that a description of the time evolution of the system would be meaningless. However, during these intervals we must take a strictly holistic perspective towards the system. If we think in terms of fields and states, we can for example not talk about electron fields and electromagnetic fields separately, but must view the system as a non-separable coupling of these fields, and nor can we talk about electron states and photon states, but only about a state for the entire observed system, where electron and photon cannot be separated — the relations within the system are at certain times and in certain regions so intimate that it is meaningless to imagine the subsystems as separate. But in that case the description cannot be considered a description of possible measurement results — the condition for meaningful observation is violated if the system is not in an asymptotic state. (If such an entangled state *is* asymptotic, then it is also observable and localisable — like a bound state.) In my view it is however not meaningless to talk about the observed system as such, at least not if we understand it as what links preparation and measurement, and assume that this is a controlled and idealised picture of processes that in fact occur. We may furthermore, if we wish to make use of the language of the latence interpretation, say that the particles exist *potentially*. In certain cases it is also possible to divide the processes into subprocesses — energy and momentum are transferred between two subprocesses by an approximately physical particle, which may be created in one subprocess and destroyed in the other. This means that in certain cases it *is* possible to describe the time evolution of the system.

As regards virtual particles, the S matrix interpretation naturally takes a more dismissive attitude. The virtual particles belong to the entangled part of the process, but to think of virtual particles is to think of separate subsystems. Virtual particles can at best be a practical point of view for calculating the S matrix; a heuristic viewpoint which according to the S matrix interpretation is highly misleadinng. If the concept is to be used at all, the word *virtual* must be emphasised much more than the word *particle*, and it must be reiterated that the interaction occurs everywhere and at all times during the process, so that the particles in reality cannot be separated. The virtual particle is thus seen as one (ore more) relation(s) in an entangled web. This is particularly the case for strong interactions, where in the low-energy domain it would be in principle wrong to view the system as consisting of a number of particles. Here it is considerably more fruitful to view the processes as expressions of the various patterns of relations that the hadrons can enter into, and the hadrons themselves as entities given primarily by the relations they have to other hadrons: what kinds of hadrons they can be formed from and what kinds of hadrons they can help create. Any hadron has a potential existence in the form of other hadrons — these possibilities constitute at least part of the hadron.

As I mentioned in the context of the Feynman interpretation, the distinction between real (free) and virtual particles can be problematic. In principle a gauge boson that is emitted and absorbed during a process is considered virtual, and this can be extended to cover intermediate states of all particle species. The problem is that all particle states strictly speaking can be considered intermediate states, and hence all particles should be virtual. The S matrix interpretation both agrees and disagrees with this argument.

It agrees, because the idea that the world in is essence a web of relations implies that no particle can be considered really free, as I already pointed out. It disagrees, because the idea of free particles forms a basis for the very concept of the S matrix: even though the world is fundamentally non-separable, the idea of separate parts is necessary. When we observe something, we perceive it as localised and separate from its surroundings — this is part of what an observation *consists* of. The idea of a free particle is an idealisation, but it is useful and perhaps unavoidable. The key is the asymptotic states. When the system is far from an asymptotic state, it is so fundamentally entangled that we cannot speak of (real) particles. It can however evolve asymptotically, and in such cases we may say that the virtual particles become more real or free — free particles are defined as the asymptotic states. Hence, an intermediate state may also be considered a free particle. The language here is close to that of the latence interpretation.

The S matrix interpretation accepts as particles only what *can* occur in an asymptotic (i.e., free) state. Since quarks and gluons cannot be free, they cannot be considered particles. But this does not need to imply a rejection of quantum chromodynamics. Quantum fields have the property that they manifest themselves not only as free or nearly-free particles, but as often or even more often in fundamentally entangled states or states with indeterminate particle number. This fundamental entanglement is exactly what the S matrix interpretation, as an interpretation of quantum field theory, emphasises so strongly. As regards the quark and gluon fields, we are here dealing with fields which are fundamentally entangled all the time, except at very high energies where asymptotic freedom takes over. The quark structure may (and must, according to the S matrix intepretation) be considered an expression of 'internal relations' in the hadrons. Quarks and gluons as particles can be said to be little more than a misleading heuristic point of view, but as quantum fields they are a good expression of the symmetries and relations that occur in and between the hadrons.

The S matrix interpretation has a strength in the strictly pragmatic approach, where the operational aspect of the theory is emphasised and explained well, and in the clear presentation of fundamental entanglement.[35] The constructive aspect, on the other hand, appears quite absent, apart from a remark that it is necessary 'to deal with representations of complementary idealisations of parts of the world, rather than a representation of the whole physical world itself.' It can be even more difficult to implement this aspect here than in the other interpretations. The S matrix interpretation (like the Feynman interpretation[36]) starts primarily from the scattering problem, which mainly appears in experimentally constructed situations. The S matrix is itself explicitly constructed as a collection of measured or measurable quantities in an experiment. It should now be clear that the scattering experiment is not fully representative of what actually happens in the world at the microlevel — the idea of the S matrix is thus itself an idealisation with respect to naturally occurring processes.

A claim that the S matrix is the only physically relevant quantity at the microlevel is therefore dangerously close to a positivist attitude, even if built on the idea of objectively occurring correlations. It must be clear that we are talking about idealisations. An attempt at directly extending the interpretation to an idea of a 'universal S matrix' will be an invalid generalisation from experiments — it assumes a controlled observation without any observer.[37]

Another possible extension is to a 'relational ontology', noting that the experimental S matrices select (idealised) parts of the actually existing web of relations. Here it is taken for granted that we really are situated within the 'universal S matrix'. This is an understanding that denies the existence of any fundamental entities or any underlying substance — everything is but parts of a web. This is an interesting but problematic point of view. It starts out as clearly anti-reductionist, but risks ending up in a 'new' type of reductionism, neither physical or mental, but rather 'ecological'. Everything is reduced to relations and connections, which it is ultimately impossible to get a handle on, since we do not know what they are relations or connections between.[38] To find our way out of this tangle, we would have to introduce the notion of something beyond (or rather, *inside*) the web of connections, so that the web itself, when we approach the

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[35] This may be considered a follow-up to (part of) the 'overlooked' part of Kant's project that I called for in the footnote on page 80: an investigation of the physical preconditions for meaningful, objective observation. This also implies a critique of measurement theories that attempt to track the path of physical signals from the observed systems to the brain and into the consciousness, in order to find the divide between subject and object somewhere along this path.

[36] It has been argued, for example by Dyson (*Phys. Rev.* **75**, 1737 (1949)), that the Feynman theory *is* an S matrix theory.

[37] Capra appears to want to make such a generalisation.

[38] The only way out would be some kind of mystical insight into or unity with everything.

everyday level, must recede in favour of the components or contents of the web. These components must to a certain extent be present at all levels. At the level of elementary particles the quantum fields can play this role, and this will not imply a major break with the ideas of the S matrix interpretation as long as they are defined primarily in terms of their relations and asymptotic states.

4.3 What is a particle?

Quarks, leptons, photons, W bosons: these are all called elementary particles, and quantum field theory is often called elementary particle physics. As I have touched on at several occasions, it can be doubtful to what extent the particles can be accorded any primary status, or whether they should be taken to be secondary quantities; for example as possible manifestations of the fields, or as idealised limiting cases. There is however no doubt that the particles play a central role in the theory, and not least in the experiments that are carried out to test it and gather more information about the phenomena it deals with.

Another question is how to define a particle: what does it mean to be a particle? We usually understand a particle to be something located at a specific point in space and following a specific path, and this is the starting point for the Feynman interpretation, although quantum mechanics forces us to relax the requirement for specificity. Looking at the states that are typically denoted as ‘particles’ in the mathematical formalism (page 42), we see that their salient feature is actually that they are not localised, but rather they have definite values for some quantum numbers. This choice between giving the particles definite positions and giving them definite energies and momenta (the particles of the Feynman formalism have no momentum or energy assigned to them) is a consequence of Heisenberg’s indeterminacy relation. An ‘alternative definition’ of a particle leads to theoretical condensed matter physics (where non-relativistic quantum field theory is used) deals with a number of ‘quasiparticles’ which are states (excitations) of the *entire* system. Other disciplines also employ the concept of quasiparticles.

I will leave this question here (and return to it in section 4.4), and assume that the particles are at least somewhat localised. (I will later on consider some consequences of the localisation not being sharp.) Two other questions concerning the particles will be discussed more thoroughly: whether a particle can be taken to be a given entity, essentially separate from its interactions, and whether a particle can be considered an individual.

4.3.1 Dressed and bare particles

With the self-interaction of the particles and the renormalisation procedure to deal with this phenomenon, the question arises: which particle is the ‘real’ one — the ‘bare’ particle which appears before renormalisation, or the renormalised particle, which includes the whole ‘cloud’ of virtual quanta which are involved in the self-interaction? Both the aether interpretation and the S matrix interpretation give a clear answer to this question: only the ‘dressed’, renormalised particle deserves to be called a particle. In the aether interpretation this is because only it represents something ‘durable’, in contrast to the elementary quanta, which are ever appearing and disappearing (the bare particle is such an elementary quantum). In the S matrix interpretation it is because only dressed particles can be measured. I will argue that also the particles of the Feynman interpretation must be dressed.

