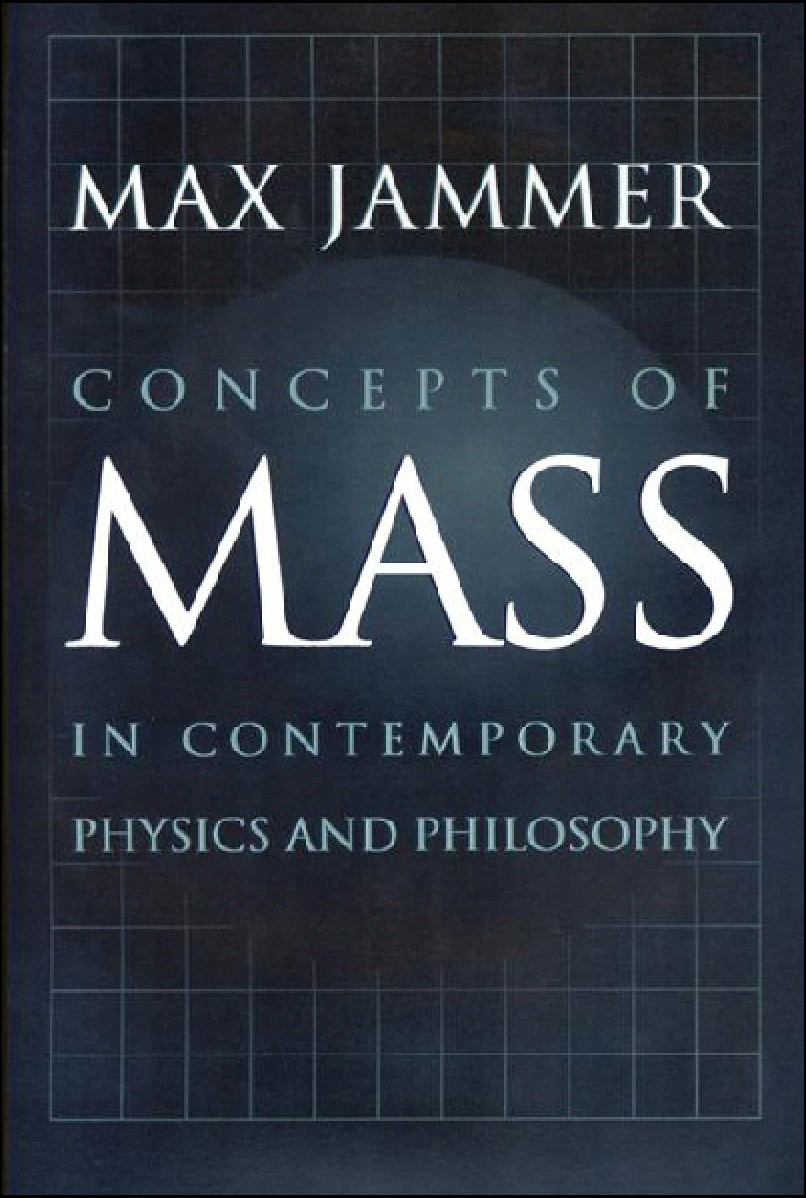

MAX JAMMER

CONCEPTS OF MASS IN CONTEMPORARY PHYSICS AND PHILOSOPHY

Concepts of Mass in Contemporary Physics and Philosophy

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* Preface *

This book intends to provide a comprehensive and self-contained study of the concept of mass as defined, employed, and interpreted in contemporary theoretical and experimental physics and as critically examined in the modern philosophy of science. It studies in particular how far, if at all, present-day physics contributes to a more profound understanding of the nature of mass.

In order to make this book accessible not only to the professional physicist but also to the nonspecialist interested in the foundations of physics, unnecessary technicalities and complicated mathematical calculations have been avoided without, however, impairing the accuracy and logical rigor of the presentation.

