THE UNIVERSE

# BY: Mohamad Eid Hamouda

# Supervisor: Abd-Al-Rahman AL-Hashem

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Introduction:

Mankind has existed for a short time, and in that time explore but a small part of the

whole universe. But humans are a curious species. We wonder, we seek answers. Living in this vast world that is by turns kind and cruel, and gazing at the immense heavens above, people have always asked a multitude of questions:

How can we understand the world in which we find ourselves?

How does the universe behave?

What is the nature of reality?

Where did all this come from?

Did the universe need a creator?

Most of us do not spend most of our time worrying about these questions, but almost all of us worry about them some of the time.

Traditionally these are questions for philosophy, but Philosophy has not kept

up with modern developments in science, particularly physics. Scientists have become the bearers of the torch of discovery in our quest for knowledge. The purpose of this research is to give the answers that are suggested by recent discoveries and theoretical advances. They lead us to a new picture of the universe and our place in it that is very different from the traditional one, and different even from the picture we might have painted just a decade or two ago. Still, the first sketches of the new concept can be traced back almost a century.

Chapter 1:

The mystery of being

According to the traditional conception of the universe, objects move on well-defined paths and have definite histories. We can specify their precise position at each moment in time. Although that account is successful enough for everyday purposes, it was found in the 1920s that this “classical” picture could not account for the seemingly bizarre behavior observed on the atomic and subatomic scales of existence. Instead it was necessary to adopt a different framework, called quantum physics. Quantum theories have turned out to be remarkably accurate at predicting events on those scales, while also reproducing the predictions of the old classical theories when applied to the macroscopic world of daily life. But quantum and classical physics are based on very different conceptions of physical reality.

Quantum theories can be formulated in many different ways, but what is probably the most intuitive description was given by Richard Feynman, according to Feynman, a system has not just one history but every possible history.

Until the advent of modern physics, it was generally thought that all knowledge of the world could be obtained through direct observation, that things are what they seem, as perceived through our senses. But the spectacular success of modern physics, which is based upon concepts such as Feynman’s that clash with everyday experience, has shown that that is not the case. The naïve view of reality therefore is not compatible with modern physics. To deal with such paradoxes we shall adopt an approach that we call model-dependent realism. It is based on the idea that our brains interpret the input from our sensory organs by making a model of the world.

When such a model is successful at explaining events, we tend to attribute to it, and to the elements and concepts that constitute it, the quality of reality or absolute truth. But there may be different ways in which one could model the same physical situation, with each employing different fundamental elements and concepts. If two such physical theories or models accurately predict the same events, one cannot be said to be more real than the other; rather, we are free to use whichever model is most convenient.

In the history of science, we have discovered a sequence of better and better theories or models, from Plato to the classical theory of Newton to modern quantum theories. It is natural to ask: Will this sequence eventually reach an end point, an ultimate theory of the universe, that will include all forces and predict every observation we can make, or will we continue forever finding better theories, but never one that cannot be improved upon? We do not yet have a definitive answer to this question, but we now have a candidate for the ultimate theory of everything, if indeed one exists.

1.1 THE M-Theory:

M-theory is the only model that has all the properties we think the final theory ought to have, M-theory is not a theory in the usual sense. It is a whole family of different theories, each of which is a good description of observations only in some range of physical situations. It is a bit like a map. As is well known, one cannot show the whole of the earth’s surface on a single map. The usual Mercator projection used for maps of the world makes areas appear larger and larger in the far north and south and doesn’t cover the North and South Poles. To faithfully map the entire earth, one has to use a collection of maps, each of which covers a limited region. The maps overlap each other, and where they do, they show the same landscape. M-theory is similar. The different theories in the M-theory family may look very different, but they can all be regarded as aspects of the same underlying theory. They are versions of the theory that are applicable only in limited ranges—for example, when certain quantities such as energy are small. Like the overlapping maps in a Mercator projection, where the ranges of different versions overlap, they predict the same phenomena. But just as there is no flat map that is a good representation of the earth’s entire surface, there is no single theory that is a good representation of observations in all situations.

We will describe how M-theory may offer answers to the question of creation. According to M-theory, ours is not the only universe. Instead, M-theory predicts that a great many universes were created out of nothing. Their creation does not require the intervention of some supernatural being or god. Rather, these multiple universes arise naturally from physical law. They are a prediction of science. Each universe has many possible histories and many possible states at later times, that is, at times like the present, long after their creation. Most of these states will be quite unlike the universe we observe and quite unsuitable for the existence of any form of life. Only a very few would allow creatures like us to exist. Thus our presence selects out from this vast array only those universes that are compatible with our existence. Although we are puny and insignificant on the scale of the cosmos, this makes us in a sense the lords of creation. To understand the universe at the deepest level, we need to know not only *how* the universe behaves, but *why.*

*Why is there something rather than nothing?*

*Why do we exist?*

*Why this particular set of laws and not some other?*

This is the Ultimate Question of Life, the Universe, and Everything. We shall attempt to answer it.

1.2 The expanding universe:

Edwin Hubble made the landmark observation that wherever you look, distant stars are moving rapidly away from us. In other words, the universe is expanding. This means that at earlier times objects would have been closer together. In fact, it seemed that there was a time about ten or twenty thousand million years ago when they were all at exactly the same place. This discovery finally brought the question of the beginning of the universe into the realm of science. Hubble's observations suggested that there was a time called the big bang when the universe was infinitesimally small and, therefore, infinitely dense. If there were events earlier than this time, then they could not affect what happens at the present time. Their existence can be ignored because it would have no observational consequences.

Our sun and the nearby stars are all part of a vast collection of stars called the Milky Way galaxy. For a long time, it was thought that this was the whole universe. It was only in 1924 that the American astronomer Edwin Hubble demonstrated that ours was not the only galaxy. There were, in fact, many others, with vast tracks of empty space between them. In order to prove this, he needed to determine the distances to these other galaxies. We can determine the distance of nearby stars by observing how they change position as the Earth goes around the sun. But other galaxies are so far away that, unlike nearby stars, they really do appear fixed. Hubble was forced, therefore, to use indirect methods to measure the distances.

Now the apparent brightness of a star depends on two factors—luminosity and how far it is from us. For nearby stars we can measure both their apparent brightness and their distance[[1]](#footnote-1), so we can work out their luminosity. Conversely, if we knew the luminosity of stars in other galaxies, we could work out them distance by measuring their apparent brightness. Hubble argued that there were certain types of stars that always had the same luminosity when they were near enough for us to measure. If, therefore, we found such stars in another galaxy, we could assume that they had the same luminosity. Thus, we could calculate the distance to that galaxy. If we could do this for a number of stars in the same galaxy, and our calculations always gave the same distance, we could be fairly confident of our estimate. In this way, Edwin Hubble worked out the distances to nine different galaxies. We now know that our galaxy is only one of some hundred thousand million that can be seen using modern telescopes, each galaxy itself containing some hundred thousand million stars. We live in a galaxy that is about one hundred thousand light-years across and is slowly rotating; the stars in its spiral arms orbit around its center about once every hundred million years. Our sun is just an ordinary, average-sized, yellow star, near the outer edge of one of the spiral arms. We have certainly come a long way since Aristotle and Ptolemy, when we thought that the Earth was the center of the universe.

Stars are so far away that they appear to us to be just pinpoints of light. We cannot determine their size or shape. So how can we tell different types of stars apart? For the vast majority of stars, there is only one correct characteristic feature that we can observe—the color of their light. Newton discovered that if light from the sun passes through a prism, it breaks up into its component colors—its spectrum—like in a rainbow. By focusing a telescope on an individual star or galaxy, one can similarly observe the spectrum of the light from that star or galaxy. Different stars have different spectra, but the relative brightness of the different colors is always exactly what one would expect to find in the light emitted by an object that is glowing red hot. This means that we can tell a star's temperature from the spectrum of its light. Moreover, we find that certain very specific colors are missing from stars’ spectra, and these missing colors may vary from star to star. We know that each chemical element absorbs the characteristic set of very specific colors. Thus, by matching each of those which are missing from a star’s spectrum, we can determine exactly which elements are present in the star’s atmosphere.

In the 1920s, when astronomers began to look at the spectra of stars in other galaxies, they found something most peculiar: There were the same characteristic sets of missing colors as for stars in our own galaxy, but they were all shifted by the same relative amount toward the red end of the spectrum. The only reasonable explanation of this was that the galaxies were moving away from us, and the frequency of the light waves from them was being reduced, or red-shifted, by the Doppler effect. Listen to a car passing on the road. As the car is approaching, its engine sounds at a higher pitch, corresponding to a higher frequency of sound waves; and when it passes and goes away, it sounds at a lower pitch. The behavior of light or radial waves is similar. Indeed, the police made use of the Doppler effect to measure the speed of cars by measuring the frequency of pulses of radio waves reflected off them.

In the years following his proof of the existence of other galaxies, Hubble spent his time cataloging their distances and observing their spectra. At that time most people expected the galaxies to be moving around quite randomly, and so expected to find as many spectra which were blue-shifted as ones which were red–shifted. It was quite a surprise, therefore, to find that the galaxies all appeared red-shifted. Every single one was moving away from us. More surprising still was the result which Hubble published in 1929: Even the size of the galaxy's red shift was not random, but was directly proportional to the galaxy's distance from us[[2]](#footnote-2). Or, in other words, the farther a galaxy was, the faster it was moving away. And that meant that the universe could not be static, as everyone previously thought, but was in fact expanding. The distance between the different galaxies was growing all the time.

The discovery that the universe was expanding was one of the great intellectual revolutions of the twentieth century. With hindsight, it is easy to wonder why no one had thought of it before. Newton and others should have realized that a static universe would soon start to contract under the influence of gravity. But suppose that, instead of being static, the universe was expanding. If it was expanding fairly slowly, the force of gravity would cause it eventually to stop expanding and then to start contracting. However, if it was expanding at more than a certain critical rate, gravity would never be strong enough to stop it, and the universe would continue to expand forever. This is a bit like what happens when one fires a rocket upward from the surface of the Earth. If it has a fairly low speed, gravity will eventually stop the rocket and it will start falling back. On the other hand, if the rocket has more than a certain critical speed–about seven miles a second–gravity will not be strong enough to pull it back, so it will keep going away from the Earth forever.

1.3 The Friedmann Model:[[3]](#footnote-3)

The equations of general relativity, which determined how the universe evolves in time, are too complicated to solve in detail. So what Friedmann did, instead, was to make two very simple assumptions about the universe: that the universe looks identical in whichever direction we look, and that this would also be true if we were observing the universe from anywhere else. On the basis of general relativity and these two assumptions, Friedmann showed that we should not expect the universe to be static. In fact, in 1922, several years before Edwin Hubble's discovery, Friedmann predicted exactly what Hubble found. The assumption that the universe looks the same in every direction is clearly not true in reality. For example, the other stars in our galaxy form a distinct band of light across the night sky called the Milky Way. But if we look at distant galaxies, there seems to be more or less the same number of them in each direction. So the universe does seem to be roughly the same in every direction, provided one views it on a large scale compared to the distance between galaxies. Now at first sight, all this evidence that the universe looks the same whichever direction we look in might seem to suggest there is something special about our place in the universe. In particular, it might seem that if we observe all other galaxies to be moving away from us, then we must be at the center of the universe. There is, however, an alternative explanation: The universe might also look the same in every direction as seen from any other galaxy. This, as we have seen, was Friedmann’s second assumption. Despite the success of his model and his prediction of Hubble’s observations, Friedmann’s work remained largely unknown in the West. It became known only after similar models were discovered in 1935 by the American physicist Howard Robertson and the British mathematician Arthur Walker, in response to Hubble’s discovery of the uniform expansion of the universe. Although Friedmann found only one, there are in fact three different kinds of models that obey Friedmann’s two fundamental assumptions. In the first kind—which Friedmann found—the universe is expanding so sufficiently slowly that the gravitational attraction between the different galaxies causes the expansion to slow down and eventually to stop. The galaxies then start to move toward each other and the universe contracts. The distance between two neighboring galaxies starts at zero, increases to a maximum, and then decreases back down to zero again. In the second kind of solution, the universe is expanding so rapidly that the gravitational attraction can never stop it, though it does slow it down a bit. The separation between neighboring galaxies in this model starts at zero, and eventually the galaxies are moving apart at a steady speed. Finally, there is a third kind of solution, in which the universe is expanding only just fast enough to avoid recollapse. In this case the separation also starts at zero, and increases forever. However, the speed at which the galaxies are moving apart gets smaller and smaller, although it never quite reaches zero. A remarkable feature of the first kind of Friedmann model is that the universe is not infinite in space, but neither does space have any boundary. Gravity is so strong that space is bent round onto itself, making it rather like the surface of the Earth. If one keeps traveling in a certain direction on the surface of the Earth, one never comes up against an impassable barrier or falls over the edge, but eventually comes back to where one started. Space, in the first Friedmann model, is just like this, but with three dimensions instead of two for the Earth’s surface. The fourth dimension—time—is also finite in extent, but it is like a line with two ends or boundaries, a beginning and an end. We shall see later that when one combines general relativity with the uncertainty principle of quantum mechanics, it is possible for both space and time to be finite without any edges or boundaries. The idea that one could go right around the universe and end up where one started makes good science fiction, but it doesn't have much practical significance because it can be shown that the universe would recollapse to zero size before one could get round. You would need to travel faster than light in order to end up where you started before the universe came to an end—and that is not allowed. But which Friedmann model describes our universe? Will the universe eventually stop expanding and start contracting, or will it expand forever? To answer this question, we need to know the present rate of expansion of the universe and its present average density. If the density is less than a certain critical value, determined by the rate of expansion, the gravitational attraction will be too weak to halt the expansion. If the density is greater than the critical value, gravity will stop the expansion at some time in the future and cause the universe to recollapse. We can determine the present rate of expansion by measuring the velocities at which other galaxies are moving away from us, using the Doppler effect. This can be done very accurately. However, the distances to the galaxies are not very well-known because we can only measure them indirectly. So all we know is that the universe is expanding by between 5 percent and 10 percent every thousand million years. However, our uncertainty about the present average density of the universe is even greater. If we add up the masses of all the stars that we can see in our galaxy and other galaxies, the total is less than one-hundredth of the amount required to halt the expansion of the universe, even in the lowest estimate of the rate of expansion. But we know that our galaxy and other galaxies must contain a large amount of dark matter which we cannot see directly, but which we know must be there because of the influence of its gravitational attraction on the orbits of stars and gas in the galaxies. Moreover, most galaxies are found in clusters, and we can similarly infer the presence of yet more dark matter in between the galaxies in these clusters by its effect on the motion of the galaxies. When we add up all this dark matter, we still get only about one-tenth of the amount required to halt the expansion. However, there might be some other form of matter which we have not yet detected and which might still raise the average density of the universe up to the critical value needed to halt the expansion. The present evidence, therefore, suggests that the universe will probably expand forever. But don’t bank on it. All we can really be sure of is that even if the universe is going to recollapse, it won’t do so for at least another ten thousand million years, since it has already been expanding for at least that long. This should not unduly worry us since by that time, unless we have colonies beyond the solar system, mankind will long since have died out, extinguished along with the death of our sun.