I will consider the renormalisation procedure itself to be unproblematic. This can be, and has been much debated — it has in fact been one of the main topics of disput in quantum field theory. The traditional method of 'subtracting infinities' appears mathematically inconsistent; this is what led Dirac and Schwinger among others to disavow the theory they had contributed strongly to formulate. It appears paradoxical that by carrying out such outrageous mathematical operations we may achieve such an astoundingly precise agreement with experiments as in quantum electrodynamics — the highest level of mathematical accuracy that any scientific theory has exhibited. This precision is one reason to believe in renormalisation — another reason is that the same results can be obtained in several different ways, for example by varying the number of dimensions of space.[39] Furthermore, all the theoretical work carried out from 1970 on is essentially dependent on renormalisation — in particular asymptotic freedom and confinement in quantum chromodynamics.[40]

We can imagine two reasons for the problems arising from the self-interaction. One is that there is an inconsistency in the theory itself, or that the theory is incomplete. When the 'correct' theory at some point is found, the problem is assumed to be solved. Whether this will require only minor changes or a complete replacement of the conceptual framework cannot be known, and the attempts that have been made to find alternatives have so far not had much success. I will however claim that even if the theory will have to be changed, the current conceptual framework has shown its validity at least at the level of the elementary particles and processes we know today, so that a qualtitative discussion and description of the phenomena at this level within the framework of quantum field theory will always be justified. By discussing renormalisation as it appears today, we can always learn something essential — any changes in the theory will not have a serious impact on these reflections. Any new theory must have quantum field theory as a limiting case (correspondence), and the approach of quantum field theory must remain applicable where it is so today (complementarity). The other reason one could imagine is considerably more flattering for physicists. It is possible that the mathematics is incomplete, and that renormalisation can be treated in a fully consistent manner once a more complete mathematical theory has been developed (analogously to how the theory of distributions was developed to deal with Dirac's δ function).[41]

The main point of renormalisation is that it is in principle impossible to see from a particle whether or not it has interacted with itself. The parameters (mass, charge, etc.) which belong to the bare particles are thus unobservable, and must be replaced with the phenomenolgocial parameters which are assumed to result from adding up the contributions from all possible self-interactions. When computing the processes, everything which arises from the self-interactions of free particles must then be subtracted, since this is included in the phenomenological parameters. This would be necessary even if all

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[39] — something that sounds terribly unphysical, but which in fact tells us somethig essential about the conditions for having a consistent and nontrivial interacting theory.

[40] *Note added in translation:* When I wrote this, I had not yet learned about the Wilsonian renormalisation group which gives a different perspective on the issue.

[41] A somewhat more thorough discussion of the problem of renormalisation aimed at non-experts can be found in a couple of papers by Paul Teller [19, 40].

contributions had been finite — the difference is that in that case the bare parameters could in principle be computed from the measured ones. These values could also have been checked against values for (bare) masses which might be determined from a more fundamental theory, if such a theory was found.

What is the implication of this for the Feynman interpretation? Well, here we pretend to start from a bare particle, and then add the interactions. However, all the parameters that are put in are (of course) phenomenological. This means that we have already renormalised ones. It can also be argued that the 'primitive' elements of Feynman's formalism — the propagators — are dressed. The starting point is that a particle moves from one place to another. It can do so in many different ways, and the propagator is obtained by summing up all these ways. It is now obvious that if interactions are possible, then the particle can not only take all possible paths from one place to the other; it can also take all possible paths and at the same time interact with itself in all possible ways an arbitrary number of times. These self-interactions could only be excluded from the propagator if they either were very unlikely, and therefore gave only a tiny contribution to the propagator (which is not the case, since they give an infinite contribution), or if the probability decreased and went to zero with the distance over which the interaction, so that we could talk about a bare propagator at small distances (which is not the case, since the probability of electromagnetic interactions, including self-interactions, increase as the distance decreases). A further argument for Feynman's particles being dressed, is the simplicity and consistency of the presentation: since all possible processes involving self-interactions must anyway be included, then starting from bare particles would imply that absolutely all problems would involve an infinite number of diagrams and/or states with indefinite particle number, which goes against the simple and perspicuous starting point.

In order for the concept of a particle to be useful, a *free particle* must thus be defined as a particle that does not interact with other particles than itself. A particle consequently becomes (literally) a wolly concept — there is always a 'cloud' of virtual quanta which must be included in the particle. This is quite far from Democritus' ideas of atoms — it is almost precisely the same particle concept as appears in the aether interpretation, which we see must be built into all interpretations. By looking more closely at this concept of a dressed particle we may gain quite considerable and significant insight into quantum field theory.

Firsly, we learn the importance of 'squinting' at the system. When looked at 'broadly', a particle can be quite sharply delimited. If we however try to look more closely at it, we do not get greater clarity, but rather more confusion. Where we thought there was only one particle, we now encounter a 'chaos' of many different particles. Several physical quantities (such as the strength of the interactions) depend on how great a resolution we have.[42] We can explain this both by the particle interacting with itself all the time, and by that we in the attempt to reach smaller distance must pour in so much energy that we in fact *create* new particles. Here it is also essential that in investigating the elementary particles we do not have any other instruments at our disposal than other elementary particles, and to have a high resolution in distance we must use particles with small wavelenghts, i.e., large momentum and energy. All this

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[42] This is after all not really incomprehensible. For example, what we consider the lenght of a coastline obviously depends on whether the ruler we measure it with is a kilometre or a millimetre long.

follows almost directly from the indeterminacy relations.

Secondly, the point of the S matrix interpretation that the entities are defined primarily by their relations is reinforced. Interactions are clearly a form of relations, and self-interactions are linked both to the coupling between the field representing a particle and other fields, and with the particle's possible interactions between other particles.[43] When for example the mass and charge of a particle now contains significant contributions from the self-interaction, we must conclude that a particle is not itself without taking its possible relations to other particles into account. In addition we obviously have the point I mentioned about how we investigate particles.

Thirdly, we see that any particle will contain all possible kinds of particles in different quantites. This means that the separation of the different particle species at most must be considered a limiting case (or rather, something we can use when squinting). This also has implications for the properties of the particles, e.g., a neutrino has electrical properties and an electron has properties with respect to strong interactions,[44] something that can be seen from the diagrams in figure 4.1. It may thus be said that the claim of the 'hadron democracy' or bootstrap theorists that 'all particles contain all particles' (at least potentially) has a great deal of truth to it, and that it holds not only for hadrons (although the phenomenon is clearest there), but for all particles.

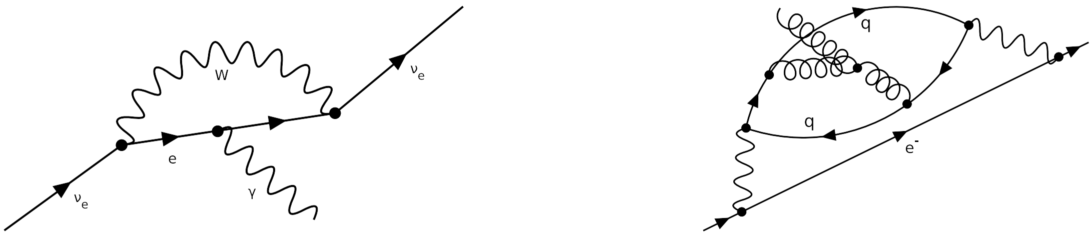

Figure 4.1: The electric properties of the neutrino and the hadronic contents of the electron.

4.3.2 The problem of identity

One of the functions of matter is, as I mentioned in section 3.2, individuation. Two things which are otherwise the same can consist of different matter, and hence be numerically different, or be considered different individuals. However, it seems that the particles, which are the carriers of matter in quantum mechanics, are *not* individuals. If two particles are qualitatively identical (i.e., they belong to the same species), then they are if not numerically identical, then at least not independent of each other. They can in other words not be treated as individuals (particulars) — but they are still particular, since there are several of them. Quantum field theory may well solve this problem by claiming that the two particles are not two particles, but one state — but then some of the 'material' aspect disappears, and we still lack an explanation for why it is practical or correct to classify them by particle number.

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[43] One may claim — as the aether interpretation possibly does — that interaction and exchange of particles in fact consists in quanta escaping from the cloud of virtual quanta that makes up a particle.

[44] Experimentally, the most precise measurements have been of the hadronic contents of the photon.

As I explained in section 3.2, there are certain conditions that must be fulfilled for the terms particulars and numerical identity to make sense, and the situation in quantum field theory is related to some of these conditions being fulfilled while others are not. If matter is to have a completely individuating function, it must be comprehensively separated and be linked to extensive quantities. This may be illustrated by linking material points to persistent, well-defined world lines, where the quantity of matter is proportional to the number of world lines.

The separability condition is *not* satisfied in quantum mechanics, and the idea of separate and unique (well-defined) world lines is not valid. The latter point is explicitly commented on by Feynman, who points out that an uncertainty interpretation of quantum mechanics — that the particle *really* took a certain path, but that we do not know which — cannot yield the results of quantum mechanics. Creation and annihilation of particles or quanta also invalidate this idea. With this, we could consider the problem solved: there are no individuals in quantum mechanics, and the particles can at least not be considered individuals, and not even as 'particles' in the ordinary sense — the particles in quantum field theory are nothing but states of the system of quantum fields, and the particle picture is only one of several possible representations (alternatively, we may have an indefinite number of particles).

This, however, is making it too easy for ourselves. Firstly it must be pointed out that the notion of spatially separated particles or states with localised energy and other additive quantum numbers plays an important role also in quantum field theory — for example, such states are the basis of measurements in most high energy experiments, as pointed out in the S matrix interpretation. Secondly, if we only consider fermions, we will find that a number of the above mentioned conditions are, in fact, satisfied. This is not irrelevant, and forms an important basis of the Feynman interpretation.

First it is important to note that only considering fermions does in a sense not represent any significant restriction in the study of the concept of matter. The vast majority of what we somewhat imprecisely can call quantity of matter can be traced back to (approximately) additive quantities associated with elementary fermions (electrons and quarks or nucleons). For many practical purposes it is thus possible to identify 'matter' with fermions. That the fermion number is conserved, and can hence itself be considered a measure of 'quantity of matter', is another reason to study fermions more closely. In practice we will almost always be able to ascribe to the system a certain net fermion number (which is more than can be said for energy) — and even the number of particles and antiparticles of the various species can often be separately taken to be numbers which are definite and conserved. Finally, we have what makes a fermion a fermion: the exclusion principle. This (or the antisymmetry of the state) implies that fermions 'detest' each other, and if the concept of space is extended to also encompass other state variables then the conclusion is that the world lines of fermions are always separated!

