

Piotr Żenczykowski

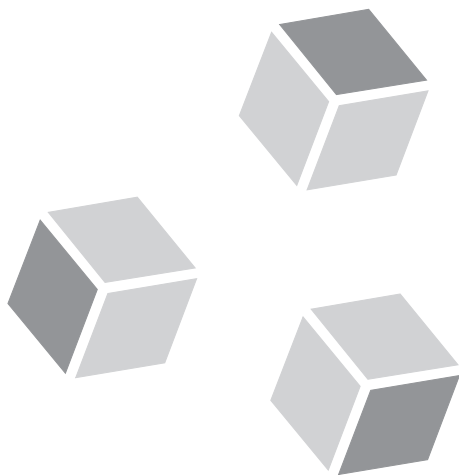
ELEMENTARY PARTICLES AND EMERGENT PHASE SPACE



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Printed in Singapore

To Dorota,
my friend and wife

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Preface

The ideas underlying this book have gradually developed over the past thirty years. At their beginnings, in the early 1980s, the Standard Model of elementary particles was already well defined and various proposals as to the roots of the observed pattern of leptons and tricolored quarks were made. Among them was the idea to generate the three-valued-color degree of freedom from the triplicity apparent in the octonion algebra. Given the important role played in the physics of elementary particles by both complex numbers and quaternions (in the form of Pauli matrices), the extension from quaternions to octonions (the next set of hypercomplex numbers) seemed very attractive. Despite that appeal, one could think of at least two problems associated with the applicability of octonions to the description of quarks. The first concern was the apparent lack of a macroscopic physical meaning that could be assigned to octonions in much the same way as complex numbers and quaternions may be related to rotations in two and three spatial dimensions. The other issue was the nonassociativity of octonions that pointed far beyond the standard formalisms.

Driven by an unwavering belief in the necessity of a conceptual connection to some macroscopic classical space, and the fact that an octonion is constructed as an ordered pair of quaternions, in the mid-1980s I became deeply convinced that the three-dimensional macroscopic arena needs to be extended to six dimensions, and that the most natural and economical way to do this would be by associating the two quaternions with the momentum and position spaces. The problem then remained what to do with the nonassociativity, an issue I kept turning over in my head for nearly two decades. Realizing the rather primitive nature of my attempts, I managed to overcome the urge to follow the nonassociative octonion route, while leaving untouched the belief in the need to connect the triplicity of quarks with the symmetries of 6D phase space.

Then, in the first decade of the new millenium Edward Kapuścik had the pivotal idea of launching *The Old and New Concepts of Physics*, an open-dialogue journal intended for the presentation of controversial papers. By publishing the critical comments of the referees alongside the original papers, the editor was expecting to generate constructive discussions and spur unorthodox ideas. The formula of the journal made it ideal for soliciting a response to my phase-space conceptions. I put them together in an ‘as is’ form, hoping that the ideas presented there might inspire some deeper thinking on the part of a couple of the most involved readers. Despite the paper’s various shortcomings, the referee’s reaction was very reassuring, thus strongly supporting my feeling that the general idea of relating the nature of quarks to phase-space symmetries would be really worth pursuing. An important bonus from the publication itself was that it helped clarify my thoughts, pointing at the next steps to be taken. This resulted in two papers published in 2007 in *Acta Physica Polonica B*, and in a *Physics Letters B* article of 2008.

Apart from the positive review received from Andrzej Horzela, I am very indebted to Matej Pavšic for his encouraging opinion on my phase-space conceptions and for his endorsement of the *Physics Letters B* paper on the arXiv. I would also like to thank Igor Kanatchikov, Ettore Minguzzi, and Enrico Prati whom I met during the DICE2008 conference. Their keen interest not only helped strengthen my belief in the idea, but must have also greatly contributed to its further dissemination. I should thank David R. Finkelstein as well for his email written to me in early 2010, which significantly boosted my confidence in the importance of my conceptual arguments. I am grateful to Andrew Beckwith whom I met during the DICE2010 conference and whose initiative triggered my decision to write this book. Finally, I should thank my family for their encouragement and support.

It goes without saying that any deficiencies of the book are to be blamed solely on the author. Still, it is my sincere hope that some readers will not only buy the book but also buy into its unorthodox ideas and perhaps develop them further.

P. Ź.

June 2013

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Chapter 1

Introduction

Elementary particles are nowadays perceived via the picture provided by the Standard Model. A well-known general message is that this model is consistent with all the experimental data gathered so far. Yet, while the Standard Model is undeniably extremely successful in providing a satisfactory description of many aspects of physical reality, it also contains several features that still call for an explanation and indicate that a deeper layer of description is needed. The pursuit of such a deeper explanation, often dubbed ‘new physics’, underlies many current cutting-edge research programmes.

The very definition of the frontier of knowledge is that there are no established routes beyond it. Still, in order to move rationally in that *terra incognita* we need proper guidance. To get it we usually apply the ideas that proved successful earlier in somewhat similar situations. Unfortunately, those ideas may lead us astray, especially if the situation we are facing is not really similar to the old ones. In other words, the more we are at the edge, the wider the spectrum of open possibilities, and — consequently — the more likely it is that our old ideas actually become a hindrance, and that in our attempts to move forward we will be misled by the explicitly or implicitly adopted old philosophy of ours.

This seems to be the situation in which we are at present, with the very successful but essentially closed theory of the Standard Model, and with no generally accepted hints on how to proceed beyond it. In order to make progress we probably need to look back into the conceptual roots of our theories, and then analyze and broaden their philosophical basis. Only a significant change in that basis may provide some ground for a truly *new* physics.

Consequently, any deeper proposal on how to move outside of the safe haven of the Standard Model should start from a sufficiently profound physico-philosophical discussion. Thus, this is where we begin. Carrying such a discussion is all the more important since the philosophical backgrounds of the contemporary theories of elementary particles and gravity are mutually incompatible, with the roots of these incompatibilities already present in the philosophy of ancient Greece. Clearly, one should suggest some philosophical resolution of these incompatibilities and form a coherent tentative ontology before actually proposing a more specific physical approach.

With our goal originally defined as the deepening of our understanding of the microworld, we have to clarify first what we accept as a satisfactory understanding and explanation. What we write on this subject is nothing really new: it has been said on many occasions by various well-known physicists and philosophers. Yet, as their insights provide the indispensable background for our further arguments, and since these insights are often not fully appreciated — in many cases to the point of being completely ignored — we consider it very important to recall them. For similar reasons, we find it also appropriate to discuss the relative placement of our theories and explanations, both among themselves and with respect to physical reality. A proper understanding of this point is a prerequisite for deciding later on the acceptability of the approach proposed herein.

Since a coherent ontology must cover *all* aspects of experience, it should place the world of elementary particles alongside the macroworld and other aspects of experienced reality. In other words, while seeking explanations for the world of elementary particles, we have to keep in mind an essential unity of reality, and thus the unity of micro- and macro-worlds in particular. Consequently, various types of hints and arguments, often not classified as typically ‘physical’, should in fact be admitted in our considerations, at least as an important background.

This book is meant to propose a general direction that — as the author believes — should be considered among the attractive routes which research on the ‘origin of the Standard Model’ should take, to substantiate the main idea with several arguments, and to present a few simple but very encouraging results that have been obtained so far. The hope is that they will appeal to the readers and motivate at least some of them to propose new and (presumably) far more mathematically sophisticated ideas in the general direction set forward here.

We start our arguments by providing in Part 1 the physico-philosophical background that will be needed later. Since the author is a particle physicist, and since our main topic is physics, the philosophical aspects will be discussed only as far as it is important for our purposes. The first chapter of that part is fairly general and deals with the issue of language, the meaning of the concept of explanation, and the proper way of thinking about our theories. The next chapter is more physical, as it is concerned with the concepts of space and time, and with their treatment in both the classical and quantum descriptions. It discusses the tension that exists between relativity and quantum physics, and is intended to question the adequacy and the range of applicability of our intuitive macroscopic spacetime-based description of reality that forms a part of the basis of the Standard Model. Then, as a step to a possible conceptual resolution of problems brought about by this tension, the general idea of macroscopic spacetime ‘emerging’ from the underlying purely quantum layer is introduced. Chapter 4 focuses on the more specific issue of ‘emergent time’. It is argued there that time should be viewed as a measure of change, or — equivalently — be derived from it. In other words, space and time should be considered as concepts logically posterior to matter and its change. The wish to treat them symmetrically fits then well into a philosophical view, known as process philosophy, according to which permanence and change, being and becoming should enter on equal footing into our description of reality. Alternatively, process philosophy may be viewed as an argument that, by assigning to being and becoming a similar ontological weight, requires their maximally symmetric treatment in the language of physics.