1.4 The Big Bang Theory:

In order to explain what my paper was about, I shall first describe the generally accepted history of the universe, according to what is known as the “hot big bang model.” This assumes that the universe is described by a Friedmann model, right back to the big bang. In such models one finds that as the universe expands, the temperature of the matter and radiation in it will go down. Since temperature is simply a measure of the average energy of the particles, this cooling of the universe will have a major effect on the matter in it. At very high temperatures, particles will be moving around so fast that they can escape any attraction toward each other caused by the nuclear or electromagnetic forces. But as they cooled off, one would expect particles that attract each other to start to clump together.

At the big bang itself, the universe had zero size and so must have been infinitely hot. But as the universe expanded, the temperature of the radiation would have decreased. One second after the big bang it would have fallen to about ten thousand million degrees. This is about a thousand times the temperature at the center of the sun, but temperatures as high as this are reached in H-bomb explosions. At this time the universe would have contained mostly photons, electrons, and neutrinos and their antiparticles, together with some protons and neutrons.

As the universe continued to expand and the temperature to drop, the rate at which electrons and the electron pairs were being produced in collisions would have fallen below the rate at which they were being destroyed by annihilation. So most of the electrons and antielectrons would have annihilated each other to produce more photons, leaving behind only a few electrons. About one hundred seconds after the big bang, the temperature would have fallen to one thousand million degrees, the temperature inside the hottest stars. At this temperature, protons and neutrons would no longer have sufficient energy to escape the attraction of the strong nuclear force. They would start to combine together to produce the nuclei of atoms of deuterium, or heavy hydrogen, which contain one proton and one neutron. The deuterium nuclei would then have combined with more protons and neutrons to make helium nuclei, which contained two protons and two neutrons. There would also be small amounts of a couple of heavier elements, lithium and beryllium. One can calculate that in the hot big bang model about a quarter of the protons and neutrons would have been converted into helium nuclei, along with a small amount of heavy hydrogen and other elements. The remaining neutrons would have decayed into protons, which are the nuclei of ordinary hydrogen atoms. These predictions agree very well with what is observed. The hot big bang model also predicts that we should be able to observe the radiation left over from the hot early stages. However, the temperature would have been reduced to a few degrees above absolute zero by the expansion of the universe. This is the explanation of the microwave background of radiation that was discovered by Penzias and Wilson in 1965. We are therefore thoroughly confident that we have the right picture, at least back to about one second after the big bang. Within only a few hours of the big bang, the production of helium and other elements would have stopped. And after that, for the next million years or so, the universe would have just continued expanding, without anything much happening. Eventually, once the temperature had dropped to a few thousand degrees, the electrons and nuclei would no longer have had enough energy to overcome the electromagnetic attraction between them. They would then have started combining to form atoms.

The universe as a whole would have continued expanding and cooling. However, in regions that were slightly denser than average, the expansion would have been slowed down by extra gravitational attraction. This would eventually stop expansion in some regions and cause them to start to recollapse. As they were collapsing, the gravitational pull of matter outside these regions might start them rotating slightly. As the collapsing region got smaller, it would spin faster—just as skaters spinning on ice spin faster as the draw in their arms. Eventually, when the region got small enough, it would be spinning fast enough to balance the attraction of gravity. In this way, disk like rotating galaxies were born. As time went on, the gas in the galaxies would break up into smaller clouds that would collapse under their own gravity. As these contracted, the temperature of the gas would increase until it became hot enough to start nuclear reactions. These would convert the hydrogen into more helium, and the heat given off would raise the pressure, and so stop the clouds from contracting any further. They would remain in this state for a long time as stars like our sun, burning hydrogen into helium and radiating the energy as heat and light.

More massive stars would need to be hotter to balance their stronger gravitational attraction. This would make the nuclear fusion reactions proceed so much more rapidly that they would use up their hydrogen in as little as a hundred million years. They would then contract slightly and, as they heated up further, would start to convert helium into heavier elements like carbon or oxygen. This, however, would not release much more energy What happens next is not completely clear, but it seems likely that the central regions of the star would collapse to a very dense state, such as a neutron star or black hole. The outer regions of the star may get blown off in a tremendous explosion called a supernova, which would outshine all the other stars in the galaxy. Some of the heavier elements produced near the end of the star’s life would be flung back into the gas in the galaxy. They would provide some of the raw material for the next generation of stars.

Our own sun contains about 2 percent of these heavier elements because it is a second– or third–generation star. It was formed some five thousand million years ago out of a cloud of rotating gas containing the debris of earlier supernovas. Most of the gas in that cloud went to form the sun or got blown away. However, a small amount of the heavier elements collected together to form the bodies that now orbit the sun as planets like the Earth. All of the Friedmann solutions have the feature that at some time in the past, between ten and twenty thousand million years ago, the distance between neighboring galaxies must have been zero. At that time, which we call the big bang, the density of the universe and the curvature of space-time would have been infinite. This means that the general theory of relativity— on which Friedmann’s solutions are based—predicts that there is a singular point in the universe.

All our theories of science are formulated on the assumption that space–time is smooth and nearly flat, so they would all break down at the big bang singularity, where the curvature of space–time is infinite. This means that even if there were events before the big bang, one could not use them to determine what would happen afterward, because predictability would break down at the big bang. Correspondingly, if we know only what has happened since the big bang, we could not determine what happened beforehand. As far as we are concerned, events before the big bang can have no consequences, so they should not form part of a scientific model of the universe. We should therefore cut them out of the model and say that time had a beginning at the big bang.

* OPEN QUESTIONS

This picture of a universe that started off very hot and cooled as it expanded is in agreement with all the observational evidence that we have today. Nevertheless, it leaves a number of important questions unanswered. First, why was the early universe so hot? Second, why is the universe so uniform on a large scale—why does it look the same at all points of space and in all directions? Third, why did the universe start out with so nearly the critical rate of expansion to just avoid recollapse? If the rate of expansion one second after the big bang had been smaller by even one part in a hundred thousand million million, the universe would have recollapsed before it ever reached its present size. On the other hand, if the expansion rate at one second had been larger by the same amount, the universe would have expanded so much that it would be effectively empty now.

Fourth, despite the fact that the universe is so uniform and homogenous on a large scale, it contains local lumps such as stars and galaxies. These are thought to have developed from small differences in the density of the early universe from one region to another. What was the origin of these density fluctuations? The general theory of relativity, on its own, cannot explain these features or answer these questions. This is because it predicts that the universe started off with infinite density at the big bang singularity. At the singularity, general relativity and all other physical laws would break down. One cannot predict what would come out of the singularity. As I explained before, this means that one might as well cut any events before the big bang out of the theory, because they can have no effect on what we observe. Space–time would have a boundary— a beginning at the big bang. Why should the universe have started off at the big bang in just such a way as to lead to the state we observe today? Why is the universe so uniform, and expanding at just the critical rate to avoid recollapse? One would feel happier about this if one could show that quite a number of different initial configurations for the universe would have evolved to produce a universe like the one we observe. If this is the case, a universe that developed from some sort of random initial conditions should contain a number of regions that are like what we observe. There might also be regions that were very different. However, these regions would probably not be suitable for the formation of galaxies and stars. These are essential prerequisites for the development of intelligent life, at least as we know it. Thus, these regions would not contain any beings to observe that they were different.

When one considers cosmology, one has to take into account the selection principle that we live in a region of the universe that is suitable for intelligent life. This fairly obvious and elementary consideration is sometimes called the anthropic principle. Suppose, on the other hand, that the initial state of the universe had to be chosen extremely carefully to lead to something like what we see around us. Then the universe would be unlikely to contain any region in which life would appear.

In the hot big bang model that I described earlier, there was not enough time in the early universe for heat to have flowed from one region to another. This means that different regions of the universe would have had to have started out with exactly the same temperature in order to account for the fact that the microwave background has the same temperature in every direction we look.

Also, the initial rate of expansion would have had to be chosen very precisely for the universe not to have recollapsed before now. This means that the initial state of the universe must have been very carefully chosen indeed if the hot big bang model was correct right back to the beginning of time. It would be very difficult to explain why the universe should have begun in just this way, except as the act of a God who intended to create beings like us.

1.5 The steady state theory:[[4]](#footnote-4)

Proposed in 1948 by Hermann Bondi, Thomas Gold and Fred Hoyle, the steady-state theory was based on an extension of something called the perfect cosmological principle. This holds that the universe looks essentially the same from every spot in it and at every time. (This applies only to the universe at large scales, obviously planets, stars, and galaxies are different from the space between them.) obviously, for the universe to look the same at all times, there could have been no beginning or no end. This struck a philosophical chord with a number of scientists, and the steady-state theory gained many adherents in the 1950s and 1960s. How could the universe continue to look the same when observations show it to be expanding, which would tend to thin out its contents? Supporters of this cosmology balanced the ever decreasing density that results from the expansion by hypothesizing that matter was continuously created out of nothing, the amount required was undetectably small –about a few atoms for every cubic mile each year. The steady state theory began to wither in the 1960s. First, astronomers discovered quasars, the highly luminous cores of very distant galaxies. Because the vast majority of quasars lie exceeding far away, their existence proves that the perfect cosmological principle cannot be true –the distant and therefore ancient universe is not the same as the younger universe nearby. The death knell for the theory sounded when radio astronomers Arno Penzias and Robert Wilson discovered the cosmic microwave background, the leftover radiation from the big bang. The steady-state had no reasonable way to explain this radiation, and their theory slowly faded away.

The steady state theory required a modification of general relativity to allow for the continual creation of matter, but the rate that was involved was so low—about one particle per cubic kilometer per year—that it was not in conflict with experiment. The theory was a good scientific theory, in the sense that it was simple and it made definite predictions that could be tested by observation. One of these predictions was that the number of galaxies or similar objects in any given volume of space should be the same wherever and whenever we look in the universe.

1.6 The inflationary model:[[5]](#footnote-5)

In order to avoid this difficulty with the very early stages of the hot big bang model, Alan Guth at the Massachusetts Institute of Technology put forward a new model. In this, many different initial configurations could have evolved to something like the present universe. He suggested that the early universe might have had a period of very rapid, or exponential, expansion. This expansion is said to be inflationary, But the inflation we think may have occurred in the size of the universe was much greater even than that—a million million million million million times in only a tiny fraction of a second. Guth suggested that the universe started out from the big bang very hot. One would expect that at such high temperatures, the strong and weak nuclear forces and the electromagnetic force would all be unified into a single force. As the universe expanded, it would cool, and particle energies would go down. Eventually there would be what is called a phase transition, and the symmetry between the forces would be broken. The strong force would become different from the weak and electromagnetic forces. One common example of a phase transition is the freezing of water when you cool it down. Liquid water is symmetrical, the same at every point and in every direction. However, when ice crystals form, they will have definite positions and will be lined up in some direction. This breaks the symmetry of the water.

In the case of water, if one is careful, one can “supercool” it. That is, one can reduce the temperature below the freezing point—0 degrees centigrade—without ice forming. Guth suggested that the universe might behave in a similar way: The temperature might drop below the critical value without the symmetry between the forces being broken. If this happened, the universe would be in an unstable state, with more energy than if the symmetry had been broken.

This special extra energy can be shown to have an antigravitational effect. It would act just like a cosmological constant.

Einstein introduced the cosmological constant into general relativity when he was trying to construct a static model of the universe. However, in this case, the universe would already be expanding. The repulsive effect of this cosmological constant would therefore have made the universe expand at an ever increasing rate. Even in regions where there were more matter particles than average, the gravitational attraction of the matter would have been outweighed by the repulsion of the effective cosmological constant. Thus, these regions would also expand in an accelerating inflationary manner.

As the universe expanded, the matter particles got farther apart. One would be left with an expanding universe that contained hardly any particles. It would still be in the supercooled state, in which the symmetry between the forces is not broken. Any irregularities in the universe would simply have been smoothed out by the expansion, as the wrinkles in a balloon are smoothed away when you blow it up. Thus, the present smooth and uniform state of the universe could have evolved from many different nonuniform initial states. The rate of expansion would also tend toward just the critical rate needed to avoid recollapse.