Next to space and time, mass is the most fundamental notion in physics, especially once its so-called equivalence with energy had been established by Albert Einstein. Moreover, it has even been argued repeatedly that "space-time does not exist without mass-energy," as a prominent astrophysicist has phrased it.[1]

Although for the sake of completeness and comprehension the text includes some historical and explanatory comments, it deals mainly with developments that occurred after 1960. In fact, the year 1960 marks the beginning of a new era of experimental and theoretical research on gravitation and general relativity, the two main bases of our modern conception of mass. In 1960 the first laboratory measurement of the gravitational redshift was performed by P. V. Pound and G. A. Rebka, and the first recording of a radar echo from a planet (Venus) was made. In 1960 the spinor approach to general relativity was developed by R. Penrose. In the same year V. W. Hughes and independently R.W.P. Drever confirmed the isotropy of inertial mass by what has been called the most precise null experiment ever performed; and R. H. Dicke, together with P. G. Roll and R. Krokov, planned the construction of their famous "Princeton experiment," which was soon to confirm the equivalence of inertial and gravitational mass with an unprecedented degree of accuracy. All these events rekindled interest in studying the properties of mass and endowed the study with a vigor that has not abated since.

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[1] D. Lynden-Bell, "Inertia," in O. Lahav, E. Terlevich, and D. J. Terlevich, eds., *Gravitational Dynamics* (Cambridge, Mass.: Cambridge University Press, 1996), p. 235.

As this book deals primarily with developments that occurred during the relatively short interval of only four decades, its presentation is predominantly thematic and not chronological. The first chapter discusses the notion of inertial mass and in particular the still problematic issue of its noncircular definability. Chapter 2 deals with problems related to the concept of relativistic or velocity-dependent mass and to the notion of velocity-independent rest mass. Chapter 3 clarifies certain misconceptions concerning the derivations of the mass-energy relation, usually symbolized by the equation $E = mc^2$, and comments on various interpretations of this relation. Chapter 4 analyzes the trichotomy of mass into the categories of inertial, active gravitational, and passive gravitational mass and studies the validity of the equivalence principle for test particles and for massive bodies. The final chapter, probably the most controversial one, discusses recently proposed global and local theories of the nature of mass.

In order to make the presentation self-contained I found it appropriate to recapitulate very briefly some antecedent developments with which the reader should be familiar in order to understand the new material. I have also included historical items, irrespective of their dates, whenever their inclusion seemed useful for the comprehension of an important issue of the discussion. The text is fully documented and contains bibliographical references that will enable readers to pursue the study of a particular issue in which they happen to be interested. Some of these bibliographical notes refer to the 1961 Harvard edition of *Concepts of Mass in Classical and Modern Physics*, abbreviated henceforth as *COM*.[2] These notes are quoted with reference to the relevant chapter or its section in *COM* and not to its pagination for the following reason. Later editions of *COM* in English—such as the 1964 paperback edition in the Torchbook Series of Harper and Row, New York, or translations into other languages (such as the Russian translation by academician N. F. Ovchinnikov, issued in 1967 by Progress Publishers, Moscow; the 1974 German translation by Prof. H. Hartmann, published by Wissenschaftliche Buchgesellschaft, Darmstadt; the Italian translation by Dr. M. Plassa and Dr. I. Prinetti of the Istituto di Metrologia in Torino, published by G. Feltrinelli Editore, Milan; and the Japanese translation by professors Y. Otsuki, Y. Hatano, and T. Saito, which appeared under the imprint of Kodansha Publishers, Tokyo)—differ in pagination but

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[2] Harvard University Press, Cambridge, Mass., 1961; republished in 1997 by Dover Publications, Mineola, New York.

not in the order of chapters or of sections. The references can therefore also be used by the reader of any of these various versions. The present monograph does not presume to resolve the problem of mass. Its purpose is rather to show that the notion of mass, although fundamental to physics, is still shrouded in mystery.

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Concepts of Mass in Contemporary Physics and Philosophy

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Introduction

THE CONCEPT of mass is one of the most fundamental notions in physics, comparable in importance only to the concepts of space and time. Isaac Newton, who was the first to make systematic use of the concept of mass, was already aware of its importance in physics. It was probably not a matter of fortuity that the very first statement in his *Principia*, the most influential work in classical physics, presents his definition of mass or of "quantitas materiae," as he still used to call it.[1] However, his definition of mass as the measure of the quantity of matter, "arising from its density and bulk conjointly," was for several reasons soon regarded as inadequate. Since then, the quest for an adequate definition of mass, combined with the search for a more profound understanding of its meaning, its nature, and its role in the physical sciences, has never ceased to engage the attention of physicists and philosophers alike.