Part 2 describes the situation from the point of view provided by the Standard Model itself and the subparticle paradigm on which it is based. Chapter 5 briefly presents the most relevant features of this model. Questions pertaining to the origin of Standard Model symmetries are raised, and an important attempt to answer some of these questions in terms of yet another, deeper level of subparticles is described. A separate issue about which the Standard Model does not have much to say, namely the problem of mass, is discussed in more detail in Chap. 6. There, the widely-used concepts of the so-called current and constituent quark masses are introduced, and their meaning is thoroughly discussed. The aim of these discussions is to separate what is known quite well about these masses from what is essentially merely imagined and believed, especially in connection with the idea of quark propagation in background space. Chapter 7 discusses a specific electroweak hadron-decay process which explicitly demonstrates the

inapplicability of standard ideas about quark mass and quark propagation. In Chap. 8, with the results of the previous discussions kept in mind, we are led to question the suitability of the standard spacetime description of hadronic interior, and argue in favor of the applicability of the idea of emergent spacetime at the quark/hadron interface, in agreement with earlier views of several distinguished physicists. We stress right here that such a conception of physical reality is not inconsistent with what we know about quarks from experiment and from their field-theoretic description within the Standard Model.

In Part 3 we present our main proposal suggesting a close connection between the symmetries of the Standard Model and those of nonrelativistic phase space. The approach, which originally followed from the desire to treat position and momentum in a maximally symmetric way possible, is supported (sometimes only implicitly) with the arguments presented in Parts 1 and 2. In particular, positions and momenta are seen as physical concepts corresponding to the more philosophical notions of permanence and change. First, in Chap. 9, a heuristic discussion of phase-space symmetries and their possible relevance to a generalization of the concept of mass is given. Then, in Chap. 10, the idea of the unity of the micro- and macro-worlds is formulated in a more technical language, and shown to lead to an explanation of the salient features of elementary particles as they are built into the Standard Model. Chapters 10 and 11 show that, if one accepts the main premises of the phase-space view, the subparticle paradigm underlying our search for the fundamental constituents of matter should be reinterpreted. For the Standard Model itself, such a reinterpretation would be of a fairly mild nature, affecting mainly our understanding of the concept of quark mass, or — more precisely — the link between the concept of quark mass and the concept of quark propagation. On the other hand, the explanation of the Standard Model symmetry structure in terms of yet another level of subparticles, as discussed in Part 2, requires such a drastic change in the meaning of the concept of division that the very subparticle paradigm becomes totally inapplicable. In Chap. 12 a more technical discussion of the generalized concept of mass is given. The last chapter contains an overview of all the main issues discussed throughout the whole text and a brief outlook.

PART 1

PHILOSOPHY AND PHYSICS

“There is no such thing as philosophy-free science; there is only science whose philosophical baggage is taken on board without examination.”

Daniel Dennett [36]

Chapter 2

Reality and Its Description

The goal of most physicists is to provide us with a deeper understanding of the world we live in, of the physical reality conceived as being ‘out there’. In order to move forward along this road we must convey our ideas to others. The impact of this transfer of ideas cannot be overestimated: the improvements in the methods of conveying information were among the decisive factors which kept boosting the development of our civilization. The first of these factors is our language itself, the language of ordinary life. Science depends on it very heavily, as all its concepts have to be expressed in it. Indeed, Niels Bohr said (as quoted in Ref. [135]):

“What is it that we human beings ultimately depend on? We depend on our words... Our task is to communicate experience and ideas to others.”

It is therefore appropriate to begin with a brief discussion of the role of language and a commentary on the way in which it is used here.

2.1 The Language Factor

The language of ordinary life evolved first of all to enable the communication of facts vital to our survival. Its form involves a trade-off between the accuracy and speed of information transfer. The relation of natural language to the surrounding classical world is therefore necessarily rough and imprecise. The language of science cannot be but its extension and refinement. It must use the words of natural language, which are often fairly ambiguous, and it defines additional words with their help. The scientific description of the world, being necessarily given within a derivative of natural language, is therefore inevitably and incurably approximate. This is so

even if it is formulated in a precise mathematical fashion, since the issues of meaning are then transferred to its very assumptions (see e.g. Ref. [84] for a related discussion given by Werner Heisenberg in the context of classical physics). For this reason (as well as others), we do not really know how well our scientific description fits physical reality, even if it were to agree with all of our experiments. Indeed, Heisenberg said [79]:

“Words have no well-defined meaning. We can sometimes by axioms give a precise meaning to words, but still we never know how these precise words correspond to reality, whether they fit reality or not. We cannot help the fundamental situation — that words are meant as a connection between reality and ourselves — but we can never know how well these words or concepts fit reality.”

Actually, the situation may be considered even worse, for — as Niels Bohr stressed [135] —

“we are suspended in language in such a way that we cannot say what is up and what is down.”

Niels Bohr’s positivistic inclinations forced him into a position more radical than Heisenberg’s, essentially banning the ontological issues from the subject of physics and, consequently, stressing the crucial role of language even further [135]:

“It is wrong to think that the task of physics is to find out about how nature is. Physics concerns what we can say about nature.”

Clearly, therefore, independently of whether the goal of physics is to be understood à la Heisenberg, or à la Niels Bohr, it depends on our natural language in an absolutely essential way.

To make things more complicated, we have not just one language of ordinary life, but a multitude of them. Since the outside world is reflected in those languages only in an imprecise and fuzzy manner, different natural languages may provide inherently different descriptions of the macroscopic world. It is well known that some natural languages are better (or worse) at expressing specific ideas and concepts of everyday life. This happens to such an extent that for any pair of languages there exist words in one of them that are untranslatable into the other language in any simple way. Thus, the uniqueness of description is a myth.

The situation in science is analogous. That is, different types of scientific description may provide better or worse vehicles for the analysis of specific

physical phenomena or their aspects. For some of these descriptions we can provide a dictionary that enables us to pass from one description to another without much loss. As simple examples, we may mention here the existence of the Lagrangian and Hamiltonian formulations, or current field-theoretic gauge theories of particle interactions in which different gauges are used, with the choice of gauge having no effect on relevant theoretical predictions. In other situations only fairly incomplete dictionaries are at hand, as is the case of classical versus quantum physics.

In fact, language hides not only the ‘outside’ physical reality generally believed to lie beneath it, but the whole of reality, including our ideas about it. Since the formation of concepts and the process of thinking require their subsequent formulation into words so that they can be presented to the world at large, our ideas are necessarily tailored to the words that we have at our disposal. A byproduct of this is that expressing one’s ideas in written form is a very laborious process. Furthermore, since the explicit use of words generally distorts the original idea, it is quite likely that also our cognitive processes and the concepts we form in our minds are affected by the languages we have been trained to use. Consequently, as Benjamin Whorf claims [169]: *“All observers are not led by the same physical evidence to the same picture of the universe, unless their linguistic backgrounds are similar.”* Although this ‘principle of linguistic relativity’ was under attack for some time, current research and most linguists now agree with it, though perhaps with some mild reservations (for more details, see e.g. Refs. [56, 100, 173]).

Since, for any given evidence, different languages in general lead to different pictures of physical reality, we face the problem which language to choose as being conceptually closer to nature. This is an important issue of decision as different descriptions will likely be conducive to different generalizations later on. Obviously, substantial conceptual progress is unlikely to follow from the refinement of a single language if the latter is not chosen judiciously — this would be like searching for a local maximum instead of the global one. Thus, one should seek additional arguments which — out of many possibilities — would single out a particular language, a particular description, and a particular conceptual viewpoint as the most promising alternative.

Our goal is to present a new variant of an old conceptual idea concerning the physical reality ‘out there’, i.e. of the idea that space and matter are related, and to provide various arguments in favor of the newly proposed perspective. While philosophical, empirical, and symmetry arguments will

be the most crucial here, some support for the new perspective will also be provided by the appearance of a related point of view in some of the natural languages.

