THE FRONTIERS COLLECTION

THE FRONTIERS COLLECTION

The books in this collection are devoted to challenging and open problems at the forefront of modern physics and related disciplines, including philosophical debates. In contrast to typical research monographs, however, they strive to present their topics in a manner accessible also to scientifically literate non-specialists wishing to gain insight into the deeper implications and fascinating questions involved. Taken as a whole, the series reflects the need for a fundamental and interdisciplinary approach to modern science. It is intended to encourage scientists in all areas to ponder over important and perhaps controversial issues beyond their own speciality. Extending from quantum physics and relativity to entropy, time and consciousness – the Frontiers Collection will inspire readers to push back the frontiers of their own knowledge.

Information and Its Role in Nature
By J.G. Roederer

Relativity and the Nature of Spacetime
By V. Petkov

Quo Vadis Quantum Mechanics?
Edited by A. C. Elitzur, S. Dolev, N. Kolenda

Life – As a Matter of Fat
The Emerging Science of Lipidomics
By O.G. Mouritsen

Quantum–Classical Analogies
By D. Dragoman and M. Dragoman

Knowledge and the World
Challenges Beyond the Science Wars
Edited by M. Carrier, J. Roggenhofer, G. Küppers, P. Blanchard

Quantum–Classical Correspondence
By A.O. Bolivar

Mind, Matter and Quantum Mechanics
By H. Stapp

Quantum Mechanics and Gravity
By M. Sachs

V. Petkov

RELATIVITY AND THE NATURE OF SPACETIME

With 58 Figures

Springer

Dr. Vesselin Petkov
Concordia University
Liberal Arts College
de Maisonneuve Blvd. West 1455
Montreal, Quebec H3G 1M8, Canada
E-mail: vpetkov@alcor.concordia.ca

Cover figure: Detail from 'Venus Beauty and Anisotropic Geometric Diffusion' by U. Clarenz, U. Diewald, and M. Rumpf. Courtesy of M. Rumpf

ISSN 1612-3018
ISBN-10 3-540-23889-1 Springer Berlin Heidelberg New York
ISBN-13 978-3-540-23889-8 Springer Berlin Heidelberg New York

Library of Congress Control Number: 2005924256

Springer is a part of Springer Science+Business Media.
springeronline.com

Typesetting by Stephen Lyle using a Springer TEX macro package
Final processing by LE-TEX Jelonek, Schmidt & Vöckler GbR, Leipzig
Cover design by KünkelLopka, Werbeagentur GmbH, Heidelberg

Printed on acid-free paper SPIN: 10977378 57/3141/YL - 5 4 3 2 1 0

To all who struggle to understand this strange world

Preface

The standard books on relativity do not usually address the questions of the physical meaning of relativistic effects and the nature of spacetime. This book deals specifically with such conceptual questions. All kinematic consequences of special relativity are analyzed by explicitly asking whether the physical objects involved in these effects are three-dimensional or four-dimensional; this is equivalent to asking whether those objects exist only at the present moment of their times, as our common sense suggests, or at all moments of their histories. An answer to the question of the dimensionality of physical objects will resolve the issue of the nature of spacetime – whether spacetime is just a mathematical space (like a seven-dimensional color space, for instance) or represents a real four-dimensional world.

This book is intended for physicists, philosophers of science, philosophers, physics and philosophy students, and anyone who is interested in what special relativity is telling us about the world.

Acknowledgements

I would like to express my gratitude to all who contributed to the appearance of this book. So many people were involved in discussions on the issues covered here that it is virtually impossible to mention them all. That is why I would merely like to thank them for their constructive comments and hope that our discussions have brought us a little closer to understanding this beautiful but strange world.

I feel I should start the short list of specific acknowledgements by thanking Springer and Dr. Angela Lahee for starting the publication of The Frontiers Collection. I think the appearance of such a series is more than timely since scientists have already started to lose sight of new developments in the various scientific fields. I would also like to thank Stephen Lyle for his excellent technical editing of the manuscript.

I owe a lot to my teacher and friend Anastas Anastassov of Sofia University. His excellent lectures on general relativity in the 1980s and our never-ending discussions prepared the ground for the ideas developed in this book. My thanks also go to Prof. Tzvetan Bonchev (at the time Dean of Sofia University's Faculty of Physics and Chair of the Department of Atomic Physics) and Prof. Ivanka Apostolova (at the time Chair of Sofia University's Department of Philosophy). Their influence is difficult to estimate.

I am grateful to my colleagues from the Department of Philosophy of Science of the Institute for Philosophical Research at the Bulgarian Academy of Sciences with whom many of the topics in this book were discussed in the late 1980s.

