Secrets of the Old One

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Einstein, 1905

Jeremy Bernstein

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Introduction: Einstein's Miracle Year

Everything should be made as simple as possible, but not simpler.
—Albert Einstein

Beginning on March 18th,1905, and ending on June 30th, at roughly eight week intervals, the leading German physics journal *Annalen der Physik* received, in its editorial offices in Berlin, three handwritten manuscripts. Written by a patent examiner in Bern, Albert Einstein, they would in their totality define physics for the next century and beyond. A fourth briefer paper—really an addendum to the third—was received by the *Annalen* on the 27th of September. It contains the one formula, $E = mc^2$, that everyone associates with Einstein. These papers, which are the subject matter of this book, are remarkable in many ways. First, there is the manifestation of creative scientific genius. Nothing like this had been seen in science since the year 1666–the *annus mirabilis* (the miracle year)—of classical science.[1] That year, 23-year-old Isaac Newton, who had sought refuge in his mother's house in Lincolnshire from an epidemic of plague that was devastating Cambridge, created the basis for physics that endured for the next two-and-half centuries. Second, there is the style. Einstein's papers contain very few references to the contemporary literature. They only rarely refer to each other, something that, as I will explain later, would in at least one significant instance have helped readers to comprehend them. This paucity of discussion of contemporary literature is one of the reasons why the papers appear so fresh. There were other very important papers of the period, some having to do with the same general subject matter, but they seem dated. One has to peel off the parts that are still valid from the parts that are not. Although vast progress has been made in our understanding of the physical world in the last century, nothing of any importance in Einstein's papers is wrong. One can teach the theory of relativity from the third paper, and one can also teach the implications of the quantum nature of light from the first. In all the papers, the writing is elegant and economical. We feel that we are in the sure hands of a master—a master who was, at the time just twenty-six.

It is not my intention to present a biography of Einstein. There are innumerable biographies, and the number is growing. But I want to describe the years leading up to 1905 to make clear the context in which the papers were written. Einstein was born on March 15, 1879, in the southern German city of Ulm at the foot of the Swabian Alps. His parents, Hermann and Pauline Koch Einstein. were Jewish, although not very practicing. There is no trace in Einstein's genealogy of anyone with scientific accomplishments. This certainly had something to do with the professional restrictions that were placed on Jews in the ghettoes. In fact,

[1] Historians of science note that the term, which was originally used by the poet John Dryden to describe the English victory over the Dutch in 1666, better designates the period in Newton's life from 1664 to 1666.

it was only in 1871 that Jews were recognized as full citizens of Germany. As a child, Einstein was very slow to speak. It worried his parents. In 1947, Einstein was persuaded by the philosopher Paul Schilpp to write a sort of autobiography, something that Einstein referred to as writing his own obituary. Actually he died in 1955. It is published as the introduction to an extraordinary collection of essays written in his honor. Most of his autobiography deals with his science, but a little of it describes his early life. At the age of four or five his father gave him a compass whose behavior made a lasting impression. He writes, "That this needle behaved in such a determined way did not at all fit into the nature of events which could find a place in the unconscious world of concepts (effect connected with direct 'touch.') I can still remember—or at least I believe I can remember—that this experience made a deep and lasting impression upon me. Something deeply hidden had to be behind things." Some years later, in his early teens, Einstein discovered Euclidean geometry. In his autobiography Einstein tells how he found for himself a proof of the Pythagorean theorem which relates the sides of a triangle with a right 90° angle. This theorem will be one of our main mathematical tools and, later in the book, I present my reconstruction of Einstein's proof.

Einstein's father was a not very successful businessman specializing in various electrical equipment enterprises. When Einstein was one year old, the family moved to Munich so that his father could set up a business with his younger brother. So, when Einstein was ready to go to school, he entered a so-called "Gymnasium"—in this case the Luitpold Gymnasium. In this school, which was a state-supported Catholic school, there was essentially a military discipline. The students wore uniforms and were drilled. Einstein thoroughly disliked the place. It strengthened the pacifist instincts he had had since early childhood and which he only abandoned in the 1930s with the rise of Hitler. It is sometimes said that he was a poor student, but he was, both in high school, and later when he entered the *Eidgenössische Technische Hochschule*—the Swiss Federal Institute of Technology in Zurich—which Einstein came to refer to as the "Poly"—a good student. He was never at the top of his class but he was always above average.