Furthermore, as the arguments used will be of different types, the language employed in the presentation will vary from place to place. Since there must be a trade-off between the accuracy of the wording and the conciseness and simplicity of the presentation, and since we are necessarily “suspended in language”, we will attempt to be linguistically and conceptually precise only as far as we deem it essential for our purposes. Sometimes, therefore, wording not fully adequate for the expression of our general idea or arguments may be used. The simplification achieved in this way should be worth the price, however. The idea itself shall become clearer as the presentation proceeds and the conceptual relations between different threads and arguments are built up.

2.2 Explanation and Understanding

In the minds of the overwhelming majority of physicists, and particle physicists in particular, the concept of ‘explanation’ is understood within the strict tradition of scientific materialism and reductionism, as modeled upon the atomistic ideas of Leucippus and Democritus. Such a position may be considered quite legitimate since the Democritean approach to the understanding of physical reality turned out to be extremely successful. Yet, various aspects of reality exist which today are either explicitly excluded from the domain of the interest of physics (the concepts of reality and physical reality need not be thought of as synonymous), or — at least — about which physics still has nothing to say. Obviously, there is no guarantee that the old ideas of ‘explanation’ and ‘understanding’ could be extended to all of these aspects. Thus, possible modifications of these ideas should be discussed. In fact, the founding fathers of quantum physics did stress that in quantum physics the meaning of these words had already changed. For example, Heisenberg said [76]:

“Whenever we proceed from the known into the unknown we may hope to understand, but may have to learn at the same time a new meaning of the word ‘understanding’.”

Furthermore, it is not only the meaning of the word ‘understanding’ that should be modified but, again in the words of Heisenberg [80],

“It must be our task to adapt our thinking and speaking — indeed our scientific philosophy — to the new situation created by the experimental evidence.”

Unfortunately, in the mind of many a particle physicist, even if the necessity of such changes is acknowledged, not much attention is paid to them. As a result, although elementary particles are regularly described via quantum approaches, the important *conceptual* change brought about by the discovery of the quantum aspects of nature is almost invariably neglected and treated as virtually irrelevant to the subject of particle physics, which — after all — is to study the properties of the microworld and provide their ‘explanations’.

In effect, ‘explanation’ is understood in a simplistic, strictly Democritean fashion. Accordingly, most contemporary physicists accept the first three of Aristotelian causes, while rejecting the fourth one. The material cause, which is identified with an answer to the question of ‘what does something consist of’ is the one with which Democritus dealt most explicitly with. It dominates the thinking of most elementary particle physicists. Also accepted is the formal cause, understood as the abstract theoretical basis of physics. Physicists’ attitudes to the efficient and final causes are, however, somewhat schizophrenic. The efficient cause tends to be accepted in general practice on the grounds that earlier events may affect later ones ‘in a causal way’. Likewise, following Democritus, the final cause is generally rejected because ‘future events cannot affect earlier happenings in such a way’. In both cases, however, the relevant concept of causality is that of ordinary causality of everyday life, which clearly is a notion at least partially subjective.

In fact, the position of Democritus was criticized already by Aristotle [7]: *“Democritus, however, neglecting the final cause, reduces to necessity all the operations of nature. Now, they are necessary, it is true, but yet they are for a final cause.”* At issue here were various meanings assigned to the Greek word ‘aition’, which Aristotle tried to clarify, and which is most often translated as a ‘cause’. A somewhat better translation of ‘aition’, however, is not the word ‘cause’ but ‘because’ or ‘explanation’ [34]. Thus, the final cause could still be understood in physically acceptable terms as an explanation in terms of the final state. In other words, it is an explanation in terms of a boundary condition, which is certainly ubiquitous in contemporary physics (e.g. in the form of the least action principle). Similarly, the efficient cause would then be understood as an explanation

in terms of the initial state. The subjective aspects of causality disappear then from the physical explanation.

On the other hand, one may wish to consider these aspects nonetheless and view the concept of e.g. the final cause in more subjective terms as the purpose, goal, or aim of something. Then, the final cause provides an explanation within a set of concepts that transcend those used in physics. While this understanding of the concept of ‘explanation’ deals with a different realm of reality, it would be unwise to exclude it from our considerations right from the start. After all, on account of the unity of nature, it may point a way to a different understanding of this concept in the objective area of physics.

As the “we are suspended...” quotation from Niels Bohr shows, the meaning of words is defined in terms of other words and so on *ad infinitum*. Thus, this meaning must lie — at least partially — in the relations between the words themselves and in their relations to the world. This may be viewed as approximately mirroring the state of affairs in the physical world itself. Indeed, in a philosophically attractive relational view of reality, things and phenomena are perceived as always related to other things and phenomena. In other words, it does not make sense to talk about a ‘thing’ unrelated to anything else: such a ‘thing’ cannot be said to exist. Ultimately therefore, following Gottfried Leibniz, one can talk about “the interconnection of all things with one another”. As is well known, such a relational view of nature was advocated by Ernst Mach and many others, and was a philosophical point of departure for Einstein’s theory of relativity. According to this view, it is then only through such relations between objects that various concepts, like e.g. the concept of position or its change, can acquire meaning. The explanation of physical phenomena should then consist in providing a description that would uncover such relations. Indeed, when talking about his approach to atomic structure, Niels Bohr said (as quoted in Ref. [89]):

“It should be made clear that this theory is not intended to explain phenomena in the sense in which word ‘explain’ has been used in earlier physics. It is intended to combine various phenomena, which seem not to be connected, and to show that they are connected.”

Not only did Bohr stress the crucial importance of the discovery of mutual relations between various observed and seemingly not interconnected phenomena, but — eschewing the ontological issues — he restricted the subject

of physics to the study of such relations only [27]:

“In our description of nature the purpose is not to disclose the real essence of the phenomena, but only to track down, as far as it is possible, relations between the manifold aspects of our experience.”

According to this view, therefore, physics is about discovering and describing correlations between various phenomena. In fact, the idea of “taking the proper subject of physics to be correlation and only correlation” underlies also some current attempts at the interpretation of quantum mechanics [114, 143]. If physics is about discovering correlations, then the search for a ‘fundamental reality’ might be considered ill-defined and vacuous. It is presumably in such a spirit that Heisenberg said [79]: *“I do not know what the words ‘fundamental reality’ mean.”*

And yet, the one-dimensional sequential nature of classical time of ordinary experience means that any explanation of any part of this network of relations has to be presented in a linear and time-ordered fashion. Since there must be a beginning and an end to any such explanation, some aspects of physical reality and the related theoretical concepts must be chosen as logically first, and the remaining ones as those implied by them. The reasons for any such choice may be purely pragmatic — it may be just easier, simpler, more promising, or more convincing to start from some particular premises and look for their implications than to try a different road. Obviously, however, such a choice does not endow the corresponding, logically first (‘fundamental’) aspects of physical reality with any ontologically deeper status. Thus, even though Heisenberg dismissed the concept of ‘fundamental reality’, he could nonetheless seek the ‘origin’ (see p. 36 in Ref. [83]):

“This modern description (...) puts a quantitative in place of a qualitative statement, it traces different types of phenomena back to the same origin, and it no longer considers the question ‘why’. ”.

This clarification of what is meant by a ‘scientific explanation’ applies both to the original Newtonian theory of gravity, which correlated the movements of stars with the free fall of bodies on Earth, and to the Niels Bohr approach correlating ‘various phenomena which seemed not to be connected’. Such a reduction of a variety of phenomena to ‘the same origin’, i.e. to a set of judiciously chosen assumptions, could be called logical reductionism, and

constitutes the essence of any scientific approach, with the Democritean materialistic reductionism being only its simplistic variant.

2.3 Theories and Physical Reality

Yet, by treating the word ‘origin’ in a way more serious than it deserves, the above words of Heisenberg may be easily misinterpreted. We all tend to forget that in physics the word ‘origin’, so unambiguous in our macroscopic classical world and of absolutely paramount importance to science, refers to our description of physical reality only, and need not correspond to the physical reality itself. The latter — according to the relational view of nature — constitutes one interconnected whole. True, the role of science is to identify those concepts and principles (‘the origin’) with the help of which a part of this whole — a specific subset of phenomena — may be described and explained *most economically*. Yet, for a different set of phenomena, a completely different ‘origin’ (i.e. different concepts) might be better suited. Thus, the notion of ‘origin’ is context dependent. Indeed, Heisenberg writes elsewhere [86]:

“We are now more conscious that there is no definite initial point of view from which radiate routes into all fields of the perceptible, but that all perception must, so to speak, be suspended over an unfathomable depth.”