Versions of the issues examined in the book have been covered in different classes I taught – in the philosophy of science classes at Sofia University in the 1980s and later in the physics and in the philosophy of science classes at Concordia University. I am grateful to all students who participated in the class discussions. I also benefited from valuable comments from colleagues and students at Concordia University, McGill University and the University of Montreal, who attended a series of lectures I gave at a weekly seminar on General Relativity in the Fall of 1994, held at Concordia University. I would like to express my sincere thanks to all anonymous referees who made constructive recommendations and comments on different issues that are now included in this book. Most of the results presented here were also reported at several international conferences and at two inter-university seminars in Montreal – on open questions in physics and on the history and philosophy of science. I am truly grateful to the colleagues and students who took part in the discussions.

And last, I would like to express my deep gratitude to my wife Svetoslava and our son Vesselin (Jr) for their understanding, unconditional support, and encouragement. The completion of this book would not have been possible without their endless love and faith in me.

Montreal, *Vesselin Petkov*
12 October 2004

Contents

Part III Spacetime, Non-Inertial Reference Frames, and Inertia

1 Introduction

This is not a typical book on relativity. It puts the emphasis on conceptual questions that lie beyond the scope of most physics books on this subject. The idea of such a book started to emerge more than twenty five years ago when I was struggling to *understand the meaning* of the consequences of special and general relativity. At that time I failed to find any physics books on relativity which addressed questions that looked so obvious to me. Here are three examples of such questions:

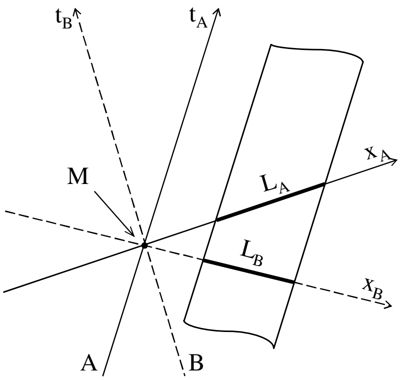
- It is stated in all books on special relativity that uniform motion is relative but no need has been seen to explain *why* absolute uniform motion does not exist. Answering this question is crucial for a genuine understanding of special relativity as the following apparent paradox demonstrates. Our common sense tells us that if a body moves *in* space it moves *with respect to* space. And indeed if we consider different examples of something moving in something else, it does appear that the expressions 'moving in' and 'moving with respect to' are equivalent. However, according to relativity such a conclusion is wrong since it is implicitly based on the idea of absolute motion. Therefore in relativity it is still correct to say that an object moves *in* space but not *with respect to* space. It is precisely here that the question of the non-existence of absolute uniform motion should be addressed in order to explain the profound depth of what lies behind the seemingly innocent difference between the two expressions.
- Another important issue that needs special attention is the physical *meaning* of the relativity of simultaneity. Logically, it comes after the question of absolute motion and can be approached differently depending on whether it is discussed in a physics or philosophy of physics class. In a physics class on relativity, my favourite problem for starting the analysis of what the physical meaning of the relativity of simultaneity is is the following:

> An inertial reference frame S' moves with respect to another inertial reference frame S in the positive x direction of S. The clocks in S and S' are synchronized at the instant $t = t' = 0$ when the coordinate origins O and O' of the two frames coincide. At this moment a light wave is emitted from the point $O \equiv O'$. After time t it is observed in S that the light wave is spherical with a radius $r = ct$ and is described by the equation $r^2 = x^2 + y^2 + z^2$, which means that the center of the light sphere as determined in S is at O. Find the shape of the light wavefront in S' at time t'. Is it also a sphere whose center is at O'? If so, does this lead to a paradox? If not, does this lead to a contradiction with the principle of relativity?

The relativity principle requires all physical phenomena to look the same in all inertial reference frames. Therefore an observer in S' should determine that the wavefront of the propagating light signal is also a sphere whose center is at O'. This conclusion is confirmed by the Lorentz transformations. But our everyday experience tells us that there must be something totally wrong here – the center of the *same* light wave cannot be at two *different* places (at O and O' which may be thousands of kilometers apart). The standard explanation of this apparent paradox is the following: the wavefront of the propagating light sphere constitutes a set of *simultaneous* events and since according to relativity simultaneity is relative, the observers in S and S' have different sets of simultaneous events and consequently *different* light spheres. This is a correct explanation. But are you satisfied? I doubt it. This explanation is conceptually incomplete since it merely shifts the paradox from the specific case of light propagation to the relativity of simultaneity itself. What remains unexplained is *why* the two observers in S and S', who are in relative motion, have *different* sets of simultaneous events and therefore different light spheres (one centered at O and the other at O') given the fact that the two spheres originated from a *single* light signal. If the *physical meaning* of the relativity of simultaneity is explained conceptually then this apparent paradox will be explained as well.

