Chapter 2
What Is the Nature of Space and Time?
(The Physics of Space Travel and Time Travel)

“People assume that time is a strict progression of cause to effect. But actually, from a nonlinear, non-subjective viewpoint, it’s more like a big ball of wibbly-wobbly, timey-wimey . . . stuff.”

–The 10th Doctor
Doctor Who, “Blink” [1]

The most successful science fiction television series in the history of the medium is undoubtedly Doctor Who. The lead character, who calls himself the Doctor, is a Time Lord, who travels through space and time in a sentient device called the TARDIS (Time And Relative Dimensions In Space). From the outside, the TARDIS looks like a 1950s British police box (Fig. 2.1), which the public could use to call the police in an emergency: slightly larger than the classic red telephone booths, which can still be found in England, and painted blue. But from the inside the TARDIS is more like the size of a small house. Evidently, the door to the TARDIS connects the exterior of a relatively small object (the police box) to the interior of a large object (the space/time machine). A device such as the TARDIS is possible only in the realm of the imagination. But from a scientific perspective, what is the nature of space and time? Is time travel possible? The answers to these questions have changed considerably over the last few centuries.

2.1 Changing Perspectives Through History

This chapter will consider three historical perspectives on the nature of space and time, and of the force of gravity. We begin our exploration by turning to another highly successful science fiction television series. A recurring theme in Star Trek the Next Generation is the quest of the android, Commander Data, to become more like his human shipmates. We will take a closer look at Data and his quest in
Chap. 3 and again in Chap. 6. Here we will use Data’s creativity and scientific curiosity as a lead-in to an exploration of the nature of space and time.

In the opening scene of the episode Descent, Part I, Data creates a holodeck simulation (a virtual reality environment, which we will discuss more in Chap. 7) to enable him to play poker with three of the most famous people in the history of physics: Sir Isaac Newton, Albert Einstein, and Stephen Hawking [2]. Data’s primary concern was to learn more about these three specific human personalities, and by extension, to understand more about what it means to be human. But here we are interested in comparing the three views of the nature of space and time represented by these three figures from the history of physics, as well as their different ways of understanding the force of gravity [3]. A brief summary of the three views is presented in Table 2.1. We will discuss each of them in some detail in the sections which follow.

2.2 Newton’s Laws

The foundation of classical physics was laid with the publication of the Philosophiae Naturalis Principia Mathematica (Mathematical Principles of Natural Philosophy). Newton’s first book of the Principia (1687) included statements of
his three Axioms or Laws of Motion, which, according to Motte’s translation [4], may be summarized as follows:

1. Every body continues in its state of rest, or of uniform motion in a right line, unless it is compelled to change that state by forces impressed upon it.
2. The change of motion is proportional to the motive force impressed and is made in the direction of the right line in which that force is impressed.
3. To every action there is always opposed an equal reaction: or the mutual actions of two bodies upon each other are always equal, and directed to contrary parts.

The second law, as originally stated, included no explicit mention of the mass of the body. By change of motion Newton was referring to the change in momentum, which he understood to be the product of the mass times the velocity. If mass is constant, then we simply have the change in velocity (or acceleration). The second law may then be written in equation form as force equals mass times acceleration:

$$F = ma.$$ (2.1)

It’s important to make a distinction between vector quantities, such as force and acceleration, which have both magnitude and direction, and a scalar quantity, such as mass, which has only magnitude. Thus it would be possible for multiple forces to act on an object from various directions, in such a way as to make the net force equal to zero. An object’s state of rest or motion will change, according to Newton’s first law, only if there is a net (nonzero) force acting on it. Similarly, the acceleration of