This is unfortunately not enough. The properties of fermions makes them easier to imagine as 'real' particles than bosons, but they still have no individuality. This can be illustrated in two ways within the Feynman interpretation.

The first of these concerns the question of whether we can say that the fermions are conserved or not, i.e., whether fermions are created and destroyed (which would make it impossible to talk about a conserved numerical identity). Feynman makes is possible to talk about persistent world lines by giving the particles the ability to go backwards in time.[45] Thus it may also (and does) happen that a particle that originally behaves 'normally' turns and goes backwards in time, 'whereupon' it turns again and continues forward in time. We may intrude and make an observation at a certain point in time, and find two particles (moving forward in time) and one antiparticle (a particle on its way backward in time). If we are to take the interpretation literally, we are forced to conclude that the two particles we saw in fact are (numerically) *the same* particle, and that they are also numerically the same particle as the antiparticle that is observed. In other words: *According to the Feynman interpretation, two particles that are observed at different points in space at the same time, may be one and the same particle.* Two particles which according to ordinary criteria are understood to be numerically different, can be numerically identical, and *will be so if* the two particle at a later time annihilate one another. In this way, whether two particles are numerically identical now depends on what will happen in the future. It is also possible that the entire universe consists of only one particle, whizzing back and forth in time loads of times!

This paradox can only be avoided by admitting that creation and annihilation of fermions in fact occurs, so that it is correct to say that the particles are numerically distinct when we are dealing with macroscopic distances. Only when the distances or time intervals are very small (and in particular when we are not 'watching') is it correct to say that a positron is in fact an electron moving backward in time. But that of course removes the basis for talking about an absolute, material, numerical identity (which does not imply that matter can disappear — the energy of the particles, which can be considered a measure of matter, is transferred to other particles).

My second illustration of the non-individuality of particles is to consider scattering processes involving two or more identical particles. In the Feynman formalism, all possible exchanges of the particles in the final state must be included as equivalent. This is also the case for particles that may have been created during the process, and particles that (at the outset) are far apart. Once a particle is born, all other particles of the same kind must adapt to this and realise that they cannot occupy the same state as the newborn. We may say that all particles of the same kind 'know about' each other or share the same history.[46] So even though we at the outset can identify each fermion with a continuous world line, and even though these world lines will always be separate, we must at the end add together all the possible world lines that link the initial to the final state in such a way that the result is that the particles must take each other into consideration (for example, some processes that would otherwise have been possible, now become impossible). And we do this not out of ignorance, but because this is how the particles *are*.

When can we then talk of individual particles? The answer is, with certain reservations: when the particles are spatially separated. The reservations are that the particles cannot constitute an isolated system prepared in a state where they are not separated, and that we should not consider or study aspects of the system that exclude detailed knowledge of the system (i.e. to the positions of the particles). The first condition is

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[45] He is also forced to insist that e.g. an electron and a neutrino are really different states of the same particle, but this is not of great importance here.

[46] That there is no 'seniority' among the particles is clearly illustrated in the aether interpretation through the claim that the quanta are created and destroyed all the time, and that there is therefore no such thing as a quantum that is not 'newborn'

violated in EPR type situations such as the Aspect experiment, where two particles (photons) are created simultaneously in a total state with a particular symmetry (total spin zero, so that the spins of the particles are equal and opposite). This system is then kept free of external influence, so that the symmetry is not broken until the particles reach the detector (which measures the polarisation of the particles). The second condition is violated in statistical mechanics, where we are interested in studying phenomena due to the statistical behaviour of a large number of particles.

It is crucial to note that the effects of dealing with identical particles become evident when the system is left alone. If we interfer with the system, e.g. by performing a measurement, the system is no longer isolated and an asymmetry can emerge. Firstly we may say that the particles in the system know about not only each other, but also all other particles; and secondly the different particles will have different environments — the variations in the environment mean that the state is changed and depends explicitly on the location. Local effects due to the configuration of nearby particles will dominate the symmetries of what once was an isolated system.

Here we also see the need to squint at the system, and at the same time we see that squinting is unproblematic. If we were to follow the trajectories and states of the particles exactly, we would have great difficulties (the 'trajectory' would consist more and more of points spread quite chaotically, which would be difficult to interpolate), and it would be impossible to consider the system as an observed system in a real sense, since it would not be given the chance to behave 'naturally' — it would never get a chance to become effectively isolated from the observing system. The condition for distinguishing between the observing and the observed system would not be satisfied. But in particle detectors we do in fact see the trajectories of particles with sufficient accuracy to give them individuality, although the resolution is no better than about 0.3–0.5 nm.[47] For high energy particles this is good enough to separate them, and at the same time energy and momentum can be determined with great accuracy.

A final question that must be asked in the context of the problem of identity is, how can particle number be a good quantum number when the conditions for talking of individual particles are not satisfied? The answer is one of two. We can observe phenomena which can be uniquely derived from the existence of a specific number of particles, or we can say that we would find a specific numerg *if* we observed. This will be independent of the details of the system and hence does not depend on the particles being individuals.

One way of understanding the non-individuality and identity of particles in quantum mechanics is (again) to compare with Leibniz' monads. Leibniz denies the existence of such a thing as numerical identity — if two entities are qualitatively identical then they are also numerically identica. He sees time and space as an expression of relations between the monads, and not as something given prior to the individual things. The monads are identified among other things by their history (not by their location in space and time). In quantum mechanics we may say that when the particles are effectively spatially separated, then they are also qualitatively different, since they have different environments and the environments in turn influence the definition of the state. When they are not separated, on the other hand, they have a common history! The difference

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[47] This is the average distance between molecules or atoms in ordinary matter — we observe the ionising effect of the particles.

is that we can have *multiple* particles, even if they are not separated and thus have a common history, and we cannot give them a specific location in space.[48]

It is of course possible to maintain strict numerical identity also at the micro-level, i.e. to say that when we have a specific number of particles, they are all individuals. We may for example introduce forces or potentials of 'fermi' and 'bose' type which can do the same job, or which at least reduce the difference between the two alternative theories to something we currently cannot observe. Such a solution will however have several disadvantages, since we then are forced to reject other cherished assumptions. The locality condition will very likely have to go — the forces will be a strange kind of action at a distance.[49] Moreoever, such a model will appear considerably less 'natural' than the one that is now commonly accepted and follows directly from quantum field theory. To obtain the fermi–bose distinction as a natural outcome without rejecting individuality would probably require a radical break with quantum mechanics, and we currently have not idea of how such an alternative theory would look. It can also be assumed that the incentive for such a revolution would come from somewhere quite different.

4.4 A fresh look at the functions of matter and forces

> 'Even to a hardened theoretical physicist it remains perpetually astonishing that our solid world of trees and stones can be built of quantum fields and nothing else. The quantum field seems far too fluid and insubstantial to be the basic stuff of the universe. Yet we have learned that the laws of quantum mechanics impose their own peculiar rigidity upon the fields they govern, a rigidity which is alien to our intuitive conceptions but which nonetheless effectively holds the earth in place.' *Freeman J. Dyson*[50]

Regardless of how elegant, beautiful and self-consistent a fundamental physical theory is, and regardless of how well it agrees with the experiments that are constructed to test it, it can be considered completely worthless if it does not serve to explain the world we live in. This means that a theory where the essential and operational aspects are intact, but which lacks the constructive aspect, cannot serve as a fundamental physical theory. It should be obvious that if a theory makes our known world and our everyday perception of reality impossible, then something must be wrong with this theory. I would also claim that if it makes the world as we experience it very unlikely, i.e. if 'our world' (of macroscopic objects) cannot broadly follow reasonably naturally from what may be considered essential features of the theory, then it is at best incomplete and at worst useless.

This implies a requirement that it should follow as a natural consequence of quantum field theory (and at least of the Standard Model) that there are rocks, stars, air etc. Our existence should not be a 'miracle' in light of the theory, and the same is the case

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[48] This is a pretty superficial comparison. There has been a great deal of debate about the relation between Leibniz and the quantum mechanical problem of identity.

[49] David Bohm introduced such an action at a distance in an attempt to salvage strict realism in quantum mechanics. However, he eventually saw this as merely a tool to understand the non-locality of quantum mechanics — as a ladder we must throw away when we have climbed up it.

[50] [35], p.64.

for our most basic physical categories. We must be able to reconstruct this without too many additional assumptions (e.g., about the parameters of the theory). It should for example not be the case that our universe could not exist if the fine structure constant α was equal to 1/138 instead of 1/137.03 — unless we can give very good reasons for α having exactly this value.

We may to a certain extent make use of the anthropic principle: the fact that we exist is sufficient explanation. If the laws had made our existence impossible, we could not have had any science about it, since we would not have been there. But the anthropic principle must be used with caution if it is to have any explanatory power at all. It should not be applied to muddle up the distinction between a natural outcome and a miracle, or to suggest that humankind is the purpose of the universe (that the universe is created so that humankind could live in it) — the latter, besides being unscientific, is an expression of an inordinate lack of humility towards the rest of creation. The anthropic principle should also not be used to block further investigations of possible theories. It can be used to show which questions are ill-posed and what kind of questions shoudl be posed. For example, the question, 'How could it be that everything conspired so that intelligent(?) life could emerge just here on earth?', can be refuted by pointing out that this question could have been posed regardless of where in the universe we had lived. On the other hand it is conceivable that investigations of the conditions for intelligent life *per se* show that it is very unlikely that it should emerge anywhere — and in that case our existence is a miracle in light of this (although unlikely does not mean impossible), and if the anthropic principle is now to be employed the temptation is there to assume the possibility of a vast number of universes (which do not contain intelligent life).