- The above two questions as well as the question of the physical meaning of length contraction, time dilation, and the twin paradox all lead to the same major issue – how spacetime should be understood. Almost a century after Hermann Minkowski united space and time into an indivisible four-dimensional entity – now called Minkowski spacetime – the question "What is the nature of spacetime?" still remains open. In my view, this question should be addressed, not only in papers and books on the philosophy of spacetime, but in every physics book or university physics course on relativity. So far this has not been done, perhaps because most physicists seem to believe that their job is to make predictions which can be experimentally tested and that they need not bother about conceptual questions such as the following: Is Minkowski spacetime nothing more than a four-dimensional *mathematical* space which represents an evolving-in-time three-dimensional world or a mathematical model of a four-dimensional world with time entirely given as the fourth dimension? However, such conceptual questions cannot be avoided since the ultimate intellectual goal of all sciences, including physics, is to *understand* the world we live in.

In fact, even apart from pure intellectual curiosity, physicists themselves do need to address issues dealing with the interpretation of relativity if they want to offer some *explanation* of relativistic effects, which can make their mathematical description more transparent. Take for example length contraction as depicted in the figure below. Two inertial observers A and B in relative motion are represented by their worldlines (the lines of their entire lives in time). A meter stick is at rest in A's reference frame and is represented by its worldtube (its entire history in time) in the spacetime diagram shown in the figure.



The length of the meter stick is measured by A and B at event M when the observers meet, i.e., at the moment they set their clocks to zero: $t^A = t^B = 0$. As any length measurement requires that both ends of the meter stick be measured at the *same* time, and since A and B have different sets of simultaneous events, it follows that what A and B regard as their meter stick is, in fact, a *different* three-dimensional cross-section of the meter stick's worldtube. As the x axes of A and B intersect the worldtube at different angles, the two cross-sections L_A

and L_B are of different lengths, and this *explains* why A and B measure different lengths for the meter stick. The exact relation between the two lengths is obtained by the Lorentz transformations, which do show that $L_B < L_A$.

It is here that physicists cannot avoid the conceptual question of the nature of the meter stick's worldtube: Is the worldtube nothing more than just a graphical representation of the length contraction or a real four-dimensional object containing the whole history in time of the three-dimensional meter stick? It is clear from the spacetime diagram that, if we reject the reality of the worldtube of the meter stick, then A and B cannot have different cross-sections since only A's meter stick of length L_A would exist. This means that the same meter stick of the *same* length L_A would exist for B as well and no length contraction would be possible. Therefore the very existence of the relativistic length contraction seems to imply the reality of the meter stick's worldtube. This in turn implies the reality of Minkowski spacetime, since four-dimensional objects exist in a four-dimensional world.

Most books on relativity do not use spacetime diagrams specifically in the discussions of kinematic relativistic effects and do not face the immediate need to address the issue of the nature of Minkowski spacetime. Once obtained through the Lorentz transformations, these effects are not usually explained any further. In my view, such an approach is unsatisfactory for two reasons. Most importantly, physics is much more than its mathematical formalism and therefore everything should be done to provide a physical explanation of the results obtained through the Lorentz transformations. Secondly, if relativists themselves make no effort to shed some light on the meaning of the relativistic effects, different accounts start to emerge which in many cases are inconsistent with relativity itself.

One of the main reasons for writing this book is to address the issue of the physical meaning of the relativistic effects and the nature of spacetime by analyzing what the mathematical formalism of relativity is telling us. More specifically this is done:

- by carrying out an analysis of the idea of absolute motion starting from Aristotle's view on motion,
- by explicitly addressing the question of existence and dimensionality of the objects (rulers, clocks, twins, etc.) involved in the relativistic effects.

Part One entitled *From Galileo to Minkowski* starts with a chapter on the idea of absolute motion and how it was brought to its logical end by Galileo's refutation of Aristotle's view on motion. Chapter 3 is devoted to exploring the internal logic of Galileo's principle of relativity. I will argue that special relativity, and more precisely its four-dimensional formulation given by Minkowski, is *logically* contained in Galileo's principle of relativity (with a single additional assumption – that the speed of light is finite, which was determined experimentally in Galileo's century). An important result of this chapter will be the non-trivial conclusion that the non-existence of absolute uniform motion implies that the world is four-dimensional (or, equivalently, if the world were three-dimensional, absolute uniform motion had to exist because, as we will see in Chap. 3, a *single* three-dimensional world implies that 'moving *in* space' is equivalent to 'moving *with respect to* space'). Further exploration of the consequences of Galileo's relativity principle leads to all kinematic relativistic effects which are derived in Chap. 4. These derivations demonstrate that the relativistic effects are merely manifestations of the four-dimensionality of the world, whose geometry is pseudo-Euclidean, since these effects have direct analogs in the ordinary three-dimensional Euclidean space. One of the objectives of Part One is to show that special relativity could realistically have been formulated significantly earlier.