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<th>The nature of space and time, according to Newton, Einstein, and Hawking</th>
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<td><strong>Sir Isaac Newton</strong>&lt;br&gt;(1642–1727)</td>
<td>• <em>Space and time</em> are separate and independent quantities&lt;br&gt;• The speed of anything is relative to one’s frame of reference&lt;br&gt;• The force of gravity acts instantaneously between any two objects and varies directly as the product of their masses and inversely as the square of the distances between the objects</td>
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<td><strong>Albert Einstein</strong>&lt;br&gt;(1879–1955)</td>
<td>• Space and time constitute a continuous, four-dimensional fabric: <em>spacetime</em>&lt;br&gt;• The speed of light is absolute (same in all reference frames)&lt;br&gt;• Nothing can travel faster than the speed of light in a vacuum&lt;br&gt;• Moving clocks run slow, relative to clocks at rest (<em>time dilation</em>)&lt;br&gt;• The phenomenon which we experience as gravity is simply a property of distorted <em>spacetime</em>, near a large mass&lt;br&gt;• Clocks in a strong gravitational field run slow, relative to clocks far from a source of gravity</td>
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<td><strong>Stephen Hawking</strong>&lt;br&gt;(1942–)</td>
<td>• The concept of spacetime as a continuous four-dimensional fabric may not be adequate&lt;br&gt;• <em>Black holes</em> (enormous amounts of matter compressed into an infinitesimal space) cause such extreme distortions of spacetime that <em>quantum mechanics</em> must be used, instead of classical physics, to describe the resulting curvature&lt;br&gt;• Ongoing quest for a consistent theory of <em>quantum gravity</em></td>
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an object, according to Newton’s second law, will be nonzero only if there is a net force acting on the object from the outside. Forces which are purely internal to a system cannot change the state of rest or motion of the system. Newton’s laws of motion affect us every moment of every day of our lives. For some illustrations of these concepts, let’s consider the following science fiction movie scenes.

The final movie in the X-Men trilogy, X-Men III: The Last Stand, revolves around the discovery of a “cure” for mutant superpowers. A young boy, held captive on Alcatraz Island, holds the key to the cure. The Brotherhood of mutants are not about to allow themselves to be rounded up and deprived of their powers. In opposition to the oppressive public policy, the leader of the Brotherhood, Magneto, plans an assault on Alcatraz Island. Since Alcatraz is accessible only by water or by air, most of the mutant Brotherhood are in need of an alternate form of transportation. Magneto uses his creativity—and his superpowers—to relocate the Golden Gate Bridge, which carries U.S. highway 101 between San Francisco and Sausalito, roughly 3 miles to the west of the island. But how can he possibly do this within the framework of classical Newtonian physics? [5].

According to the story, Magneto has the ability to “manipulate magnetic fields and metal.” We will explore the properties of materials in some detail in Chap. 3, including magnetic materials. For now, however, let us temporarily suspend disbelief in superpowers and stipulate that Magneto actually does have this extraordinary ability. Can he use these powers to relocate the Golden Gate Bridge, without violating Newton’s Laws of Motion?

As the scene opens, we observe traffic on the bridge turned into chaos. Cars and trucks are pushed out of the way (but without any physical contact), as Magneto walks onto the bridge—hands raised, palms facing forward—leading the first wave of the Brotherhood. Having brought traffic to a standstill, Magneto then turns around, stretches one arm toward the near end of the bridge, and the other toward the far end and (again without physical contact) uses his power to rip the end of the bridge away from the road connecting it to the shore. Finally, Magneto uses his power to rip the entire bridge off of its supporting piers, and moves it 3 miles to the east, to enable the rest of the Brotherhood to walk across the bay to Alcatraz Island.

Discussion Topic 2.1
Think carefully about each of the three scenarios from X-Men III, described above. Magneto uses his superpowers to do the following: (a) push cars out of the way while walking on the bridge, (b) rip the end of the bridge away from the land, while standing on the bridge, and (c) move the entire bridge 3 miles to the east while standing on the bridge. Discuss how these feats might or might not be possible within the framework of Newton’s laws of motion. In each case, identify the system (object at rest or in motion) and the source of the outside force acting on the system to change its state of rest or motion.

Next we consider a scene, which does not involve superpowers, but rather a mountain-climbing accident, combined with a bit of futuristic technology. Toward the beginning of Star Trek V: The Final Frontier, James T. Kirk is free-climbing El Capitan, a popular landmark in Yosemite National Park, while on shore leave from
his usual post as Captain of the U.S.S. Enterprise [6]. He is distracted from his ascent by his First Officer, Mr. Spock, who suddenly comes alongside Kirk, hovering on jet boots. Spock fails to understand the logic of mountain climbing and questions whether Kirk appreciates the gravity of his situation. Kirk assures him that gravity is foremost on his mind (obvious pun intended). Unfortunately, the philosophical discussion comes to an abrupt end, when Kirk slips off the rock face and falls to his apparent doom. Spock, with the aid of his jet boots, dives to the rescue. Quickly overtaking Kirk, and grabbing him by the ankle, Spock brings him safely to a stop at the last possible moment, just inches above the rocks at the base of the mountain.