Moreover, the idea of inflation could also explain why there is so much matter in the universe. There is something like 1,080 particles in the region of the universe that we can observe. Where did they all come from? The answer is that, in quantum theory, particles can be created out of energy in the form of particle/antiparticle pairs. But that just raises the question of where the energy came from. The answer is that the total energy of the universe is exactly zero.

The matter in the universe is made out of positive energy. However, the matter is all attracting itself by gravity. Two pieces of matter that are close to each other have less energy than the same two pieces a long way apart. This is because you have to expend energy to separate them. You have to pull against the gravitational force attracting them together. Thus, in a sense, the gravitational field has negative energy. In the case of the whole universe, one can show that this negative gravitational energy exactly cancels the positive energy of the matter. So the total energy of the universe is zero.

Now, twice zero is also zero. Thus, the universe can double the amount of positive matter energy and also double the negative gravitational energy without violation of the conservation of energy. This does not happen in the normal expansion of the universe in which the matter energy density goes down as the universe gets bigger. It does happen, however, in the inflationary expansion, because the energy density of the supercooled state remains constant while the universe expands. When the universe doubles in size, the positive matter energy and the negative gravitational energy both double, so the total energy remains zero. During the inflationary phase, the universe increases its size by a very large amount. Thus, the total amount of energy available to make particles becomes very large. As Guth has remarked, “It is said that there is no such thing as a free lunch. But the universe is the ultimate free lunch.”

**1.6.1 The End of inflation:**

The universe is not expanding in an inflationary way today. Thus, there had to be some mechanism that would eliminate the very large effective cosmological constant. This would change the rate of expansion from an accelerated one to one that is slowed down by gravity, as we have today. As the universe expanded and cooled, one might expect that eventually the symmetry between the forces would be broken, just as supercooled water always freezes in the end. The extra energy of the unbroken symmetry state would then be released and would reheat the universe. The universe would then go on to expand and cool, just like the hot big bang model. However, there would now be an explanation of why the universe was expanding at exactly the critical rate and why different regions had the same temperature.

In Guth’s original proposal, the transition to broken symmetry was supposed to occur suddenly, rather like the appearance of ice crystals in very cold water. The idea was that “bubbles” of the new phase of broken symmetry would have formed in the old phase, like bubbles of steam surrounded by boiling water. The bubbles were supposed to expand and meet up with each other until the whole universe was in the new phase. The trouble was, the universe was expanding so fast that the bubbles would be moving away from each other too rapidly to join up. The universe would be left in a very nonuniform state, with some regions having symmetry between the different forces. Such a model of the universe would not correspond to what we see.

Andrei Linde said that the difficulty with the bubbles not joining up could be avoided if the bubbles were very big. In this case, our region of the universe could be contained inside a single bubble. In order for this to work, the change from symmetry to broken symmetry must have taken place very slowly inside the bubble, but this is quite possible according to grand unified theories.

Linde’s idea of a slow breaking of symmetry was very good, but his bubbles would have been bigger than the size of the universe at the time, instead the symmetry would have broken everywhere at the same time, rather than just inside bubbles. This would lead to a uniform universe, like we observe. The slow symmetry breaking model was a good attempt to explain why the universe is the way it is. However, it predicted much greater variations in the microwave background radiation than are observed. Also, later work cast doubt on whether there would have been the right kind of phase transition in the early universe. A better model, called the chaotic inflationary model, was introduced by Linde in 1983. This doesn’t depend on phase transitions, and it can give us the right size of variations of the microwave background. The inflationary model showed that the present state of the universe could have arisen from quite a large number of different initial configurations. It cannot be the case, however, that every initial configuration would have led to a universe like the one we observe. So even the inflationary model does not tell us why the initial configuration was such as to produce what we observe. Must we turn to the anthropic principle for an explanation? Was it all just a lucky chance?

That would seem a counsel of despair, a negation of all our hopes of understanding the underlying order of the universe.

1.7 The Theory of Everything:

It would be very difficult to construct a complete unified theory of everything all at one go. So instead we have made progress by finding partial theories. These describe a limited range of happenings and neglect other effects, or approximate them by certain numbers. In chemistry, for example, we can calculate the interactions of atoms without knowing the internal structure of the nucleus of an atom. Ultimately, however, one would hope to find a complete, consistent, unified theory that would include all these partial theories as approximations. The quest for such a theory is known as “the unification of physics.”

Einstein spent most of his later years unsuccessfully searching for a unified theory, but the time was not ripe: Very little was known about the nuclear forces. Moreover, Einstein refused to believe in the reality of quantum mechanics, despite the important role he had played in its development. Yet it seems that the uncertainty principle is a fundamental feature of the universe we live in A successful unified theory must therefore necessarily incorporate this principle.

The prospects for finding such a theory seem to be much better now because we know so much more about the universe. But we must beware of overconfidence. We have had false dawns before. At the beginning of this century, for example, it was thought that everything could be explained in terms of the properties of continuous matter, such as elasticity and heat conduction. The discovery of atomic structure and the uncertainty principle put an end to that. Then again, in 1928, Max Born told a group of visitors to Göttingen University, “Physics, as we know it, will be over in six months.”[[6]](#footnote-6) His confidence was based on the recent discovery by Dirac of the equation that governed the electron. It was thought that a similar equation would govern the proton, which was the only other particle known at the time, and that would be the end of theoretical physics. However, the discovery of the neutron and of nuclear forces knocked that one on the head, too.

Having said this, I believe there are grounds for cautious optimism that we may now be near the end of the search for the ultimate laws of nature. At the moment, we have a number of partial theories. We have general relativity, the partial theory of gravity, and the partial theories that govern the weak, the strong, and the electromagnetic forces. The last three may be combined in so-called grand unified theories. These are not very satisfactory because they do not include gravity. The main difficulty in finding a theory that unifies gravity with the other forces is that general relativity is a classical theory. That is, it does not incorporate the uncertainty principle of quantum mechanics. On the other hand, the other partial theories depend on quantum mechanics in an essential way. A necessary first step, therefore, is to combine general relativity with the uncertainty principle. As we have seen, this can produce some remarkable consequences, such as black holes not being black, and the universe being completely self–contained and without boundary. The trouble is, the uncertainty principle means that even empty space is filled with pairs of virtual particles and antiparticles. These pairs would have an infinite amount of energy. This means that their gravitational attraction would curve up the universe to an infinitely small size.

Rather similar, seemingly absurd infinities occur in the other quantum theories.

However, in these other theories, the infinities can be canceled out by a process called renormalization. This involves adjusting the masses of the particles and the strengths of the forces in the theory by an infinite amount. Although this technique is rather dubious mathematically, it does seem to work in practice. It has been used to make predictions that agree with observations to an extraordinary degree of accuracy. Renormalization, however, has a serious drawback from the point of view of trying to find a complete theory. When you subtract infinity from infinity, the answer can be anything you want. This means that the actual values of the masses and the strengths of the forces cannot be predicted from the theory. Instead, they have to be chosen to fit the observations. In the case of general relativity, there are only two quantities that can be adjusted: the strength of gravity and the value of the cosmological constant. But adjusting these is not sufficient to remove all the infinities. One therefore has a theory that seems to predict that certain quantities, such as the curvature of space–time, are really infinite, yet these quantities can be observed and measured to be perfectly finite. In an attempt to overcome this problem, a theory called “supergravity” was suggested in 1976. This theory was really just general relativity with some additional particles.

In general relativity, the gravitational force can be thought of as being carried by a particle of spin 2 called the graviton. The idea was to add certain other new particles of spin 3/2, 1, 1/2, and 0. In a sense, all these particles could then be regarded as different aspects of the same “superparticle.” The virtual particle/ antiparticle pairs of spin 1/2 and 3/2 would have negative energy. This would tend to cancel out the positive energy of the virtual pairs of particles of spin 0, 1, and 2. In this way, many of the possible infinities would cancel out, but it was suspected that some infinities might still remain. However, the calculations required to find out whether there were any infinities left uncanceled were so long and difficult that no one was prepared to undertake them. Even with a computer it was reckoned it would take at least four years. The chances were very high that one would make at least one mistake, and probably more. So one would know one had the right answer only if someone else repeated the calculation and got the same answer, and that did not seem very likely.

Because of this problem, there was a change of opinion in favor of what are called string theories. In these theories the basic objects are not particles that occupy a single point of space. Rather, they are things that have a length but no other dimension, like an infinitely thin loop of string. A particle occupies one point of space at each instant of time. Thus, its history can be represented by a line in space-time called the “world–line.” A string, on the other hand, occupies a line in space at each moment of time. So its history in space–time is a two–dimensional surface called the “world–sheet.” Any point on such a world–sheet can be described by two numbers, one specifying the time and the other the position of the point on the string. The world-sheet of a string is a cylinder or tube. A slice through the tube is a circle, which represents the position of the string at one particular time.

Two pieces of string can join together to form a single string. It is like the two legs joining on a pair of trousers. Similarly, a single piece of string can divide into two strings. In string theories, what were previously thought of as particles are now pictured as waves traveling down the string, like waves on a washing line. The emission or absorption of one particle by another corresponds to the dividing or joining together of strings. For example, the gravitational force of the sun on the Earth corresponds to an H-shaped tube or pipe. String theory is rather like plumbing, in a way. Waves on the two vertical sides of the H correspond to the particles in the sun and the Earth, and waves on the horizontal crossbar correspond to the gravitational force that travels between them. String theory has a curious history. It was originally invented in the late 1960s in an attempt to find a theory to describe the strong force. The idea was that particles like the proton and the neutron could be regarded as waves on a string. The strong forces between the particles would correspond to pieces of string that went between other bits of string, like in a spider’s web. For this theory to give the observed value of the strong force between particles, the strings had to be like rubber bands with a pull of about ten tons.

In 1974 Joël Scherk and John Schwarz published a paper in which they showed that string theory could describe the gravitational force, but only if the tension in the string were very much higher—about 1039tons. The predictions of the string theory would be just the same as those of general relativity on normal length scales, but they would differ at very small distances—less than 10-33 centimeters. Their work did not receive much attention, however, because at just about that time, most people abandoned the original string theory of the strong force. Scherk died in tragic circumstances. He suffered from diabetes and went into a coma when no one was around to give him an injection of insulin. So Schwarz was left alone as almost the only supporter of string theory, but now with a much higher proposed value of the string tension. There seemed to have been two reasons for the sudden revival of interest in strings in 1984. One was that people were not really making much progress toward showing that supergravity was finite or that it could explain the kinds of particles that we observe. The other was the publication of a paper by John Schwarz and Mike Green which showed that string theory might be able to explain the existence of particles that have a built–in left–handedness, like some of the particles that we observe. Whatever the reasons, a large number of people soon began to work on string theory. A new version was developed, the so–called heterotic string. This seemed as if it might be able to explain the types of particle that we observe. String theories also lead to infinities, but it is thought they will all cancel out in versions like the heterotic string. String theories, however, have a bigger problem. They seem to be consistent only if space–time has either ten or twenty–six dimensions, instead of the usual four. Of course, extra space–time dimensions are a commonplace of science fiction; indeed, they are almost a necessity. Otherwise, the fact that relativity implies that one cannot travel faster than light means that it would take far too long to get across our own galaxy, let alone to travel to other galaxies. The science fiction idea is that one can take a shortcut through a higher dimension. One can picture this in the following way. Imagine that the space we live in had only two dimensions and was curved like the surface of a doughnut or a torus. If you were on one side of the ring and you wanted to get to a point on the other side, you would have to go around the ring. However, if you were able to travel in the third dimension, you could cut straight across. Why don’t we notice all these extra dimensions if they are really there? Why do we see only three space and one-time dimension? The suggestion is that the other dimensions are curved up into a space of very small size, something like a million million million million millionth of an inch. This is so small that we just don’t notice it. We see only the three space and one-time dimension in which space-time is thoroughly flat. It is like the surface of an orange: if you look at it close up, it is all curved and wrinkled, but if you look at it from a distance, you don’t see the bumps and it appears to be smooth. So it is with space–time. On a very small scale, it is ten–dimensional and highly curved. But on bigger scales, you don’t see the curvature or the extra dimensions. If this picture is correct, it spells bad news for would-be space travelers. The extra dimensions would be far too small to allow a spaceship through. However, it raises another major problem. Why should some, but not all, of the dimensions be curled up into a small ball? Presumably, in the very early universe, all the dimensions would have been very curved. Why did three space and one-time dimension flatten out, while the other dimensions remained tightly curled up? One possible answer is the anthropic principle. Two space dimensions do not seem to be enough to allow for the development of complicated beings like us. For example, two–dimensional people living on a one-dimensional Earth would have to climb over each other in order to get past each other. If a two dimensional creature ate something it could not digest completely, it would have to bring up the remains the same way it swallowed them, because if there were a passage through its body, it would divide the creature into two separate parts. Our two–dimensional being would fall apart. Similarly, it is difficult to see how there could be any circulation of the blood in a two-dimensional creature. There would also be problems with more than three space dimensions. The gravitational force between two bodies would decrease more rapidly with distance than it does in three dimensions. The significance of this is that the orbits of planets, like the Earth, around the sun would be unstable. The least disturbance from a circular orbit, such as would be caused by the gravitational attraction of other planets, would cause the Earth to spiral away from or into the sun. We would either freeze or be burned up. In fact, the same behavior of gravity with distance would mean that the sun would also be unstable. It would either fall apart or it would collapse to form a black hole. In either case, it would not be much use as a source of heat and light for life on Earth. On a smaller scale, the electrical forces that cause the electrons to orbit around the nucleus in an atom would behave in the same way as the gravitational forces. Thus, the electrons would either escape from the atom altogether or it would spiral into the nucleus. In either case, one could not have atoms as we know them.