Part Two entitled *On the Nature of Spacetime – Conceptual and Philosophical Issues* is the most provocative of the three parts of the book. But it had to be written since the issues raised by the theory of relativity have challenged our entire world view in an unprecedented way. Never before has a scientific theory called for such a drastic revision of concepts that we have hitherto regarded as self-evident, such as the existence of:

- objective change,
- objective flow of time,
- free will.

In my view, special relativity has posed perhaps the greatest intellectual challenge humankind has ever faced. In this situation the best way to take on the challenge is to deal directly with its very core – the question of the nature of spacetime – since this question *logically precedes* the questions of change, flow of time, and free will. As we will see in Chap. 5, these issues crucially depend on what the dimensionality of the world is, which demonstrates that they are indeed preceded by the issue of the nature of spacetime.

For this reason the first chapter of Part Two (Chap. 5) examines the issue of the nature of Minkowski spacetime and argues that it is special relativity *alone* and the experimental evidence that confirms its predictions that can resolve this issue. This argument comes from the analysis carried out in the chapter which shows that special relativity is valid only in a four-dimensional world represented by Minkowski spacetime. Otherwise, if the world were three-dimensional, none of the kinematic relativistic effects would be possible, provided that the existence of the physical objects involved in the relativistic effects is assumed to be absolute (frame-independent). The only way to preserve the three-dimensionality of the world is to relativize existence. However, even this extreme step contradicts relativity itself and more specifically the twin paradox effect.

The profound implications of relativity (and its requirement that the world be four-dimensional) for a number of fundamental issues such as conventionality of simultaneity, temporal becoming, flow of time, free will, and even consciousness are also discussed in Chap. 5. It is shown that, in the four-dimensional Minkowski world:

- the definition of simultaneity is necessarily conventional,
- there are no objective becoming and time flow,
- there is no free will,
- the concept of consciousness (implicitly defined by Hermann Weyl [1] as an entity which makes us aware of ourselves and the world only at the moment 'now' of our proper time) is needed to reconcile the major consequence of special relativity that external reality is a timelessly existing four-dimensional world with the fact from our experience that we realize ourselves and the world only at the present moment.

It is these conclusions that constitute the intellectual challenge mentioned above. The most tempting way out of it is to declare them absurd or undoubtedly wrong. That is fine, if such a declaration is backed up by arguments demonstrating why those conclusions are wrong. A way to avoid facing the challenge is to subscribe to the view that we should accept the theory of relativity but should make no metaphysical pronouncement regarding the nature of spacetime. Such a view, however, completely ignores the fact that an analysis of the consequences of special relativity clearly shows that the challenge is there.

There exist two other approaches which try to avoid the challenge posed by special relativity. They purport to show that we should not bother about metaphysical conclusions drawn from special relativity for two reasons. According to the first approach the fact that relativity describes the world as four-dimensional and deterministic should not be taken as the whole truth since quantum mechanics, quantum gravity, and other modern physical theories are telling us different stories. Leaving aside the fact that quantum gravity and some of the modern physical theories are not yet accepted theories, Chap. 6 will make use of the results of Chap. 5 that it is the *experimental evidence* confirming the consequences of special relativity that contradicts the three-dimensionalist view. It would be really another story if the experimental evidence confirming the predictions of quantum mechanics contradicted the four-dimensionalist view. But this is not the case. Chap. 6 will present two arguments which demonstrate that quantum mechanics has nothing to say on the nature of spacetime.

Chapter 7 deals with the second approach according to which special relativity cannot tell us anything definite about the external world because, like any other theory, it may be disproved one day. We will see that this desperate attempt to avoid the challenge posed by relativity fails too. Again, this argument completely ignores the fact that it is the *experimental evidence* confirming the predictions of special relativity that contradicts the three-dimensionalist view. As experimental evidence cannot be disproved, any attack on the four-dimensionalist view should challenge the claim that experiment itself contradicts the accepted three-dimensionalist view. I will argue in this chapter that a scientific theory will never be disproved in its area of applicability where its predictions have been experimentally confirmed.

The main purpose of Part Two is to show convincingly that the challenge to our world view arising from special relativity – that the world is four-dimensional – is real. That is why it is only fair to face it now instead of leaving it for future generations.