The constructive aspect is quite absent in the interpretations of quantum field theory that I presented in section 4.2. That does however not imply that it is trivial or uninteresting. Taking the constructive aspect seriously will ultimately mean justifying all other science (in the sense of grounding the existence of or at least the possibility of all the objects of the rest of science) starting from quantum field theory. It would be necessary to study all of our known world and all our known science to find out on which physical conditions it is based, and then see if these conditions can be naturally satisfied by quantum field theory. This task will probably be out of reach for all the foreseeable future. Studying the conditions for the processes characterising living organisms being physically possible and natural is for example a vast project (not to mention the conditions for *conscious* life, of which we know next to nothing). Here I will focus on illuminating the physical origin of the fundamental categories (thing, matter and force) which I discussed in chapter 3, as well as the conditions for having chemistry. The latter is intimately connected with the conditions for having things in our sense. I will also focus on how quantum field theory explains that things *can* exist *here and now*, and not how they might have been formed. The latter is described for example by Weinberg [24].

4.4.1 Matter

The most importan functions of matter are, as I presented in section 3.2,

- matter is conserved;
- it is located in space and fills it;

- it has an individuating function;
- it is movable;
- it may take on all possible forms.

There should not be any serious problems with the final point. It is hard to accuse the quantum field of lacking flexibility. The number of possible states, with different properties with regard to energy, lifetime, transition amplitudes, etc., appears all but inexhaustible. They are not even tied to a certain character of being in space.

As regards the first point, we can identify not only one, but several quantities that are exactly conserved; the most important one for our understanding of the concept of matter is energy. The exact conservation of energy is in itself not that interesting — at the level of classical physics we think of energy as kinetic energy, potential energy and heat (internal energy), which are not considered forms of 'matter', but rather as something matter can have. It is of much greater importance that energy is concentrated in massive particles, whcih at low energies (in the non-relativistic limit) can be considered stable — they are neither created nor destroyed. If the theory ensures the existence of such particles (preferably massive, stable fermions) then matter can be considered conserved at ordinary temperatures. At high temperature or energy we must instead consider the exactly conserved quantum numbers, but the conservation of matter is in any case unproblematic.

Filling space, movability and individuality require a lot more. The most important condition is that at a certain level it is possible to talk about entities with an internal *structure* — a structure that can only be found in bound states. This structure must be evident and not confined: a confined structure (like the quark structure of hadrons at normal energies) is equivalent to no structure. The importance of structure is perhaps best exhibited by considering an entity at the transition between purely quantum mechanical matter, which does not have the properties above, and classical matter, which has them: an atom.

An atom can for most practical purposes be considered an individual — something with its own 'personality'. This is because its structure allows us to have a continuous knowledge of the position of the atom separate from other atoms as we can have a persistent interaction with the atom without destroying it. This requires us to give up the aim of obtaining a detailed knowledge of the internal structure of the atom and instead consider it a 'woolly object'. The structure of the atom can absorb the changes in its state that might be induced by position measurements or interactions. All this also depends on us considering the atom as an ensemble of states rather than e.g. a single state.

The extension or size of the atom (which is a function of its internal structure) implies that it makes sense to say that it has a well-defined, 'real' position independently of whether we measure its position, and that we effectively can indentify the measured position with the real one. The 'indeterminacy' of the atom itself means that the indeterminacy relations are no hindrance, and we do not need to measure the position *all the time* to determine the path. A completely precise determination is not necessary to distinguish it from other atoms — the atoms naturally keep distances larger than the atomic size and the indeterminacy that follows from the Heisenberg relations. In cases where this does not happen, the atoms are destroyed, either by entering into molecules, or by strong ionisation occurring. In these cases two atoms must be described as a single system.

Before taking a closer look at the transformation of matter or the concept of matter that occurs at the atomic level, I must explain how such a structure is at all possible (and even natural). First of all I must take yet another step back, all the way to the field operators and their states or excitations.

The crucial point in the reconstruction of matter from quantum field theory is the transition from considering (having to consider) the fields as entities to considering individual particles or systems of individual particles which are (potentially) localised. This transition has already been carried out in the Feynman formulation — but, as I have pointed out, this is not adequate for describing or understand all phenomena within the domain of validity of quantum field theory. The transition to a space-time description is essential, both for the operational and the constructive aspect of the theory. This transition can be said to consist in a shift to consider *ensembles of states* as entities. This approach can cast light on both 'elementary particles' and 'composite' entities like atoms.

If we are to consider the particles entities, we cannot think of them as states of the system of fields. An entity must itself be able to be in states, or in other words, it must be capable of undergoing accidental changes. If a particle is identified with one state, it is impossible to distinguish between creation or annihilation and other (accidental) canges. It is also difficult to view multi-particle states as states of several particles. By defining a particle as an ensemble of states satisfying certain conditions (e.g., a definite charge, mass and lifetime, possibly with a certain slack), and noting that multi-particle states (usually) can be constructed from single-particle states, these problems are solved. We may also allow ourselves to view the particle as a continuous existent in space and time. This can be done by allowing it do be in a 'fuzzy' state (with fuzzy values of energy and momentum, but with the energy and momentum densities reasonably localised), and need not worry about quantum mechanical dispersion — it is unneccesary to keep it in a definite statee. It also does not matter if we perform measurements. In general all processes that localise a particle (determine its position relative to surrounding particles or entities) are allowed, since they (in general) will not destroy it as particle. Nor does the particle being dressed cause any problems.

The particles are however structureless — they are described as point particles. We have essentially ended up in the Feynman description. The only changes that are possible here are changes in 'state of motion' (in a generalised sense) — changes that can be taken to be equivalent to a change of coordinates. This also includes things such as change in spin orientation or quark colour.

For an entity to have an internal structure it must be in a *bound state* of several particles (or entities). This means that it must be possible in certain contexts to consider the entity as composite, and to somehow (indirectly) identify the 'parts'.

When it comes to bound states I must admit that my intuitive understanding is better than my conceptual one. In quantum field theory it is not easy to grasp the meaning of the term. Firstly, bound states must be distinguished from dressed particles, and secondly, it must be possible to characterise bound states as a certain type of states of the fields, not just as a combination of particles. Key features are that the state has a (more or less) definite energy, and that it (spontaneously or by additional energy being supplied) may dissociate into a state of two or more free particles. It is also essential that contributions from different 'parts' at different locations in space may be seen e.g. in scattering experiments. However, the particles will have undergone a substantial change when they enter into the bound state — they have completely lost their identity. A real bound state, as opposed to a metastable state or a resonance, is energetically favoured over a state consisting of the free particles. Finally it should be mentioned that also bound states may be considered ensembles of states, both due to their possible motion and (not least) due to the possible existence of excited states.

How naturally bound states emerge from the formalism is also somewhat obscure. However, it seems reasonable, in view of the non-separability feature of quantum mechanics, that a system of interacting fields will have states that cannot (directly) be described in terms of the free modes (particles). Whether such states can be stable and localised will presumably not be immediately evident from the field equations but will depend on the shape of the interaction. We will therefore from now on take this into consideration. We have three kinds of bound states that should appear in the standard theory.

- The first one is the confined (colourless) states of quantum chromodynamics — the hadrons. As bound states they are fairly uninteresting — all signs that they have a structure are effectively hidden at low energies, where they behave as point particles. These states are critically dependent on the group-theoretical aspects of the gauge theory. It is important for the idea of a gauge theory to be of any use that these states can be shown to exist; thereafter they can be considered elementary.[51]

- Next we have the atomic nuclei. The existence of nuclear forces based on exchange of mesons (pions) between nucleons should ideally be derivable from QCD — but this is as yet a pipe-dream. We may qualitatively imagine a mechanism for such meson exchange (as in figure 4.2)[52] but there are no certain indications for this giving rise to attractive forces (binding of nucleons) which do not at the same time 'break down' the nucleons. Even if we were to calculate the probability of the meson processes, this would not be of much help — we would still be trapped in the problems of the 1950s. The existence of atomic nuclei is however (obviously) necessary for the existence of chemistry — which in turn, as we shall see, is necessary for the existence of things.

- Finally we have the electromagnetic bound states, which we have a much better grip on. By performing a certain gauge transform of the electromagnetic field we arrive at *Coulomb gauge*, where the field explicitly splits into an electrostatic part and a part consisting of free waves (photons). In the first approximation the binding energy is given by the electrostatic part.[53] If we have a system containing

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[51] Note also that excited QCD states are typically not considered excited states, but as separate particles or resonances. The reasons for this are in part historical, but are also related to the large differences between different energy levels in bound QCD states, and that they only are created in collisions between particles at high energies, and decay into several particles.

[52] This figure must of course *not* be taken literally; it is merely a schematic illustration of a partial process.

[53] This was the picture introduced by Heisenberg and Pauli and used throughout the 1930s.

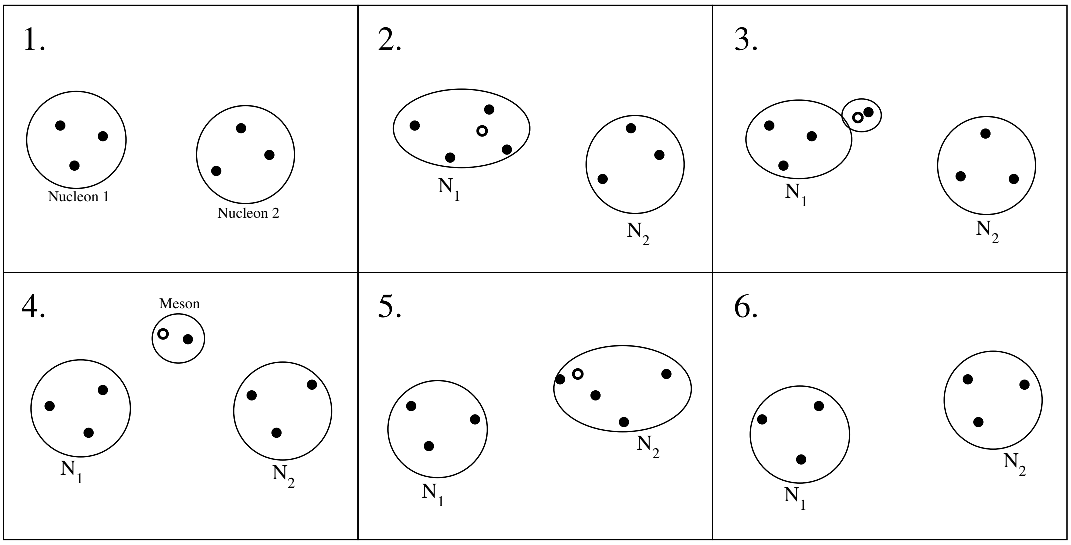

Figure 4.2: Exchange of a meson between two nucleons. The solid dots are quarks, the open circles are antiquarks.