Einstein's problems at the Gymnasium, and the Poly could be attributed to what his teachers perceived as an attitude. He never had much respect for authority, especially if it was associated with a manifest lack of competence. It reached such a point at the Gymnasium that, by mutual consent, Einstein withdrew in December of 1894. By this time, his family had moved to Italy, where his father started another ultimately unsuccessful business. Einstein had been left to live with relatives in Munich, but in 1895 he joined his family in Italy where he spent what he remembered as a delightful six months. Part of the time he studied for the entrance examination to the Poly. He took it at age sixteen-and-a-half and did well in the scientific parts but not very well in the rest which dealt with languages. He was advised to take an additional year of study. For this purpose, he chose a progressive school in Aarau, Switzerland. By this time he had decided to give up his German citizenship, which really meant giving up his citizenship in the state of Württemberg, which was done for a payment of three German marks. He remained stateless until 1901, when he became a Swiss citizen. Like all Swiss men, this meant that he was obligated to serve in the army. He was exempted because of flat feet.

In 1896, he passed the entrance examination and spent the next four years at the Poly. In his autobiography, however, he wrote that he could have received a better education, especially in mathematics, than he did, as there were very good mathematicians there whose courses he was not interested in. He also decided the teaching of physics was inadequate, so he spent most of his time teaching himself. He complained, for example, that the electromagnetic theory of the Scottish physicist James Clerk Maxwell, the greatest advance in physics since Newton and which was then some twenty five years old, was not being taught. He had to learn it on his own. Einstein's professors were aware that he was not attending all his classes, and they did not appreciate his attitude. Nonetheless, his grades were quite good because he studied from the meticulous notes of his friend, Marcel Grossman, who later became a mathematician with whom Einstein collaborated. But when he graduated, he was not asked to stay on as an instructor or laboratory assistant, something that several of his fellow students were invited to do. His teachers did not want him around. He then tried unsuccessfully to find employment in several physics institutions in a variety of European countries. This was certainly due in part to anti-Semitism, but it was also the result of what were very likely not very enthusiastic letters of recommendation.

Einstein began a two-year period of odd tutoring jobs. One wonders what would have happened if Marcel Grossman's father had not helped him to get a job in 1902 as a patent examiner at the Swiss Federal Patent Office in Bern. He became a "technical expert third class," with an annual salary of 3,500 Swiss francs (see Figure I.1). I have read different accounts of how much time his job left him for doing physics. One thing is certain. It was a serious job which he took seriously. A few of his patent assessments are still extant. They are thorough and sometimes sharply negative. Einstein may have, especially in his later years, looked like a benign presence, but he had a very cutting tongue that also got him in trouble. He had no time to actually carry out calculations during patent office working hours, but that nothing could stop him from

Figure I.1. Einstein at the patent office. (Courtesy AIP Niels Bohr Library) thinking about physics. One reasons, why he did not have a better knowledge of the contemporary physics literature was that the university library in Bern was closed when Einstein was free on nights and weekends. I think it is also true that he did not much care and did not want to waste his time reading about physics that he was quite sure was wrong.

With his new job he was able to get married. While at the Poly he had met a fellow student, a somewhat older Serbian woman named Mileva Marić. The Poly was one of the few places in Europe where a woman could study science. Their relationship started as a school friendship, but by 1898, they were considering marriage. Einstein's mother was vehemently opposed. By the end of 1901, Mileva became pregnant and gave birth in Hungary to a daughter we only know by the nickname "Lieserl." Einstein never saw his daughter, and no one knows what happened to her. In any event, in 1902, Mileva and Einstein were married. In 1904, they had the first of their two sons, Hans Albert. The second, Eduard, was born six years later. The marriage ultimately ended in a painful divorce. Einstein gave, as part of the settlement, the proceeds of the Nobel Prize which he had won in 1921.[2]

This is the context in which the papers were written. I cannot imagine where he found the time. He had a full-time job, family responsibilities, and a social life. He played music—the violin—and had friends with whom he spent time. When could he work on his papers? Each of them has scores of equations. He must have been able to calculate with incredible speed and precision. To add to everything else, he wrote them out by hand for submission to the journal. Further, he was writing a doctoral thesis, published the next year, also written by hand.