Part Three entitled *Spacetime, Non-Inertial Reference Frames, and Inertia* further explores the consequences of the four-dimensionality of the world for physics itself. Chapter 8 starts by showing that relativity has resolved the debate over acceleration – whether it is absolute as Newton thought or relative as Leibnitz and Mach insisted. A body moving by inertia (with no acceleration) is represented in Minkowski spacetime by a straight worldtube; if the body accelerates, its worldtube is curved. Therefore, special relativity clearly shows that acceleration is absolute – there is an absolute difference between straight and curved worldtubes (and these worldtubes are, as argued in the book, not just convenient graphical representations but real four-dimensional objects).

The situation in general relativity is the same. The analog of a straight worldtube in a curved spacetime is a geodesic worldtube. A body moving by inertia (with *no curved spacetime acceleration*) is represented by a geodesic worldtube; if the body accelerates, its worldtube is deformed, i.e., deviated from its geodesic shape. Unlike relative velocity which cannot be discovered, an absolute acceleration should be detected experimentally. And indeed the propagation of light in a non-inertial reference frame, in which an accelerating body is at rest, turns out to be anisotropic – the average velocity of light depends on the body's acceleration. (The speed of light is c in all inertial reference frames in special relativity and in all local inertial reference frames in general relativity.) Most of Chap. 8 is devoted to the propagation of light in non-inertial reference frames – a topic that has received little attention up to now. The chapter ends with a discussion of the gravitational redshift effect and the Sagnac effect.

Chapter 9 shows that the potential and the electric field of a non-inertial charge can be calculated *directly* in the non-inertial reference frame in which the charge is at rest (without the need to transform the field from a comoving or local inertial frame) if the anisotropic velocity of light in that frame is taken into account. It is shown that the average anisotropic velocity of light in a non-inertial reference frame gives rise to a hitherto unnoticed anisotropic (Liénard–Wiechert-like) volume element which leads to the correct expressions for the potential and electric field of a charge in such a frame.

Chapter 10 addresses a natural question: If the deformed worldtube of an accelerating body is a real four-dimensional object, can the inertial force resisting the body's acceleration be regarded as originating from a four-dimensional stress in the body's worldtube which arises when the worldtube is deformed? It is argued in this chapter that inertia is another manifestation of the four-dimensionality of the world. Although the existence of inertia cannot be regarded as a definite proof of the reality of spacetime, it is shown in the chapter that, if the world is four-dimensional, inertia must exist.

Part I

From Galileo to Minkowski

Part I Objectives

The main objective of this part is to show that there exists a logical link between Galileo's principle of relativity and Minkowski's four-dimensional formulation of special relativity.

Chapter 2 revisits Galileo's arguments used in his refutation of Aristotle's view on motion that led him to his principle of relativity according to which absolute uniform motion cannot be detected with mechanical experiments.

Chapter 3 carries out an analysis to reveal the physical meaning of this principle. The results of this analysis are quite unexpected – absolute uniform motion cannot be detected since it does not exist. What lies behind the non-existence of absolute uniform motion is even more unexpected – there exists not just one three-dimensional space, but many such spaces. This in turn is possible only in a world of at least four-dimensions. The analysis in this chapter implies that Minkowski's four-dimensional formulation of special relativity is *logically* contained in Galileo's principle of relativity and could have been discovered earlier.

Chapter 4 develops a simple idea – if the world is four-dimensional with time entirely given as the fourth dimension, it should be a monolithic entity given at once and should resemble the ordinary three-dimensional Euclidean space since it is also given at once. In such a case the relations between worldlines (containing the whole histories of physical objects) in this four-dimensional world should be similar to the corresponding relations between lines in the Euclidean space. That is why a translation of Euclidean relations between lines into the corresponding relations between worldlines in the four-dimensional world should be regarded as a manifestation of the four-dimensionality of the world that can be tested experimentally. When those translations are obtained in Chap. 4, it turns out that they coincide with the kinematic consequences of special relativity. This shows, as Minkowski argued, that it is a theory of a four-dimensional world.

2 On the Impossibility of Detecting Uniform Motion

One of the major events that marked the beginning of modern science in the seventeenth century was the acceptance of the heliocentric system of the world. In 1543 Copernicus [2] published his book on the heliocentric model of the solar system, but the acceptance of the new revolutionary view became possible only after the works of Kepler [3] and especially Galileo [4].