> one very heavy charged particle, this can be considered a static (classical) point charge which hence gives rised to a real electrostatic potential. Then the Dirac equation can be used to compute in the lowest approximation bound states for the system consisting of this heavy particle, matter fields (e.g. electrons) and the electromagnetic field. We have atoms!

A couple of remarks are in place. We have had a certain success in computing electromagnetically bound states of other systems as well. One of the early successes of (renormalised) quantum electrodynamics was positronium — a bound state of $e^+$and e^-. This means we are not limited to the highly asymmetric systems of atomic nuclei and electrons, but the difficulties are greater. It is unclear whether it is possible to 'conjure up' a Coulomb phase also for other gauge fields (e.g. Coulomb gluons?).[54] This would however not serve much other purpose than to make the binding force of the field explicit. The electromagnetic field is actually different from the others: only electromagnetism can give us chemistry as we know it.

For our understanding of the atom it is important to view it as an ensemble of bound states between a nucleus and a number of electrons. Because the atom is an ensemble we can say that it is the same atom when it is excited, and partly also when it is ionised or forms part of molecules. Furthermore we must be aware that the electrons undergo a substantial change when they are incorporated into the atom. (The nucleus will however mostly remain 'itself'.) In an atom it is in principle impossible to distinguish between different individual electrons. What is relevant is the state and the charge density that they together constitute for the atom as a whole.

Atoms are extended objects. This extension is still 'fuzzy' and ill-defined, but marks a clear transformation of the concept of matter. This transformation is based on several

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[54] *Note added in translation:* I am suprised that at the time of writing this I was not aware of the success of the potential model for charmonium.

important requirements, in particular if we are to account for the existence of other elements than hydrogen.

The duality between nuclear and atomic forces is crucial. For heavier atoms than hydrogen to be formed it is necessary to have strong forces binding the nucleons into compact nuclei. At the same time it is necessary that the electrons do not feel these forces. Weinberg writes about this: ‘If the electrons in atoms and molecules could be influencedby nuclear forces, there would not have been any chemistry or crystallography or biology in nature — only nuclear physics!’ [24, p. 153]. Granted, the nuclei have structure and extension, and can to a large extent be considered individuals. With only nuclear forces we could have had a ‘compact body physics’ where nuclei exhibited behaviour similar to Democritean atoms. However, it is not the structure and extension of the nuclei that gives matter structure and extension, and nuclei or Democritean atoms have no capability to form stable, differentiated and extended matter.

It is also essential that it is in fact a Coulomb potential that is responsible for the atomic forces, so that the atoms do not collapse or dissolve. Some slack may be permissible, but a variation of the force with distance departing too much from $1/r^2$ will not do the job. Other values of the electron mass and the elementary charge might however be possible. The chemistry would look somewhat different, and nuclear physics might have a chance of having a greater impact, but we would still have atoms with properties largely like those we know. But we need not worry too much about this as long as we maintain the premise that the fundamental theory is a gauge quantum field theory — the simplest of all gauge groups is the one giving rise to electromagnetism. It is therefore quite natural that our theory would contain this interaction.

For the structure of heavier atoms than hydrogen, the Pauli principle — the fermionic character of electrons — plays a crucial role. This is even more important when we come to chemistry, as we will see.

The extension of the atom implies (or is equivalent to) that within a certain region of space, the structure of the atom is important. Outside this region the structure is ‘invisible’ — the atom may be viewed as a point particle, where some properties (e.g., electric dipole moment) may reveal that it has a structure, but cannot tell us anything about what kind of structure this might be. Within the ‘atomic radius’ the structure reveals itself as a finitely extended charge density (‘electron cloud’) and as something that affects scattering or collisions between atoms. The typical atomic distances in molecules and lattices may also serve either as a definition of the extension or as an indicator of the structure.

This diffuse, quantum mechanical extension, and the quasi-individuality that the atoms acquire at this stage, is sufficient to form a common denominator for all matter. A more clearly defined extension, individuality and mobility which is common for all matter does not exist. From the atomic level on, different kinds of effects are prominent in the constitution of the various kinds of matter — in particular, the aggregate states of matter are constituted in very different ways.

4.4.2 Things

Things, and in general everything consisting of solid material, has a *clearly limited* extension, and can be handled directly (mechanically). For this to be possible requires chemical bonds between the atoms. What in turn makes these possible is the quantum mechanical system of states, the nature of the electromagnetic interaction, and the Pauli principle. On reflection it is not unreasonable that the discrete, stationary quantum states are necessary to provide stability — these give the system a certain level of 'stiffness' (unresponsiveness). A certain amount of energy must be supplied for any change to happen, and the system naturally returns to its ground state if it is disturbed. It has also been shown that electromagnetism, or more precisely the Coulomb force with its $1/r^2$ dependence, is critical — a more slowly decreasing force would lead to collapse, and the same is the case for purely attractive forces.[55] Finally it may be argued that fermionic matter is necessary. Chemistry as we know it has as perhaps its most fundamental precondition that atomic and molecular states are 'filled'; the ideas of vacant states, filled shells, valences, etc., are direct effects of the Pauli principle. It can also be explicity shown as a general result that stable matter is impossible without fermions. In the words of Lévy-Leblond,

> 'In other words, it is the Pauli principle ruling the electrons which ensures the stability of the world ... The specific quantum nature of the Pauli principle thus is a proof of the need for a quantum explanation of the most fundamental aspects of the physical world, namely its consisting of separate pieces of matter with roughly constant density.'[56]

I may add that these conditions for stability are naturally fulfilled as a consequence of quantum field theory. As soon as the existence of atomic nuclei is ensured, no further assumptions are required to show that macroscopic solid matter and things will exist within a certain temperature interval.

It is however not sufficient that we have solids. A condition for our experience of reality is also that there is something material filling the space between the things — a gas phase. The gas phase is also necessary for our surroundings to have a certain continuity, so that there are not for example extreme temperature variations. And of course we depend on the air around us to breathe. The gas is considerably less 'tangible' than solids — its extension, separability, etc. are quite diffuse. The reason we can ascribe such properties to the gas at all is statistical effects: instead of trying to keep track of every single atom or molecule, we look at collections of a large number, and these will in thermal equilibrium and assuming certain external conditions (such as gravity) take up a certain amount of space. Most molecules will also stay in more or less the same region (individuality or separability at large) and on average be moved in the same way by external forces. All of this is quite independent of the details of the interactions and the structure of the atoms; it only requires the existence of relatively stable smallest particles with a certain (but not too strong) degree of interaction. For our experience of the relation between gas and solid it is also essential that the gas particles mostly are repelled by solids.

4.4.3 Forces

The concept of force was perhaps Newton's greatest innovation in physics. In quantum field theory there is not much left of it. We still often talk about 'forces', but they have

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[55] Forces decreasing faster with distance *may* give rise to stable matter.

[56] J.-M.Lévy-Leblond: *Towards a Proper Quantum Theory.* Reproduced in [17], pp. 197–198. References to the original articles may be found here.

little in common with those of Newton, and the language must be considered mostly a relic of the past. It is really more a shorthand for tendencies or transition probabilities which are related to which processes are possible. It is indeed possible to define 'potential' and 'force', but those concepts are not very relevant. The relevance increases when dealing with very heavy particles (which are nonetheless stable) or averaging over a large number of elementary processes. In the case of the electromagnetic field we can also take the limit of large field strengths of source strengths (charges) and large spatial dimensions (wavelengths) and obtain the classical field, with well-defined field strengths. In this level we recover the Newtonian force concept. But we do not find the other forces. Where do they come from?

It could be said that Newton's summarising of a wide range of different forces in one form (Newton's second law, $\vec{F} = d\vec{p}/dt$) contributed to muddling the 'actual reality', where the forces as a matter of fact have very different forms and very different origins. Some forces (in particular chemical forces) were never amenable to the force law. We might say that almost everything in some way or other involves electromagnetic forces or process, but it would be grossly misleading to claim on that basis that the forces can be reduced to electromagnetism. Many of the macroscopic forces would for example not even have existed unless a statistical averaging had been performed.

It turns out that macroscopic forces have very little to do with the 'ultimate forces' of quantum field theory. I will attempt to briefly sketch the origin of these forces. As I tried to explain in section 3.2, the forces as they appear to us may tentatively be divided into three main groupings:

- Mechanical forces (contact forces between bodies or pieces of matter). Naturally, these are closely related to the extension of matter. Here we should strictly speaking distinguish between those resulting from the stiffness of solids (impacts in the proper sense of the word) and the others (pressure and friction), which have a more statistical origin. In particular we may note that viscosity in liquids and gases is an almost purely statistical effect — the same is the case for the elasticity of rubber!

- External, non-mechanical forces. These may be attractive like gravity, repulsive like the electrostatic force between two equal charges, or reorganising like heat. Some of these forces come within the remit of Newton's force law. These are the ones that most require an explanation from quantum field theory and are most sensitive to variations in the theory. In general quantum field theory contains the possibility of coherent states of bosonic fields, which may give rise to forces. The only force that survives from quantum field theory up to large distances is electromagnetism. Howeve, macroscopic electromagnetism does not give us any fundamental categories, although modern, industrialised humans are completely dependent on electrical phenomena. The most important distance force — gravity — is one quantum field theory gives us no clue to understanding.

- Internal forces or spontaneous changes in state. These forces have been more or less 'banned' since the Aristotelian physics (which was based almost exclusively on internal, 'formal' causes) was replaced by Galilean or Newtonian physics. However, they find their way back in; they are typically an expression of the system being in a non-equilibrium states and relaxes towards equilibrium — be it thermodynamic

> (a state with the largest possible entropy) or mechanical (lowest possible energy).[57] Processes within thermodynamics and quantum mechanics or quantum field theory are perhaps better seen as expressions of ‘internal forces’ than of the classical, effective, deterministic ones.