It may be only the condition of simplicity of the presentation that singles out this or that set of concepts as ‘the origin’ for a given set of phenomena. The ‘origins’ for some other sets of phenomena may be completely different and seemingly unrelated to that of the first set. This was presumably the original insight of Bohr, who as Heisenberg recalls [79], “would probably have expected that one would never get such a self-consistent mathematical scheme [as quantum mechanics], that one would always be bound to use different concepts for different experiments...”. Fortunately, the situation did not turn out that bad. In general, however, blending successful explanations of different aspects of physical reality into a single explanation need not be as straightforward as in the case which led to the formulation of quantum mechanics. In particular, seeking a common origin of different sets of phenomena may be difficult if one treats their individual partial origins as already established. It may well be that accepting alternative partial origins might be more conducive to the formulation of a joint explanation. Consequently, one should adopt a fairly flexible position which

would make such shifts in perspective possible.

In addition to the issue of establishing the ‘origin’ of phenomena, an acceptable explanation must yield a quantitative prediction of at least some aspects of those phenomena. For this to happen, the conceptual ideas must be translated into a precise mathematical scheme. Yet, as Heisenberg writes [78]:

“... the scientific concepts are idealizations; they are derived from experience obtained by refined experimental tools, and are precisely defined through axioms and definitions. Only through these precise definitions is it possible to connect the concepts with a mathematical scheme and to derive mathematically the infinite variety of possible phenomena in this field. But through this process of idealization and precise definition the immediate connection with reality is lost. The concepts still correspond very closely to reality in that part of nature which had been the object of the research. But the correspondence may be lost in other parts containing other groups of phenomena.”

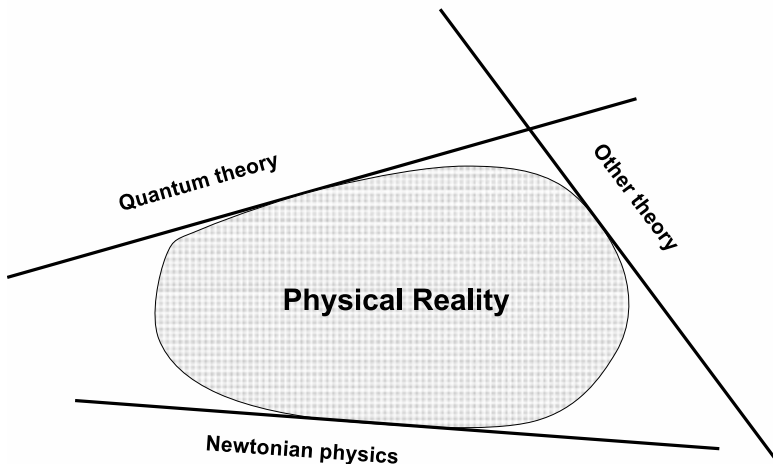


Fig. 2.1 Heisenbergian closed theories and physical reality.

This distinction between physical reality and its theoretical descriptions (stressed earlier by Mach) may be schematically represented as in Fig. 2.1. The physical reality is conceived as having many different aspects (classical, quantum, and most likely also other aspects — the latter either still beyond the limits of current physics or even completely unidentified today). For example, the classical aspects are those that are dominant in our everyday experience with inanimate macroscopic matter. We idealize this experience by assuming the existence of objective events occurring in space and time. Relations between these events are then abstracted from experiment and translated into a mathematical scheme that permits us to predict physical events in situations similar to those from which our theory was abstracted. This situation is visualized in Fig. 2.1, where the elongated blob is meant to symbolize physical reality, while the abstracted theoretical structure of classical Newtonian physics is represented by one of the straight lines tangent to the blob. This straight line fits the blob of physical reality in a certain range extremely well, and provides ‘rails’ for our thinking, but — outside this range of applicability — its predictions start to deviate more and more from the real world. A similar situation applies to quantum theory, which started from introducing abstract concepts appropriate to the description of atomic systems. Although both classical and quantum descriptions must be correlated, so far we have failed to reach a deeper understanding of this correlation. Indeed, the quantum predictions do not seem to be adequate enough to describe the classical aspects of physical reality: despite the time elapsed since the birth of quantum theory, the measurement problem or, in other words, the problem of the interpretation of quantum theory has not been disentangled. It seems, therefore, that classical and quantum theories simply describe different aspects of physical reality. In other words, classical physics could be nearly as ‘fundamental’ as quantum physics, with both theories missing important aspects of physical reality. This point of view should be compared with the typical reductionist belief in the classical stemming from the quantum, as expressed e.g. by Greenberger [8]: *“I believe there is no classical world. There is only a quantum world.”*, and with the position of Niels Bohr [135]: *“There is no quantum world. There is only an abstract physical description.”* Actually, Niels Bohr’s philosophical stance would probably be better expressed if we generalized his words to:

“There is no classical world, there is no quantum world. There are only abstract classical or quantum descriptions.”



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This is also the position of Werner Heisenberg [78], Carl F. von Weizsäcker [163], and many other physicists and philosophers.

The problem of how to fit classical physics and quantum mechanics together contributed to Heisenberg's development of the idea of 'closed theories' of exact science (such as e.g. Newtonian mechanics, Maxwell theory and special relativity, nonrelativistic quantum mechanics, thermodynamics) and the issue of their acceptance by the scientific community [87], which is reminiscent of the Kuhnian notion of paradigms (or rather the other way around). According to Heisenberg, one should relinquish the hope of ever finding the ultimate unified theory [85] (with 'unification' understood as a goal much more ambitious than the simple search for correlations between some of the multifarious aspects of physical reality):

"The edifice of exact science can hardly be looked upon as a consistent and coherent unit in the naive way we had hoped. Simply following the prescribed route from any given point will not lead us to all other rooms of this building; for it consists of specific parts, and though each of these is connected to the others by many passageways and each may encompass some others or be encompassed by others, nevertheless each is a unit complete in itself."

Needless to say, Heisenberg's view itself is also an idealization of the situation (as is the corresponding schematic representation of Fig. 2.1). Yet, overcoming this idealization might require conceptual changes so substantial that the picture presented may be viewed as a good approximate rendering of the actual state of affairs. This Kuhnian view was pushed further by Paul Feyerabend [49], who stressed the possible incompatibility of different theories, their parts, or pieces:

"Knowledge (...) is not a series of self-consistent theories that converges towards an ideal view; it is not a gradual approach to the truth. It is rather an ever increasing ocean of mutually incompatible (and perhaps even incommensurable) alternatives, each single theory, each fairy tale, each myth that is part of the collection forcing the others into greater articulation (...)."

Obviously, there is no contradiction between the belief in an internal consistency and the unity of physical reality itself, and the acceptance of mutual incompatibilities between scientific descriptions of various aspects of this reality or between pieces of such descriptions. Different — even incompatible — views and different perspectives on a problem may significantly broaden our understanding and help in the introduction of new concepts

that could represent physical reality in a more adequate manner. Consequently, one should never assign too much weight to our theories, however well established they might seem, for any such theory necessarily describes *selected* aspects of physical reality only and, in the words of Heisenberg, “*extends just as far as the conceptions which form its basis can be applied*” [85]. In particular, we should not consider our best theories as ‘true’ or ‘correct’ (since this “narrows people’s vision” as Feyerabend puts it [50]), but only as theories at present most appropriate to the task for which they were constructed. Thus, there is also no reason that we should not entertain and simultaneously accept different theories that might be considered mutually incompatible.

Given any two such conflicting theories, the great challenge obviously is how to connect them into a single, unifying, and internally consistent description, and thus move forward on the road to a broader and more adequate explanation. Although such a description in principle should exist (we might view reality as a complete description of itself), achieving any such partial unification may be extremely difficult, as the case with quantum and classical descriptions proves. In reality therefore, instead of solving such problems, we produce hybrid theories, with ugly patches and epicycles, in which concepts belonging to different tales are out of necessity carelessly combined. The history of science is littered with such hybrids, “dilapidated ruins” as Feyerabend calls them [51]. It is our task as physicists to try to remove at least some of such hybridity so that the new idealization of a similar range of physical reality could be considered simpler and more economical.