In this chapter we will see that Galileo played a crucial role in the Copernican revolution. He was the first scientist to apply systematically what we now call the hypothetico-deductive method (formulating hypotheses, deducing conclusions, and testing them experimentally) which is recognized as the key ingredient of a genuine scientific activity that leads to the formulation of a new theory. This approach helped him realize why Aristotle's view on motion had been the main reason for the dominance of the geocentric world system due to Aristotle and Ptolemy over the two preceding millennia. And indeed Aristotle's view on motion looked self-evident even in the seventeenth century since it appeared to be in perfect agreement with the common-sense view based on people's everyday experience. This view was almost certainly the ultimate reason for the rejection of the first heliocentric model put forward by Aristarchus of Samos (310–230 B.C.) immediately after Aristotle's geocentric system of the world.

With this in mind we can better appreciate Galileo's role in the acceptance of the heliocentric system. His disproof of Aristotle's view on motion was so important that one may wonder how many more years would have been needed for the ideas of Copernicus to be recognized if Galileo had not written his *Dialogue Concerning the Two Chief World Systems – Ptolemaic and Copernican*.

2.1 Aristotle's View on Motion

Aristotle did not hold any counter-intuitive views on motion as the Eleatics did.[1] His view reflected people's everyday experience and was summarized in the first sentence in Book VII of his *Physics*: "Everything that is in motion must be moved by something." Aristotle believed that there were two types of motion – natural motion of a body which tends to reach its natural place (the center of the Earth) and violent motion which is the motion that needs a mover. Aristotle himself realized that his view led to a problem since it could not explain the motion of projectiles [7, Book VIII, Chap. 10]:

> If everything that is in motion with the exception of things that move themselves is moved by something else, how is it that some things, e.g., things thrown, continue to be in motion when their movent is no longer in contact with them?

This is really an obvious argument against the way Aristotle explained motion: if we throw a stone it should stop at the moment it leaves our hand but this is not what is observed – the stone continues its motion *on its own* until it hits the ground. Aristotle seemed to believe that the observed continuing motion of projectiles can be explained by assuming that the medium in which projectiles travel is moving them. In the case of the stone it is our hand, while throwing the stone, that moves the medium (the air) which in turn acts as a mover of the stone.

Before discussing Galileo's crushing arguments against Aristotle's view on motion, let us examine in more detail how it contradicts the heliocentric system. Here is an excerpt from Ptolemy's *The Almagest* in which he employs Aristotle's view on motion in order to demonstrate that the Earth does not move [8]:

> Now some people, although they have nothing to oppose to these arguments, agree on something, as they think, more plausible. And it seems to them there is nothing against their supposing, for instance, the heavens immobile and the earth as turning on the same axis from west to east very nearly one revolution a day; or that they both should move to some extent, but only on the same axis as we said, and conformably to the overtaking of the one by the other.

[1] The Eleatic school of philosophy held that the observed motion and change are just illusions; the true reality, according to them, is an eternal existence [5, 6]. The Eleatic view is amazingly similar to the view suggested by special relativity, as we will see in Chap. 5.

> But it has escaped their notice that, indeed, as far as the appearances of the stars are concerned, nothing would perhaps keep things from being in accordance with this simpler conjecture, but that in the light of what happens around us in the air such a notion would seem altogether absurd. For in order for us to grant them what is unnatural in itself, that the lightest and subtlest bodies either do not move at all or no differently from those of contrary nature, while those less light and less subtle bodies in the air are clearly more rapid than all the more terrestrial ones; and to grant that the heaviest and most compact bodies have their proper swift and regular motion, while again these terrestrial bodies are certainly at times not easily moved by anything else – for us to grant these things, they would have to admit that the earth's turning is the swiftest of absolutely all the movements about it because of its making so great a revolution in a short time, so that all those things that were not at rest on the earth would seem to have a movement contrary to it, and never would a cloud be seen to move toward the east nor anything else that flew or was thrown into the air. For the earth would always outstrip them in its eastward motion, so that all other bodies would seem to be left behind and to move towards the west.
>
> For if they should say that the air is also carried around with the earth in the same direction and at the same speed, nonetheless the bodies contained in it would always seem to be outstripped by the movement of both. Or if they should be carried around as if one with the air, neither the one nor the other would appear as outstripping, or being outstripped by, the other. But these bodies would always remain in the same relative position and there would be no movement or change either in the case of flying bodies or projectiles. And yet we shall clearly see all such things taking place as if their slowness or swiftness did not follow at all from the earth's movement.

The above arguments can be summarized in a single argument discussed by Galileo in his *Dialogue Concerning the Two Chief World Systems – Ptolemaic and Copernican* published in 1632 [4, p. 139]. Consider dropping a stone from the top of a tower. If the Earth is not moving as the Ptolemaic view holds, the stone will fall at the base of the tower. Assume now that the Earth is moving (consider just its rotation). During the time a stone dropped from the tower falls the Earth will move and the stone will not fall at the base of the tower.

Since no one had ever observed such an effect the supporters of the Ptolemaic system maintained that the heliocentric system was wrong.