Now let me explain this book. There are four chapters and an epilogue. The first is an account of the relevant physics history up to 1905, especially as it deals with electromagnetism and Newtonian mechanics. Other chapters recount the corresponding history for the subject matter at hand. The second chapter is an account of Einstein's papers on the

[2] He actually collected the Prize in 1922. The divorce was in 1919, after which he married his cousin Elsa Löwenthal Einstein.

theory of relativity, with additional relevant prehistory, and a sketch of what happened to the theory after 1905. The third chapter deals with what is known as "Brownian movement," that is, the random motion of microscopic particles suspended in liquids. This development, and the experiments it led to, persuaded most of the skeptics—and there were some important ones—that atoms existed as real physical objects and not as mathematical abstractions. The last chapter deals with the quantum. It was the first paper of the series chronologically; the relativity papers were the last. This first paper was the only one Einstein thought truly revolutionary. I will explain the reasons. The reader may be surprised that this chapter begins with the history of the steam engine. You will see why. It is important that I make clear my overall objective. I want to explain all of this using mathematics no more difficult than that taught in high school—simple geometry and algebra. This does not mean that I skimp on the ideas. I think that they are all there, as simple as I can make them—but no simpler. Before turning to the first chapter, let me explain briefly how I got into all this. It will also enable me to introduce you to someone you will meet from time to time in the book.

In the fall of 1947, I entered Harvard University as a freshman, where I discovered there was a science requirement. If you were not a prospective science major, which I was not, you had to take a Natural Science course in the then rather newly created General Education program. I took what was reputed to be the easiest one—Natural Sciences 3—which was taught by the late I. Bernard Cohen, a historian of science and a Newton expert. That is how I first learned something about Newton. Toward the end of the first semester, Cohen touched a little on Einstein's physics and a bit about his life. Einstein was then at the Institute for Advanced Study in Princeton. I learned that as people, Einstein and Newton had almost nothing in common. Newton was austere and virginal and spent at least as much time on biblical dating and alchemy as he did on what we would call science. There is only one recorded instance where he was heard to laugh. Einstein was bohemian, much interested in women, and loved to laugh. When he heard a good Jewish joke it was said that he had the laugh of a barking seal. Both men were

Figure I.2. Philipp Frank. (AIP Emilio Segré Archives)

in their ways profoundly religious. Both men were, and are, to historians and biographers and to me, endlessly interesting.

Although I understood relatively little of the science, it took hold of me, and I decided to learn more about it. Cohen told me that a successor course was being taught that spring and that I could, if I wanted, take both simultaneously. He also said it would be taught by a man named Philipp Frank (see Figure I.2). Frank, he added, had known Einstein for decades. Indeed, he had succeeded Einstein at the German University in Prague when Einstein left in 1912 to return to Switzerland, and he had just published a biography of Einstein, *Einstein, His Life and Times*. It sounded perfect.

The class met once a week, on Wednesday afternoons as I recall, in the large lecture hall in the Jefferson Laboratories. There were perhaps fifty students. Professor Frank turned out to be a shortish man with something of a limp acquired in an accident in his native Vienna, where he had been born in 1884. What hair remained was distributed around the side of his head in wisps. He had, I thought, the face of a very intelligent basset hound. His accent was somewhat difficult to place. I used to say that the languages he knew—God knows how many—were piled one on top of each other like the cities of Troy, with shards belonging to one popping through to the others. On one notable occasion in response to a question from a student, he wrote on the black board a quotation in Persian, a language he later told me, he had learned in night school in Vienna. He would lecture for about an hour and then announce that he would now make a "certain interval." After the interval, you could return to ask questions. Sometimes he would give an answer that he said could be understood "if you knew a little of mathematics." The only mathematics I knew was what I had learned in high school—a smattering of algebra, trigonometry, and Euclidean geometry. That is all you needed to know for his course. I decided to learn "a little of mathematics" and ended up majoring in it.

I think that the reason Professor Frank could explain things so clearly and simply is because he understood them so well. He had taken his PhD in physics in 1906 under the direction of Ludwig Boltzmann, about whom we will hear later. Professor Frank understood the importance of Einstein's physics from the beginning, and was soon in contact with him. He made significant contributions to the development of relativity. We owe to Professor Frank the term "Galilean relativity." We will soon examine Galileo's relativity and learn what the term means. I owe to Professor Frank my life-long interest in Einstein and his life and times, which have led to this book. I dedicate it to his memory.