In fact, under closer scrutiny it turns out that the present quantum theories may also be considered hybrids in some respects, for, as David R. Finkelstein remarks [53]:

“The development of physics, if we see it right, looks like ...c...cq...q. (...) In [the c period], time and matter were both classical systems. The cq period is now (...); a brief interregnum during which vigorous hybrids of c (classical) time and space with q (quantum) matter have been created. (...) The q period (...) is one in which both time and matter are q systems.”

In our search for a deeper connection between space and matter, the following remarks should therefore be kept in mind:

- The search might benefit from a shift in the scientific philosophy, away from the strictly Democritean approach.

- One should admit various possible vantage points, and in particular: the standpoint of logical reductionism in which matter could be considered as the ‘origin’ of space and a more symmetric Bohr-like perspective, with space properties being simply *correlated* with matter properties.
- The conceptual structure of the space–matter connection and the mathematical language used for its idealization need not be compatible with the already ‘established’ theoretical descriptions of physical reality, as all our theories are only idealizations of its selected aspects while they ignore its other aspects. Yet, some basic connections between the new and the standard descriptions must obviously be admitted, and the possibility of establishing in the future some further passageways should at least be made plausible.
- Given great likelihood of a mismatch between theoretical extrapolation and physical reality it is better to propose just one step towards the suggested goal — a step supported with a wide range of plausible arguments so that it may be accepted as a development in roughly the right direction — than to keep adding on to it poorly substantiated ‘improvements’, a procedure that would most likely only add hybridity to the description and almost certainly veer away from some appropriate but unknown path.

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Chapter 3

Classical and Quantum Aspects of Reality

In the classical Newtonian physics we describe the world of inanimate matter in terms of objective events occurring at well-defined points in absolute Euclidean space and time. This description obviously involves an idealization removed from our subjective experiences, for, as Alfred North Whitehead puts it in his 1925 *Science and the Modern World*, his first metaphysical book [167],

“among the primary elements of nature as apprehended in our immediate experience, there is no element whatever which possesses this character of simple location.”

According to Whitehead, our spatial experience is limited to volumes, subvolumes, subsubvolumes, ... and the whole network of relations between them. The concept of a point appears then as a mere abstraction, much the same way as in the case of an infinite set of nested Russian dolls. Similar considerations also apply of course to time, with the concept of a durationless interval of time being again, in Whitehead's words, an *“imaginative logical construction”*. Most of us view this abstraction of a space and time continuum as a real thing, instead of treating it as a tremendously useful, but simplifying description of the whole set of intervolumes and interinterval relationships. Whitehead calls this conceptual “error of mistaking the abstract for the concrete” a *“Fallacy of Misplaced Concreteness”*.

Once the idea of mathematical points in space and time is created in our minds in this way, further concepts such as motion, forces, or interactions inherit its idealized abstract character. As a result of this procedure, the classical picture of reality admits arbitrary subdivisibility of all things and phenomena. According to this description, therefore, measurements can be made using interactions that could interfere with the investigated objects in

an arbitrarily weak manner and, consequently, we may learn the positions and momenta of those objects with any required precision.

Coming back to Whitehead's conception of space, it should be obvious that one cannot extract a particular subvolume of space so understood without demolishing the whole set of relationships: any given subvolume has no existence independent of the whole. Consequently, the spatio-temporal location of every object involves in its definition its relations with respect to all other volumes or intervals [167]:

"For each volume of space, or each lapse of time, includes in its essence aspects of all volumes of space, or of all lapses of time. (...) In a certain sense, everything is everywhere at all times."

Such a point of view might originally seem very odd to a modern physicist trained to perceive the individual objects as placed at specific locations of the Democritean background space and time continuum. Yet, upon deeper reflection he should notice some conceptual affinity of the Whiteheadian view to the fundamental tenet of quantum physics. Indeed, the classical concept of individual localized objects, possessing purely intrinsic properties and a reality completely independent of the surrounding world, appears grossly inadequate in the quantum description. Accordingly, individual quantum objects cannot be 'taken out' for examination. Behavior of 'individual quantum particles' depends on the whole experimental setup. In quantum physics the classical idealization breaks down severely.

Now, while Whitehead's book provides a philosophical discussion of the discontinuous aspects of quantum physics as known prior to 1925, his global conception of space precedes all discussions of quantum alocality. In particular, it predates the quantum revolution initiated by Heisenberg the very same year, and the 1927 Solvay conference during which Albert Einstein discussed the worrying example of the instantaneous collapse of the arbitrarily spread wave function and the resulting conceptual conflict of new quantum theory with local causality. Thus, the philosophical conceptions of Whitehead could be treated in the mid 1920s as providing arguments (albeit vague), or even 'predictions', for the likely existence of alocal aspects in physics. Obviously, the creation of a physical description exhibiting such features would then be up to the physicists themselves. The actual development of quantum physics was not based on such philosophical arguments in favor of alocality and globality. Yet, it might have been.

Although quantum theory has dispensed with a part of classical idealization, i.e. with the concept of individual localized objects independent of the

surrounding world, it has not dispensed with classical idealization totally. In fact, it still involves the classical concepts of positions (or momenta), and, consequently, it inherits at least some of the idealizations of classical theories (it is a cq theory in Finkelstein's terminology). In particular, it inherits the classical idealization of the infinitely small and the infinitely large; it also involves the concept of idealized instantaneous measurements.

3.1 Classical Locality and Quantum Nonseparability

The classical Newtonian description of reality involves idealization in terms of the continuum of absolute space and time, in which well localized objects (approximated by 'material points') are placed and interact with each other. Yet, the description of these interactions is not wholly local. Indeed, in Newton's theory the gravitational effects are instantaneously transferred to infinite distances, a nonlocal feature which troubled Isaac Newton very deeply as it was totally against his macroscopic classical intuition (see e.g. Ref. [66]). It was only Einstein, who — driven by the same intuition — managed to exorcize from classical physics the nonlocality of the Newtonian theory of gravitation. According to his general theory of relativity, information about the changes here and now is conveyed to distant points of the Universe via signals propagating with the speed of light (via photons intuitively understood as little 'billiard balls' [66]). Thus, a closed description of reality, in the sense of a description given solely in terms of well localized phenomena and with all interactions treated as strictly pointlike, was finally achieved.

3.1.1 *Distant simultaneity*

Although the search for a local description of classical physical reality ended with success, one has to remember that both the general and special theories of relativity, as any of our theories, must be viewed as idealized descriptions of only certain aspects of physical reality. In particular, in the standard formulation of special relativity, given in terms of the four-dimensional Minkowskian spacetime continuum, there is virtually no trace of a couple of important physical assumptions originally made by Einstein.

The first of them concerns the definition of simultaneity for contiguous events. It is there that the concept of time at a given point in space is defined. This 'local' time is simply identified with the readings of a

macroscopic clock located in the ‘immediate vicinity’ of the point. Einstein assumes that this concept of ‘local simultaneity’ poses no physical problems. For the purposes of the theory of relativity, the neighborhood of the clock, of an unspecified but sufficiently small size, is therefore treated as a mathematical point. Thus, the macroscopic volume — in which the physical clock and the observer are located — is shrunk in our minds to an unexperienced concept of a point, just as Whitehead argued.