Kirk falling off the face of the mountain provides a dramatic illustration of another of Newton’s famous laws: the universal law of gravitation. The law states that the magnitude of the force of gravity acting between two objects depends on the product of their masses and inversely on the square of the distance between them, or

\[ F = G \frac{m_1 m_2}{r^2}. \]  

(2.2)

The constant, \( G \), in Eq. (2.2) is the universal gravitational constant. When Newton published this law in the Principia, along with his three laws of motion, he was accused of plagiarism by his contemporary, Robert Hooke (1635–1703). Hooke is perhaps better known for his law concerning the force exerted by springs, which we will examine in the next chapter, when we explore materials science.

For a small object (such as Kirk) falling over a short distance near the surface of the Earth, Eq. (2.2) can be expressed as

\[ F = mg, \]  

(2.3)

where \( g \) is the acceleration due to gravity at the particular location. Note that Eq. (2.3) is just a special case of Newton’s more general second law of motion [Eq. (2.1)], with the acceleration, \( a \), replaced by the local acceleration due to gravity, \( g \). The precise value of \( g \) depends on both latitude and altitude, with an average value of around the globe of approximately 9.8 m/s\(^2\).

**Example 2.1: Kirk, Spock, and Jet Boots**

Using information in the movie scene, plus a few reasonable assumptions, we can come up with an estimate of the force which Spock must exert on Kirk’s ankle to stop his fall.

We will ultimately use Eq. (2.1), \( F = ma \), to calculate the force. The first ingredient we need is an estimate of Kirk’s mass. Let’s take \( m = 80 \) kg as a reasonable estimate. Next we need to estimate the acceleration, \( a \). Recall from Chap. 1 that acceleration is the change in velocity over the change in time, \( \Delta v / \Delta t \). The force that Spock exerts on Kirk’s leg brings him quickly to a stop. So his final velocity is zero. All we need are estimates of Kirk’s initial velocity, at the instant that Spock grabs his ankle, and the amount of time, \( \Delta t \), required to stop him from that instant. The time interval is easy to estimate by watching the movie scene, but
how do we estimate Kirk’s initial velocity? As an object falls under the influence of gravity, its speed increases. But as it falls through the air, the force of air resistance opposes the force of gravity. Air resistance is a force, which increases with speed. So if an object falls long enough, eventually the force of air resistance will equal the force of gravity. If the net force is zero, there is no longer any acceleration, and the object will fall at a constant speed, which we call terminal velocity. Let’s make the reasonable assumption that Kirk has fallen long enough to reach terminal velocity before Spock catches up with him. Terminal velocity actually depends on the shape and size of the object and the density of the air, but a reasonable value is about 56 m/s for an adult human. If we assume that it takes about 1 s for Spock to stop Kirk completely, we are now in a position to calculate the force.

\[ F = ma = m \frac{\Delta v}{\Delta t} = 80 \text{ kg} \times \frac{56 \text{ m/s}}{1 \text{ s}} = 4,480 \text{ kg m/s}^2. \]

The result is expressed in units of kg m/s^2, which is the unit of force named for Sir Isaac Newton (N). But most of us are used to thinking about force in units of pounds. So if we want to appreciate what effect this force is likely to have on Kirk’s leg, let’s convert from Newtons to pounds, using the approximate conversion factor, 1 N = 0.225 lb. This gives a force of about 1,007 lb!

**Estimation 2.1: Kirk, Spock, and Jet Boots, Revisited**

We have just estimated that Spock would have to exert a force of 1,007 pounds on Kirk’s ankle in order to stop him before he hits the rocks at the bottom of El Capitan. But what about forces exerted on Spock? Make any additional assumptions you need to estimate the force that the jet boots must exert on Spock’s ankles, in order to stop both Spock and Kirk.

A simple but dramatic illustration of Newton’s third law of motion (action–reaction) is rocket-propelled space flight. Hot gas is pushed out of the back of the rocket, which pushes the rocket (and the remaining fuel) in the opposite direction. The same effect is experienced in the recoil of a gun, when a bullet is fired, as the cartoon character Woody Woodpecker demonstrated in the 1950 movie *Destination Moon*. The animated shot was incorporated into the movie as a teaching tool to convince skeptics of the plausibility of space flight to the moon, more than 10 years before President John F. Kennedy proposed the real-life Apollo mission [7].