That still today "mass is a mess," as a contemporary physicist punningly phrased it,[2] should not come as a surprise. For "in the world of human thought generally, and in physical science particularly, the most important and most fruitful concepts are those to which it is impossible to attach a well-established meaning."[3]

Yet, the remarkable progress in experimental and theoretical physics made during the past few decades has considerably deepened our knowledge concerning the nature of mass. In particular, recent advances in the general theory of relativity and in the theory of elementary particles have opened new vistas that promise to lead us to a more profound understanding of the nature of mass. It is the intention of the present study to review these developments in a rigorous and yet concise fashion.

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[1] I. Newton, *Philosophiae Naturalis Principia Mathematica* (London: J. Streater, 1687, 1713, 1726), p. 1; *Isaac Newton's Mathematical Principles of Natural Philosophy and His System of the World* (Berkeley: University of California Press, 1934), p. 1.

[2] W. T. Padgett, "Problems with the Current Definitions of Mass," *Physics Essays* **3**, 178–182 (1990).

[3] H. A. Kramers, statement at the Princeton Bicentennial Conference on the Future of Nuclear Energy, 1946, in K. K. Darrow, ed., *Physical Science and Human Values* (Princeton: Princeton University Press, 1947), p. 196.

✻ CHAPTER ONE ✻

Inertial Mass

Mechanics, as understood in post-Aristotelian physics,[1] is generally regarded as consisting of kinematics and dynamics. Kinematics, a term coined by André-Marie Ampère,[2] is the science that deals with the motions of bodies or particles without any regard to the causes of these motions. Studying the positions of bodies as a function of time, kinematics can be conceived as a space-time geometry of motions, the fundamental notions of which are the concepts of length and time. By contrast, dynamics, a term probably used for the first time by Gottfried Wilhelm Leibniz,[3] is the science that studies the motions of bodies as the result of causative interactions. As it is the task of dynamics to explain the motions described by kinematics, dynamics requires concepts additional to those used in kinematics, for "to explain" goes beyond "to describe."[4]

The history of mechanics has shown that the transition from kinematics to dynamics requires only *one* additional concept—either the concept of mass or the concept of force. Following Isaac Newton, who began his *Principia* with a definition of mass, and whose second law of motion, in Euler's formulation $F = ma$, defines the force F as the product of the mass m and the acceleration a (acceleration being, of course, a kinematical concept), the concept of mass, or more exactly the concept of inertial mass, is usually chosen. The three fundamental notions of mechanics are therefore length, time, and mass, corresponding to the three physical

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[1] In Aristotelian physics the term "mechanics" or μηχανική (τέχνη), derived from μήχος (contrivance), meant the application of an artificial device "to cheat nature," and was therefore not a branch of "physics," the science of nature. "When we have to produce an effect contrary to nature . . . we call it mechanical." Cf. the pseudo-Aristotelian treatise *Mechanical Problems* (847 a 10).

[2] "C'est à cette science où les mouvements sont considérés en eux-mêmes . . . j'ai donné le nom de *cinématique*, de κίνημα, mouvement." A.-A. Ampère, *Essai sur la philosophie des sciences* (Paris: Bachelier, 1834), p. 52.

[3] G. W. Leibniz, "Essai de Dynamique sur les loix du mouvement," in C. I. Gerhardt, ed. *Mathematische Schriften* (Hildesheim: Georg Olms, 1962), vol. 6, pp. 215–231; "Specimen Dynamicum," ibid., pp. 234–254.