1
The Prehistory

The Science of Mechanics

> Absolute, true, and mathematical time of itself, and by its own nature, flows uniformly on, without regard to anything external. It is also called *duration*.
>
> Relative, apparent and common time, is some sensible and external measure of absolute time (duration), estimated by the motions of bodies, whether accurate or in equable, and is commonly employed in place of true time; as an hour, a day, a month, a year. . . .
>
> —Isaac Newton

Our study of the prehistory of relativity begins with Galileo Galilei who was born in Pisa in 1564. We shall focus on one paragraph in one of his books, *Dialogue Concerning the Two Chief World Systems*. When he published it in 1632, he must have known that there would be trouble. He had brought the manuscript to Rome two years earlier to get permission from the Church to publish it. When this was not rapidly forthcoming, he returned to Florence, where he was living, and published it anyway with a Florentine *imprimatur*. Not only that, but he had written it in vernacular Italian as opposed to Latin, so that it could be widely read. The "world systems" in question are the Ptolemaic and the Copernican.[1] Ptolemy–Claudius Ptolemaeus–was an Alexandrine, probably of Greek origin, who lived in the second century BC. His astronomical system was a response to two apparently discordant requirements. On the one hand, he had inherited the notion from Aristotle that the heavenly objects, being made out of a different "essence" than earth, air, fire, and water, must move around the Earth in uniform circular motions while attached to crystalline spheres. The second requirement was that this system describe what one actually observed. This came to be called "saving the appearances." One of the "appearances," when it came to planetary motion, was that periodically, as seen from the Earth, planets go backward in their orbits–something that is known as "retrograde motion." To deal with this, Ptolemy introduced a remarkably ingenious system, which he adumbrated in his book *Almagest*. To take the simplest case, imagine a "virtual" planet that moves in a uniform circular motion around the Earth. Around this virtual planet the actual planet moves with a uniform circular motion. The combined orbits will show periodic retrograde motion. You can try this out by making the circles. In fact, by adding up circles you can simulate any observed planetary motion if you are willing to add up enough of them.[2]

[1] Galileo courted additional trouble by ignoring a third system that was currently in favor by the Church. In this system, invented by the Danish Astronomer Tycho Brahe, the Earth was at rest with the Sun in orbit around it, while the planets were in orbit around the Sun.

[2] Mathematically speaking, what Ptolemy did, unknown to him, was to generate what we would call a kind of Fourier analysis of the motion—an expansion in

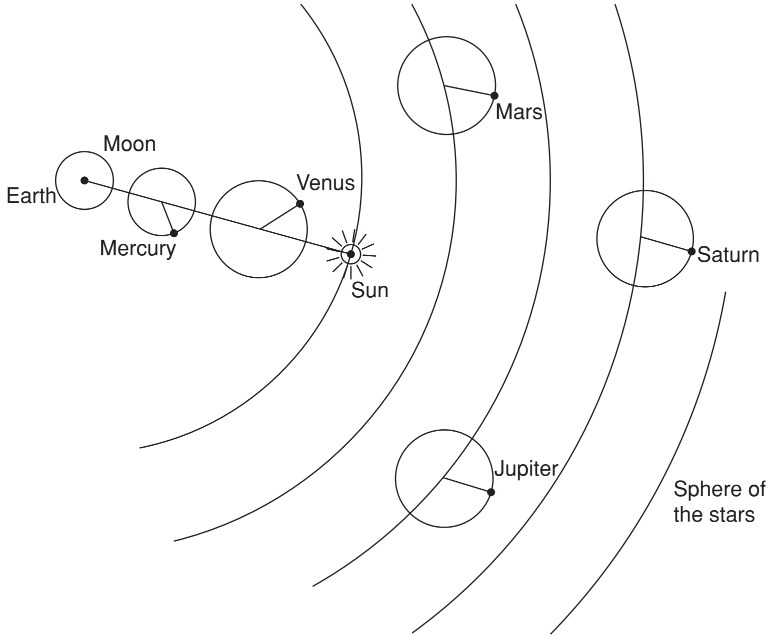

Figure 1.1. The Ptolemaic system.

Ptolemy used some fifteen for the Moon and planets.[3] Figure 1.1 is a rough idea of how it worked.

The second world system in the dialogues is the Copernican. Copernicus had presented this in his great book *De revolutionibus orbium caelestium*, which was published in 1543, the year of his death. People who have not actually studied what Copernicus wrote often misunderstand what he was proposing. What is usually recalled is that Copernicus moved the Sun to the center of the planetary system and made it stationary, with the Earth in motion. But, he also employed uniform circular motions and needed epicycles–even **more** than Ptolemy; in fact, some eighteen (see Figure 1.2). Figure 1.2 shows an additional complexity of the scheme, namely a displacement of the centers of the circles.

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trigonometric functions. If you keep enough terms in the Fourier series, you can reproduce the original motion to any accuracy.

[3] I would like to thank Owen Gingerich for helpful communications.

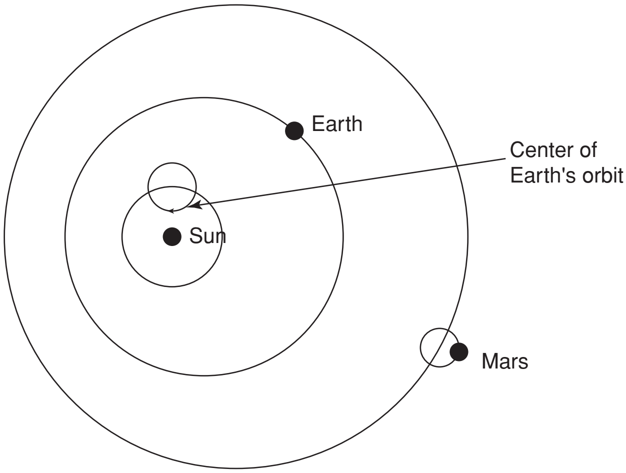

Figure 1.2. The treatment of Mars on the Copernican system. Thanks to Owen Gingerich for the drawing.

The solar system that is often depicted as "Copernican," with its elliptical orbits, as opposed to the uniformly moving crystalline spheres, was actually the discovery of Galileo's contemporary Johannes Kepler, whose diagram of the Martian orbit—an ellipse inside a circle for comparison, is shown in Figure 1.3. About the only thing it has in common with Copernicus is the resting Sun.

Galileo's concern in the "dialogues" was to show that the motion of the Earth, which is at the heart of the Copernican or Keplerian system, does not lead to absurdities. In the book, the dialogues, which take place over four days, are among three people. The setting, Galileo tells us, is in the palace of one Sagredo, who was modeled after a personal friend. Sagredo acts as the host and intelligent layman. Then there is Salviati, also modeled on a real person. Salviati, who is Galileo's stand-in, takes the Copernican side of the debate. Finally, there is Simplicius, an Aristotelean *pure et dure*, who, as one might imagine from the name, gets the worst of all the arguments. By this time the Aristotelean world view had become Church doctrine. So no matter how much he denied it, Galileo was challenging the Church. Indeed, in 1633, not long after the dialogues were published, he was summoned to Rome to face the

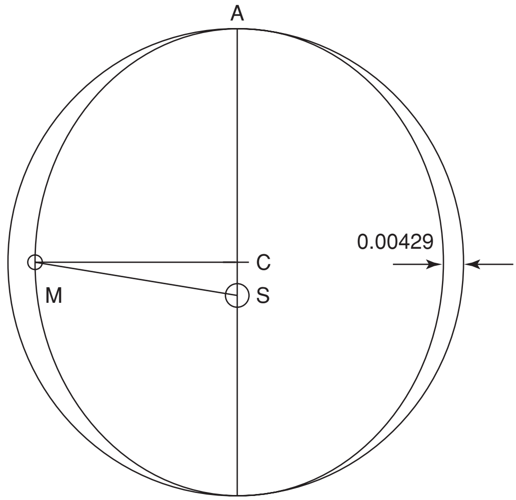

Figure 1.3. Kepler's diagram of the Martian orbit.