The arguments against the heliocentric system, which appeared to be so convincing for centuries, are based on Aristotle's view that everything that moves needs a mover. And indeed if we assume that the Earth is moving and we are on the top of the tower holding a stone, it does follow from Aristotle's view that the stone will stop moving with the tower at the moment our hand releases it – the mover (our hand) is not acting on the stone any more and it will stop moving in a horizontal direction. For this reason it will land at a given distance from the tower. At first sight such arguments appear irrefutable, and this is perhaps the most probable explanation for why the Ptolemaic system prevailed over the heliocentric system of Aristarchus of Samos.

2.2 Copernicus and Ptolemy's Arguments Against the Earth's Motion

In the sixteenth century Nicholas Copernicus (1473–1543) again argued that the Earth was not stationary at the center of the cosmos but rather rotated on its axis and also orbited the Sun. In his fundamental work *On the Revolutions of the Heavenly Spheres*, he advanced the argument that it was more natural to assume that the Earth is orbiting the Sun. However, as seen from the following quote he did not disprove Ptolemy's arguments against the Earth's motion [2, p. 519]:

> But let us leave to the philosophers of nature the dispute as to whether the world is finite or infinite, and let us hold as certain that the Earth is held together between its two poles and terminates in a spherical surface. Why therefore should we hesitate any longer to grant to it the movement which accords naturally with its form, rather than put the whole world in a commotion – the world whose limits we do not and cannot know? And why not admit that the appearance of daily revolution belongs to the heavens but the reality belongs to the Earth? And things are as when Aeneas said in Virgil: "We sail out of the harbor, and the land and the cities move away." As a matter of fact, when a ship floats on over a tranquil sea, all the things outside seem to the voyagers to be moving in a movement which is the image of their own, and they think on the contrary that they themselves and all the things with them are at rest. So it can easily happen in the case of the movement of the Earth that

> the whole world should be believed to be moving in a circle. Then what would we say about the clouds and the other things floating in the air or falling or rising up, except that not only the Earth and the watery element with which it is conjoined are moved in this way but also no small part of the air and whatever other things have a similar kinship with the Earth? Whether because the neighbouring air, which is mixed with earthly and watery matter, obeys the same nature as the Earth or because the movement of the air is an acquired one, in which it participates without resistance on account of the contiguity and perpetual rotation of the Earth.

Copernicus essentially *postulated* that all objects should participate in the Earth's motion. As the history of science has shown, this was not the best way to respond to an argument. Given the fact that Aristotle's view on motion was still the accepted doctrine in the sixteenth century, the arguments against the Earth's motion, which were based on Aristotle's view, were at that time valid arguments that had to be addressed properly. That is why the resurrection of the heliocentric system by Copernicus' ideas only became possible after Galileo disproved both Aristotle's view on motion and Ptolemy's arguments against the Earth's motion.

It is tempting to assume from this text that Copernicus implicitly advanced the idea of relative motion. A careful reading of his argument, however, shows that he simply wanted to point out that, just as it appears to the sailors that the harbor and the cities move away (whereas in fact it is the ship that is moving), it only looks to us that the heavens are rotating, whereas *in reality* it is the Earth that (absolutely) moves.

2.3 Galileo's Disproof of Aristotle's View on Motion

Galileo clearly realized that the arguments against the motion of the Earth and therefore against the heliocentric system were based on the Aristotelian doctrine of motion. For this reason he critically examined it and found it to contradict well-known facts about motion at that time. He did that in two independent ways. First, he showed that Aristotle's explanation of the motion of projectiles was wrong – in reality, once thrown, projectiles move on their own, not by the medium in which they travel. Second, he presented analyses of different experiments which independently arrived at the conclusion that in order to maintain their uniform motion, bodies do not need a constant mover. On the basis of the new view on motion, Galileo demonstrated that the arguments against the Earth's motion no longer hold, and this paved the way for the acceptance of the heliocentric model of the solar system.

Let us now see how Galileo achieved such an enormous result. In his *Dialogue Concerning the Two Chief World Systems – Ptolemaic and Copernican*, Simplicio defends the Ptolemaic system, whereas Salviati and Sagredo provide arguments against it.

First, Galileo gives an example of how a scientific debate should be conducted by stating the main arguments of his opponents. He does this through Salviati [4, p. 126]:

> As the strongest reason of all is adduced that of heavy bodies, which, falling down from on high, go by a straight and vertical line to the surface of the earth. This is considered an irrefutable argument for the earth being motionless. For if it made the diurnal rotation, a tower from whose top a rock was let fall, being carried by the whirling of the earth, would travel many hundreds of yards to the east in the time the rock would consume in its fall, and the rock ought to strike the earth that distance away from the base of the tower. This effect they support with another experiment, which is to drop a lead ball from the top of the mast of a boat at rest, noting the place where it hits, which is close to the foot of the mast; but if the same ball is dropped from the same place when the boat is moving, it will strike at that distance from the foot of the mast which the boat will have run during the time of fall of the lead, and for no other reason than that the natural movement of the ball when set free is in a straight line toward the center of the earth.