It seems clear that life, at least as we know it, can exist only in regions of space-time in which three space and one-time dimension are not curled up small. This would mean that one could appeal to the anthropic principle, provided one could show that string theory does at least allow there to be such regions of the universe. And it seems that indeed each string theory does allow such regions. There may well be other regions of the universe, or other universes (whatever that may mean) in which all the dimensions are curled up small, or in which more than four dimensions are nearly flat. But there would be no intelligent beings in such regions to observe the different number of effective dimensions. Apart from the question of the number of dimensions that space-time appears to have, string theory still has several other problems that must be solved before it can be acclaimed as the ultimate unified theory of physics. We do not yet know whether all the infinities cancel each other out, or exactly how to relate the waves on the string to the particular types of particle that we observe. Nevertheless, it is likely that answers to these questions will be found over the next few years, and that by the end of the century we shall know whether string theory is indeed the long sought-after unified theory of physics. Can there really be a unified theory of everything? Or are we just chasing a mirage? There seem to be three possibilities:

• There really is a complete unified theory, which we will someday discover if we are smart enough.

• There is no ultimate theory of the universe, just an infinite sequence of theories that describe the universe more and more accurately.

• There is no theory of the universe. Events cannot be predicted beyond a certain extent but occur in a random and arbitrary manner.

Some would argue for the third possibility on the grounds that if there were a complete set of laws, that would infringe on God’s freedom to change His mind and to intervene in the world. It’s a bit like the old paradox: Can God make a stone so heavy that He can’t lift it? But the idea that God might want to change His mind is an example of the fallacy, pointed out by St. Augustine, of imagining God as a being existing in time. Time is a property only of the universe that God created. Presumably, He knew what He intended when He set it up. With the advent of quantum mechanics, we have come to realize that events cannot be predicted with complete accuracy but that there is always a degree of uncertainty. If one liked, one could ascribe this randomness to the intervention of God. But it would be a very strange kind of intervention. There is no evidence that it is directed toward any purpose. Indeed, if it were, it wouldn’t be random. In modern times, we have effectively removed the third possibility by redefining the goal of science. Our aim is to formulate a set of laws that will enable us to predict events up to the limit set by the uncertainty principle. The second possibility, that there is an infinite sequence of more and more refined theories, is in agreement with all our experience so far. On many occasions, we have increased the sensitivity of our measurements or made a new class of observations only to discover new phenomena that were not predicted by the existing theory. To account for these, we have had to develop a more advanced theory. It would therefore not be very surprising if we find that our present grand unified theories break down when we test them on bigger and more powerful particle accelerators. Indeed, if we didn’t expect them to break down, there wouldn’t be much point in spending all that money on building more powerful machines. However, it seems that gravity may provide a limit to this sequence of “boxes within boxes.” If one had a particle with an energy above what is called the Planck energy, 1019 GeV, its mass would be so concentrated that it would cut itself off from the rest of the universe and form a little black hole. Thus, it does seem that the sequence of more and more refined theories should have some limit as we go to higher and higher energies. There should be some ultimate theory of the universe. Of course, the Planck energy is a very long way from the energies of around a GeV, which are the most that we can produce in the laboratory at the present time. To bridge that gap would require a particle accelerator that was bigger than the solar system. Such an accelerator would be unlikely to be funded in the present economic climate. However, the very early stages of the universe are an arena where such energies must have occurred. I think that there is a good chance that the study of the early universe and the requirements of mathematical consistency will lead us to a complete unified theory by the end of the century—always presuming we don’t blow ourselves up first. What would it mean if we actually did discover the ultimate theory of the universe? It would bring to an end a long and glorious chapter in the history of our struggle to understand the universe. But it would also revolutionize the ordinary person’s understanding of the laws that govern the universe. In Newton’s time it was possible for an educated person to have a grasp of the whole of human knowledge, at least in outline. But ever since then, the pace of development of science has made this impossible. Theories were always being changed to account for new observations. They were never properly digested or simplified so that ordinary people could understand them. You had to be a specialist, and even then you could only hope to have a proper grasp of a small proportion of the scientific theories. Further, the rate of progress was so rapid that what one learned at school or university was always a bit out of date. Only a few people could keep up with the rapidly advancing frontier of knowledge. And they had to devote their whole time to it and specialize in a small area. The rest of the population had little idea of the advances that were being made or the excitement they were generating. Seventy years ago, if Eddington is to be believed, only two people understood the general theory of relativity. Nowadays tens of thousands of university graduates understand it, and many millions of people are at least familiar with the idea. If a complete unified theory were discovered, it would be only a matter of time before it was digested and simplified in the same way. It could then be taught in schools, at least in outline. We would then all be able to have some understanding of the laws that govern the universe and which are responsible for our existence. Einstein once asked a question: “How much choice did God have in constructing the universe?” If the no boundary proposal is correct, He had no freedom at all to choose initial conditions. He would, of course, still have had the freedom to choose the laws that the universe obeyed. This, however, may not really have been all that much of a choice. There may well be only one or a small number of complete unified theories that are self-consistent and which allow the existence of intelligent beings. We can ask about the nature of God even if there is only one possible unified theory that is just a set of rules and equations. What is it that breathes fire into the equations and makes a universe for them to describe? The usual approach of science of constructing a mathematical model cannot answer the question of why there should be a universe for the model to describe. Why does the universe go to all the bother of existing? Is the unified theory so compelling that it brings about its own existence? Or does it need a creator, and, if so, does He have any effect on the universe other than being responsible for its existence?

Up until now, most scientists have been too occupied with the development of new theories that describe what the universe is, to ask the question why. On the other hand, the people whose business it is to ask why—the philosophers— have not been able to keep up with the advance of scientific theories. In the eighteenth century, philosophers considered the whole of human knowledge, including science, to be their field. They discussed questions such as: Did the universe have a beginning? However, in the nineteenth and twentieth centuries, science became too technical and mathematical for the philosophers or anyone else, except a few specialists. Philosophers reduced the scope of their inquiries so much that Wittgenstein, the most famous philosopher of this century, said, “The sole remaining task for philosophy is the analysis of language.” What a comedown from the great tradition of philosophy from Aristotle to Kant.

However, if we do discover a complete theory, it should in time be understandable in broad principle by everyone, not just a few scientists. Then we shall all be able to take part in the discussion of why the universe exists. If we find the answer to that, it would be the ultimate triumph of human reason.

Chapter 2:

The nature of reality

AFEW YEARS AGO the city council of Monza, Italy, barred pet owners from keeping goldfish

in curved goldfish bowls. The measure’s sponsor explained the measure in part by saying that it is cruel to keep a fish in a bowl with curved sides because, gazing out, the fish would have a distorted view of reality. But how do we know we have the true, undistorted picture of reality?

Might not we ourselves also be inside some big goldfish bowl and have our vision distorted by an enormous lens? The goldfish’s picture of reality is different from ours, but can we be sure it is less real?

The goldfish view is not the same as our own, but goldfish could still formulate scientific laws governing the motion of the objects they observe outside their bowl. For example, due to the distortion, a freely moving object that we would observe to move in a straight line would be observed by the goldfish to move along a curved path. Nevertheless, the goldfish could formulate scientific laws from their distorted frame of reference that would always hold true and that would enable them to make predictions about the future motion of objects outside the bowl. Their laws would be more complicated than the laws in our frame, but simplicity is a matter of taste. If a goldfish formulated such a theory, we would have to admit the goldfish’s view as a valid picture of reality.

A famous example of different pictures of reality is the model introduced around AD 150 by Ptolemy (ca. 85—ca. 165) to describe the motion of the celestial bodies. Ptolemy published his work in a thirteen-book treatise usually known under its Arabic title, *Almagest.* The *Almagest* begins by explaining reasons for thinking that the earth is spherical, motionless, positioned at the center of the universe, and negligibly small in comparison to the distance of the heavens. Despite Aristarchus’s heliocentric model, these beliefs had been held by most educated Greeks at least since the time of Aristotle, who believed for mystical reasons that the earth should be at the center of the universe. In Ptolemy’s model the earth stood still at the center and the planets and the stars moved around it in complicated orbits involving epicycles, like wheels on wheels. This model seemed natural because we don’t feel the earth under our feet moving (except in earthquakes). Later European learning was based on the Greek sources that had been passed down, so that the ideas of Aristotle and Ptolemy became the basis for much of Western thought. Ptolemy’s model of the cosmos was adopted by the Catholic Church and held as official doctrine for fourteen hundred years. It was not until 1543 that an alternative model was put forward by Copernicus in his book *De revolutionibus orbium coelestium* (*On the Revolutions of the Celestial Spheres*), published only in the year of his death (though he had worked on his theory for several decades). Copernicus, like Aristarchus some seventeen centuries earlier, described a world in which the sun was at rest and the planets revolved around it in circular orbits. Though the idea wasn’t new, its revival was met with passionate resistance. The Copernican model was held to contradict the Bible, which was interpreted as saying that the planets moved around the earth, even though the Bible never clearly stated that. In fact, at the time the Bible was written people believed the earth was flat. The Copernican model led to a furious debate as to whether the earth was at rest, culminating in Galileo’s trial for heresy in 1633 for advocating the Copernican model, and for thinking “that one may hold and defend as probable an opinion after it has been declared and defined contrary to the Holy Scripture.” He was found guilty, confined to house arrest for the rest of his life, and forced to recant. He is said to have muttered under his breath “*Eppur si muove,*” “But still it moves.” In 1992 the Roman Catholic Church finally acknowledged that it had been wrong to condemn Galileo. So which is real, the Ptolemaic or Copernican system? Although it is not uncommon for people to say that Copernicus proved Ptolemy wrong, that is not true. As in the case of our normal view versus that of the goldfish, one can use either picture as a model of the universe, for our observations of the heavens can be explained by assuming either the earth or the sun to be at rest. Despite its role in philosophical debates over the nature of our universe, the real advantage of the Copernican system is simply that the equations of motion are much simpler in the frame of reference in which the sun is at rest.

A different kind of alternative reality occurs in the science fiction film *The Matrix,* in which the human race is unknowingly living in a simulated virtual reality created by intelligent computers to keep them pacified and content while the computers suck their bioelectrical energy (whatever that is). Maybe this is not so far-fetched, because many people prefer to spend their time in the simulated reality of websites such as Second Life. How do we know we are not just characters in a computer-generated soap opera? If we lived in a synthetic imaginary world, events would not necessarily have any logic or consistency or obey any laws. The aliens in control might find it more interesting or amusing to see our reactions, for example, if the full moon split in half, or everyone in the world on a diet developed an uncontrollable craving for banana cream pie. But if the aliens did enforce consistent laws, there is no way we could tell there was another reality behind the simulated one. It would be easy to call the world the aliens live in the “real” one and the synthetic world a “false” one. But if—like us—the beings in the simulated world could not gaze into their universe from the outside, there would be no reason for them to doubt their own pictures of reality. This is a modern version of the idea that we are all figments of someone else’s dream.

These examples bring us to a conclusion that will be important in this research: *There is no picture- or theory-independent concept of reality.[[7]](#footnote-7)* Instead we will adopt a view that we will call model dependentrealism: the idea that a physical theory or world picture is a model (generally of amathematical nature) and a set of rules that connect the elements of the model to observations.This provides a framework with which to interpret modern science.

Philosophers from Plato onward have argued over the years about the nature of reality. Classical science is based on the belief that there exists a real external world whose properties are definite and independent of the observer who perceives them. According to classical science, certain objects exist and have physical properties, such as speed and mass, that have well-defined values. In this view our theories are attempts to describe those objects and their properties, and our measurements and perceptions correspond to them. Both observer and observed are parts of a world that has an objective existence, and any distinction between them has no meaningful significance. In other words, if you see a herd of zebras fighting for a spot in the parking garage, it is because there really is a herd of zebras fighting for a spot in the parking garage. All other observers who look will measure the same properties, and the herd will have those properties whether anyone observes them or not. In philosophy that belief is called realism. Though realism may be a tempting viewpoint, as we’ll see later, what we know about modern physics makes it a difficult one to defend. For example, according to the principles of quantum physics, which is an accurate description of nature, a particle has neither a definite position nor a definite velocity unless and until those quantities are measured by an observer. It is therefore *not* correct to say that a measurement gives a certain result because the quantity being measured had that value at the time of the measurement. In fact, in some cases individual objects don’t even have an independent existence but rather exist only as part of an ensemble of many. And if a theory called the holographic principle proves correct, we and our four dimensional world may be shadows on the boundary of a larger, five-dimensional space-time. In that case, our status in the universe is analogous to that of the goldfish. Strict realists often argue that the proof that scientific theories represent reality lies in their success. But different theories can successfully describe the same phenomenon through disparate conceptual frameworks. In fact, many scientific theories that had proven successful were later replaced by other, equally successful theories based on wholly new concepts of reality. Traditionally those who didn’t accept realism have been called anti-realists. Anti-realists suppose a distinction between empirical knowledge and theoretical knowledge. They typically argue that observation and experiment are meaningful but that theories are no more than useful instruments that do not embody any deeper truths underlying the observed phenomena. Some anti-realists have even wanted to restrict science to things that can be observed. For that reason, many in the nineteenth century rejected the idea of atoms on the grounds that we would never see one. George Berkeley (1685–1753) even went as far as to say that nothing exists except the mind and its ideas. When an English author and lexicographer Dr. Samuel Johnson (1709–1784) remarked that Berkeley’s claim could not possibly be refuted, so he wasn’t really refuting Berkeley’s ideas. But his act did illustrate the view of philosopher David Hume (1711–1776), who wrote that although we have no rational grounds for believing in an objective reality, we also have no choice but to act as if it is true. Model-dependent realism short-circuits all this argument and discussion between the realist and anti-realist schools of thought.