The other assumption pertains to the definition of simultaneity at two distant points A and B . In order to define the concept of distant simultaneity (or simultaneity for short) — say, from the point of view of what is observed at point A — Einstein utilizes light signals and assumes that it takes light as much time when it travels from point A to the faraway point B as when it travels back from the faraway point B to point A . An assumption of this type, which says how much of the total $A \rightarrow B \rightarrow A$ time of flight should be assigned to the flight in one direction only, is unavoidable. Different partitions of the total time may be parametrized with the Reichenbach parameter $\epsilon \in (0, 1)$, with ϵ denoting the fraction of the total time assigned to the one-way $A \rightarrow B$ route [138]. Obviously, such partitions define different velocities of light in the two opposite directions. This freedom in the choice of ϵ cannot be removed by a physical measurement procedure, as there is no way to experimentally determine the one-way velocity of light, say from A to B . Indeed, in order to perform the measurement of the one-way velocity of light, the clocks located at points A and B would have to be synchronized prior to that measurement, i.e. it would have to be specified what it means that the events occurring at these two distant points are simultaneous. This, however, requires prior knowledge of the velocity in question. In other words, a vicious ‘velocity–simultaneity’ logical circle is involved. As Einstein writes, the fact that “light requires the same time to traverse the path $A \rightarrow B$ as for the path $B \rightarrow A$ is in reality neither a supposition nor a hypothesis about the physical nature of light, but a stipulation which I can make of my own freewill in order to arrive at a definition of simultaneity” [46]. On the same issue, Hans Reichenbach comments [138]: “this circularity proves that simultaneity is not a matter of knowledge, but of a coordinate definition”. In other words, distant simultaneity is a conventional concept. It is true that Einstein’s choice of this convention, the so-called ‘standard signal synchrony’ (corresponding to $\epsilon = 1/2$) leads to a great simplification, which is an important aesthetic condition on theory construction. Yet, this simplification “cannot be interpreted as providing a set of relations that are ‘more true’ than

those obtained for other admissible values of the Reichenbach synchronization parameter” ([97], p. 179). Thus, we are dealing with a kind of gauge freedom, whose presence does not affect any physically testable predictions of the theory of special relativity.

In particular, it is possible to perform Einstein’s standard synchronization procedure first, select one arbitrary frame as the ‘ether’ frame E , and then — in all other frames moving with respect to it — readjust their clocks in such position-dependent ways that all dependence of time transformation formulas on positions is ‘swallowed’ by the corresponding redefinitions of time. In this way, one obtains that time t in an arbitrary frame is simply proportional to time t_E in the preferred frame E [156] (specifically, $t = \sqrt{(1 - v^2)}t_E$, where v is the velocity of the frame moving with respect to the ether). The resulting proportionality between the times defined in this way for all frames moving with arbitrary velocities $v, v', \dots$ ensures that simultaneity in the ether frame ($t_E = 0$ everywhere in space) entails simultaneity in all the other frames ($t = t' = \dots = 0$). Thus, in the words of Mansouri and Sexl [113], one obtains “the remarkable result that a theory maintaining absolute simultaneity is equivalent to special relativity”.

Both for Einstein and for Reichenbach the concept of local simultaneity logically precedes that of time. Furthermore, since the concept of length for a moving rod is defined as the distance between simultaneous positions of its ends, it follows that “space measurements are reducible to time measurements”. Thus, within the theory of special relativity, “time is (...) logically prior to space” [138]. Similar arguments in favor of clock measurements being more fundamental than those made with the help of both clocks and rigid rods (or using rods alone) were voiced by Milne [115].

3.1.2 *Local time of special relativity and quantum*

In quantum mechanics, time also plays a distinguished role. Yet, contrary to the case of special relativity, no prescription is given as to how to measure it. In fact, it is treated altogether differently from spatial variables: while the (measurable) position of a particle in space is represented by an operator, its (non-measurable) location in time is represented by a c-number, an evolution parameter. In addition, while real phenomena and measurements always extend over a certain period of time, standard quantum mechanics uses the notion of an idealized instantaneous measurement, during which the state of the system ‘instantaneously jumps’ into an eigenstate of the operator corresponding to the observable being measured. If the relevant

observable is that of a particle's position, a sudden localization of the particle usually takes place.

What really bothered Einstein from around 1925 onwards was that — just 10 years after he exorcized Newtonian nonlocality from classical physics — nonlocal features sneaked into physics in a new quantum outfit, in a way seemingly contradicting special relativity. Einstein saw that if a particle described by probability distribution $|\psi|^2$ “is localized, a peculiar action-at-a-distance must be assumed to occur”. Further consideration of the problem led him to the famous Einstein–Podolsky–Rosen (EPR) paper [47], which was based on a couple of premises. From our point of view, and as it is now well known, the most crucial of those premises was an essentially tacit assumption of locality in the sense of the special theory of relativity. This assumption forbids the transfer of information between two spatially separated particles as there are no ‘billiard balls’ that could travel faster than light. Since one may choose such a system of two particles that its quantum description involves logical nonseparability of the particles, a conflict between classical relativistic separability and quantum nonseparability could be anticipated. And indeed, the penetrating EPR conclusions regarding the incompleteness of quantum mechanics followed precisely from this apparent conflict. Much has been written about Bohr's reply [28] and what he really meant when he claimed that there was an ambiguity in the EPR words “without in any way disturbing a system”. Although the crucial fragment of Bohr's enigmatic reply could be interpreted as endorsing nonlocality, a deeper and broader inquiry into his position indicates that this was not the case [18]. In fact, it was dissatisfaction with Bohr's orthodox arguments that prompted David Bohm to propose his genuinely nonlocal interpretation of quantum theory [23], an interpretation based on a fully deterministic realistic ontology of ‘hidden’ variables.

As far as we can see, the conflict identified by EPR stems from a conceptually hybrid consideration of two descriptions of reality: the quantum description and the classical relativistic one. Indeed, the theory of special relativity starts from the concept of local simultaneity and builds upon it the concept of distant simultaneity. It is based on direct observations of clock readings and on the measurements of inter-event spatial distances performed with the help of rigid rods. This is completely different from the quantum case which provides a hybrid cq description, with the c part not defined in some quantum way, but taken over from the classical tale. Thus, a question appears: can the whole measurement procedure of special relativity be transferred in a straightforward way into the microscopic

.....

quantum realm? This issue was addressed by Helmut Salecker and Eugene Wigner [146], who discussed quantum limitations imposed on the possibility of measuring microscopic distances between events in space and time. They discarded the use of rods as essentially macroscopic objects and considered employing microscopic clocks only (the distances hopefully being then measured with some yet unspecified accuracy using light signals propagating with assumed constant velocity c). They accepted that the microscopic clock should have accuracy τ . Consequently, in the best case scenario, its reading may be achieved by the emission of a single photon of period no longer than τ . If such a clock is to be of any use to us, it must run for a reasonably long period of time T , i.e. significantly larger than τ . Salecker and Wigner show then that in order to reduce the disturbance caused by the recoil of the clock during the whole of its running time T , the mass of the clock must be sufficiently large. If the clock wave packet spreading is taken into account, one obtains $M > (T/\tau)\Delta m$, where $\Delta m \approx \hbar/c^2\tau$ is a simple estimate based on the uncertainty principle. Thus, Wigner says [168]: *“what we vaguely call an atomic clock, a single atom which ticks of its periods, is surely an idealization which is in conflict with fundamental concepts of measurability.”* The Einsteinian procedure upon which the concept of the standard relativistic spacetime is built breaks down already at the level of a single microscopic clock. What we really observe when studying microscopic systems are, as Wigner says, “[macroscopic] coincidences between the particles emanating from the microscopic system and parts of the [macroscopic] framework.” As a result, *the “so-called observables of the microscopic system” cannot be consistently assigned to the microscopic system alone.* They acquire meaning only when adequate reference to the whole surrounding macroscopic classical framework is included. Quantum-level effects exhibit holistic relationist features.

3.1.3 Tension

Actually, we are now fairly certain that the Einsteinian billiard ball view of reality breaks down in the quantum realm in a much more profound way. The crucial step in the Einstein–Bohm line of reasoning was supplied by John Bell, with a conclusion that imparted an almost devastating blow to the Einsteinian idea of local realism [16]. In addition, Bell’s proof that no local deterministic hidden variable theories can reproduce all statistical predictions of quantum mechanics, later understood to apply to general lo-

cal realistic theories ¹ [32, 151], was amenable to experimental testing. In such tests a composite system of two particles moving away from each other is prepared in an entangled quantum state (i.e. involving logical nonseparability of the particles), and sets of measurements of particle properties ‘after they have moved’ into two faraway spatially separated regions A and B are performed in those regions (the two regions being in a relativistically spacelike configuration). A study of experimental results of those sets then exhibits correlations between events registered in the two regions. It is these correlations that cannot be explained in the local Einsteinian way: what Alice does of her own free will in region A affects the results which Bob observes in a spacelike separated region B . Even though this nonlocal dependence can be ascertained only after their observations are compared, it certainly represents a novel nonclassical kind of causality.