Newton’s third law applies to pulling, as well as pushing, as illustrated in the opening scene of the original *Star Wars* movie. After Princess Leia’s small ship is disabled by Darth Vader’s huge star destroyer, some sort of tractor beam is used to pull the disabled ship inside. Regardless of the nature of the force exerted by the large ship on the smaller one, the small ship will exert an equal and opposite force on the large ship (action–reaction). If there are no other forces acting from outside the system (large ship + small ship), the center of mass of the system will not move. They both pull toward each other. But since the large ship has much greater mass, what we see in the movie is the small ship being pulled inside the nearly stationary large ship [8].
As a final illustration of Newton’s laws of motion we consider the giant city-destroying spaceships from *Independence Day*. Early scenes in the movie show the approach toward Earth of an object, at first thought to be an asteroid, with a diameter of 550 km, and a mass of approximately one-quarter the mass of the Moon. But the object begins to slow down, which suggests that it is not of natural origin. Soon a number of smaller objects break off from the primary object and descend to the surface of the Earth. These are roughly disk-shaped, with a diameter of 15 miles. They proceed to position themselves over the centers of several major cities, with as yet unknown intent. Their arrival prompts a broad range of responses, from fear and panic, to simple curiosity, and even delight at the prospect of being taken away by alien visitors. But at the conclusion of an ominous countdown, each one fires a powerful beam of energy, destroying the city below [9].

The attack ships are shown hovering over the surface of the earth, at a constant low altitude, and either moving at a slow, constant speed, or stopped above some significant U.S. landmark, such as the Empire State Building in New York, or the White House in Washington, D.C. Newton’s first and second laws of motion tell us that the net force on each attack ship must be zero, if the acceleration is zero. But the Earth’s gravity is pulling the ship down. So in order to stay aloft (i.e., no change in its state of motion or rest, and no acceleration), each ship must also be experiencing an upward force, which is equal in magnitude to the force of gravity, but opposite in direction. Given that such a force must be acting on the ship in order to keep it aloft, what are the implications for the objects on the surface of the Earth, directly below the ship? To understand this we must invoke Newton’s third law: action and reaction. The Earth’s gravity acts on the ship, pulling it downward toward the surface of the Earth. By Newton’s third law, the ship is also exerting a gravitational force on the Earth, pulling it upward. This is the action–reaction pair for the force of gravity between the two objects. If there is some other mysterious force acting upward on the ship, which prevents the ship from being pulled down to the surface of the Earths, Newton’s third law tells us that there must also be a reaction force of some kind. What could that reaction force be? Several possibilities come to mind.

One possible mechanism for keeping the attack ships aloft is to have some object pulling on the attack ships from above—the mother ship perhaps? In this case the reaction force would be the attack ship pulling downward on that object. But the mother ship can only be in one place in orbit around the Earth at a time. So it can’t be exerting an upward force on all of the attack ships at various places around the world all at once. Another possibility is that the invaders have discovered a form of antigravity and are somehow able to cancel the gravitational interaction between the Earth and the attack ships. But to the best of our current understanding, the force of gravity can only be an attractive force, and never repulsive. So within the realm of known physics, the only remaining option is for the attack ships to be exerting pressure downward on the Earth, in much the same way that a hovercraft uses a cushion of air to float over the surface of the Earth. If the attack ships are pushing down on the surface of the Earth to counter the force of gravity, then anything in between the ship and the surface of the Earth will feel the force. The magnitude of
this force must be equal to the weight of the ship (which we can estimate from data given in the movie). The resulting pressure can be calculated by dividing the force by the surface area under the ship.

**Example 2.2: Giant City-Destroying Spaceships**

Let’s use the data presented in the movie Independence Day to estimate the pressure underneath the giant city-destroying attack ships. One possible complication is the fact that we are given dimensions of both the mother ship (550 km in diameter) and the attack ships (15 miles wide), but we are only given the mass of the mother ship (1/4 the mass of the Moon). One reasonable assumption we can make is that the attack ships are approximately disk-shaped. (Recall that the volume of disc is $4\pi r^2 h$, where $r$ is the radius and $h$ is the height of the disc.) Another reasonable assumption we could make is that the density (mass per unit volume) of the mother ship and the attack ships might be comparable to each other. Although this is not quite true, let’s further assume that the mother ship is roughly spherical in shape. (Recall that the volume of a sphere is $4/3 \pi r^3$.) We can then take the following approach to solve the problem:

Assumption: Density of mother ship = density of attack ship = mass/volume = constant.

\[
\frac{m_{\text{attack\_ship}}}{4\pi r_{\text{attack\_ship}}^2 h} = \frac{m_{\text{mother\_ship}}}{\frac{4}{3} \pi r_{\text{mother\_ship}}^3},
\]

Rearranging and simplifying, we obtain

\[
m_{\text{attack\_ship}} = \frac{m_{\text{mother\_ship}}}{\frac{4}{3} \pi r_{\text{mother\_ship}}^3} \cdot \frac{4\pi r_{\text{attack\_ship}}^2}{4\pi r_{\text{attack\_ship}}^2 h},
\]

\[
m_{\text{attack\_ship}} = \frac{m_{\text{mother\_ship}}}{r_{\text{mother\_ship}}^3} \cdot \frac{3 h}{r_{\text{attack\_ship}}^2}.
\]

The force required to keep one of these ships aloft (balanced against the force of gravity) is $F = mg$. The resulting pressure under one of these ships is the force divided by the area of the disc, or

\[
\text{Pressure} = \frac{mg}{A} = \frac{m_{\text{mother\_ship}}}{r_{\text{mother\_ship}}^3} \cdot \frac{3 r_{\text{attack\_ship}}^2 h g}{\pi r_{\text{attack\_ship}}^2},
\]

which simplifies to

\[
\text{Pressure} = \frac{m_{\text{mother\_ship}}}{r_{\text{mother\_ship}}^3} \cdot \frac{3 h g}{\pi}.
\]

In the end, the radius of the attack ship cancels out. All we need to do is to take a guess as to the height, $h$, of one of the attack ships. Then it remains simply to put all
of the quantities given in the movie into the same system of units and look up a value for the mass of the moon. The completion of this calculation is left as an exercise.

**Estimation 2.2: Pressure Underneath One of the Independence Day Attack Ships**

Complete the calculation, which we set up in Example 2.2. Be sure to convert all quantities into a consistent set of units (mass in kilograms, linear dimensions in meters, acceleration due to gravity in m/s\(^2\)). Compare this pressure to the pressure at the bottom of the Mariana Trench—the deepest part of the ocean. Do the attack ships really need to use a death ray to destroy the major cities of Earth?

### 2.3 Einstein and Relativity

Newton’s laws of motion and his universal law of gravitation transformed our understanding of the way in which the universe works. Without them, spaceflight to the Moon and the planets simply would not be possible. Although they apply perfectly well in the realm of most of everyday experience, and always will, they are not the last word. In particular, Newton’s concept of space and time as separate and independent quantities is only an approximation to reality. As we will see shortly, an important piece of modern technology, which was unimaginable in Newton’s time, but has become commonplace in the twenty-first century, simply would not work without another refinement to our understanding of space and time. We will also discover that this same refinement opens another possibility, which Newton never could have anticipated: time travel!

Einstein’s special theory of relativity, published in 1905, included the concepts of *time dilation* (moving clocks run slow, relative to clocks at rest), *length contraction* (to an observer at rest, moving objects appear shorter along the direction of relative motion), and the equivalence of matter and energy (the famous equation \(E = mc^2\)). His general theory of relativity, published in 1916, described space and time not as separate and independent quantities, but as a single four-dimensional quantity, *spacetime*. In the vicinity of a large mass, this *spacetime* is distorted: space is stretched out and clocks run slower, the deeper they are into the distortion (closer to the mass). According to Einstein, the phenomenon which we experience as gravity is simply a property of this distorted *spacetime*. But the concept of existence in four dimensions and the possibility of time travel predate the publication of Einstein’s special theory of relativity by 10 years and show up in a work of science fiction. H.G. Wells published his debut novel, the Time Machine, in 1895, the first chapter of which includes the following:

“You must follow me carefully. I shall have to controvert one or two ideas that are almost universally accepted. The geometry, for instance, they taught you at school is founded on a misconception.”
“Is that rather a large thing to expect us to begin upon?” said Filby, an argumentative person with red hair.