According to model-dependent realism, it is pointless to ask whether a model is real, only whether it agrees with observation. If there are two models that both agree with observation, like the goldfish’s picture and ours, then one cannot say that one is more real than another. One can use whichever model is more convenient in the situation under consideration. For example, if one were inside the bowl, the goldfish’s picture would be useful, but for those outside, it would be very awkward to describe events from a distant galaxy in the frame of a bowl on earth, especially because the bowl would be moving as the earth orbits the sun and spins on its axis. We make models in science, but we also make them in everyday life. Model-dependent realism applies not only to scientific models but also to the conscious and subconscious mental models we all create in order to interpret and understand the everyday world. There is no way to remove the observer—us—from our perception of the world, which is created through our sensory processing and through the way we think and reason. Our perception—and hence the observations upon which our theories are based—is not direct, but rather is shaped by a kind of lens, the interpretive structure of our human brains.

Model-dependent realism corresponds to the way we perceive objects. In vision, one’s brain receives a series of signals down the optic nerve. Those signals do not constitute the sort of image you would accept on your television. There is a blind spot where the optic nerve attaches to the retina, and the only part of your field of vision with good resolution is a narrow area of about 1 degree of visual angle around the retina’s center, an area the width of your thumb when held at arm’s length. And so the raw data sent to the brain are like a badly pixilated picture with a hole in it. Fortunately, the human brain processes that data, combining the input from both eyes, filling in gaps on the assumption that the visual properties of neighboring locations are similar and interpolating. Moreover, it reads a two-dimensional array of data from the retina and creates from it the impression of three-dimensional space. The brain, in other words, builds a mental picture or model. The brain is so good at model building that if people are fitted with glasses that turn the images in their eyes upside down, their brains, after a time, change the model so that they again see things the right way up. If the glasses are then removed, they see the world upside down for a while, then again adapt. This shows that what one means when one says “I see a chair” is merely that one has used the light scattered by the chair to build a mental image or model of the chair. If the model is upside down, with luck one’s brain will correct it before one tries to sit on the chair. Another problem that model-dependent realism solves, or at least avoids, is the meaning of existence. How do I know that a table still exists if I go out of the room and can’t see it? What does it mean to say that things we can’t see, such as electrons or quarks—the particles that are said to make up the proton and neutron—exist? One could have a model in which the table disappears when I leave the room and reappears in the same position when I come back, but that would be awkward, and what if something happened when I was out, like the ceiling falling in? How, under the table-disappears-when-I-leave-the-room model, could I account for the fact that the next time I enter, the table reappears broken, under the debris of the ceiling? The model in which the table stays put is much simpler and agrees with observation. That is all one can ask.

In the case of subatomic particles that we can’t see, electrons are a useful model that explains observations like tracks in a cloud chamber and the spots of light on a television tube, as well as many other phenomena. It is said that the electron was discovered in 1897 by British physicist J.J. Thomson at the Cavendish Laboratory at Cambridge University. He was experimenting with currents of electricity inside empty glass tubes, a phenomenon known as cathode rays. His experiments led him to the bold conclusion that the mysterious rays were composed of minuscule “corpuscles” that were material constituents of atoms, which were then thought to be the indivisible fundamental unit of matter. Thomson did not “see” an electron, nor was his speculation directly or unambiguously demonstrated by his experiments. But the model has proved crucial in applications from fundamental science to engineering, and today all physicists believe in electrons, even though you cannot see them.

Quarks, which we also cannot see, are a model to explain the properties of the protons and neutrons in the nucleus of an atom. Though protons and neutrons are said to be made of quarks, we will never observe a quark because the binding force between quarks increases with separation, and hence isolated, free quarks cannot exist in nature. Instead, they always occur in groups of three (protons and neutrons), or in pairings of a quark and an anti-quark (pi mesons), and behave as if they were joined by rubber bands.

The question of whether it makes sense to say quarks really exist if you can never isolate one was a controversial issue in the years after the quark model was first proposed. The idea that certain particles were made of different combinations of a few sub-subnuclear particles provided an organizing principle that yielded a simple and attractive explanation for their properties. But although physicists were accustomed to accepting particles that were only inferred to exist from statistical blips in data pertaining to the scattering of other particles, the idea of assigning reality to a particle that might be, in principle, unobservable was too much for many physicists. Over the years, however, as the quark model led to more and more correct predictions, that opposition faded. It is certainly possible that some alien beings with seventeen arms, infrared eyes, and a habit of blowing clotted cream out their ears would make the same experimental observations that we do, but describe them without quarks. Nevertheless, according to model-dependent realism, quarks exist in a model that agrees with our observations of how subnuclear particles behave. Model-dependent realism can provide a framework to discuss questions such as: If the world was created a finite time ago, what happened before that? An early Christian philosopher, St. Augustine (354–430), said that the answer was not that God was preparing hell for people who ask such questions, but that time was a property of the world that God created and that time did not exist before the creation, which he believed had occurred not that long ago. That is one possible model, which is favored by those who maintain that the account given in Genesis is literally true even though the world contains fossil and other evidence that makes it look much older. One can also have a different model, in which time continues back 13.7 billion years to the big bang. The model that explains the most about our present observations, including the historical and geological evidence, is the best representation we have of the past. The second model can explain the fossil and radioactive records and the fact that we receive light from galaxies millions of light-years from us, and so this model—the big bang theory—is more useful than the first. Still, neither model can be said to be more real than the other.

Some people support a model in which time goes back even further than the big bang. It is not yet clear whether a model in which time continued back beyond the big bang would be better at explaining present observations because it seems the laws of the evolution of the universe may break down at the big bang. If they do, it would make no sense to create a model that encompasses time before the big bang, because what existed then would have no observable consequences for the present, and so we might as well stick with the idea that the big bang was the creation of the world.

A model is a good model if it:

1. Is elegant

2. Contains few arbitrary or adjustable elements

3. Agrees with and explains all existing observations

4. Makes detailed predictions about future observations that can disprove or falsify the model

if they are not borne out.

For example, Aristotle’s theory that the world was made of four elements, earth, air, fire, and water, and that objects acted to fulfill their purpose was elegant and didn’t contain adjustable elements. But in many cases it didn’t make definite predictions, and when it did, the predictions weren’t always in agreement with observation. One of these predictions was that heavier objects should fall faster because their purpose is to fall. Nobody seemed to have thought that it was important to test this until Galileo. There is a story that he tested it by dropping weights from the Leaning Tower of Pisa. This is probably apocryphal, but we do know he rolled different weights down an inclined plane and observed that they all gathered speed at the same rate, contrary to Aristotle’s prediction.

The above criteria are obviously subjective. Elegance, for example, is not something easily measured, but it is highly prized among scientists because laws of nature are meant to economically compress a number of particular cases into one simple formula. Elegance refers to the form of a theory, but it is closely related to a lack of adjustable elements, since a theory jammed with fudge factors is not very elegant. To paraphrase Einstein, a theory should be as simple as possible, but not simpler. Ptolemy added epicycles to the circular orbits of the heavenly bodies in order that his model might accurately describe their motion. The model could have been made more accurate by adding epicycles to the epicycles, or even epicycles to those. Though added complexity could make the model more accurate, scientists view a model that is contorted to match a specific set of observations as unsatisfying, more of a catalog of data than a theory likely to embody any useful principle.

As for the fourth point, scientists are always impressed when new and stunning predictions prove correct. On the other hand, when a model is found lacking, a common reaction is to say the experiment was wrong. If that doesn’t prove to be the case, people still often don’t abandon the model but instead attempt to save it through modifications. Although physicists are indeed tenacious in their attempts to rescue theories they admire, the tendency to modify a theory fades to the degree that the alterations become artificial or cumbersome, and therefore “inelegant.” If the modifications needed to accommodate new observations become too baroque, it signals the need for a new model. One example of an old model that gave way under the weight of new observations was the idea of a static universe. In the 1920s, most physicists believed that the universe was static, or unchanging in size. Then, in 1929, Edwin Hubble published his observations showing that the universe is expanding. But Hubble did not directly observe the universe expanding. He observed the light emitted by galaxies. That light carries a characteristic signature, or spectrum, based on each galaxy’s composition, which changes by a known amount if the galaxy is moving relative to us. Therefore, by analyzing the spectra of distant galaxies, Hubble was able to determine their velocities. He had expected to find as many galaxies moving away from us as moving toward us. Instead he found that nearly all galaxies were moving away from us, and the farther away they were, the faster they were moving. Hubble concluded that the universe is expanding, but others, trying to hold on to the earlier model, attempted to explain his observations within the context of the static universe. For example, Caltech physicist Fritz Zwicky suggested that for some yet unknown reason light might slowly lose energy as it travels great distances. This decrease in energy would correspond to a change in the light’s spectrum, which Zwicky suggested could mimic Hubble’s observations. For decades after Hubble, many scientists continued to hold on to the steady-state theory. But the most natural model was Hubble’s, that of an expanding universe, and it has come to be the accepted one. In our quest to find the laws that govern the universe we have formulated a number of theories or models, such as the four-element theory, the Ptolemaic model, the phlogiston theory, the big bang theory, and so on. With each theory or model, our concepts of reality and of the fundamental constituents of the universe have changed. For example, consider the theory of light. Newton thought that light was made up of little particles or corpuscles. This would explain why light travels in straight lines, and Newton also used it to explain why light is bent or refracted when it passes from one medium to another, such as from air to glass or air to water.

The corpuscle theory could not, however, be used to explain a phenomenon that Newton himself observed, which is known as Newton’s rings. Place a lens on a flat reflecting plate and illuminate it with light of a single color, such as a sodium light. Looking down from above, one will see a series of light and dark rings centered on where the lens touches the surface. This would be difficult to explain with the particle theory of light, but it can be accounted for in the wave theory. According to the wave theory of light, the light and dark rings are caused by a phenomenon called interference. A wave, such as a water wave, consists of a series of crests and troughs. When waves collide, if those crests and troughs happen to correspond, they reinforce each other, yielding a larger wave. That is called constructive interference. In that case the waves are said to be “in phase.” At the other extreme, when the waves meet, the crests of one wave might coincide with the troughs of the other. In that case the waves cancel each other and are said to be “out of phase.” That situation is called destructive interference.

In Newton’s rings the bright rings are located at distances from the center where the separation between the lens and the reflecting plate is such that the wave reflected from the lens differs from the wave reflected from the plate by an integral (1, 2, 3,…) number of wavelengths, creating constructive interference. (A wavelength is the distance between one crest or trough of a wave and the next.) The dark rings, on the other hand, are located at distances from the center where the separation between the two reflected waves is a half-integral (½, 1½, 2½,…) number of wavelengths, causing destructive interference—the wave reflected from the lens cancels the wave reflected from the plate.

In the nineteenth century, this was taken as confirming the wave theory of light and showing that the particle theory was wrong. However, early in the twentieth century Einstein showed that the photoelectric effect (now used in television and digital cameras) could be explained by a particle or quantum of light striking an atom and knocking out an electron. Thus light behaves as both particle and wave. The concept of waves probably entered human thought because people watched the ocean, or a puddle after a pebble fell into it. In fact, if you have ever dropped two pebbles into a puddle, you have probably seen interference at work, as in the picture above. Other liquids were observed to behave in a similar fashion, except perhaps wine if you’ve had too much. The idea of particles was familiar from rocks, pebbles, and sand. But this wave/particle duality—the idea that an object could be described as either a particle or a wave—is as foreign to everyday experience as is the idea that you can drink a chunk of sandstone.

Dualities like this—situations in which two very different theories accurately describe the same phenomenon—are consistent with model-dependent realism. Each theory can describe and explain certain properties, and neither theory can be said to be better or more real than the other.

Regarding the laws that govern the universe, what we can say is this: There seems to be no single mathematical model or theory that can describe every aspect of the universe. Instead, as mentioned in the opening of the chapter, there seems to be the network of theories called M-theory. Each theory in the M-theory network is good at describing phenomena within a certain range. Wherever their ranges overlap, the various theories in the network agree, so they can all be said to be parts of the same theory. But no single theory within the network can describe every aspect of the universe— all the forces of nature, the particles that feel those forces, and the framework of space and time in which it all plays out. Though this situation does not fulfill the traditional physicists’ dream of a single unified theory, it is acceptable within the framework of model-dependent realism. Now we turn to a

fundamental principle upon which our modern view of nature is based: quantum theory, and in particular, the approach to quantum theory called alternative histories. In that view, the universe does not have just a single existence or history, but rather every possible version of the universe exists simultaneously in what is called a quantum superposition. That may sound as outrageous as the theory in which the table disappears whenever we leave the room, but in this case the theory has passed every experimental test to which it has ever been subjected.

But know we'll ask a question: " Are we living the present or the past??"

In order to know the answer, we need to analyze the conception of time and what affect it.

As we all know the light coming to the earth from the sun is already late about 8 minutes so we see through light and without it we can't see anything so we are living in a controversial situation because we are living the past (considering that time relative to the light) so the universe maybe destroyed now and we don't even feel it!

Chapter 3:

Relativity

The general theory

The general theory:

General relativity can be understood by examining its similarities with and departures from classical physics. The first step is the realization that classical mechanics and Newton's law of gravity admit a geometric description. The combination of this description with the laws of special relativity results in a heuristic derivation of general relativity.