Now the stage is set for Galileo to show that these arguments against the Earth's motion are not irrefutable. As we will see the power of Galileo's arguments, presented by Salviati and Sagredo, is determined by the fact that they combine references to experiments and logical analysis. As one cannot perform the tower experiment on a moving Earth and on a motionless Earth to test whether it will produce different results, Salviati concentrates on the ship version of the experiment and asks Simplicio [4, p. 144]:

> You say, then, that since when the ship stands still the rock falls to the foot of the mast, and when the ship is in motion it falls apart from there, then, conversely, from the falling of

> the rock at the foot it is inferred that the ship stands still, and from its falling away it may be deduced that the ship is moving. And since what happens on the ship must likewise happen on the land, from the falling of the rock at the foot of the tower one necessarily infers the immobility of the terrestrial globe. Is that your argument?

After Simplicio agrees, Salviati continues [4, p. 144]:

> Now tell me: If the stone dropped from the top of the mast when the ship was sailing rapidly fell in exactly the same place on the ship to which it fell when the ship was standing still, what use could you make of this falling with regard to determining whether the vessel stood still or moved?

Simplicio's reply is: "Absolutely none". Salviati's next question is on whether Simplicio ever carried out "this experiment of the ship". He did not do it himself but insisted he believed the authorities "who adduce it had carefully observed it." At this point Salviati provides perhaps the clearest hint that Galileo performed the experiment with a stone falling from the mast of a moving ship [4, pp. 144–145]:

> For anyone who does will find that the experiment shows exactly the opposite of what is written; that is, it will show that the stone always falls in the same place on the ship, whether the ship is standing still or moving with any speed you please. Therefore the same cause holding good on the earth as on the ship, nothing can be inferred about earth's motion or rest from the stone falling always perpendicularly to the foot of the tower.

As Simplicio remains skeptical about what the result of a real experiment will be, Salviati virtually threatens him to make him realize the true conclusion without the need of any experiment [4, p. 145]:

> Without experiment, I am sure that the effect will happen as I tell you, because it must happen that way; and I might add that you yourself also know that it cannot happen otherwise, no matter how you may pretend not to know it – or give that impression. But I am so handy at picking people's brains that I shall make you confess this in spite of yourself.

What Salviati had in mind is the famous experiment involving inclined planes (see Fig. 2.1a) [4, p. 145]:

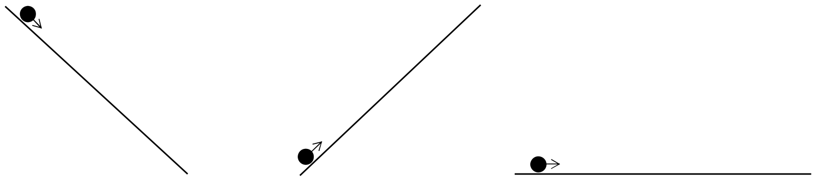


Fig. 2.1. Galileo's experiment with inclined planes

> Suppose you have a plane surface as smooth as a mirror and made of some hard material like steel. This is not parallel to the horizon, but somewhat inclined, and upon it you have placed a ball which is perfectly spherical and of some hard and heavy material like bronze. What do you believe this will do when released?

Simplicio gives the obvious answer: "the ball will continue to move indefinitely, as far as the slope of the surface is extended, and with a continually accelerated motion." Then Salviati asks what will happen to the ball if it is made to move upward on an inclined plane by a forcibly impressed impetus upon it (Fig. 2.1b). Simplicio does not have any difficulty responding to this question either [4, p. 146]:

> The motion would constantly slow down and be retarded, being contrary to nature, and would be of longer or shorter duration according to the greater or lesser impulse and the lesser or greater slope upward.

After discussing the two types of slope, Salviati takes the next logical step [4, p. 147]:

> Now tell me what would happen to the same movable body placed upon a surface with no slope upward or downward.

Simplicio seems to be a little perplexed [4, p. 147]:

> Here I must think a moment about my reply. There being no downward slope, there can be no natural tendency towards motion; and there being no upwards slope, there can be no resistance to being moved, so there would be an indifference between the propensity and the resistance to motion. Therefore it seems to me that it ought naturally to remain stable.

Now Salviati asks the crucial question [4, p. 147]: