

Mendel Sachs



CONCEPTS OF MODERN PHYSICS

The Haifa Lectures

Imperial College Press



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Mendel Sachs

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To the Memory of
Abraham Kaplan and Nathan Rosen
Philosopher and Physicist par excellence

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PREFACE

This book is based on a lecture course that I taught in Israel, entitled ‘Concepts of Modern Physics.’ It was given in the spring term, 2006, in the Philosophy Department, University of Haifa.

The main emphasis of this course is the *concepts* of modern physics: the quantum theory and the theory of relativity, and their relation to problems of modern astrophysics and cosmology. The discussion is largely from the point of view of the ideas of modern physics, rather than from their mathematical expressions. [*The reader may skip some of the unavoidable mathematical terms, especially in Lecture VI on the quantum theory, without losing too much of the thread of ideas of the entire book.*]

As a professional physicist, I learned in the early stages of my career that physics without philosophy does not fulfill the goal of science. It does fulfill its obligation of providing empirical descriptions of the ways of nature. This is the *descriptive stage* of science. But it is essential that one must then proceed to the *explanatory stage*, including some of the philosophical understandings. Einstein made the following poignant comment: “Physics without Philosophy would be blind; Philosophy without Physics would be lame.”

Some who attended my Haifa lectures asked this question: Is not a *complete* description of a phenomenon in nature a sufficient explanation of it? My answer is No! The goal of science — the truths about the natural world — comes in the two stages. The first

stage is at the *descriptive* level. It is based on experimentation. Once this is achieved, one must then use rational analyses as well as human intuition to proceed to the second stage — the stage of *explanation*. The explanation is in terms of underlying principles. With logical and mathematical analyses, one may then deduce *from these alleged first principles* the features of the derived facts of natural phenomena. If these are in agreement with the empirical facts, one may then claim (at least contingently!) to have achieved an increase in our comprehension of the real world.

This course consists of ten lectures: I. Philosophy of Science, II. Classical Precursors for the Concepts of Modern Physics, III. Nineteenth Century Physics: Atomism and Continuity, IV. Early Anomalies and Elementary Particles, V. From the Old Quantum Theory to Quantum Mechanics, VI. Quantum Mechanics: Heisenberg's Matrix Mechanics and the Copenhagen School, VII. Concepts of the Theory of Relativity, VIII. From Special to General Relativity, IX. The Universe, X. Conflicts in the Foundations of the Quantum and Relativity Theories.

The idea of this course of lectures is to discuss modern physics primarily from a critical point of view — *thus the view of philosophy* — as well as the view of the history of science.

The ideas expressed in these lectures evoked controversial discussions about the concepts of modern physics. Out of these controversies, I believe that: (1) There developed an incitement for the participants in the course to think for themselves about the ideas of science, (2) the idea was conveyed that controversy is essential for progress in science (and in any other fields of ideas that search for the truth), (3) a belief that we can never reach a *complete* understanding of the real world. Thus, physics remains a never-ending adventure into unknown territory. We have indeed achieved more comprehension about the real world at this stage of our history than was achieved in past times. But we should also know that our comprehension of the world, so far achieved, is infinitesimal in comparison with what there is to be understood!

Mendel Sachs
Buffalo, New York, September, 2006

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I thank Robert R. Sachs for his excellent and critical reading of these lectures. His philosophical insights were invaluable. I also thank the students and faculty who attended these lectures in the Department of Philosophy, University of Haifa, Israel, for their pertinent questions and comments.

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Lecture I

PHILOSOPHY OF SCIENCE

Introduction

In the following lectures, I wish to discuss in a mainly non-mathematical way, the concepts of modern physics. The word “concepts” refers to the *ideas* that underlie modern physics.

It is true that for the training of professional physicists, to make progress in the exploration of the truths of nature one must learn the mathematical language to facilitate an expression of the laws of nature. Plato advised that: for the students to become educated, they must first master the field of mathematics. Once this is done, he continued, they are ready to study the field of physics. After this, they are finally ready to study philosophy.

It is interesting that about 15 centuries after Plato, in the Middle Ages, the Jewish philosopher/theologian, Rambam (known in the western world as Maimonides) added to Plato’s advice. He wrote a book aimed at the ‘true’ student, called The Guide for the Perplexed (University of Chicago, 1963, transl. S. Pines). In this treatise he advised the student that after following Plato’s advice, in mastering mathematics, physics and philosophy, he was ready to study the spiritual side of the real world — to attempt to understand the Biblical Scriptures in terms of first principles.

I do not generally agree that an education necessitates Plato’s first requirement — a broad knowledge of how to facilitate and to

understand the intricacies of mathematics. Galileo correctly commented that *the book of nature is written in the language of mathematics*. However, according to Plato's own teaching, a language, *per se*, is not the set of concepts that it is meant to express. In this course, we will stress the concepts of physics rather than its mathematical language.

The adjective, "modern," in the title of this course, refers to 20th century physics, from the concepts that underlie elementary particle physics — the physics of the smallest domain — to those of cosmology — the physics of the universe as a whole.

It is significant that the 20th century has witnessed the confluence of two scientific revolutions, rather than one at a time. These are the theory of relativity, led primarily by Albert Einstein, and the quantum theory, led primarily by Niels Bohr. What was fascinating about two rather than one revolution in science was that, on the one hand, each of these theories is incompatible with the other, both mathematically and conceptually, on foundational terms. But on the other hand, each of these theories requires the other for its completion. This is the major problem of modern physics that will be emphasized throughout this course of lectures.¹

Because of their conceptual and mathematical incompatibility, it follows that if one of these two dichotomous theories of matter is true, the other must be false, as foundational truths of nature, even though each has been empirically successful in its own domain of nature. A way out of this dilemma would be to fully reject the underlying concepts of one of these theories while generalizing the other theory so as to recover the empirically successful features of the rejected theory, *as a mathematical approximation*. [This relies on the well-known *principle of correspondence* to tell us how to approach the formal expression of an earlier rejected theory — where it works! — from a later accepted theory in science.] I will argue, toward the end of the course, that, in my judgment, it is the theory of general relativity that will survive to *explain* the basic nature of matter in all domains — from elementary particle physics to cosmology. But the main thrust of the course will be to *explain* the basic concepts of both the quantum and relativity theories. The

readers may then make up their own minds as to which of these theories is more true to nature than the other, in all domains.

At this juncture, I wish to qualify my earlier use of the term “scientific revolution.” I do not believe that the history of science is indeed characterized by ‘revolutions’ — a total rejection of earlier concepts and replacing them with entirely new concepts to explain natural phenomena.² I do believe, based on my study of the history of science, that science progresses in an ‘evolutionary’ manner. Here, there are ‘threads of truth’ that persist from one period of ‘normal science’ to another. Indeed, it is the persistence of these threads of truth that gives us confidence that some of the past ideas play an important role in the shaping of present day ideas as well as the future of science.

It is for this reason that I will begin this course (in Lecture II) with ideas from the past that serve as important precursors for present day ideas and the physics of the future. But before we start it is important to discuss some of the ideas of the philosophy of science.

Philosophy of Science

The first question we must answer is: What is the meaning of “physics”? The word was introduced by Aristotle in ancient Greece. It signifies the ‘science of inanimate matter.’³ Of course, there are other sciences — *psychology* is the science of human consciousness, *anthropology* is the science of human cultural systems, *biology* is the science of life systems, etc. But it is thought that physics is the queen of the sciences because it is framed in foundational terms, starting with first principles, while the other sciences, at this stage of our understanding, are more phenomenological — more descriptive than explanatory. Hopefully, some of these latter sciences will proceed to foundational levels at a later stage.

Then what is the meaning of the word “science”? It is the pursuit toward the fundamental *truths* of the natural world. These are expressed in terms of the *laws of nature*. That is to say, the fundamental goals of science are the ‘truths’ of the natural world. These truths, in turn, are at the *explanatory level* of our understanding.

They follow from the *descriptive level* of scientific knowledge. Though some scientists believe that the descriptive level of science is all that there is to know, that is, they believe that scientists should only ask ‘what’ questions, I believe that the explanatory level that follows the descriptive level is the actual goal of science — the answers to the ‘why’ questions. It is the approach that provides the *understanding* of the natural world that we seek. The former philosophical (epistemological) view is that of *positivism* while the latter view is that of *realism*. The latter view was that of Einstein, when he said: “the most incomprehensible thing to me is that we can comprehend anything at all about the real world.”⁴

Truth

Our primary goal in science, then, is to acquire the truth about the natural world. It is important to be cognizant, in this regard, that there are different kinds of truth, defined in different contexts.

As I see it, there are three types of truth that we signify in science. The first is ‘analytic truth.’ This is an irrefutable type of truth — it is a *necessary truth*. All mathematical truths are of this sort. For example, the statement $2 + 3 = 5$, is a necessary truth. Defining the integers 2 and 3 as intervals along a linear scale, and the logical definitions of + and =, the conclusion 5 is a necessary, irrefutable truth. It is not tied to nature — it comes from the thinking of the human mind that leads to the invention of the rules of a logical system.

The second type of truth is *scientific truth*. It is, in principle, a *refutable truth* — it is ‘contingent.’ The conclusion of a scientific truth starts with a *guess* about a law of nature to underlie some physical phenomenon. One arrives at this law from hints received from our perceptions of the phenomenon itself as well as from our intuition. The alleged law of nature then leads, by logical deduction, to particulars that are the predictions of empirical facts of nature. If these predictions agree with the empirical facts, then we may say that the original law that led to these results is *scientifically true*. But this is not a necessary truth. It is only as true as the premises that led to the alleged law of nature. Such a law may be

confirmed in terms of different empirical facts predicted by this law for a very long time, perhaps centuries, but it may then be refuted by new empirical evidence that is not predicted by this law of nature, or a demonstration of logical inconsistency in its expression. An example is Newton's second law of motion, $F = ma$. It was empirically verified from the 17th century until the 20th century. Then, Einstein's relativistic mechanics refuted and replaced it. Einstein had then refuted Newton's alleged law of motion. It is important, then, that a scientific truth, tied to nature, is in principle refutable, while an analytic truth, tied to logic, is in principle not refutable. Thus, they are in different contexts. One may then not answer a scientific question with an analytic argument, or answer an analytic question with a scientific argument — they would be non-sequiturs. For example, Pythagoras, in ancient Greece, claimed to come to scientific conclusions about the structure of the universe from mathematical (analytic) arguments.⁵ This is a false claim, as it is a non-sequitur.

A third type of truth is a *religious truth*. It is a truth that is based on faith. This truth is irrefutable as is an analytic truth, but it is not subject to the rules of an invented logical system, as is mathematics. A belief in God is an example of a religious truth. Another example is the scientists' belief that for every effect in the world, there is an underlying cause. (*This is a law of total causation.*) Indeed, it is the *raison d'être* of the scientist to pursue the cause-effect relation that is a law of nature. The pursuit is based on his or her *faith* in the law of total causation. Because this type of truth is in a different context than the analytic or scientific truths, one cannot prove a scientific statement (or an analytic statement) with a religious argument. It would be a non-sequitur. Because scientific truth is in a different context than religious truth, a scientist may have faith in the existence of God (or not have such faith) without giving up his or her integrity as a scientist!

An example that demonstrates this fallacy is in the subject of cosmology (as we will discuss more fully in Lecture IX). It was discovered in the 1920s by E. Hubble, that the galaxies of the universe are moving away from each other at a particular rate, in accordance

with the ‘Hubble law,’ $v = Hr$, where v is the speed of one galaxy relative to another and r is their mutual separation.⁶ Thus, as r increases, v increases linearly — i.e. the galaxies are accelerating relative to each other’s positions, linearly. That is, if, for example, the distance between galaxies doubles, so would their relative speed of separation double. This is called the “expansion of the universe.” [*What is meant by this expansion is not that the universe as a whole is expanding into empty space — because there is no empty space! The universe, by definition, is all that there is! What is meant by the expansion of the universe is that the density of the matter of the universe, at any location within the universe, relative to any observer, is decreasing with respect to any observer’s time measure.*]

Thus if we extrapolate backwards in time, we come to greater and greater densities of the matter of the universe. In the limit, we come to a maximum density and a maximum instability. At that point in time, there is predicted to be a gigantic explosion — the ‘big bang’ — when all of the matter of the universe starts its expansion phase. From the present day astrophysical measurement of the expansion, the Hubble constant H may be determined and the time when the ‘big bang’ happened may be estimated. It is found to be between 12 and 15 billion years ago.

The *scientific question* then arises: How did all of the matter of the universe get into the state of maximum density and instability in the first place? Some (including a number of astrophysicists and physicists) have answered: The ‘big bang’ occurred when God created the universe! But this *religious answer* to a scientific question is a non-sequitur! Indeed, a bona fide scientific question requires a bona fide scientific answer!

The only answer that I see is that before the matter of the universe reached the critical state of maximum density and instability, it was contracting (imploding) from a less dense state toward this more dense state. And before the contraction, the matter of the universe was expanding, and so on *ad infinitum*. This is the *oscillating universe cosmology*. We will discuss it in more detail toward the end of this course of lectures. Suffice it to say at this point that the theory of general relativity allows for this resolution because the parts

of this theory that relate to the force of matter on matter (the affine connection terms) are not ‘positive-definite.’ This implies that gravitational forces entail both attractive and repulsive forces. Under the conditions of sufficiently high density of matter and relative speeds, the repulsive force dominates. This leads to the expanding universe — that matter repels other matter. But when the matter becomes sufficiently rarefied, the attractive force dominates the repulsive force and the expansion changes to a contraction.

This view then predicts, from General Relativity, that the universe is a closed system, undergoing a continual cyclic process of expansion and contraction. The ‘big bang’ we talk about, then, about 12 to 15 billion years ago, is only the beginning of this particular cycle. One might then ask: when was the *actual* ‘beginning’ of the universe — the ‘beginning’ of all of the cycles? (This is the ‘beraisheet’ — the opening word of the Bible.) This is not a scientific question! It is a religious question. It is not definable in terms of our concept of ‘time.’ The idea of ‘timelessness’ is reflected in one of the Kabbalistic names for God — ‘haya-hoveh-yeeheeyeh (*was-is-will be*).

We see here how important it is to clearly distinguish between scientific truth and religious truth. It is only the former that we focus on in this course of lectures. *[It is the recognition of this difference between scientific truth and religious truth that led the courts in the US to the ruling that the religious assertion, called “intelligent design,” may not be taught in the schools as though it were a scientific explanation for the creation of the universe — that it would be a violation of the Constitution’s separation between church and state.]*

Significant Questions in Science

Finally, on the subject of the philosophy of science, it is noteworthy that the theoretical scientists spend most of their time on either answering questions or asking questions. The former is tied mostly to questions of phenomenology (*description* — the ‘what’ questions) and the latter is tied mostly to questions of foundation (*explanation* — the ‘why’ questions).

The difficult thing about asking a question in science is to know in advance if this would be a significant question — that is, a question whose answer could add to our comprehension of the natural world. For it is possible that a scientist may spend most of his or her professional life, as well as the lives of admiring colleagues and students, in trying to answer an insignificant question! Thus it would be useful if there would be some criteria that could help the scientist to decide beforehand if a question in science is indeed significant. One criterion that I have proposed is that if a question leads to *more questions*, it is more likely significant than if it leads to no more questions. The reason is my belief, based on the history of science is that the total understanding of any phenomenon in nature is unbounded — it is infinite in extent. Thus if there would be no more questions about it, the phenomenon would appear to be totally understood — the investigator would claim to have infinite knowledge about it! Since human beings are finite, this would be impossible (i.e. human beings cannot be omniscient)!

I believe that it is for this reason that in the 16th century Galileo said: “there is not a single effect in nature, even the least that exists, such that the most ingenious theorists can arrive at a complete understanding of it.”⁷ This idea stands against the current claims that physicists have discovered a ‘theory of everything!’⁸

In the next lecture, we will present some of the ideas of classical physics from the 16th century onward that were important precursors for the ideas of physics of the 20th century — the quantum and relativity theories.

Lecture II

CLASSICAL PRECURSORS FOR THE CONCEPTS OF MODERN PHYSICS

Galileo Galilei

The Thought Experiment

We start with the researches of Galileo, who lived in the 16th–17th centuries. He is sometimes known as the ‘father of modern physics.’ It is because he taught us a method for approaching scientific truth that has been followed to this day. It is based on an interweaving of theoretical and experimental physics. We start with the ‘thought experiment.’ This is an assumed *ideal* experiment in which assumed conditions are not met in the real world, such as the motion of a body on a frictionless plane. This logical experiment then yields conclusions that may be tested in real experiments. If these experiments give results that are in agreement with the conclusions of the thought experiment, then we may say that the original assumptions of the thought experiment are *scientifically true*.

Galileo’s Principle of Inertia

An interesting example of the thought experiment is Galileo’s deduction of his *Principle of Inertia*. This is the idea that if a material body moves at a constant speed on a horizontal plane, in a

straight line, it will maintain this state of motion forever, unless it is made to alter it by some external influence.⁹ That is, constant motion of a body is one of its natural attributes (in contradiction with the idea of Aristotle, who believed that rest is the natural state of a material body).

The thought experiment that led Galileo to this conclusion is as follows: Consider a material body at the top of a frictionless inclined plane, at the vertical height h . He then argued that the force that would cause the *free fall* of the body (if the inclined plane were not in the way) is directed toward the center of the earth. The original height h of the body, at the top of the inclined plane, corresponds to the state of 'rest' of the body. After the body is released, it slides down the frictionless plane with ever increasing speed, reaching a maximum speed at the bottom. Suppose it then faces a second inclined plane. It would then proceed to move up this plane. When would it stop? He concluded (intuitively!) that at a continuously slower pace, it must stop when it reaches the same vertical height h it had when it started to move on the first downward plane. If the angle of inclination of the (second) upward slope is less than the angle of inclination of the downward slope, the body would have to go further along the upward plane to reach the vertical height h , than the distance it traveled down the first plane from this height. It would then take more time to come to rest on the upward slope, than it did to travel the length of the downward slope. Thus, if one should decrease the angle of inclination of the second slope to be horizontal, i.e. at 0 degrees, after moving down from the first inclined path, it would then be moving on the horizontal plane and it would never come to rest — because it would never reach the vertical height h . The material body would then move forever at the speed v (that it acquired at the bottom of the first slope). Thus, Galileo concluded his *Principle of Inertia* in this way — *a body moves naturally in a straight line, at a constant speed, forever, if no external forces would act on it.*

Of course, this is an *ideal* experiment because there is no such thing as a frictionless plane. In the real case, the body would continually lose energy because of the frictional forces exerted on it by the horizontal plane, until it would stop. But the *Principle of*

Inertia, as stated, is a scientifically true assertion. It was stated a generation later by Newton, who called it his ‘first law of motion.’

Laws of Motion in Two- and Three-Dimensional Space

Galileo discovered that the motion of a body in two or three dimensions may be represented as a superposition of motions in each of the dimensions, separately. It is the way that he discovered the path of projectile motion. The vertical motion is governed by his law of gravity $g = \text{constant}$, where g is the downward acceleration due to gravity, while the superposed horizontal motion is governed by his principle of inertia. This superposition of motions then yields the parabolic trajectory of the projectile. *Later on, it was found that such a superposition of motions in the different directions may be expressed in a vectorial form.*¹⁰

Galileo’s Principle of Relativity

A generation before Galileo, Copernicus discovered that he could not explain the motions of the stars in a single night and a day, that he observed if he assumed that the earth is at rest at the center of the universe, and all of the heavenly bodies, including the Sun, revolve about it. He then postulated that the Sun is at the center of the universe and all heavenly bodies, including the Earth, revolve about it. This is Copernicus’ heliocentric model of the universe — that the Sun is at the absolute center of the universe. His assertion that the ‘Earth moves’ was in contradiction with the teachings of Aristotle and with the Church!

The Copernican concept was a difficult one for human beings (and the Church) to accept in his day. They were taught that the universe was created for mankind, who were placed at its absolute center, on Earth. This pre-Copernican idea has been revived in modern times with the assertion of the *anthropic principle* — the idea that the entire universe was created to accommodate the human race!¹¹

It was in the generation after Copernicus that Galileo asserted the *Principle of Relativity*. He agreed with Copernicus that ‘the Earth moves,’ but he asserted further that ‘motion’ *per se*, is *subjective*.

That is to say, the motion of matter is not one of its *objective* features. With this Galilean view, it is just as *scientifically true* to say that, from the Earth's perspective (i.e. frame of reference), the sun revolves about it, as it is to say that from the Sun's perspective, the Earth revolves about it! That is to say, Galileo saw that 'motion' is not an intrinsic, objective property of matter. He then concluded that, in contrast with Copernicus' heliocentric model of the universe, where it is postulated that the Sun is at the center of the universe, *there is no center of the universe!* [It is often asserted by contemporary physicists that it was discovered in the 15th century that the Earth revolves about the Sun, and not vice versa. This statement is not extended to say what Galileo discovered — that motion is subjective and thus that it is as equally true to say that the Sun revolves about the Earth as it is to say that the Earth revolves about the Sun!]

All that is required in Galileo's view is that the law of nature (in this case a law of gravity) that governs the motion of matter is independent of the perspective from which it is described, in one way or another. This is *Galileo's principle of relativity*.¹² It is an important precursor for *Einstein's principle of relativity* — the primary axiom that underlies the theory of relativity of modern times. A major change in going from Galileo's principle of relativity to that of Einstein is the following: In the former, the spatial coordinates alone are relative to the reference frame in which the laws of nature is expressed, while in the latter the temporal as well as the spatial coordinates are relative to the reference frame.

Threads of Truth – Astronomy

One of Galileo's important contributions was his law of gravity, $g = \text{constant}$.¹³ That is, the acceleration due to gravity g for a freely falling object, along a radial direction of the Earth toward its center, is independent of the weight or size of the body. Of course, in the real world heavier weights are seen to fall more rapidly than lighter weights. But this is due to the different air resistance to these falling weights. Galileo did an experiment to prove this. He placed a heavy and a light weight on a platform in an evacuated jar. Releasing them simultaneously, he saw that they landed at the bottom at the

same time, proving the constancy of g ($= 980 \text{ cm/sec}^2$) for any matter, heavy or light, large or small.

Galileo's law of gravity is a good approximation for Newton's law of universal gravitation near the Earth's surface. With the empirical equivalence of gravitational mass (defined in Newton's law of universal gravitation), and inertial mass (defined in Newton's second of motion), it turned out that in Newton's theory, near the Earth's surface $g = GM/R^2 = 980 \text{ cm/sec}^2$, where G is the universal gravitational constant, M is the mass of the earth and R is the radius of the Earth.

Three hundred years after Newton's discovery, Einstein's theory of general relativity superseded it. This will be discussed later on in the course.

Galileo was the first astronomer to use the telescope to study the heavens. He saw that the moon is not a gas, as Aristotle thought. Rather he discovered that it is a solid mass with craters on its surface. He saw that Jupiter has many moons revolving about it. He (mistakenly) thought that the *Milky Way* — our galaxy — is the entire universe. There were no observations that refuted this conclusion. Two centuries later it was discovered that the *Milky Way* is only one of an infinitude of galaxies of the universe. It was found in the centuries after Galileo that our *Milky Way* has a neighboring galaxy, Andromeda, that forms a binary with our galaxy. *[There is a legend that when Galileo had his telescope focused on Jupiter, he asked a colleague to look at its moons. After the colleague looked, he was upset because what he saw was not what the Church believed. He declared that Galileo was trying to trick him — in setting up pictures of these moons inside of his telescope! Later on, when his colleague was on his deathbed, Galileo whispered in his ear: "You are a good man and will most likely soon go to heaven. On your way up, you will pass Jupiter. When you do, take a look at the vicinity of Jupiter and you will see its moons!"]*

Rene Descartes¹⁴

Rene Descartes was a contemporary of Galileo. It was his idea that the essences of matter are extension and motion. The extension of matter is in space. Since space is continuous, he argued that matter

must be continuous, rather than atomistic. On the other hand, he argued that the expansion or contraction of a piece of metal under changes of temperature implies that its constituent atoms are moving away from or toward each other. With this conclusion, he took the atomistic view of matter. But in the final analysis, Descartes did adhere to the continuous view. He saw the fundamental aspects of matter as vortices in a continuous field. Further, he believed that ‘motion’ is an intrinsic (objective) feature of matter, rather than the subjective feature that Galileo discussed.

These conflicting views of matter and its motion in Descartes are an important precursor for the 20th century dichotomy of wave and particle as foundational elements of matter that arise in the modern quantum theory. This will be addressed in more detail later on in the course.

One problem that concerned Descartes is the dichotomy between *mind* and *matter*. At first, he believed that the fundamental laws of mind and matter are independent, yet they seem to be coupled in some way. For example, I *see* a rose (matter), I *think* about picking it up (mind), I pick it up and put it close to my nose (matter), I sniff it (matter), and I feel good because of its pleasant aroma (mind). Thus, mind and matter are seemingly coupled. Yet, Descartes felt that they are still uncoupled, dynamically. In his view, it is not unlike moving trains on parallel tracks. The trains do not cause each others motions, but there is a correspondence between their motions and positions.

Later on in his career, Descartes seemed to revert to the idea that the laws of mind and matter are unified. He thought that perhaps the pineal gland of the human body is the source of this coupling (since in his day there was no knowledge of the purpose of this gland).

Descartes’ initial studies of the science of human consciousness led some to consider him as the first psychologist.

Baruch Spinoza¹⁵

Spinoza was another of the great contemporaries of Galileo. His method of arriving at the truth was to use the logic of Euclid and

the assertion of *self-evident* facts. He strongly disagreed with the separation of mind and matter in Descartes (or with a *fundamental separation* of observer and observed, or of subject and object). These different components of the whole, such as observer and observed, are to Spinoza only the modes of a continuum. His was a view of *holism* — the idea that there are no singular, separable entities in the universe. Rather, everything is a manifestation (a mode) of a continuous whole. It is an idea that carried over to the continuous field concept in Einstein's theory of general relativity in the 20th century, as a foundational theory of matter.

For example, there is symmetry in Spinoza's view of the cause–effect relations. From the perspective of one component (its frame of reference), one entity (mode) of the whole is the source of the cause of an effect on the other. But from a different perspective, from the frame of reference of the entity that was formerly thought of as the affected one; it is instead the cause and the first entity becomes the one affected.

This view brings in an interesting interpretation of the 'time' parameter in the cause–effect relation. For if the cause is earlier and the effect is later, then one may correlate a time change with the evolution from cause to effect. But when the cause and effect change places, the time must then reverse. Thus, time, *per se*, is not an absolute change. It is only a parameter that is used to represent one's environment in terms of cause–effect relations, from one frame of reference or another. This idea is a very important precursor for a subjective view of time as a relative measure, in the theory of relativity that emerged with Einstein's theory in the 20th century.

Isaac Newton

Isaac Newton was born in the same year (1642) that Galileo died. He is known for his discovery of laws of motion, his law of universal gravitation and his discoveries in the field of optics. He is also known as a great mathematician. He discovered calculus; it was useful for the description of variable motion in the laws of nature.

Newton's Three Laws of Motion¹⁶

Newton's first two laws of motion were derivative from *Galileo's principle of inertia*: If a material body is unimpeded by any external influence, it will move at a constant speed in a straight line, forever. That is, a constant speed (or rest, as a special case) is a natural feature of matter. This statement is also called *Newton's First Law of Motion*.

Thus, there can be no acceleration of a material body without an external force acting on it. *Newton's Second Law of Motion* states that *if an external force F acts on a material body, then it causes it to accelerate at a rate a , in a linear relation, $F = ma$, where m is the constant of proportionality between F and a . m is a measure of the intrinsic inertia of a body — it is its resistance to a change of state of rest or constant speed. It is called the 'inertial mass' of the body.*

Newton's Third Law of Motion does not come from Galileo. It is the assertion that *for any force exerted by a body A on another body B , there is an equal magnitude force in the opposite direction exerted by B on A . Thus, A – B is a closed system. It is easy to see that the implication of Newton's third law of motion is that, fundamentally, any material system is closed. Further, though Newton did not discuss this mathematical implication of his third law (that appears in the theory of relativity of the present period), any mathematical equation that describes a closed system is *non-linear*.¹⁷ Newton's third law of motion plays a very important role as a precursor for Einstein's theory of general relativity, 300 years later. It is one of the 'threads of truth' that persist throughout the history of science.*

Newton's Law of Universal Gravitation

Newton derived his law of universal gravitation to explain the phenomenon of gravity, and to explain Galileo's finding that the acceleration of *any* body in 'free fall' near the Earth's surface is the constant $g = 980 \text{ cm/sec}^2$.

To start, Newton used Kepler's empirical law that for any orbiting body, $r^3\omega^2 = K$, where r is the distance from the orbiting body

to the center of rotation (such as the distance from an orbiting planet to the Sun), ω is the angular frequency of the orbiting body (in radians/sec) and K , Kepler's constant, depends on the parameters of the body at the center of rotation (e.g. those of the Sun in the case of planetary motion). Newton applied Kepler's law to the motion of the moon, orbiting the Earth. He saw that the centripetal force that keeps the moon in its orbit, due to the gravitational force of the earth, is $F(\text{gravity}) = F_c(\text{centripetal force}) = m_{\text{moon}} a_c \equiv m_{\text{moon}} r \omega^2$, where $a_c = r \omega^2$ is the centripetal acceleration of the orbiting moon. According to Kepler's result for any orbiting body, this gives: $F(\text{gravity}) = m_{\text{moon}} K/r^2$.

For the moon's orbital motion, Newton then found the relation for the force of gravity (that keeps the moon from veering off of its orbit in a straight line path) is $F(\text{gravity}) = F_c = G m_{\text{moon}} m_{\text{earth}} / r^2$, where $K = G m_{\text{earth}}$ is Kepler's constant. *[In this formula, m_{earth} is called the "gravitational mass" of the orbiting body — the Earth in this case. It was found empirically to be equal to the inertial mass of the orbiting body.]*

Thus Newton found that the force of gravity is inversely proportional to the square of the distance between the interacting bodies.

Applied to the case of a body falling freely to the Earth near its surface, the force of gravity is (using Newton's second law of motion and his law of gravitation), $mg = GmM/r^2$, where $r = R + h$, R is the radius of the Earth and h is the height of the body with mass m , above the surface of the earth. Thus, Newton derived the constant $g = GM/R^2$. With $r \approx R$, the known parameters of the Earth, M (the mass of the Earth) and R (the radius of the Earth), he then found that $g = 980 \text{ cm/sec}^2$, in agreement with Galileo's measurements. Thus Newton claimed to *explain* Galileo's law of gravity.

Newton then applied his finding to all gravitationally interacting bodies. He applied his calculus to finding a solution for his equation of the gravitational force: $ma \equiv m(d^2r(t))/dt^2 = -GmM/r(t)^2$, (the minus sign denotes an attractive force). He found that the solution $r(t)$ traces an elliptical path of the orbit of a planet, with the Sun's center of mass at one of the focal points of this ellipse — in agreement with Kepler's observation in regard to the orbit of the planet Mars. *[Newton said that if he had not been standing on the*

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shoulders of two giants, Galileo and Kepler, he would not have been able to see as far as he did.]

Newton's law of universal gravitation was then applied successfully to other cases. For example, the orbits of all of the planets of our solar system, the tides (caused by the moon's gravitational pull on the oceans of Earth) the trajectory of Halley's Comet (as it was seen by the astronomer Halley in Newton's day). Newton's law of universal gravitation was then billed as a triumph of science. It was claimed that it should apply to all of the material bodies of the universe. His theory predicted that all bodies must rotate about other bodies of the universe in cyclical orbits, as the planets of our solar system rotate about the sun. The universe was then seen as a giant clock, full of spinning wheels — millions of millions of bodies rotating about other bodies.

It should be noted that the prediction of these orbital paths of all bodies follows from the mathematical separation of the functions of spatial coordinates from the functions of temporal coordinates in the mathematical structure of Newton's theory of the gravitational force. In this way, Newton predicted *stationary orbits* for all bodies of the universe. This is in contrast with Einstein's relativity theory, where the time and space coordinates do not objectively separate. In this case, there are no stationary orbits. The observation of the non-stationary orbit of Mercury about the Sun was then a confirmation of a prediction of Einstein's theory of general relativity and a refutation of Newton's prediction. A second important confirmation is the 20th century observation (by Hubble) of the 'expansion' of the universe, as we will discuss toward the end of this course.

Newton's Concepts

Newton objected to the feature of his law of gravity that is 'action at a distance.' This is the result that gravitationally interacting bodies depend on their mutual spatial separation but not on the time. Thus, if a stellar body, millions of light-years from us should suddenly explode out of existence, we should respond *immediately*. It seemed wrong to Newton. But (perhaps out of frustration) he dismissed the

objection with the claim “I do not form hypotheses!” Still, he had the following criticism of this concept: “Action at a distance through a vacuum, without mediation of anything else by and through which their action and force may be conveyed from one to another, is to me so great an absurdity, that I believe no man who has in philosophical matters competent faculty of thinking, can ever fall into it.” [Both Faraday, of the 19th century, and Einstein, of the 20th century, agreed with Newton’s assessment of the error in the concept of ‘action at a distance.’ But in contrast with Newton, they tried to do something about replacing it with a paradigm change in physical thought!]

Newton’s view of the infinitude of the universe is atomistic. It is made up of individual, separable ‘things’ that interact (or not) with each other. This model is a precursor for the particle view of matter of quantum mechanics (except for its determinism versus the indeterminism of quantum mechanics). But this is in contrast with Einstein’s theory of relativity wherein the world of matter is *holistic* — there are no separate, individual, material particles in the first place. The universe is a continuum whereby the ‘things’ of it are the modes of this continuum, similar to the ripples of a pond.¹⁸

Newton’s Optics

As a generalist, Newton believed that if the material world is atomistic, so must ‘light’ be atomistic. He explained the dispersion of white light (as the light coming from the Sun) as it propagates through a dispersive medium, such as the droplets of water vapor after a rainstorm, or through a prism, as a combination of different colored particles of light — red, orange, yellow, green, blue, indigo, violet — each having the same speed in a vacuum but different speeds in dispersive media. Thus they emerge from a dispersive medium at different times, separating out, as in the view of the rainbow.

With this model he also explained in a mechanical fashion the reflection of light (from a perfect mirror) and refraction of light, i.e. the bending of a light beam as it propagates from one medium to a denser medium). But he could not explain the diffraction of light. He looked for this effect, but he did not see it in his own

experimentation. [Leonardo da Vinci saw the diffraction of light effect 200 years before Newton's time!] An example of the diffraction effect is that of a monochromatic beam of light moving through a screen with holes in it (or past a hair, as in Newton's own experiment) and landing on a second screen with interference maxima and minima. (Newton did not have enough resolution in his experiment to see this effect.) The interference phenomenon is characteristic of waves, not particles! In Newton's day, Robert Hooke and Christiaan Huygens believed in the wave theory of light and, with experimentation, they showed its validity, including the refraction effect and that of the diffraction of light. In the final analysis, it was the wave theory of light that won over the particle theory. The Maxwell theory of electromagnetism, discovered in the 19th century, showed that light is a manifestation of the electromagnetic field, and all of the known features of optics follow from the 'radiation solutions' of Maxwell's equations, representing light as a wave phenomenon. In the 20th century it appeared that units of light (photons) seemed to be particles in some experimentation and waves in other experimentation. This led, in modern times, to the concept of *wave-particle dualism*, which we will discuss later on in our analysis of the quantum theory.

In the next lecture, we will discuss the ideas of 19th century physics, yielding the particle and continuous field views as fundamental, under separate types of experimentation. It is pertinent that the science of the 19th century served as an important bridge between the classical period and that of the revolutionary movements of 20th century physics.

Lecture III

NINETEENTH CENTURY PHYSICS: ATOMISM AND CONTINUITY

The *threads of truth* that carried on through the 19th century, since the earlier classical period of Galileo and Newton, focused on two major trends. One was the description of matter explained with a model of atomism, as studied initially in terms of the gaseous state of matter. This led, in turn, to the laws of gases, thermodynamics and the conservation of energy.

The second trend was toward a view opposite to that of atomism — the continuous field concept as a fundamental notion. It was applied initially to the nature of electricity and magnetism, and thence to an understanding of optics and other radiation phenomena. The atomistic view is based on the idea that all matter is composed of singular, separable, independent *things*, that may or may not interact with each other. The continuous field concept is one of *holism*, wherein the underlying basis of matter is in terms of continuous fields that have as manifestations modes that give the impression of things, but are in reality all correlated through one continuous entity. [*One might see this view as akin to that of Spinoza, in the 16th century — which, in the 20th century, Einstein acknowledged to be very influential in his understanding of the nature of matter. The latter holistic view did not come to full fruition in physics until the discovery of Einstein's theory of general relativity.*]

The Ideal Gas Law

Matter occurs in the universe in three distinct states: gas, solid and liquid, depending on the physical conditions of its environment. At the beginning of the 19th century a great deal of attention was focused on the gaseous state of matter. Measurements were made of the pressure P and the temperature τ of a gas, confined to a volume V . It was found that, to a first approximation, the relationship between these parameters of the gas is: $PV = R(\tau + 273)$, where R is the *universal gas constant*, and τ is the temperature in *degrees Celsius*, as read on a thermometer (that is calibrated so that $\tau = 0$ *degrees Celsius* is the temperature where water freezes and $\tau = 100$ *degrees Celsius* is the temperature where water boils). Changing the temperature scale to $T = (\tau + 273)$ *degrees absolute*, the ideal gas law is: $PV = RT$.

A problem of temperature was then to explain the constant quantity 273 *degrees Celsius*. That is, when $\tau = -273$ *degrees Celsius*, so that $T = 0$ *degrees absolute*, the ideal gas law becomes $PV = 0$. What is its meaning as it pertains to a real gas? The question was not addressed until the analysis of Ludwig Boltzmann (1844–1906) and his model of the gas in terms of a very large ensemble of atoms (or molecules).

It is interesting that Boltzmann was born in the same year that John Dalton (1766–1844) died. Dalton discovered the existence of distinct atomic weights. This followed from his discovery of the *law of partial pressures*.

What Dalton did was to study a mixture of gases, such as air (about 80% Nitrogen and 20% Oxygen). He used chemical means to evacuate from a box of such a mixture only one of its ingredients. He then saw that the pressure of the mixture of gases against its walls had a sudden change.

The pressure of the gas, by definition, is the perpendicular force per unit area that is exerted by the gas on the walls of its container. The sudden change of the pressure in Dalton's experiment then meant that the gas that was evacuated from the box, was *characterized by a discrete mass*, which no longer acted on the walls of the box. Thus Dalton learned that all of the atomic (or molecular)

species have their own discrete atomic weights. It was then found that discrete atomic weights may be correlated with discrete atomic numbers: that of atomic Nitrogen N is 14, that of molecular Nitrogen N_2 is 28, the atomic number of Hydrogen H is 1 and that of molecular hydrogen H_2 is 2, and so on.

Amedeo Avogadro (1776–1856) was a contemporary of Dalton. He discovered the ‘mole’ of a gas. He found that the weight of any atomic species, in grams, that is numerically equal to the atomic number of that atom or molecule, called a ‘mole,’ must contain the same number of constituent atoms (or molecules). It is called *Avagadro’s number* N , which he found was the order of magnitude of 10^{24} atoms/mole. That is, one gram of hydrogen contains 10^{24} atoms of Hydrogen, 28 grams of molecular Nitrogen contains this same number of Nitrogen molecules, and so on.

Later in the 19th century, Boltzmann studied the question of the meaning of the temperature in the gas law. He saw that in fundamental terms, he would have to analyze the motion of 10^{24} atoms of matter — their mutual interactions and forces on the walls of the container, in terms of their Newtonian trajectories. Of course, for such a number this is an impossible task! So he invented the ‘kinetic theory of gases,’ whereby he was able to determine the *average values* of the physical properties of the atoms of the gas without the need to know their individual energies, momenta, etc.¹⁹

In this way, Boltzmann discovered that the average kinetic energy of a single constituent atom of a gas is $\langle (1/2)mv^2 \rangle = (3/2)(R/N)T = (3/2)kT$, where k , the ratio of the universal gas constant to Avogadro’s number, R/N , is called ‘Boltzmann’s constant.’ Thus Boltzmann discovered that the gas temperature (in *degrees absolute*) is related to the average kinetic energy of the constituent atoms of the gas. This result then answered his question about the meaning of temperature, in terms of the dynamics of the atoms of the gas. Thus, at $T = 0$ *degrees absolute*, the average kinetic energy of the atoms of the gas is zero. That is, they are not (on the average) moving! As the temperature increases from this value, the atoms increase their speeds. But at $T = 0$ *degrees absolute*, according to Boltzmann’s discovery, it is as though all of the constituent atoms of the gas are sitting in a pile at the bottom of the container. In this case,

there is no force of the atoms on the walls of the container, so that the pressure of the gas, $P = 0$, and the volume of the atoms is infinitesimal compared with the volume of the container, so that $V = 0$.

Heat and the Conservation of Energy

During the 19th century, there was a great deal of discussion and research on the subject of heat. Some of the seminal work on this problem was done by James Joule (1818–1889), a student of John Dalton. He discovered the mechanical theory of heat — he was able to correlate the mechanical energy of a paddle turning in a bucket of water with the temperature increase of the water. He then concluded that the heat energy thereby generated in the water was converted from the mechanical energy of the paddle.

In this period of the history of science, the *law of energy conservation* was discovered. It is the assertion that among the different sorts of energy (potential, kinetic, mechanical, chemical, electrical, heat, ...) their total must be constant *in time*. An example is the consideration of a rock, initially sitting on the top of a cliff. At that time it has potential energy, by virtue of its height above the bottom of the cliff. When it is pushed from the edge of the cliff, in falling to the ground it continuously converts its initial potential energy into increasing kinetic energy (of motion), such that the sum of the remaining potential energy at any distance from the ground and its kinetic energy, at any time during the fall, is constant. Near the bottom of the fall, the rock loses all of its initial potential energy to a maximum kinetic energy and when it hits the ground this is converted to either heating the ground (heat energy) or the mechanical energy of breaking apart. Thus the total energy of the rock, that is constant in time, was initially all potential energy, and then a combination of potential and kinetic energy, is converted into the work required to break the rock apart or to heat the ground. The total energy of matter, *per se*, is then *defined to be the work that this matter is capable of doing. It is a quality of matter that is constant in time*. This is the *law of the conservation of energy*.

The Laws of Thermodynamics and Atomism

The *first law of thermodynamics* is a consequence of the conservation of energy. It is this: if ΔQ is the increase in the heat energy injected into a material system, ΔU is the corresponding increase in the internal energy of the system, and $P\Delta V$ is the change in the work exerted by the gas against the walls containing this system of matter, then $\Delta Q = \Delta U + P\Delta V$. [Of course, if the walls of the material system are infinitely rigid, then $\Delta V = 0$ and $\Delta Q = \Delta U$.]

The *second law of thermodynamics* is more subtle than the first. It concerns a quality of the gas called “entropy” — the measure of *disorder* of a complex system. The *second law of thermodynamics* asserts that if a complex system is initially in a state of non-equilibrium, then it will proceed *in time* toward the equilibrium state, as the entropy (disorder) of the system increases toward its maximum value, at equilibrium. The system will then remain in this state forever.

An example to illustrate this process was proposed by Josiah W. Gibbs, one of the discoverers of the subject of *statistical mechanics*. Suppose that a drop of dark blue ink is inserted into a beaker containing a clear liquid. At first, there would be maximum order in the sense that *one would know* where all of the ink molecules are located (i.e. in the confines of the drop of ink). But *in time*, the ink molecules would break away from the drop and they would diffuse into the clear liquid — until the entire drop of ink diffuses and the liquid becomes pale blue in color. The liquid would then stay in this pale blue state. In the latter state of equilibrium of the liquid with the ink in it, the disorder (entropy) is a maximum in the sense that *one would have minimal knowledge* of where any particular ink molecule would be located.

In this example, we see the idea of the ‘arrow of time’ — that time flows in only one direction, the direction of the increase of the entropy of the system, from non-equilibrium to equilibrium.²⁰ Here, ‘time’ is *defined* in terms of the *observation* of the evolution of the system from a more ordered state to less ordered state. [This is not the same concept of ‘time’ that Newton introduced in his laws of

motion — as the parametrization of the evolution of a single body along a trajectory, or the time that is involved in the single trajectory of a moving body in Einstein's relativity theory.]

Boltzmann was able to formulate the two laws of thermodynamics in terms of the *statistical mechanics* of a many particle system of the atoms (or molecules) of matter. He invoked 'statistics' for the description of this matter. But he assumed all the while that *underlying* the statistical analysis, were the predetermined Newtonian trajectories of the atomic (or molecular) constituents of a macro-quantity of matter.

In the 20th century, the statistical aspect comes in a more fundamental way in the quantum theory. For the quantum theory is indeed a statistical theory of micromatter, in which it is asserted that a particular law of statistics (i.e. quantum mechanics) is itself a fundamental law of matter. Thus we see here a 'thread' in the use of statistics in physics, from a *subjective* meaning of matter (Boltzmann) to an *objective* meaning (according to Bohr, and his interpretation of quantum mechanics). In the latter view, the basic laws of matter are laws of statistics. This transition in the use of statistics in physics (a 'thread') will be developed later on in the course, in our discussion of the quantum theory.

In this regard, there is a question about the *fundamental nature* of the law of entropy (the second law of thermodynamics). For it is based on our human observations of the order of a system, not on the intrinsic order of the system itself. Similarly, in the 20th century, the 'observer' plays a seminal role in the laws of matter according to the view of quantum mechanics. Here, the trajectories of the atoms of matter are not predetermined. They are only specified after an 'observer' makes a measurement. In this sense, the quantum theory is non-deterministic. On the other hand, in the theory of relativity of the 20th century, the 'observer' plays no fundamental role and there is no objective 'arrow of time.' The laws of nature and the variables of matter are *predetermined*, according to relativity theory — which in this sense is *deterministic*.

A question that follows is this: Can it be meaningful to talk about the 'entropy of the universe'? I do not believe so because the

universe is *by definition*, whatever else we may know about it, a *totally ordered* and a closed entity. It cannot be described in the context of disorder. It is only *our knowledge* of the universe that can be disordered. We should not confuse what it is that we know or do not know with what exists, independent of our knowledge of it (i.e. confusion between questions of epistemology and ontology)!

This is a monumental error, in my view, in modern day science — to confuse an objective entity, such as an electron, or the universe itself, with our knowledge of these entities! Some scientists say that it is a definition of science that it deals *only* with the empirical facts — our *description* of nature. But in my view, the basic goal of science is at a level underlying this — it is the *explanatory* level of understanding. Those who believe in the former as the goal of science are the *positivists*. Those who believe the latter are the *realists*.

Ludwig Boltzmann's and Ernst Mach's Philosophy of Science

Boltzmann's epistemological view was that of *naïve realism*. This is the belief that the fundamental ways of the world that one responds to with one's senses are the same as those aspects of the world that one does not directly respond to. That is, because we see the world atomistically, as 'things,' he believed that any macromatter must be composed of smaller, unobservable things — the atoms of matter that we do not respond to directly.²¹

Thus Boltzmann concluded that the laws of nature are laws of the atoms of matter — their motions and mutual interactions (as unobservable constituents of macromatter).

Boltzmann's adversarial colleague, Ernst Mach, disagreed with him about the reality of atoms. He argued that the atom, an unobservable entity, is but a mathematical artifice whose only purpose is to facilitate a description of macromatter. His contention was based on his philosophical view of *positivism*. This view asserts that the only reality is our human reactions to the outside world.

Boltzmann's belief in the atomistic view of matter was strengthened by his success in representing a gas (or other macromatter) by

a large number of composite atoms or molecules to underlie the laws of nature. As we discussed earlier, the absolute temperature T in the ideal gas law, $PV = RT$, was explained in terms of the *average* kinetic energy of a constituent atom (or molecule) of the gas containing about 10^{24} atoms, without the need to know the precise kinetic energy of any single one of them.

With this mindset, Boltzmann was able to formulate the two laws of thermodynamics in terms of such a collection of atoms with a statistical analysis of the system, i.e. using the methods of *statistical mechanics*. Along the way, he demonstrated the unidirectional character of time's arrow in a formulation of the entropy of a many-atom physical system, in accordance with the second law of thermodynamics.

Agreements between Boltzmann and Mach and 'Mach's Principle'

As I indicated earlier, Boltzmann and Mach disagreed on the correct epistemology for the philosophy of science — Boltzmann's naive realism and Mach's positivism. But they did agree that all of the laws of physics are in principle refutable. [*This is a view, propounded in our own day, by the philosopher Karl Popper — an avid follower of Boltzmann.*] Also, both Boltzmann and Mach were anti-dogmatic about the laws of nature; they did not believe that any of the principles that are alleged to underlie the ways of nature should be advocated dogmatically, as would be the attitude of a *religious truth* (as we discussed in Lecture I)! In particular, they both felt that one should always look for alternative interpretations of the descriptive aspect of physics that might equally explain phenomena.²²

A good example was Mach's view against atomism in his interpretation of Newton's second law of motion, $F = ma$. According to Newton's atomistic view, his second law of motion comes from the empirical observation that if F_1 and F_2 are the magnitudes of two different forces *that act on the same body* (i.e. having the same mass m), that cause its different accelerations a_1 and a_2 , then the empirical value of the ratio of forces is *linearly* equal to the ratio of

caused accelerations, $F_1/F_2 = a_1/a_2$. Thus m , the intrinsic inertial mass of the atom of matter acted upon, is introduced by Newton as the constant of proportionality between F and a , i.e. $F = ma$. In the ratio of forces acting *on the same body*, the parameter m cancels.

But Mach argued that one may interpret the empirically correct formula, $F = ma$, by noting that for *two different bodies*, with masses, m_1 and m_2 , *accelerating at the same rate* (e.g. in the case of different bodies that fall freely at the rate g , according to Galileo's law of gravity), the empirically correct result is: $F_1/F_2 = m_1/m_2$.

This result may then be expressed as the law: $m = KF$, where the constant of proportionality between the inertial mass and the *total external force* acting on it is K (say $K = m_2/F_2$, taken as a standard for all other measurements).

The meaning of Mach's equation (that is consistent with Newton's second law of motion), is that the inertial mass of any local matter is not intrinsic to that matter!

Rather, the inertial mass of any localized matter is *caused by* the total external force that acts on it. This is a non-atomistic view of matter. The interpretation of inertial mass of any quantity of matter, that defines it to be dependent on all other matter — *of a closed universe* — was named by Einstein, "The Mach Principle."²³ This principle signifies that the most distant stars of the universe must affect the mass of a local bit of matter. But it is *all of the matter* of the universe, not only the distant stars that contribute to the mass of any local matter! Indeed, the nearby matter also has (most predominantly) an effect on the mass of any local matter. This idea will be discussed toward the end of the course. It will be seen that this principle plays an important role in the theory of general relativity that was to emerge in 20th century physics.

***The Continuous Field Concept*²⁴**

The primary introduction of the continuous field concept in 19th century physics was that of Michael Faraday (1791–1867). His interpretation of the laws of electricity and magnetism were seminal in this discovery. Faraday started his study with a criticism of