In general it may be said that ‘the law of large numbers’ plays a huge role in generating macroscopic forces, and the details of the microscopic are less important. With a large number of processes at the microlevel incoherent contributions will cancel each other out or give rise to friction, while coherent contributions result in a macroscopic force which looks effective and deterministic. If there is little we can say *a priori* about ultimate matter, there is even less we can say about ultimate force.

Finally I may mention two phenomena which are crucial for our existence and our experience of the world, and which it is difficult or impossible to describe adequately without quantum field theory. The first is the existence of light, which enables us to see. The second is thermal radiation or emission and absorption of radiation, which contributes to our ability to see as well as giving a temperature balance which makes our planet habitable. The thermal radiation from the Sun heats up the Earth, while the atmosphere absorbs much of the Earth’s thermal radiation — the famous greenhouse effect.

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[57] The second law of themodynamics, stating that entropy always increases, may perhaps be interpreted to turn Aristotle’s concept of change as ‘realisation of potentiality’ on its head?

Chapter 5

Future prospects

5.1 Where does quantum field theory stand today?

5.1.1 New theories

The Standard Model is not complete. It prompts too many unanswered questions for that to be the case. It contains a large number (17–26, depending on how you count) of arbitrary parameters, including all masses and coupling constants. The Higgs mechanism has the air of being introduced to 'patch together' everything — it is remarkable that so many parameters are pushed on to the Higgs field, without any explanation for why a field with such properties should exist. It appears unlikely that this field should be fundamental. We may also ask why nature has chosen just the symmetry group that appears in the Standard Model — could this be merely a manifestation of a deeper, more fundamental structure?

In an attempt to answer such questions, and possibly also to bring gravity into the picture, a series of new theories or models have seen the light of day. However, the idea of quantum field theories with gauge symmetries has such a strong position that most new theories have taken this as their starting point. The proposals have then consisted in introducing new symmetry groups (replacing the 'old' ones), new (alternative) symmetry-breaking mechanisms and more particle species (allowing for a new symmetry principle). The individual proposals are mostly only of historical and theoretical interest, and it is unnecessary to discuss them in more detail. Some general features may however be identified.

The first direction to gain popularity was 'grand unified theories' which sought to describe strong and electroweak forces as manifestations of one and the same 'fundamental force' — or, in the language of gauge theories, as subgroups of one symmetry group. The separation of the strong from the electroweak forces would then be due to symmetry breaking with a Higgs type mechanism. This also implies that all our known particles (at least those in the same 'family') are 'related'. The first variant — SU(5) — had the advantages of using a (relatively) simple group, keeping the number of arbitrary parameters low (no more than 22), and all particles in each family were naturally grouped into two multiplets. The disadvantage was that it predicted a lifetime of the proton of 10^{30} years, while experiments have managed to set a lower limit of $> 10^{31}$ years. Later variants became more 'artificial'; they often predicted new particles that have not been found; and one should ask why on earth nature should have chosen such a model — the Standard Model appears more natural. Moreover, all these theories are based on the assumption of 'no new physics' between here and the GUT scale, which is 10^{15} GeV, while today's experiments reach $\sim 10^3$ GeV. That means an extrapolation over 13 orders of magnitude, which must at least be considered a very bold leap.

Other models feature composite Higgs particles, to make the Higgs mechanism appear more natural, or composite quarks and leptons (preon models), to explain the existence of the three families. And then we have the attempts at quantum gravity theories, perhaps in part inspired by the short distance from the GUT scale to the Planck scale (10^{19} GeV), where gravity plays an important role. I will say something about these in section 5.3. None of these theories has been in a position to be experimentally tested.

On a somewhat less ambitious level we also have investigations of the consequences of alternative Higgs models, massive neutrinos and other minor revisions of the Standard Model, with effects that should be observable at 'normal' energies.

5.1.2 The experimental situation

So, what have the experiments contributed? In short, the predictions of the Standard Model are confirmed, and no new physics has been found. The big accelerator experiments have found $W^{\pm}$ and Z^0 with the predicted masses, and their mass ratio agrees well with what the Standard Model Higgs mechanism would imply. The search is now on for evidence for the two missing 'pieces' in the 'puzzle': the top quark and the Higgs boson, but so far the result is negative.[1] The theory gives no direct predictions for the masses of these particles, but some limits exist. There is however some way to go before these limits are reached.

Apart from this there has been a painstaking collecting of data about processes within the Standard Model, with scattering experiments at different energies. Several parameters have been measured with quit high accuracy, and a large number of processes have been studied. This has for the most part not led to any great surprises. The Standard Model has been confirmed here too.

Some years ago there was quite a fuss created when evidence of a fifth force was reported, with a range of a few hundred metres and effect opposite to that of gravity. Several models were proposed to explain this force: scalar fields with different couplings to baryon number, isospin and other quantum numbers. Several experiments were also constructed to attempt to test this effect. These experiments were of a quite different kind than the scattering experiments in the accelerators — a high degree of inventiveness was shown in constructing methods for measuring small differences in gravity in wells, towers, on the sides of mountains, etc. The result was negative: no reliable effect was found.

5.1.3 Non-perturbative QCD etc.

One area where there could be a fertile interplay between theory and experiment is those parts of quantum chromodynamics that do not relate to deep inelastic scatter-

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[1] *Note added in translation:* The top quark was found in 1995, 4 years after this was written. The Higgs, more famously, was confirmed in 2012.

ing and hadron showers. Unfortunately, non-perturbative QCD struggles with finding mathematical methods to compute anything at all. Some qualitative and very uncertain results may be found, but there is not much material to be tested.

One phenomenon that should be expected from QCD is bound states of gluons without any quarks — so-called *glueballs*. These should be able to exist as free particles (but with a very short lifetime), and could give very direct evidence for the validity of quantum chromodynamics — they should leave quite specific 'traces'. There are experiments searching for such effects, but so far no concrete results.

It has also been speculated that there could be a 'phase transition' in systems with extremely large matter or energy density, so that instead of nuclear matter'we were dealing with a 'soup' of quarks and gluons, which because of the large density were asymptotically free — a *quark–gluon plasma*. There are experiments that attempt to find traces of such a phase transition by firing heavy ions at each other. It is also conceivable that this phase transition can occur in neutron stars — i.e., that a kind of star even more compact than neutron stars may exist. Some expected properties of such stars have been calculated.

Non-perturbative QCD is perhaps the greatest challenge the Standard Model faces today. A breakthrough here would be of great importance for our understanding of the theory, while the experiments that are required to test any results need not be insurmountably costly.

5.1.4 Particle physics meets cosmology

One of the most interesting things that has happened over the past 15–20 years is the encounter between particle physics or quantum field theory (the science of the very small) and cosmology (the science of the very large) in the study of the 'birth' of the universe. This has traditionally been considered more an area of religion and metaphysical speculation than serious research. When George Gamow in 1948 proposed his 'Big Bang' theory, based on Einstein's general relativity and the observation that the universe is expanding, he was for the most part not taken seriously. However, in 1965 two radio astronomers discovered by pure chance a completely isotropic 'background radiation' with properties corresponding to thermal radiation with a temperature of 3 K. This radiation could be explained by Gamow's theory, more precisely from the assumption that the universe at a very early stage had a very large energy density and was in thermal equilibrium, and that the cosmic background radiation was a remnant from this age.

According to this model, by following the evolution of the universe in 'reverse', closer and closer to the starting point, we should find ever higher temperatures and energy densities. If we go far enough back the temperature should be high enough that creation and annihilation of particles could occur easily, and quantum field theory would be the correct theory to describe the universe at this time.

If there now are possibilities for observing effects of these early phases in the history of the universe, this would mean that the early universe is a unique 'laboratory' for particle physics. Early in the universe there were energies which cannot be reached in any terrestrial laboratories, and even the most exotic of the new theories can hope for evidence by seeing possible effects of things that happened at these early times. Particle physicists can thus try to go to cosmology to have their theories confirmed or refuted.

Similarly, cosmologists may seek the solutions to their problems in particle physics. Several general features of our universe may depend on what kinds of particles, fields and interactions existed in the early stages of the universe. Such a feature may be the relation between the amount of matter and antimatter in the universe. The fact that space is homogeneous, isotropic and approximately flat, which is a mystery in the 'classic' Big Bang theory, can also be explained in cosmological models that rely to a large extent on quantum field theory. More in-depth presentations of the relation between particle physics and cosmology can be found for example in [24, 25, 42].

5.2 The opportunities and limitations of quantum field theory

Quantum field theory today is based on the concept of quantities (quantum fields) which are defined everywhere in space–time, and which are described by a Lagrangian theory. These fields can have (quantised) excitations, which correspond to physical particles (and more complicated entities). Introducing interactions by postulating a local gauge symmetry has proved fertile, and can now be said to be part of the core of the theory.

In attempting to judge whether future problems of physics can be solved within this conceptual framework we of course run up against the difficulty that we know nothing about what the problems of the future might be. If we did know, we would already be well underway in trying to solve them. It requires a lot of imagination to envisage all the problems that may appear — it often (usually) turns out that the imagination of nature far exceeds that of humankind. Some implicit developments and problems may however be read out of the theory.

As a fundamental physics theory, quantum field theory (or the Standard Model) is quite successful. It encompasses (in principle) all phenomena in the physical universe except gravity, and where it gives clear predictions these agree with observations — sometimes with an astounding level of precision. There are also no confirmed observations of phenomena that cannot be accounted for in the Standard Model or some other gauge field theory. There are still problems with obtaining sensible results for the strong interaction at low energies and making the connection with nuclear physics. This may be simply because we are not yet in possession of the correct mathematical techniques, but it is not inconceivable that there is something about the theory itself that makes solving these problems difficult, even impossible. If this were the case it would be a serious problem — the theory would then lack an important constructive aspect.

Quantum field theory also gives rise to consistent world-views. In some respects these may jar with our everyday understanding of reality, but I would assume that this problem could be resolved — both through the everyday understanding of reality (the content or connotations of the concepts thing, matter and force) undergoing a certain revision, and through the two views being considered complementary, since they deal with different levels of reality. The essence of quantum field theory could therefore, if it survives as a fundamental physical theory, become an integral part of the general consciousness.

The very concept of a quantum field appears to be flexible enough to encompass most of what can be observed at the subatomic level (at least with the observational methods we know of), although there may quite conceivably be phenomena that cannot be adequately described using this concept. I consider it a reasonable assumption that if or when we are forced to reject quantum field theory, other principles which have been considered central will also be jettisoned. This can possibly be illustrated by pointing out that there is a theory or research programme which views itself as an alternative to quantum field theory, namely S matrix theory. To a certain extent it exhibits a greater level of flexibility, which is related to its rejection of the principles of locality and microcausality as featured in quantum field theory.

There is one inherent inconsistency in the theory as of today, in my opinion: the quantities 'bare particle' and 'free field' still appear. These are entities which are defined such that they strictly speaking do not exist (since they cannot have any effects), and after renormalisation they are replaced by 'dressed' quantities, which are the relevant ones. It would be an advantage, I believe, if we could find a way of avoiding these quantities. The conceptual basis for such a revision is already present in the aether interpretation and the S matrix intepretation. This would automatically solve the problem of renormalisation, and could perhaps also help in the development of non-perturbative methods. I believe the concept of quantum fields would survive such a revision, even though the formulation would be different.

An open question is whether we really have hit upon something fundamental in gauge theories. The basis for judging this is not overwhelming: 2 interactions (electroweak and strong), where our knowledge of one (strong) is still quite poor. That these can be described as gauge theories may well be a coincidence; it may well be that new interactions and particles will be found that cannot (or can only with great difficulty) be fitted into a gauge theory. On the other hand it is conceivable that more gauge interactions will be found at higher energies. The concept of gauge invariance gives quite clear guidelines for extending the theory as it stands: both by placing strong restrictions on the shape of the theory and at the same time by suggesting possible new interactions and groupings of particles. There are two important reasons for wanting to keep these concepts. Firstly, all the properties of the interaction may be derived from a symmetry principle, and secondly, all gauge theories are renormalisable. If the gauge principle were to turn out not to be generally applicable, it would result in a crisis for the theory, in particular unless something had happened with the problem of renormalisation in the meantime.

If new interactions are discovered at higher energies, and these also can be described by gauge theories, then this will of course give greater confidence that gauge field theories have hit upon a fundamental aspect of reality. This will however give rise to two new challenges, which are already present now, but cannot then be avoided.

The first is of a more philosophical, not to say purely speculative, nature: What is it that makes gauge symmetries so fundamental? Most symmetries we know of are fairly intuitive and refer to operations we can perform (or imagine) — for example repeating an experiment at a different time, with the apparatus in motion with constant velocity, or with particles and antiparticles exchanged. This is even the case for the abstract coordinate transforms of general relativity: we may imagine accelerating our system or reparametrising space. Gauge transformations, however, are in their totality operations on abstract quantities (field operators) in an abstract mathematical space (the representation space of a Lie algebra). There is no way we can physically perform or imagine these transformations. It appears like a glimpse of a hidden structure. What kind of structure is that? One suggestion (Kaluza–Klein theories) is that gauge symmetries reflect the symmetries of ‘hidden’ spatial dimensions (dimensions beyond the four we know).

The second question is much better suited to research and theory formation. If there are several interactions which originate from different gauge groups it appears unnatural to postulate all these as fundamental features of nature. Why should nature have chosen just these groups, and no other ones? It is possible to try to derive them from one larger, more fundamental, group with a broken symmetry (as in grand unified theories), but this group will necessarily be more complicated and less natural, and the Higgs mechanism (or whatever caused the symmetry breaking) would also be very complicated. The question would then arise: why has nature chosen just this group and this symmetry breaking? There is thus no way around the problem of trying to give a dynamic explanation for the origin of the different gauge groups. This requires a new level, behind the gauge groups, where these groups emerge as states or similar. We have now reached a pretty high level of abstraction: from the individual particles we have gone to quantum fields describing particle species. From there we have abstracted to the gauge groups describing the symmetries of the fields, and from there again to something underlying those…

Another challenge that is known and which is being worked on is quantum gravity. The theory is not complete until it at least also encompasses gravity. I assume that this involves a limit to the validity of the theory — that a fundamental revision of the conceptual framework (and hence also of the implicit ontology) will be necessary to include gravity. We are however far from having any empirical basis for any statements about this (unless cosmology can give us some hints). This means it may take a long time before there is any breakthrough. I will say a bit more about this in the next section.

There may be a certain amount of frustration that nothing much ‘happens’ in quantum field theory nowadays. It is not clear that there is anything wrong with that. It may be a good thing for quantum field theory to be ‘normal science’ for a while, so that the main effort in research is on exploring the consequences of the theory, collecting new data and (possibly) developing new mathematical techniques and formulations, rather than on groundbreaking theories and prestigious experiments. Such ‘normal research’ would be a positive and fertile field within any theory, and will also provide opportunities for consolidating the theory. We cannot expect that there will always be new, revolutionary discoveries — although we have been a bit spoilt in this respect in the twentieth century. It is moreover not unreasonable to assume that any breakthrough will be built on painstaking work on the theory over a long time — that it might for example be more important to have a large amount of precise data and a thorough knowledge of various formalisms than experiments at higher energies. The breakthrough may also come from a completely unexpected corner, far from what one might have thought of today.

5.3 Theories of everything

5.3.1 What is a 'theory of everything'?

Physics has as its aim (as I said in section 3.4) to give a unified explanation and description of nature, i.e. a theory which in principle should be able to explain *all* phenomena in the world. This is an aim to strive for (a regulative aim for physics), regardless of whether it is achievable. It is this ambition for an all-encompassing theory, or a theory that does not assume any underlying theory or underlying level, which distinguishes physics from all other disciplines, with the possible exception of psychology. A 'final' theory, which encompasses all (physical) phenomena, may be called a *theory of everything* (TOE). It will of course be subject to the limitations I described in section 3.4 (theories at different levels are complementary), and will hence in no way replace previous theories or the other sciences. It will however form a kind of 'ontological basis' for at least all sciences dealing with the inanimate part of the world.

Postulating something as a TOE requires a good portion of self-confidence, and is obviously not something that is done willy-nilly. It is not sufficient that the theory encompasses all phenomena that are known at the time it is put forward. The basic principles of the theory must be simple and natural and should not give rise to further questions — the theory must be philosophically satisfactory (or have the potential to become so). Moreover there must be very good reasons for claiming that qualitatively new phenomena will not be discovered.[2] To believe that a TOE can be found (and even more so to claim that one has already found it) is really an expression of a rationalist view of nature and science: that nature (the things in themselves) follow a set of rational principles, which we are capable of knowing and perhaps discovering by way of reasoning. This view goes well beyond what is implied by the regulative principle of seeking a TOE, and later on I will argue that it is very doubtful whether such a view is defensible to begin with.

There are some reasons to expect that a TOE may be found, and that it is possible to guess what it would look like. Today we have two theories which together describe (in principle) all known physical phenomena: the Standard Model of quantum field theory, and general relativity (the theory of gravity). It therefore does not seem unreasonable to assume that if we succeeded in constructing a theory that unified these, this would be a TOE. There is also a scale which there are good reasons to believe is fundamental, so that all natural phenomena can be explained in terms of phenomena at this scale. If we combine three constants of nature: Planck's constant $\hbar$ (from quantum mechanics), the speed of light c (from relativity), and Newton's gravitational constant G (from general relativity), we get the *Planck units*:

$$\begin{array}{lrr} \text{The Planck length} & \ell_{Pl} = \sqrt{G\hbar/c^3} & = 4,05 \cdot 10^{-35}\text{m} \\ \text{The Planck time} & t_{Pl} = \sqrt{G\hbar/c^5} & \sim 10^{-43}\text{s} \\ \text{The Planck mass} & M_{Pl} = \sqrt{\hbar/Gc} & \sim 10^{-5}\text{g} \sim 10^{19}\text{GeV}/c^2 \end{array}$$

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[2] There are several examples where it was believed that a TOE had been found or was around the corner — only for completely new and unexpected phenomena to be discovered shortly after. For example, 100 years ago many people thought that the end of physics was near…

What might occur beyond this scale can be assumed to be irrelevant, or may be in principle unknowable — or it is conceivable that there simply is nothing beyond the Planck scale: it constituetes the 'absolute' dimensions of the world, just as there are no speeds greater than the speed of light or temperatures below absolute zero.

5.3.2 Proposed theories

Quantum gravity

As mentioned in section 5.1, quite soon after quantum field theory had restored its status people started working on theories for quantum gravity, which could possibly be candidates for theories of everything. A number of models were proposed during the 1970s and 1980s. Here is a short summary.

First came the idea of supersymmetry — at about the same time as the Standard Model was designed. This introduces a symmetry between fermions and bosons, so that they can be transformed into one another. This would imply that for every particle there is a 'sparticle' with opposite statistics, i.e., a doubling of the number of particles — something that need not be too bad if there is a good reason and it is possible to 'explain away' the unobserved particles. If supersymmetry is made into a gauge theory we get *supergravity* — a gravity-like field appears naturally. Independently of these theories there was a renewed interest in *Kaluza–Klein theories.* These had been proposed by Kaluza and Klein in the 1920s, as a way of unifying electromagnetism and gravity. This could be done by giving space 5 dimensions and identifying the geometry of the 5th dimension with the electromagnetic field. Introducing even more space dimensions should make it possible to fit in the 'new' gauge fields, at the same time as spontaneous symmetry breaking at the Planck scale could 'curl up' or 'hide away' the extra dimensions at our energies. Combining supergravity and Kaluza–Klein theory resulted in *extended supergravity*, where preon ideas could be recovered and exploited. All this was and remains a paradise for any lover of abstract mathematics — but the experimental evidence is pretty absent.