[4] M. Jammer, "Cinematica e dinamica," in *Saggi su Galileo Galilei* (Florence: G. Barbèra Editore, 1967), pp. 1–12.

dimensions L, T, and M with their units the meter, the second, and the kilogram. As in the last analysis all measurements in physics are kinematic in nature, to define the concept of mass and to understand the nature of mass are serious problems. These difficulties are further exacerbated by the fact that physicists generally distinguish among three types of masses, which they call inertial mass, active gravitational mass, and passive gravitational mass. For the sake of brevity we shall often denote them by m_i, m_a, and m_p, respectively.

As a perusal of modern textbooks shows, contemporary definitions of these concepts are no less problematic than those published almost a century ago.[5] Today, as then, most authors define the inertial mass m_i of a particle as the ratio between the forced F acting on the particle and the acceleration a of the particle, produced by that force, or briefly as "the proportionality factor between a force and the acceleration produced by it." Some authors even add the condition that F has to be "mass-independent" (nongravitational), thereby committing the error of circularity.

The deficiency of this definition, based as it is on Newton's second law of motion

$$F = m_i a \tag{1.1}$$

is of course its use of the notion of force. For if "force" is regarded as a primitive, that is, as an undefined term, then this definition defines an *ignotum per ignotius*; and if "force" is defined, as it generally is, as the product of acceleration and mass, then the definition is obviously circular.

The active gravitational mass m_a of a body, roughly defined, measures the strength of the gravitational field produced by the body, whereas its passive gravitational mass m_p measures the body's susceptibility or response to a given gravitational field. More precise definitions of the gravitational masses will be given later on.

Not all physicists differentiate between m_a and m_p. Hans C. Ohanian, for example, calls such a distinction "nonsense" because, as he says, "the equality between active and passive mass is required by the equality of action and reaction; an inequality would imply a violation of momentum conservation."[6]

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[5] E. V. Huntington, "Bibliographical Note on the Use of the Word Mass in Current Textbooks," *The American Mathematical Monthly* **25**, 1–15 (1918).

[6] H. C. Ohanian, *Gravitation and Spacetime* (New York: Norton, 1973), p. 17.

These comments are of course not intended to fault the authors of textbooks, for although it is easy to employ the concepts of mass it is difficult, as we shall see further on, to give them a logically and scientifically satisfactory definition. Even a genius such as Isaac Newton was not very successful in defining inertial mass!

The generally accepted classification of masses into m_i, m_a, and m_p, the last two sometimes denoted collectively by m_g for gravitational mass, gives rise to a problem. Modern physics, as is well known, recognizes three fundamental forces of nature apart from gravitation—the electromagnetic, the weak, and the strong interactions. Why then are non-inertial masses associated only with the force of gravitation? True, at the end of the nineteenth century the concept of an "electromagnetic mass" played an important role in physical thought.[7] But after the advent of the special theory of relativity it faded into oblivion. The problem of why only gravitational mass brings us to the forefront of current research in particle physics, for it is of course intimately related to the possibility, suggested by modern gauge theories, that the different forces are ultimately but different manifestations of one and the same force. From the historical point of view, the answer is simple. Gravitation was the first of the forces to become the object of a full-fledged theory which, owing to the scalar character of its potential as compared with the vector or tensor character of the potential of the other forces, proved itself less complicated than the theories of the other forces.

Although the notions of gravitational mass m_a and m_p differ conceptually from the notion of inertial mass m_i, their definitions, as we shall see later on,[8] presuppose, implicitly at least, the concept of m_i. It is therefore logical to begin our discussion of the concepts of mass with an analysis of the notion of inertial mass.

There may be an objection here on the grounds that this is not the chronological order in which the various conceptions of mass emerged in the history of civilization and science. It is certainly true that the notion of "weight," i.e., $m_p g$, where g is the acceleration of free fall, and hence, by implication m_p, is much older than m_i. That weights were used in the early history of mankind is shown by the fact that the equal-arm balance can be traced back to the year 5000 B.C. "Weights" are also mentioned

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[7] For the history of the notion of "electromagnetic mass" see chapter 11 in M. Jammer, *Concepts of Mass in Classical and Modern Physics* (Cambridge, Mass.: Harvard University Press, 1961), referred to henceforth as *COM*.

[8] See the beginning of chapter 4.