A great variety of experiments were carried out (see Ref. [151]), including the most famous of Alain Aspect *et al.* [9], in which the first attempt was made to ensure that measurements are performed in regions of truly spacelike separation. The fact that in the Aspect experiment the choices of measurements in the two faraway regions were made during the flight of the particles (photons) helped in closing the communication loophole of earlier investigations. More recent experiments [157] have shown that entanglement effects do not diminish with separation. Consequently, experiments strongly favor quantum mechanics over local realistic theories, though there are still some loopholes left, mainly related to the issue of particle detection [151]. This situation is usually summarized by saying that a kind of tension appears between the experimentally confirmed locality of special relativity and the experimentally confirmed nonlocality of quantum mechanics.

It was argued in the past that this tension is not serious since the nonlocal correlations, and indeed the new kind of causality involved in quantum physics, cannot be used to send superluminal messages between experimenters [44], i.e. that there is no ‘signalling’ involved (although this terminology is unfortunate due to its anthropocentric connotations — see Bell as quoted in Ref. [151]). This absence of signalling is obviously also true in relativistic quantum (cq) field theories since the locally causal structure

¹As Bell himself wrote, (pp. 143, 157 in Ref. [17]) his original argument is composed of two logical steps. The first step (the EPR part) is from locality to deterministic hidden variables. The second step starts from hidden variables and ends with Bell’s theorem itself. These steps, when considered together, indicate that the problem is with our macroscopic concept of locality (see also, e.g. Ref. [119]). Indeed, already in his first paper Bell pointed out that it is “*the requirement of locality ... that creates the essential difficulty*”.

of special relativity is directly built into their assumptions. Indeed, Henry Stapp writes [153]: “The failure of EPR locality does not jeopardize (...) the relativistic quantum field theory, which is constructed to ensure that its predictions do not depend either on the frame of reference or upon the order in which one imagines performing measurements on spacelike separated regions.” Note not only the word ‘constructed’ (i.e. encoding into quantum field theories the classical ideas of special relativity together with the standard concept of a mathematical point in space and time), but also the word ‘imagines’ which in fact covers an aspect of the simultaneity issue beyond the picture of simultaneity usually formed in our minds. Indeed, even in a given frame, in agreement with the conventionality thesis, standard distant simultaneity is simply *imagined*, for, as Poincaré stressed: “The simultaneity of two events, or the order of their succession, the equality of two durations, are to be so defined that the enunciation of the natural laws may be as simple as possible. In other words, all these rules, all these definitions are only fruit of an unconscious opportunism.” Hence, any talk about the globally *instantaneous* wave function collapse in a given frame is simply inconsistent with the conceptual foundations of special relativity which admit all choices of the Reichenbach parameter $\epsilon \in (0, 1)$. Perhaps there is a way to fix the gauge freedom of special relativity and define distant simultaneity in a sensible, unambiguous, and unique way. Yet, any such procedure must be based on physics beyond the conceptual structure of special relativity (say, one might think of the preferred frame furnished by the cosmic background radiation).

As already mentioned, the relativistic and quantum aspects of physical reality are built into contemporary quantum theories in peaceful coexistence. Despite that these theories are hybrid cq structures. The question is how to remove this hybridity and the tension resulting from it, thus obtaining a wider and more adequate description of reality. Referring to this problem, Bell said (p. 172 in Ref. [17]):

“For me then this is the real problem with quantum theory: the apparently essential conflict between any sharp formulation [of quantum theory] and fundamental relativity. That is to say, we have an apparent incompatibility, at the deepest level, between the two fundamental pillars of contemporary theory (...) It may be that a real synthesis of quantum and relativity theories requires not just technical developments but radical conceptual renewal.”

In other words, a better synthesis of the two theories should presumably start from some ontological view on the relation between quantum and

classical descriptions, a view that would answer the ontological question of ‘how does nature do this’. In fact, various such views have been tentatively proposed, bearing also on the issue of locality vs. nonlocality. We will mention but a few.

The first proposal is that nonlocality is only apparent, while ‘in reality’ all experimental results and all choices on the part of experimenters are predetermined in the overlap of their backward light cones, in full agreement with local causality. Yet, this superdeterminism — which denies free will and makes all our scientific discussions preordained — seems, as John Bell put it, “*even more mind boggling than the one in which causal chains go faster than light*” (p. 154 in Ref. [17]). The whole scientific enterprise is based on the idea of free-willed scientists deciding what kind of experiments and theories to propose and test. All this would have to be considered an illusion. It seems that as scientists we really do not have a choice, but to reject this possibility.

Then there is the many-worlds option, which claims that all mutually inconsistent experimental outcomes are actually realized. In such an interpretation everything is quantum, and nonlocality cannot be inferred. Besides being mind boggling again, this option has been criticized for leaving no place for free will (again) [68], and for causing problems with the uniqueness of conscious experience [133]. Another argument against it is based on the Whiteheadian fallacy of misplaced concreteness: the many-worlds interpretation takes abstract theory for reality. Given the fact that all our non-quantum theories have turned out to be merely approximations of reality, i.e. its idealizations with restricted domains of applicability, it is hard to treat the many-worlds option seriously. As Günther Ludwig said (recall also Fig. 2.1) [109]:

“I do not believe quantum mechanics to be the theory of nature as a whole. Furthermore, I do not believe that there will ever be a physical theory of the whole of nature. A theory of the whole of nature means for me a limit that can never be reached, but a useful limit for accelerating the development of science”

The third option is what today might be informally called an ‘on-line creation’. Its main ideas are implicit or explicit in papers of many physicists and philosophers, although the details may vary. On the physicists’ side it presumably starts with the Heisenbergian idea of potentialities and actualities, tendencies and facts [77]. The connection between quantum tendencies and classical facts was described in this way by Stapp [153]:



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“[the] objective reality is built upon myriads of macroevents which, rising from the sea of micro-level potentialities, create or actualize attributes that weave together to form the fabric of a macroscopic spacetime reality that is describable in terms of the concepts of classical physics.”

Heisenberg’s philosophy is also endorsed by Abner Shimony [151]:

“the domain governed by relativistic locality is the domain of actuality, while potentialities have carriers (...) which modify and even violate the restrictions that space-time structure imposes upon actual events.”

Relativistic locality, or perhaps better — relativistic distant causality — is correlated with our concept of macroscopic relativistic spacetime. The latter is built upon the classical concept of local time which is used as a primitive notion in the description of the macroworld. The classical relativistic description of reality is completely symmetric under reversal of that (local) time. Consequently, just as the Newtonian description, it misses the basic feature of experienced time — it lacks its arrow.

Nonlocal quantum causality (quantum distant causality), on the other hand, does not seem to pay much attention to time and/or space. And yet, quantum physics appears to have something to say about time that classical description does not: it provides the classical time with an arrow. Indeed, quantum mechanical state-vector reduction, an idealized description of the process of measurement, is irreversible (see e.g. Penrose’s argument in Ref. [133]). Thus, it provides a glimpse of an underlying irreversible process, of a transition from potentiality to actuality. In other words, at least in this respect the quantum description is somewhat closer to the experienced reality than is the classical description ²: it describes — even though in a hybrid way — the observed irreversible change, i.e. the emergence of the arrow of time, and therefore of time itself. In the words of Nicholas Gisin [67]:

“Quantum events are not mere functions of variables in space-time, but true creations: time does not merely unfold, true becoming is at work. The accumulation of creative events is the fabric of time.”

Obviously, what the nature of this underlying process is constitutes a different question. We will not enter into it here. But the arrow of time is certainly present in quantum physics (at least in quantum physics as it is

²This does not seem to be the only such place. According to Bohm [22] “quantum theory (...) gives a picture of the process of motion that is considerably closer to our simplest concepts than does classical theory. We cannot visualize simultaneously a particle having a definite momentum and position.”

practised). Thus, quantum description seems to be somewhat deeper ontologically than the classical relativistic one, the latter looking more like a higher-level description from which some aspects of reality are erased [66].

Consequently, any attempt to formally unite quantum and relativistic descriptions is presumably bound to result in a hybrid approach (recall the hybridity of relativistic quantum field theories). If time is indeed born out of a myriad of creative events, and in a way which according to quantum description is inherently nonlocal, a truly deep insight is needed into how to derive relativity from quantum. Lacking such a conceptual renewal when discussing quantum aspects of reality, it seems better to stick to a simple framework based on the concept of absolute time, within which the quantum concept of ‘instantaneous wave function collapse’ is certainly more acceptable. For this reason in particular we do not attempt to extend our quantum-level proposal of Part 3 beyond the nonrelativistic scheme.