Inquisition. He returned to Florence a broken man and died there in 1642, the year Newton was born. The purpose of the dialogues, as I read them, is not to present the details of the Keplerian solar system. Indeed, Galileo's only interest in Kepler seems to have been to request from him additional proofs of the Earth's motion. In 1610, Kepler received from Galileo a copy of his book *Siderius nuncius*, which described his telescopic discoveries, such as mountains and craters on the moon and a system of moons revolving around Jupiter, all of which showed that the heavenly bodies were not so different from the Earth. Kepler was able to confirm these observations with a borrowed telescope. The purpose of the dialogues is rather to show that the objections that were being made to a moving Earth, at least the scientific objections, did not stand up to scrutiny. It is in this context that they begin our preamble to Einstein.

On the second day, Sagredo makes the following observation, "Ptolemy and his followers produce another experiment like that of projectiles, and it pertains to things, which separated from the earth, remain in the air a long time, such as clouds and birds in flight. [For these purposes projectiles also fall into this category.] Since of these it cannot be said that they are carried by the earth, as they do not adhere to it, it does not seem possible that they could keep up with its swiftness, rather it ought to look to us as they were being moved very rapidly westward." Why, in short, were objects aloft in the air not left behind by the moving Earth? This very reasonable concern provokes an extensive response from Salviati. In the course of it Salviati–Galileo–presents the following simple but extraordinarily profound insight. Einstein liked to use trains in his examples. Galileo used a sailing ship. Here is what he writes,

> Shut yourself up with some friend in the main cabin below deck on some large ship, and have with you some flies, butterflies, and other small animals. Have a large bowl of water with some fish in it; hand up the bottle that empties drop by drop into a narrow-mouthed vessel beneath it. With the ship standing still, observe carefully how the little animals fly with equal speed to all sides of the cabin. The fish swim indifferently in all directions; the drops fall into the vessel; and in throwing something to your friend, you need throw it no more strongly in one direction than another, the distances being equal; jumping with your feet together, you pass equal spaces in every direction.

Now comes the crucial observation.

> When you have observed all these things carefully (though there is no doubt that when a ship is standing still everything must happen this way), have the ship proceed with any speed you like so long as the motion is uniform, and not fluctuating this way and that. You will discover not the least change in all the effects named, nor could you tell from any of them whether the ship was moving or standing still.

This is the first time in which what we call a "relativity" principle was described explicitly. We can restate Galileo's charming folkloric presentation somewhat more austerely as follows: In no experiment done in a uniformly moving system, does the speed of that system with respect to any other uniformly moving system, play a role. In other words, for purposes of any experiment, we can take our uniformly moving system to be at rest. It is called a "relativity principle" because, as far as uniform motions are concerned, all that is measurable is the "relative" velocity of one system "relative" to another. In a uniformly moving train or car or plane, we only know we are in motion when we view the tracks, the road, or the ground. If we want to be perverse about it, we can say that we are at rest and these reference systems are the one's in motion. This seems totally innocuous and commonsensical–but wait until we come to Einstein. In the meanwhile let us see how the principle is realized in the mechanics of Newton.

Newton's mechanics were laid out formally in his seminal book *Phliosophiae naturalis principia mathematica*, which was first published in 1687. Newton not only created new science, but a new scientific paradigm. He invented what we think of as theoretical physics. You start with some general principles that aid you in formulating a set of equations. You solve these equations as best you can and check the result against experiment. No one prior to Newton had done things in this way. For example, Kepler did not try to *derive* the elliptical planetary orbits. He showed empirically that this was how the planets move. In the *Principia*, Newton was able to derive the planetary motions from a few general principles. I will now present some of them, beginning with Newton's "second law," not quite as stated in the *Principia*–we will come to that shortly–but in a form that will be familiar to many of you. I will write the formula and then say what the letters mean, or at least crudely what they mean. A little later I am going to critically analyze these equations in the sprit of Einstein's influential contemporary Ernst Mach, the Austrian physicist-philosopher whose book *The Science of Mechanics* played a very important role in Einstein's thinking.

Put in the simplest language, Newton's Second Law says that the acceleration an object experiences is proportional to the force applied to it. The constant of proportionality is the mass of the object. In short, $F = ma$. I am assuming for the moment that we have some general idea of what these terms mean. When I come to Mach's critique, it is this we will have to examine. I want to focus on the acceleration. To say that an object is accelerated is to say that its motion has been changed. This can mean that its direction has changed or that while moving in a given