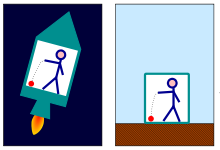
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Figure (1) : According to general relativity, objects in a gravitational field behave similarly to objects within an accelerating enclosure. For example, an observer will see a ball fall the same way in a rocket (left) as it does on Earth (right), provided that the acceleration of the rocket is equal to 9.8 m/s2 (the acceleration due to gravity at the surface of the Earth).

At the base of classical mechanics is the notion that a body's motion can be described as a combination of free (or inertial) motion, and deviations from this free motion. Such deviations are caused by external forces acting on a body in accordance with Newton's second law of motion, which states that the net force acting on a body is equal to that body's (inertial) mass multiplied by its acceleration. The preferred inertial motions are related to the geometry of space and time: in the standard reference frames of classical mechanics, objects in free motion move along straight lines at constant speed. In modern parlance, their paths are geodesics, straight world lines in curved space-time.

Conversely, one might expect that inertial motions, once identified by observing the actual motions of bodies and making allowances for the external forces (such as electromagnetism or friction), can be used to define the geometry of space, as well as a time coordinate. However, there is an ambiguity once gravity comes into play. According to Newton's law of gravity, and independently verified by experiments such as that of Eötvös and its successors (see Eötvös experiment), there is a universality of free fall (also known as the weak equivalence principle, or the universal equality of inertial and passive-gravitational mass): the trajectory of a test body in free fall depends only on its position and initial speed, but not on any of its material properties. A simplified version of this is embodied in Einstein's elevator experiment, illustrated in the figure on the right: for an observer in a small enclosed room, it is impossible to decide, by mapping the trajectory of bodies such as a dropped ball, whether the room is at rest in a gravitational field, or in free space aboard a rocket that is accelerating at a rate equal to that of the gravitational field.

Given the universality of free fall, there is no observable distinction between inertial motion and motion under the influence of the gravitational force. This suggests the definition of a new class of inertial motion, namely that of objects in free fall under the influence of gravity. This new class of preferred motions, too, defines a geometry of space and time—in mathematical terms, it is the geodesic motion associated with a specific connection which depends on the gradient of the gravitational potential. Space, in this construction, still has the ordinary Euclidean geometry. However, space-time as a whole is more complicated. As can be shown using simple thought experiments following the free-fall trajectories of different test particles, the result of transporting space-time vectors that can denote a particle's velocity (time-like vectors) will vary with the particle's trajectory, mathematically speaking, the Newtonian connection is not integrable. From this, one can deduce that space-time is curved. The result is a geometric formulation of Newtonian gravity using only covariant concepts, a description which is valid in any desired coordinate system. In this geometric description, tidal effects—the relative acceleration of bodies in free fall—are related to the derivative of the connection, showing how the modified geometry is caused by the presence of mass. As intriguing as geometric Newtonian gravity may be, its basis, classical mechanics, is merely a limiting case of (special) relativistic mechanics. In the language of symmetry: where gravity can be neglected, physics is Lorentz invariant as in special relativity rather than Galilei invariant as in classical mechanics. (The defining symmetry of special relativity is the Poincaré group, which includes translations and rotations.) The differences between the two become significant when dealing with speeds approaching the speed of light, and with high-energy phenomena. With Lorentz symmetry, additional structures come into play. They are defined by the set of light cones. The light-cones define a causal structure: for each event A, there is a set of events that can, in principle, either influence or be influenced by A via signals or interactions that do not need to travel faster than light (such as event B in the image), and a set of events for which such an influence is impossible. These sets are observer-independent. In conjunction with the world-lines of freely falling particles, the light-cones can be used to reconstruct the space–time's semi-Riemannian metric[[8]](#footnote-8), at least up to a positive scalar factor. In mathematical terms, this defines a conformal structure or much better, a conformal geometry, as it is difficult to understand how space or time or space-time can have a structure. Special relativity is defined in the absence of gravity, so for practical applications, it is a suitable model whenever gravity can be neglected. Bringing gravity into play, and assuming the universality of free fall, an analogous reasoning as in the previous section applies: there are no global inertial frames. Instead there are approximate inertial frames moving alongside freely falling particles. Translated into the language of space-time: the straight time-like lines that define a gravity-free inertial frame are deformed to lines that are curved relative to each other, suggesting that the inclusion of gravity necessitates a change in space-time geometry. A priori, it is not clear whether the new local frames in free fall coincide with the reference frames in which the laws of special relativity hold—that theory is based on the propagation of light, and thus on electromagnetism, which could have a different set of preferred frames. But using different assumptions about the special-relativistic frames (such as their being earth-fixed, or in free fall), one can derive different predictions for the gravitational redshift, that is, the way in which the frequency of light shifts as the light propagates through a gravitational field. The actual measurements show that free-falling frames are the ones in which light propagates as it does in special relativity. The generalization of this statement, namely that the laws of special relativity hold to good approximation in freely falling (and non-rotating) reference frames, is known as the Einstein equivalence principle, a crucial guiding principle for generalizing special-relativistic physics to include gravity. The same experimental data shows that time as measured by clocks in a gravitational field—proper time, to give the technical term—does not follow the rules of special relativity. In the language of space-time geometry, it is not measured by the Minkowski metric. As in the Newtonian case, this is suggestive of a more general geometry. At small scales, all reference frames that are in free fall are equivalent, and approximately Minkowskian. Consequently, we are now dealing with a curved generalization of Minkowski space. The metric tensor that defines the geometry—in particular, how lengths and angles are measured—is not the Minkowski metric of special relativity, it is a generalization known as a semi- or pseudo-Riemannian metric. Furthermore, each Riemannian metric is naturally associated with one particular kind of connection, the Levi-Civita connection, and this is, in fact, the connection that satisfies the equivalence principle and makes space locally Minkowskian (that is, in suitable locally inertial coordinates, the metric is Minkowskian, and its first partial derivatives and the connection coefficients vanish). Having formulated the relativistic, geometric version of the effects of gravity, the question of gravity's source remains. In Newtonian gravity, the source is mass. In special relativity, mass turns out to be part of a more general quantity called the energy–momentum tensor, which includes both energy and momentum densities as well as stress (that is, pressure and shear) Using the equivalence principle, this tensor is readily generalized to curved space-time. Drawing further upon the analogy with geometric Newtonian gravity, it is natural to assume that the field equation for gravity relates this tensor and the Ricci tensor, which describes a particular class of tidal effects: the change in volume for a small cloud of test particles that are initially at rest, and then fall freely. In special relativity, conservation of energy–momentum corresponds to the statement that the energy–momentum tensor is divergence-free. This formula, too, is readily generalized to curved space-time by replacing partial derivatives with their curved-manifold counterparts, covariant derivatives studied in differential geometry. With this additional condition—the covariant divergence of the energy–momentum tensor, and hence of whatever is on the other side of the equation, is zero— the simplest set of equations are what are called Einstein's (field) equations:[[9]](#footnote-9)

|  |
| --- |
| **Einstein's field equations**  G_{\mu \nu }\equiv R_{\mu \nu }-{\textstyle 1 \over 2}R\,g_{\mu \nu }={8\pi G \over c^{4}}T_{\mu \nu }\, |

On the left-hand side is the Einstein tensor, a specific divergence-free combination of the Ricci tensor R_{\mu \nu }and the metric. Where G_{\mu \nu }is symmetric. In particular,

R=g^{\mu \nu }R_{\mu \nu }\,

is the curvature scalar. The Ricci tensor itself is related to the more general Riemann curvature tensor as

R_{\mu \nu }={R^{\alpha }}_{\mu \alpha \nu }.\,

On the right-hand side, *T_{\mu \nu }*is the energy–momentum tensor. All tensors are written in abstract index notation. Matching the theory's prediction to observational results for planetary orbits (or, equivalently, assuring that the weak-gravity, low-speed limit is Newtonian mechanics), the proportionality constant can be fixed as κ = 8π*G*/*c*4, with *G* the gravitational constant and *c* the speed of light. When there is no matter present, so that the energy–momentum tensor vanishes, the results are the vacuum Einstein equations,

R_{\mu \nu }=0.\,

There are alternatives to general relativity built upon the same premises, which include additional rules and/or constraints, leading to different field equations. Examples are Brans–Dickey theory, tele parallelism, and

The derivation outlined in the previous section contains all the information needed to define general relativity, describe its key properties, and address a question of crucial importance in physics, namely how the theory can be used for model-building. General relativity is a metric theory of gravitation. At its core are Einstein's equations, which describe the relation between the geometry of a four-dimensional, pseudo-Riemannian manifold representing space-time, and the energy–momentum contained in that space-time Phenomena that in classical mechanics are ascribed to the action of the force of gravity (such as free-fall, orbital motion, and spacecraft trajectories), correspond to inertial motion within a curved geometry of space-time in general relativity; there is no gravitational force deflecting objects from their natural, straight paths. Instead, gravity corresponds to changes in the properties of space and time, which in turn changes the straightest-possible paths that objects will naturally follow. The curvature is, in turn, caused by the energy–momentum of matter. Paraphrasing the relativist John Archibald Wheeler, space-time tells matter how to move; matter tells space-time how to curve. While general relativity replaces the scalar gravitational potential of classical physics by a symmetric rank-two tensor, the latter reduces to the former in certain limiting cases. For weak gravitational fields and slow speed relative to the speed of light, the theory's predictions converge on those of Newton's law of universal gravitation. As it is constructed using tensors, general relativity exhibits general covariance: its laws—and further laws formulated within the general relativistic framework—take on the same form in all coordinate systems. Furthermore, the theory does not contain any invariant geometric background structures, it is background independent. It thus satisfies a more stringent general principle of relativity, namely that the laws of physics are the same for all observers. Locally, as expressed in the equivalence principle, space-time is Minkowskian, and the laws of physics exhibit local Lorentz invariance. The core concept of general-relativistic model-building is that of a solution of Einstein's equations. Given both Einstein's equations and suitable equations for the properties of matter, such a solution consists of a specific semi-Riemannian manifold (usually defined by giving the metric in specific coordinates), and specific matter fields defined on that manifold. Matter and geometry must satisfy Einstein's equations, so in particular, the matter's energy–momentum tensor must be divergence-free. The matter must, of course, also satisfy whatever additional equations were imposed on its properties. In short, such a solution is a model universe that satisfies the laws of general relativity, and possibly additional laws governing whatever matter might be present. Einstein's equations are nonlinear partial differential equations and, as such, difficult to solve exactly. Nevertheless, a number of exact solutions are known, although only a few have direct physical applications. The best-known exact solutions, and also those most interesting from a physics point of view, are the Schwarzschild solution, the Reissner–Nordström solution and the Kerr metric, each corresponding to a certain type of black hole in an otherwise empty universe, and the Friedmann–Lemaître–Robertson–Walker and de Sitter universes, each describing an expanding cosmos. Exact solutions of great theoretical interest include the Gödel universe (which opens up the intriguing possibility of time travel in curved space-times), the Taub-NUT solution (a model universe that is homogeneous, but anisotropic), and anti-de Sitter space (which has recently come to prominence in the context of what is called the Maldacena conjecture).

Given the difficulty of finding exact solutions, Einstein's field equations are also solved frequently by numerical integration on a computer, or by considering small perturbations of exact solutions. In the field of numerical relativity, powerful computers are employed to simulate the geometry of space-time and to solve Einstein's equations for interesting situations such as two colliding black holes in principle, such methods may be applied to any system, given sufficient computer resources, and may address fundamental questions such as naked singularities. Approximate solutions may also be found by perturbation theories such as linearized gravity and its generalization, the post-Newtonian expansion, both of which were developed by Einstein. The latter provides a systematic approach to solving for the geometry of a space-time that contains a distribution of matter that moves slowly compared with the speed of light. The expansion involves a series of terms; the first terms represent Newtonian gravity, whereas the later terms represent ever smaller corrections to Newton's theory due to general relativity. An extension of this expansion is the parametrized post-Newtonian (PPN) formalism, which allows quantitative comparisons between the predictions of general relativity and alternative theories.

General relativity has a number of physical consequences. Some follow directly from the theory's axioms, whereas others have become clear only in the course of many years of research that followed Einstein's initial publication.

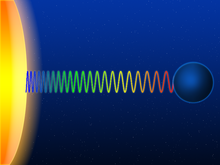
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Figure (2): Schematic representation of the gravitational redshift of a light wave escaping from the surface of a massive body

Assuming that the equivalence principle holds, gravity influences the passage of time. Light sent down into a gravity well is blue-shifted, whereas light sent in the opposite direction (climbing out of the gravity well) is red-shifted; collectively, these two effects are known as the gravitational frequency shift. More generally, processes close to a massive body run more slowly when compared with processes taking place farther away; this effect is known as gravitational time dilation.

Gravitational red-shift has been measured in the laboratory and using astronomical observations. Gravitational time dilation in the Earth's gravitational field has been measured numerous times using atomic clocks, while ongoing validation is provided as a side effect of the operation of the Global Positioning System (GPS). Tests in stronger gravitational fields are provided by the observation of binary pulsars. All results are in agreement with general relativity. However, at the current level of accuracy, these observations cannot distinguish between general relativity and other theories in which the equivalence principle is valid.

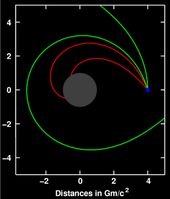
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Figure (3): Deflection of light (sent out from the location shown in blue) near a compact body (shown in gray)

General relativity predicts that the path of light is bent in a gravitational field, light passing a massive body is deflected towards that body. This effect has been confirmed by observing the light of stars or distant quasars being deflected as it passes the Sun. This and related predictions follow from the fact that light follows what is called a light-like or null geodesic—a generalization of the straight lines along which light travels in classical physics. Such geodesics are the generalization of the invariance of light speed in special relativity. As one examines suitable model space-times (either the exterior Schwarzschild solution or, for more than a single mass, the post-Newtonian expansion), several effects of gravity on light propagation emerge. Although the bending of light can also be derived by extending the universality of free fall to light, the angle of deflection resulting from such calculations is only half the value given by general relativity.