3.2 Emergent Space and Time

The conceptual problems encountered when trying to combine special relativity and quantum physics result from the divergence of two lines of philosophical thought concerning the notion of space, which originated already in ancient Greece. Special relativity, with its material clocks, rods, and light signals, is a remote descendant of Aristotle’s thinking, with his concept of space being defined by the extension of material objects that occupy it (p. 17 in Ref. [95]). This acceptance of the matter-first attitude constitutes a basic similarity between special relativity and Aristotelian view, even though in the latter there is no void in between the objects. Such a logical priority of matter over space is also a cornerstone of the relational conceptions of space advocated by Leibniz, Huygens, and Mach, which later contributed to Einstein’s creation of general relativity.

Quantum theory, on the other hand, is deeply rooted in the Democritean approach. The latter is characterized by two main features: a separation of matter and space, and an end to the divisibility of matter. Atoms, the indivisible blocks of matter and thus its quanta, move through the undifferentiated void, an empty space which does not affect their motion in any way (this view of space as a mere container is actually due to Lucretius, see Ref. [95]). It is this conception that was used by Newton when he introduced his absolute space and time. And it is this conception that was used as the point of departure in the construction of both quantum

mechanics and relativistic quantum field theories, in which space and time are treated as unaffected by matter.

Thus, the contemporary theories include various aspects of the conceptual positions of Aristotle and Democritus, which work in their respective areas of applicability. Yet, combining these positions in a direct way is clearly impossible because of their fundamental intrinsic incompatibility as regards the nature of space. It is this incompatibility that propagates into various contemporary theories and leads to their hybrid nature. Space cannot be consistently viewed — in a given *single* description — as a mere container for matter, completely independent of it, and — in *the same* description — as a derivative of matter, dependent on it. This clash between quantum and relativistic conceptions shows up at the levels of both special and general relativity. That there is a kind of conflict between quantum theory and special relativity was repeatedly stressed by Bell and his followers. An analogous tension between the ontological bases of quantum theory and general relativity may be found in many attempts to quantize gravity, such as e.g. canonical quantum gravity or string theory [165]. Yet, it seems that it is the problem of ‘quantum theory vs. special relativity’ that should be attacked first since it touches on the very adequacy of the use of such abstract concepts as those of a point and a manifold. Indeed, Travis Norsen writes [120]:

“A much higher-level inconsistency between quantum theory and (general) relativity has been the impetus, in recent decades, for enormous efforts spent pursuing (what Bell once referred to as) “presently fashionable ‘string theories’ of ‘everything’.” (...) How might a resolution of the more basic inconsistency identified by Bell shed light on (or radically alter the motivation and context for) attempts to quantize gravity?”

In view of the basic conflict between the Aristotelian and Democritean approaches it seems therefore that our attempts to resolve the apparent tension between quantum theory and relativity would benefit from some internally consistent ontological proposal which would scrap one or more elements of the two conflicting views. A call for such an ontological proposal has also been voiced by both physicists [144] and philosophers in connection with quantum gravity (see Ref. [165]).

Now, we have argued that the quantum description seems to be a little closer to the experienced reality, at least in some aspects of it, such as the appearance of the arrow of time (or in the description of motion as Bohm argued [22]). In this quantum description matter is quantized

Thus, it seems that a proper non-hybrid way to combine the Aristotelian and Democritean positions would be to keep the Democritus (i.e. quantum) approach to matter, while at the same time replacing the Democritean ‘space-as-a-void’ ontology with the Aristotelian ‘space-from-matter’ ontology. In other words, one should somehow link the concept of classical space to the concept of quantum matter, and the classical concept of the experienced arrow of time (and thus time itself) to the quantum concept of a transition from potentiality to actuality. With quantum description being arguably somewhat closer to the underlying reality, we may vaguely speak of the underlying quantum level.

This way of extending the atomism of Democritus is clearly different from a naive application of reductionist ideas directly to the Democritean ‘void’. One does not simply postulate an end to the divisibility of space and time, one does not imagine some minimal length and minimal time, or — in other words — ‘atoms’ of space and time, ‘atoms’ that would be independent of atoms of matter. The suggested non-hybrid way of combining elements of Democritean and Aristotelian positions means that the classical concepts of space and time could be viewed as emerging from a deeper, quantum layer of the description of matter. One of the first more complete statements presenting this idea of ‘emergent space-time’ was given in 1962 by E. J. Zimmerman [186]. Later, the vision was framed in various outfits by C. F. von Weizsäcker (ur theory) [162], D. R. Finkelstein (spacetime code) [53], J. A. Wheeler (pregeometry) [166], and - most importantly for our purposes - by Roger Penrose [131] in his spin network approach to the generation of a continuous array of directions of ordinary 3D space.³ We will discuss Penrose’s version of the classical-space-from-quantum-matter idea at the end of Part 2, after the relevant aspects of the current standard description of elementary particles have been presented in some detail.

As already mentioned, in the standard quantum mechanical description the classically defined concepts of space and time are treated in different ways. Likewise, in Penrose’s proposals [133, 131], the quantum source of the arrow of time and that of the continuous 3D array of directions (i.e. the quantum-mechanical state-vector reduction and the spin network) look quite different. In other words, in spite of the famous Minkowski statements about space by itself and time by itself disappearing into mere shadows, with only a kind of their union having an ‘independent reality’, one can safely repeat after Max Jammer (p. 300 in Ref. [97]) that “despite

³Penrose’s spin network approach has turned out to also be related to the ideas of loop quantum gravity [142].

the just-mentioned symmetry, time differs from space". A similar problem with the asymmetric treatment of space and time, and the disappearance of the latter, was also encountered in the context of quantum gravity [39]. Yet, according to the philosophical position advocated above, both space and time are to emerge from the underlying purely quantum description (obviously without identifying that description with physical reality). Consequently, one would like to have a more parallel treatment of the emergence of space and time. Presumably following such a line of thought, Don Page and William Wootters used the spin picture as a model for the description of the generation of time [123, 171]. In their proposal, the temporal (internal) dimension of the universe is created from quantum correlations between a clock (or clocks) and the rest of the universe. This approach to the generation of time is linked to the many-worlds interpretation. Indeed, Wootters writes in Ref. [171]: "(...) measurement, being made entirely within the universe, does not collapse the state of the universe as a whole but only *gives the observer the experience of being in one of the many different states which are possible for him* (...). (...) The correlations he thus observes between his own state and the state of the world around him (...) are interpreted by him as the passage of time." Given our renunciation of the many-worlds option, we should look for a different way to generate time. Presumably, we should first take a step away from the quantum description itself and inquire somewhat deeper into the very conceptual basis of how the temporal description of reality was introduced and how it could be rephrased. This is what we will attempt to do in the next chapter.

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Chapter 4

Time for a Change

In the preceding chapters Democritus' and Aristotle's conflicting views of the relation between matter and space were juxtaposed. We proposed to reconcile them by accepting the general Aristotelian 'space-from-matter' philosophy, yet with the material 'source' of space treated in an atomistic, Democritean (and therefore quantum) way. Now, even though the views of Democritus and Aristotle were significantly different, they had an important thing in common: they were both preoccupied with matter, i.e. with individual *things* and *substances*, although for Aristotle the concepts of time and change were also of great interest. This preoccupation with the concept of things together with the towering position of Aristotle, The Philosopher, certainly contributed to the emergence of reductionist materialism much later, when proper physics finally developed. As a result of this attitude, the concept of being is generally regarded today as primary, while that of becoming — as secondary. Accordingly, processes are now considered in science as ontologically subordinate to things, and are simply thought of as changes of things in time. And yet, already before Democritus and Aristotle, a different way of looking at nature was advocated by Heraclitus, a way which stressed the view that processes should also be considered ontologically fundamental.

4.1 Things and Processes

Since Heraclitus purposefully chose words laden with many meanings, his statements were variously understood and easily misinterpreted by later philosophers, including in some cases Aristotle himself [70]. Today, the dominant opinion of philosophers is that what Heraclitus actually meant was not exactly that 'everything is flux', and 'all is change', but a much more