Superstrings

According to superstring theory the fundamental physical entities are not particles, but *strings*, i.e. 1-dimensional objects. String theory was originally proposed around 1970 as an attempt to describe hadrons (as vibrational states of the strings), but was abandoned partly because it predicted some unwanted massless particles. It was discovered much later by Green and Schwarz that these massless particles were very similar to photons and gravitons (gravitational quanta), and if string models were used to describe all elementary particles this naturally gave rise to a theory of quantum gravity.

If this had been the only advantage of the theory, it would perhaps not have become so popular — theories of quantum gravity existed already. But it also turned out that the theory was nearly inconsistent — one had very little choice in designing the theory. For example, it predicted which gauge groups would be present — the vast majority of gauge groups would give an inconsistent theory. In general the hope was that there would only be one consistent string theory — given the requirement that the theory of everything would be a string theory, everything else would follow. This is close to

Einstein's aims for the last 30 years of his working life: a unified theory of all interactions, based exclusively on principles of consistency.

String theory cannot be consistent in 4-dimensional space. The simplest superstring model required 25 space dimensions and 1 time dimension; if interactions were also included the requirement became 10 dimensions. The hope would then be that the 6 unknown dimensions were 'curled up' as in Kaluza–Klein theories, without having any specific mechanism for this. It has also proved difficult to obtain any results from the theory with any connection to the energy levels we have reached experimentally — to try to derive our known physics (the Standard Model) from string theory requires quite a lot of arbitrary parameters to be added. It also turns out that there are several possible string models, destroying the hope of finding a TOE by only requiring consistency. But superstrings is still an active area of research — it is at least a possible model of reality at the Planck scale, and the only consistent way of quantising gravity that is known so far.[3]

Random dynamics

The random dynamics programme, proposed by Holger Bech Nielsen, has a completely different starting point from string theory. Where string theorists claimed that God had no choice regarding the fundamental theory, random dynamics asserts that God could choose whatever He wanted — as long as it was complicated enough. Fundamental physics can be completely arbitrary or chaotic, or there may simply not be any fundamental theory. The aim was then to show that our known physics emerges as a natural consequence — that almost regardless of what kind of complicated model is chosen for 'fundamental' physics, the Standard Model and general relativity will emerge at lower energies. In other words, the physics we know is very insensitive to changes at the Planck scale. This happens in many other fields. I have pointed out that macroscopic forces (with two or three exceptions) have very little connection to the microscopic ones. Chemistry does not depend on the details of nuclear physics (only that nuclei exist), and very much of biology can be explained just by the principle of evolution. Similarly, of all the effects occurring at the Planck scale, only a few will 'survive' to our energies.

In practice it is obviously not possible to deal with random theories. What is done instead is taking various sufficiently complicated models and allowing the parameters to be varied stochastically. What can be shown to be the case for all these models can be said to be a reasonable outcome of random dynamics. For example it can be shown that gauge theories can emerge naturally from theories without gauge symmetry — and only gauge theories will 'survive' to lower energies. Of all possible gauge theories it is the simplest that will survive the longest, and these are the ones we see in the Standard Model. One has therefore 'explained' both why nature has a liking for gauge symmetries and given a dynamical explanation for the gauge groups of the Standard Model. Whether random dynamics should be called a TOE or an anti-TOE can be a matter of taste …

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[3] — and illustrates how exotic physical theories can become at levels far from our own.

5.3.3 Critique of theories of everything

There are several reasons to be very sceptical towards any proposals for 'theories of everything'. Usually it can be asserted at the outset that the proposal is premature: it implies an attempt at formulating general principles for an area we still know very little about. For example, string theory and all other attempts at putting forward principles for physics at the Planck level suffer from a serious lack of empirical evidence — there is even less to go by than Einstein had when he proposed general relativity in 1915.[4] It turns out time and time again that the imagination of nature far surpasses ours — there are far more possibilities for how matter can behave than we had thought of. Either nature refuses to obey our principles, or it follows these principles but they are far from sufficient to cover all that happens in nature.

There is also a case to be made against the very possibility of a TOE. If we start from the fact that humans are finite beings, it is not natural to assume that we should have the capability of grasping the behaviour of all of (infinite) nature. Firstly, we have no reason to believe that the behaviour of nature can be summarised in a finite number of principles. Secondly, even if it could it does not follow that these principles are of such a kind that we can grasp them — that would imply that our consciousness has a very special status, or that nature is very 'kind'.

There are a couple of things to note regarding the theories we formulate. We cannot pick concepts without restriction when constructing the theories — the concepts must necessarily be ones that we know of already, concepts that we have constructed and which originate from something known. All our concepts of the world thus have a certain character of anthropomorphism — we are bound by our concepts of understanding.[5] To adapt the world to our (available) concepts we must perform a certain idealisation.[6] When we describe phenomena at a deeper level of nature we try to rid ourselves as much as possible of these anthropomorphic idealisations and be guided instead by 'pure' observations. But, since our concepts can never be completely rid of anthropomorphisms, and since merely distinguishing between the observing and observed system is a (necessary) idealisation — and (not least) because of the 'reverse requirements' of our experience discussed in section 3.4, this aim can never be fully achieved. It may also be said that in physics we seek the things in themselves[7] — but they will always evade our concepts of understanding.

A third reason to be sceptical towards all proposals for TOEs is of a more ideological kind. If a TOE were to be found this would (eventually) put an end to basic research in physics. Within at least one area of human intellectual pursuit we would have reached a final stage where nothing happened any more. To me, this — that history (even within one field) should come to an end — seems implausible. We may also ask whether

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[4] He had both the perihelion precession of Mercury and the idea of testing the bending of light around the Sun.

[5] Although I have here chosen a form of words which is close that of Kant, it is not intended to be taken as a 'correct' interpretation of Kant. Rather, I have used Kant's starting point and conceptual framework and adapted it to what I wish to express here.

[6] There is nothing wrong with this. Idealisations are necessary to have a concept of the world. Some can be taken to be constitutive for our experience, such as the concept of things.

[7] A TOE can be considered a theory of the things in themselves, since it gives a complete description of the behaviour of everything in the world and of 'ultimate reality'. There is nothing beyond the TOE.

humanity for ever after[8] will be content with what is claimed to be the final theory, or whether there will not be speculation about why just this theory holds — is there more behind it? A last question may be whether it is at all desirable that a TOE is found. These questions take us into the next and final section, where much of the content is based on the reflections in Wigner's article [29].

5.4 The future of physics

There are two important criteria for a physical theory to be good, besides agreeing with observations. It should be philosophically satisfactory (simple, beautiful and comprehensible), and it should be fertile (give a good foundation for further research). These two criteria are mutually contradictory. If a theory is very satisfactory (and has a closed form) it gives little inspiration for further research (and does not give much of an idea for where to investigate), and conversely, if a theory has many loose ends it feels unsatisfactory — an 'ugly' theory. Aristotle's physics was very satisfactory, and obstructed research for 1000 years. The optimally satisfactory theory is the theory of everything, which bars all further research. I have presented reasons for doubting that a theory of everything will ever be found, and I also do not consider it desirable that physics should die in this way. On the other hand it is hard to imagine that physics will continue to evolve forever, at the same speed as now or with increasing speed, always pushing the frontiers, and still keep its interest. What then will happen to physics?

There is one tendency which is worth noting in this context: physics (and science in general) is becoming ever larger and less transparent. It is impossible for one person to have an overview of all areas of theoretical physics (not to mention experimental physics); it requires a substantial effort to be sufficiently acquainted with a small field to conduct research and move the frontiers of knowledge within this field. And the experiments required to collect qualitatively new data or test the groundbreaking theories are becoming ever larger and more costly — the big accelerators gobble up billions, and the groups working in these experiments count hundreds of people. If this development continues it will be suicidal for physics — few if anyone will be interested in putting in such a big effort in order to perhaps shift the frontiers a tiny bit in a small area.

I can imagine three scenarios for physics in the long term.

1. A theory of everything is found. This can of course not be completely excluded. If so, it means the end of physics. For a while people will work on finding consequences of the theory, and a certain amount of dissemination will happen, but after a while the theory will be transformed into a rigid and dogmatic ontology. Only those parts of physics which are of technological interest will survive. Active research will be diverted into other fields.

2. A final theory is not found, but the frontiers of physics become more and more inaccessible, and the interest in physics will gradually decrease in favour of other sciences and completely different intellectual pursuits. A long time later physics may experience a renaissance — possibly with completely new approaches to the problems — or it may go into cold storage until humans become extinct. We

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[8] Well, humans are going to die out some time, so it is in any case a finite period of time.

may imagine that the knowledge that has been obtained will be completely lost, since it requires a big effort just to maintain it. But we may also imagine that since the interest will only gradually abate there will be time to process the insights that have been obtained and extract the philosophical or conceptual essence of the theory that has been arrived at. Physics will once more be absorbed by philosophy. This is not the worst that could happen.

3. The most optimistic scenario is that physics remains an active area of research. Interest may move between different areas of physics, and there will not always be revolutionary discoveries, but some interesting things will always be happening. This requires that the frontiers of physics do not become more inaccessible. One way for this to happen is that the science is 'slimmed down' — only the knowledge that is required to reach the frontiers is taught. There may also be increased specialisation, so that each researcher has a full overview only of their own small field, and is completely dependent on others for knowledge beyond this. This may give good collaboration within research, but will naturally hinder creativity. Another requirement is that experiments do not become more costly. This is likely to require a somewhat lower level of ambition than today.

Regardless of what happens, I do not think physics will completely lose its interest — the question is whether it takes the form of dogmatics, philosophical reflection, or active research. After all, fundamental physics touches on a core existential question, which I assume will be asked for as long as humans will exist: What kind of world do we really live in?

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