Closely related to light deflection is the gravitational time delay (or Shapiro delay), the phenomenon that light signals take longer to move through a gravitational field than they would in the absence of that field. There have been numerous successful tests of this prediction. In the parameterized post-Newtonian formalism (PPN), measurements of both the deflection of light and the gravitational time delay determine a parameter called γ, which encodes the influence of gravity on the geometry of space.

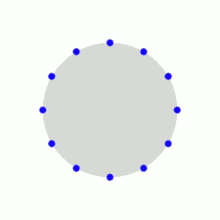


Figure (4): Ring of test particles influenced by gravitational wave

One of several analogies between weak-field gravity and electromagnetism is that, analogous to electromagnetic waves, there are gravitational waves: ripples in the metric of space-time that propagate at the speed of light. The simplest type of such a wave can be visualized by its action on a ring of freely floating particles. A sine wave propagating through such a ring towards the reader distorts the ring in a characteristic, rhythmic fashion (animated image to the right). Since Einstein's equations are non-linear, arbitrarily strong gravitational waves do not obey linear superposition, making their description difficult. However, for weak fields, a linear approximation can be made. Such linearized gravitational waves are sufficiently accurate to describe the exceedingly weak waves that are expected to arrive here on Earth from far-off cosmic events, which typically result in relative distances increasing and decreasing by 10-21 or less. Data analysis methods routinely make use of the fact that these linearized waves can be Fourier decomposed. Some exact solutions describe gravitational waves without any approximation, a wave train traveling through empty space or so-called Gowdy universes, varieties of an expanding cosmos filled with gravitational waves. But for gravitational waves produced in astrophysically relevant situations, such as the merger of two black holes, numerical methods are presently the only way to construct appropriate models. General relativity differs from classical mechanics in a number of predictions concerning orbiting bodies. It predicts an overall rotation (precession) of planetary orbits, as well as orbital decay caused by the emission of gravitational waves and effects related to the relativity of direction.

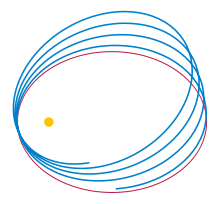


Figure (5): Newtonian (red) vs. Einsteinian orbit (blue) of a lone planet orbiting a star

In general relativity, the apsides of any orbit (the point of the orbiting body's closest approach to the system's center of mass) will process—the orbit is not an ellipse, but akin to an ellipse that rotates on its focus, resulting in a rose curve-like shape. Einstein first derived this result by using an approximate metric representing the Newtonian limit and treating the orbiting body as a test particle. For him, the fact that his theory gave a straightforward explanation of the anomalous perihelion shift of the planet Mercury, discovered earlier by Urbain Le Verrier in 1859, was important evidence that he had at last identified the correct form of the gravitational field equations.

The effect can also be derived by using either the exact Schwarzschild metric (describing space-time around a spherical mass) or the much more general post-Newtonian formalism. It is due to the influence of gravity on the geometry of space and to the contribution of self-energy to a body's gravity (encoded in the nonlinearity of Einstein's equations) Relativistic precession has been observed for all planets that allow for accurate precession measurements (Mercury, Venus, and Earth) as well as in binary pulsar systems, where it is larger by five orders of magnitude

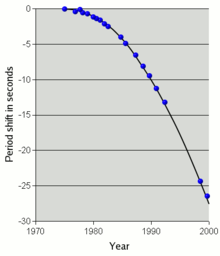


Figure (6): Orbital decay for PSR1913+16: time shift in seconds, tracked over three decades.

According to general relativity, a binary system will emit gravitational waves, thereby losing energy. Due to this loss, the distance between the two orbiting bodies decreases, and so does their orbital period. Within the Solar System or for ordinary double stars, the effect is too small to be observable. This is not the case for a close binary pulsar, a system of two orbiting neutron stars, one of which is a pulsar: from the pulsar, observers on Earth receive a regular series of radio pulses that can serve as a highly accurate clock, which allows precise measurements of the orbital period. Because neutron stars are immensely compact, significant amounts of energy are emitted in the form of gravitational radiation. [[10]](#footnote-10)

The first observation of a decrease in orbital period due to the emission of gravitational waves was made by Hulse and Taylor, using the binary pulsar PSR1913+16 they had discovered in 1974. This was the first detection of gravitational waves, albeit indirect, for which they were awarded the 1993 Nobel Prize in physics. Since then, several other binary pulsars have been found, in particular the double pulsar PSR J0737-3039, in which both stars are pulsars.

Several relativistic effects are directly related to the relativity of direction. One is geodetic precession: the axis direction of a gyroscope in free fall in curved space-time will change when compared, for instance, with the direction of light received from distant stars—even though such a gyroscope represents the way of keeping a direction as stable as possible ("parallel transport"). For the Moon–Earth system, this effect has been measured with the help of lunar laser ranging. More recently, it has been measured for test masses aboard the satellite Gravity Probe B to a precision of better than 0.3%.

Near a rotating mass, there are so-called gravitomagnetic or frame-dragging effects. A distant observer will determine that objects close to the mass get "dragged around". This is most extreme for rotating black holes where, for any object entering a zone known as the ergo sphere, rotation is inevitable. Such effects can again be tested through their influence on the orientation of gyroscopes in free fall Somewhat controversial tests have been performed using the LAGEOS satellites, confirming the relativistic prediction. Also the Mars Global Surveyor probe around Mars has been used.

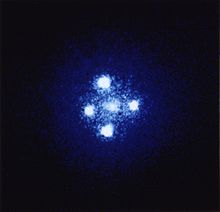


Figure (7): Einstein cross: four images of the same astronomical object, produced by a gravitational lens

The deflection of light by gravity is responsible for a new class of astronomical phenomena. If a massive object is situated between the astronomer and a distant target object with appropriate mass and relative distances, the astronomer will see multiple distorted images of the target. Such effects are known as gravitational lensing. Depending on the configuration, scale, and mass distribution, there can be two or more images, a bright ring known as an Einstein ring, or partial rings called arcs. The earliest example was discovered in 1979; since then, more than a hundred gravitational lenses have been observed. Even if the multiple images are too close to each other to be resolved, the effect can still be measured, e.g., as an overall brightening of the target object; a number of such "microlensing events" have been observed.

Gravitational lensing has developed into a tool of observational astronomy. It is used to detect the presence and distribution of dark matter, provide a "natural telescope" for observing distant galaxies, and to obtain an independent estimate of the Hubble constant. Statistical evaluations of lensing data provide valuable insight into the structural evolution of galaxies.

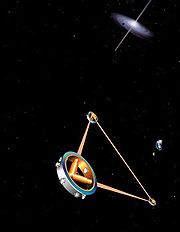


Figure (8): Artist's impression of the space-borne gravitational wave detector LISA

Observations of binary pulsars provide strong indirect evidence for the existence of gravitational waves (see Orbital decay, above). However, gravitational waves reaching us from the depths of the cosmos have not been detected directly. Such detection is a major goal of current relativity-related research. Several land-based gravitational wave detectors are currently in operation, most notably the interferometric detectors GEO 600, LIGO (two detectors), TAMA 300 and VIRGO. Various pulsar timing arrays are using millisecond pulsars to detect gravitational waves in the 10−9 to 10−6 Hertz frequency range, which originate from binary supermassive black holes. European space-based detector, eLISA / NGO, is currently under development, with a precursor mission (LISA Pathfinder) due for launch in 2015.

Observations of gravitational waves promise to complement observations in the electromagnetic spectrum. They are expected to yield information about black holes and other dense objects such as neutron stars and white dwarfs, about certain kinds of supernova implosions, and about processes in the very early universe, including the signature of certain types of hypothetical cosmic string.

Whenever the ratio of an object's mass to its radius becomes sufficiently large, general relativity predicts the formation of a black hole, a region of space from which nothing, not even light, can escape. In the currently accepted models of stellar evolution, neutron stars of around 1.4 solar masses, and stellar black holes with a few to a few dozen solar masses, are thought to be the final state for the evolution of massive stars. Usually a galaxy has one supermassive black hole with a few million to a few billion solar masses in its center and its presence is thought to have played an important role in the formation of the galaxy and larger cosmic structures.

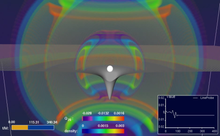


Figure (9): Simulation based on the equations of general relativity: a star collapsing to form a black hole while emitting gravitational waves

Astronomically, the most important property of compact objects is that they provide a supremely efficient mechanism for converting gravitational energy into electromagnetic radiation Accretion, the falling of dust or gaseous matter onto stellar or supermassive black holes, is thought to be responsible for some spectacularly luminous astronomical objects, notably diverse kinds of active galactic nuclei on galactic scales and stellar-size objects such as micro quasars. In particular, accretion can lead to relativistic jets, focused beams of highly energetic particles that are being flung into space at almost light speed. General relativity plays a central role in modelling all these phenomena, and observations provide strong evidence for the existence of black holes with the properties predicted by the theory.

Black holes are also sought-after targets in the search for gravitational waves (cf. Gravitational waves, above). Merging black hole binaries should lead to some of the strongest gravitational wave signals reaching detectors here on Earth, and the phase directly before the merger ("chirp") could be used as a "standard candle" to deduce the distance to the merger events–and hence serve as a probe of cosmic expansion at large distances. The gravitational waves produced as a stellar black hole plunges into a supermassive one should provide direct information about the supermassive black hole's geometry.



Figure (10): This blue horseshoe is a distant galaxy that has been magnified and warped into a nearly complete ring by the strong gravitational pull of the massive foreground luminous red galaxy.

The current models of cosmology are based on Einstein's field equations, which include the cosmological constant Λ since it has important influence on the large-scale dynamics of the cosmos,

R_{\mu \nu }-{\textstyle 1 \over 2}R\,g_{\mu \nu }+\Lambda \ g_{\mu \nu }={\frac {8\pi G}{c^{4}}}\,T_{\mu \nu }[[11]](#footnote-11)

where *g_{\mu \nu }*is the space-time metric? Isotropic and homogeneous solutions of these enhanced equations, the Friedmann–Lemaître–Robertson–Walker solutions, allow physicists to model a universe that has evolved over the past 14 billion years from a hot, early Big Bang phase. Once a small number of parameters (for example the universe's mean matter density) have been fixed by astronomical observation, further observational data can be used to put the models to the test. Predictions, all successful, include the initial abundance of chemical elements formed in a period of primordial nucleosynthesis, the large-scale structure of the universe, and the existence and properties of a "thermal echo" from the early cosmos, the cosmic background radiation.

Astronomical observations of the cosmological expansion rate allow the total amount of matter in the universe to be estimated, although the nature of that matter remains mysterious in part. About 90% of all matter appears to be so-called dark matter, which has mass (or, equivalently, gravitational influence), but does not interact electromagnetically and, hence, cannot be observed directly. There is no generally accepted description of this new kind of matter, within the framework of known particle physicsor otherwise. Observational evidence from redshift surveys of distant supernovae and measurements of the cosmic background radiation also show that the evolution of our universe is significantly influenced by a cosmological constant resulting in an acceleration of cosmic expansion or, equivalently, by a form of energy with an unusual equation of state, known as dark energy, the nature of which remains unclear.

A so-called inflationary phase, an additional phase of strongly accelerated expansion at cosmic times of around 10^{-33}seconds, was hypothesized in 1980 to account for several puzzling observations that were unexplained by classical cosmological models, such as the nearly perfect homogeneity of the cosmic background radiation. Recent measurements of the cosmic background radiation have resulted in the first evidence for this scenario However, there is a bewildering variety of possible inflationary scenarios, which cannot be restricted by current observations. An even larger question is the physics of the earliest universe, prior to the inflationary phase and close to where the classical models predict the big bang singularity. An authoritative answer would require a complete theory of quantum gravity, which has not yet been developed (cf. the section on quantum gravity, below).

Kurt Gödel showedthat solutions to Einstein's equations exist that contain closed time like curves (CTCs), which allow for loops in time. The solutions require extreme physical conditions unlikely ever to occur in practice, and it remains an open question whether further laws of physics will eliminate them completely. Since then other—similarly impractical—GR solutions containing CTCs have been found, such as the Tipler cylinder and traversable wormholes.

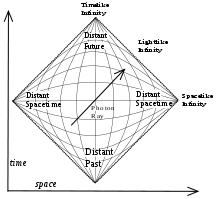


Figure (11): Penrose–Carter diagram of an infinite Minkowski universe

In general relativity, no material body can catch up with or overtake a light pulse. No influence from an event A can reach any other location X before light sent out at A to X. In consequence, an exploration of all light worldliness (null geodesics) yields key information about the space-time's causal structure. This structure can be displayed using Penrose–Carter diagrams in which infinitely large regions of space and infinite time intervals are shrunk ("compactified") so as to fit onto a finite map, while light still travels along diagonals as in standard space-time diagrams.

Aware of the importance of causal structure, Roger Penrose and others developed what is known as global geometry. In global geometry, the object of study is not one particular solution (or family of solutions) to Einstein's equations. Rather, relations that hold true for all geodesics, such as the Raychaudhuri equation, and additional non-specific assumptions about the nature of matter (usually in the form of so-called energy conditions) are used to derive general results.

Using global geometry, some space-time can be shown to contain boundaries called horizons, which demarcate one region from the rest of space-time. The best-known examples are black holes: if mass is compressed into a sufficiently compact region of space (as specified in the hoop conjecture, the relevant length scale is the Schwarzschild radius), no light from inside can escape to the outside. Since no object can overtake a light pulse, all interior matter is imprisoned as well. Passage from the exterior to the interior is still possible, showing that the boundary, the black hole's *horizon*, is not a physical barrier.

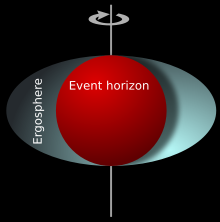


Figure (12): The ergo sphere of a rotating black hole, which plays a key role when it comes to extracting energy from such a black hole

Early studies of black holes relied on explicit solutions of Einstein's equations, notably the spherically symmetric Schwarzschild solution (used to describe a static black hole) and the axisymmetric Kerr solution (used to describe a rotating, stationary black hole, and introducing interesting features such as the ergo sphere). Using global geometry, later studies have revealed more general properties of black holes. In the long run, they are rather simple objects characterized by eleven parameters specifying energy, linear momentum, angular momentum, location at a specified time and electric charge. This is stated by the black hole uniqueness theorems: "black holes have no hair", that is, no distinguishing marks like the hairstyles of humans. Irrespective of the complexity of a gravitating object collapsing to form a black hole, the object that results (having emitted gravitational waves) is very simple.

Even more remarkably, there is a general set of laws known as black hole mechanics, which is analogous to the laws of thermodynamics. For instance, by the second law of black hole mechanics, the area of the event horizon of a general black hole will never decrease with time, analogous to the entropy of a thermodynamic system. This limits the energy that can be extracted by classical means from a rotating black hole (e.g. by the Penrose process). There is strong evidence that the laws of black hole mechanics are, in fact, a subset of the laws of thermodynamics, and that the black hole area is proportional to its entropy. This leads to a modification of the original laws of black hole mechanics: for instance, as the second law of black hole mechanics becomes part of the second law of thermodynamics, it is possible for black hole area to decrease—as long as other processes ensure that, overall, entropy increases. As thermodynamical objects with non-zero temperature, black holes should emit thermal radiation. Semi-classical calculations indicate that indeed they do, with the surface gravity playing the role of temperature in Planck's law. This radiation is known as Hawking radiation (cf. the quantum theory section, below).

There are other types of horizons. In an expanding universe, an observer may find that some regions of the past cannot be observed ("particle horizon"), and some regions of the future cannot be influenced (event horizon). Even in flat Minkowski space, when described by an accelerated observer (Rindler space), there will be horizons associated with a semi-classical radiation known as Unruh radiation.

Another general feature of general relativity is the appearance of space-time boundaries known as singularities. Space-time can be explored by following up on time like and light like geodesics—all possible ways that light and particles in free fall can travel. But some solutions of Einstein's equations have "ragged edges"—regions known as space-time singularities, where the paths of light and falling particles come to an abrupt end, and geometry becomes ill-defined. In the more interesting cases, these are "curvature singularities", where geometrical quantities characterizing space-time curvature, such as the Ricci scalar, take on infinite values. Well-known examples of space-time with future singularities—where worldliness end—are the Schwarzschild solution, which describes a singularity inside an eternal static black hole or the Kerr solution with its ring-shaped singularity inside an eternal rotating black hole. The Friedmann–Lemaître–Robertson–Walker solutions and other space-time describing universes have past singularities on which worldliness begin, namely Big Bang singularities, and some have future singularities (Big Crunch) as well.

Given that these examples are all highly symmetric—and thus simplified—it is tempting to conclude that the occurrence of singularities is an artifact of idealization The famous singularity theorems, proved using the methods of global geometry, say otherwise: singularities are a generic feature of general relativity, and unavoidable once the collapse of an object with realistic matter properties has proceeded beyond a certain stage and also at the beginning of a wide class of expanding universes. However, the theorems say little about the properties of singularities, and much of current research is devoted to characterizing these entities' generic structure (hypothesized e.g. by the so-called BKL conjecture). The cosmic censorship hypothesis states that all realistic future singularities (no perfect symmetries, matter with realistic properties) are safely hidden away behind a horizon, and thus invisible to all distant observers. While no formal proof yet exists, numerical simulations offer supporting evidence of its validity.

Each solution of Einstein's equation encompasses the whole history of a universe — it is not just some snapshot of how things are, but a whole, possibly matter-filled, space-time. It describes the state of matter and geometry everywhere and at every moment in that particular universe. Due to its general covariance, Einstein's theory is not sufficient by itself to determine the time evolution of the metric tensor. It must be combined with a coordinate condition, which is analogous to gauge fixing in other field theories.

To understand Einstein's equations as partial differential equations, it is helpful to formulate them in a way that describes the evolution of the universe over time. This is done in so-called "3+1" formulations, where space-time is split into three space dimensions and one-time dimension. The best-known example is the ADM formalism. These decompositions show that the space-time evolution equations of general relativity are well-behaved: solutions always exist, and are uniquely defined, once suitable initial conditions have been specified. Such formulations of Einstein's field equations are the basis of numerical relativity.

The notion of evolution equations is intimately tied in with another aspect of general relativistic physics. In Einstein's theory, it turns out to be impossible to find a general definition for a seemingly simple property such as a system's total mass (or energy). The main reason is that the gravitational field—like any physical field—must be ascribed a certain energy, but that it proves to be fundamentally impossible to localize that energy.

Nevertheless, there are possibilities to define a system's total mass, either using a hypothetical "infinitely distant observer" (ADM mass) or suitable symmetries (Komar mass). If one excludes from the system's total mass the energy being carried away to infinity by gravitational waves, the result is the so-called Bondi mass at null infinity Just as in classical physics, it can be shown that these masses are positive. Corresponding global definitions exist for momentum and angular momentum. There have also been a number of attempts to define *quasi-local* quantities, such as the mass of an isolated system formulated using only quantities defined within a finite region of space containing that system. The hope is to obtain a quantity useful for general statements about isolated systems, such as a more precise formulation of the hoop conjecture.

If general relativity were considered to be one of the two pillars of modern physics, then quantum theory, the basis of understanding matter from elementary particles to solid state physics, would be the other. However, how to reconcile quantum theory with general relativity is still an open question.

Ordinary quantum field theories, which form the basis of modern elementary particle physics, are defined in flat Minkowski space, which is an excellent approximation when it comes to describing the behavior of microscopic particles in weak gravitational fields like those found on Earth. In order to describe situations in which gravity is strong enough to influence (quantum) matter, yet not strong enough to require quantization itself, physicists have formulated quantum field theories in curved space-time. These theories rely on general relativity to describe a curved background space-time, and define a generalized quantum field theory to describe the behavior of quantum matter within that space-time. Using this formalism, it can be shown that black holes emit a blackbody spectrum of particles known as Hawking radiation, leading to the possibility that they evaporate over time. As briefly mentioned above, this radiation plays an important role for the thermodynamics of black holes

The demand for consistency between a quantum description of matter and a geometric description of space-time, as well as the appearance of singularities (where curvature length scales become microscopic), indicate the need for a full theory of quantum gravity: for an adequate description of the interior of black holes, and of the very early universe, a theory is required in which gravity and the associated geometry of space-time are described in the language of quantum physics. Despite major efforts, no complete and consistent theory of quantum gravity is currently known, even though a number of promising candidates exist.

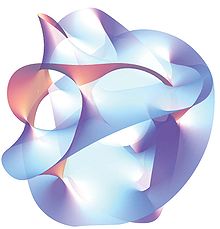


Figure (13): Projection of a Calabi–Yau manifold, one of the ways of compactifying the extra dimensions posited by string theory

Attempts to generalize ordinary quantum field theories, used in elementary particle physics to describe fundamental interactions, so as to include gravity have led to serious problems. At low energies, this approach proves successful, in that it results in an acceptable effective (quantum) field theory of gravity. At very high energies, however, the result are models devoid of all predictive power ("non-renormalizability").

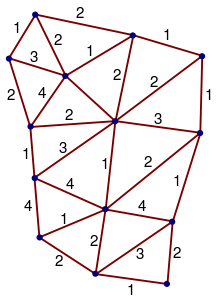


Figure (14): Simple spin network of the type used in loop quantum gravity

One attempt to overcome these limitations is string theory, a quantum theory not of point particles, but of minute one-dimensional extended objects the theory promises to be a unified description of all particles and interactions, including gravity; the price to pay is unusual features such as six extra dimensions of space in addition to the usual three. In what is called the second superstring revolution, it was conjectured that both string theory and a unification of general relativity and supersymmetry known as supergravity[]](mhtml:file://C:\Users\Hamouda\Desktop\General%20relativity%20-%20Wikipedia,%20the%20free%20encyclopedia.mht!https://en.wikipedia.org/wiki/General_relativity#cite_note-176) form part of a hypothesized eleven-dimensional model known as M-theory, which would constitute a uniquely defined and consistent theory of quantum gravity.

Another approach starts with the canonical quantization procedures of quantum theory. Using the initial-value-formulation of general relativity (cf. evolution equations above), the result is the Wheeler–deWitt equation (an analogue of the Schrödinger equation) which, regrettably, turns out to be ill-defined. However, with the introduction of what are now known as Ashtekar variables this leads to a promising model known as loop quantum gravity. Space is represented by a web-like structure called a spin network, evolving over time in discrete steps.

Depending on which features of general relativity and quantum theory are accepted unchanged, and on what level changes are introduced, there are numerous other attempts to arrive at a viable theory of quantum gravity, some examples being dynamical triangulations, causal sets, twistor modelsor the path-integral based models of quantum cosmology. All candidate theories still have major formal and conceptual problems to overcome. They also face the common problem that, as yet, there is no way to put quantum gravity predictions to experimental tests (and thus to decide between the candidates where their predictions vary), although there is hope for this to change as future data from cosmological observations and particle physics experiments becomes available. General relativity has emerged as a highly successful model of gravitation and cosmology, which has so far passed many unambiguous observational and experimental tests. However, there are strong indications the theory is incomplete. The problem of quantum gravity and the question of the reality of space-time singularities remain open. Observational data that is taken as evidence for dark energy and dark matter could indicate the need for new physics. Even taken as is, general relativity is rich with possibilities for further exploration. Mathematical relativists seek to understand the nature of singularities and the fundamental properties of Einstein's equations, and increasingly powerful computer simulations (such as those describing merging black holes) are run. The race for the first direct detection of gravitational waves continues, in the hope of creating opportunities to test the theory's validity for much stronger gravitational fields than has been possible to date. A century after its publication, general relativity remains a highly active area of research.

Conclusions

1. We described the theories of the creation of the universe and mentioned the common theories but now it's time to show our theory of the universe:

The star more than three times the size of our sun ought to end its life but how?

According to Jim Penrose, with a collapse, the gravitational forces of the mass overcoming the electromagnetic forces of individual atoms and so collapsing inwards if the star is massive enough, it will continue this collapse, creating a black hole where the warping of space-time is so great that nothing can escape. Not even light. It gets smaller and smaller, the star in fact get denser. As atoms even subatomic particles get literally crushed into smaller and smaller space. And at its end point, what are we left with?? A space-time singularity, space and time come to a stop. So I wonder if we applied Penrose's theory about black holes to the entire universe. If Einstein is right or if the general relativity is correct then the universe is expanding. So, if we reverse time, then the universe is getting smaller. So what if I reverse the process all the way back to see what happen at the beginning of time itself?

So the universe is getting smaller and smaller, getting denser and denser, hotter and hotter while we wind back the clock so if we keep winding until we get a space-time singularity, so the universe born from a black hole exploding

1. The universe definitely need a creator.
2. We are living the past.
3. All that we can know about the universe that it's expanding and we don't know anything more about it but we have some predictions of what will happen.

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| Figure 1 | According to general relativity, objects in a gravitational field behave similarly to objects within an accelerating enclosure. For example, an observer will see a ball fall the same way in a rocket (left) as it does on Earth (right), provided that the acceleration of the rocket is equal to 9.8 m/s2 (the acceleration due to gravity at the surface of the Earth). |
| Figure 2 | Schematic representation of the gravitational redshift of a light wave escaping from the surface of a massive body |
| Figure 3 | Deflection of light (sent out from the location shown in blue) near a compact body (shown in gray) |
| Figure 4 | Ring of test particles influenced by gravitational wave |
| Figure 5 | Newtonian (red) vs. Einsteinian orbit (blue) of a lone planet orbiting a star |
| Figure 6 | Orbital decay for PSR1913+16: time shift in seconds, tracked over three decades |
| Figure 7 | Einstein cross: four images of the same astronomical object, produced by a gravitational lens |
| Figure 8 | Artist's impression of the space-borne gravitational wave detector LISA |
| Figure 9 | Simulation based on the equations of general relativity: a star collapsing to form a black hole while emitting gravitational waves |
| Figure 10 | This blue horseshoe is a distant galaxy that has been magnified and warped into a nearly complete ring by the strong gravitational pull of the massive foreground luminous red galaxy. |
| Figure 11 | Penrose–Carter diagram of an infinite Minkowski universe |
| Figure 12 | The ergo sphere of a rotating black hole, which plays a key role when it comes to extracting energy from such a black hole |
| Figure 13 | Projection of a Calabi–Yau manifold, one of the ways of compactifying the extra dimensions posited by string theory |
| Figure 14 | Simple spin network of the type used in loop quantum gravity |

The End

1. The Theory of Everything Stephen W. Hawking 2005. [↑](#footnote-ref-1)
2. The Theory of Everything Stephen W. Hawking 2005. [↑](#footnote-ref-2)
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