“I do not mean to ask you to accept anything without reasonable ground for it. You will soon admit as much as I need from you. You know of course that a mathematical line, a line of thickness nil, has no real existence. They taught you that? Neither has a mathematical plane. These things are mere abstractions.”

“That is all right,” said the Psychologist.

“Nor, having only length, breadth, and thickness, can a cube have a real existence.”

“There I object,” said Filby. “Of course a solid body may exist. All real things –”

“So Most people think. But wait a moment. Can an instantaneous cube exist?”

“Don’t follow you,” said Filby.

“Can a cube that does not last for any time at all, have a real existence?”

Filby became pensive. “Clearly,” the Time Traveler proceeded, “any real body must have extension in four directions: it must have Length, Breadth, Thickness, and – Duration. But through a natural infirmity of the flesh, which I will explain to you in a moment, we incline to overlook this fact. There are really four dimensions, three which we call the three planes of Space, and a fourth, Time. There is, however, a tendency to draw an unreal distinction between the former three dimensions and the latter, because it happens that our consciousness moves intermittently in one direction along the latter from the beginning to the end of our lives” [10].

We now turn our attention to several science fiction TV and movie scenes, which will help us to develop an appreciation of these concepts, and to see how they are relevant to some technology which has become part of everyday life.

In the opening scene of The City on the Edge of Forever, an episode from the first season of Star Trek (the original series), the U.S.S. Enterprise is buffeted by “ripples in time”—waves of distortion of spacetime, emanating from a previously unexplored planet. Dr. McCoy, responding to a medical emergency on the bridge, accidentally receives an overdose of medication, which induces extreme paranoia. The doctor, followed by several of the crew, beams down to the surface of the planet, where they discover the source of the spacetime distortions: a sentient time portal, which calls itself the Guardian of Forever. The doctor leaps through the portal, into the past, and all of history is changed. The rest of the episode is devoted to determining what McCoy did to change history, and to set things right [11].

Moving through space is an everyday occurrence. Not necessarily interstellar space, as in Star Trek, but the everyday space within the walls of your house or the streets of your neighborhood. It’s usually not as dramatic as Magneto moving the Golden Gate Bridge, or Kirk falling off the face of a mountain, but it’s something that most of us experience literally every day of our lives. What about traveling through time? The City on the Edge of Forever deals with traveling back into the past and changing the course of history. There is no conceivable way of doing this within the framework of Newtonian physics, in which space and time are completely separate quantities, and time flows always in one direction. But according to Albert Einstein, space and time are not independent quantities. Rather they constitute a four-dimensional fabric of spacetime. If this is really so, what are some of the implications of this interconnectedness? Is it possible to travel far into the future or back into the past?
2.3.1 Special Relativity and Time Dilation

Einstein revolutionized our concept of space and time. The big idea that led to this breakthrough was the realization that the laws of physics, specifically Maxwell’s equations of electricity and magnetism, can only be consistent in all frames of reference if the speed of light is the same in all frames of reference. According to Newton, space and time were absolute quantities, and your perception of the speed of anything depended on your relative state of motion with respect to absolute space. But according to Einstein, the speed of light is the one absolute quantity, and your perception of space and time is altered by motion. Another episode from the original series of Star Trek will serve to illustrate the concept. In Wink of an Eye the starship Enterprise is taken over by a race of aliens, who move so quickly that the only direct evidence of their presence is an annoying buzzing sound, like that of a flying insect. A few drops of strange liquid in Captain Kirk’s coffee cause him to be “accelerated” to their speed. As a result, the Captain perceives the rest of his crew as nearly stationary, in extremely slow motion. The queen of the alien race explains that Kirk is to become their king. Kirk doesn’t like the idea and prepares to stun the queen with his phaser weapon. But in their fast-moving frame of reference, the phaser beam propagates slow enough for the alien queen to step out of the way, unharmed. This would make sense if Newton’s view of absolute space were correct. The phaser is a directed energy weapon. But what kind of energy does a phaser emit? If it is any form of electromagnetic energy, the phaser beam must propagate through space at the speed of light. Now if the perceived speed of anything is relative to your own speed, as it is in Newton’s view, then you could step out of the way of an incoming electromagnetic energy beam. But if Einstein’s view is correct, and the speed of light is the same in all frames of reference, then what we have just described would be impossible. Fortunately for the Scalosian queen, Star Trek’s phaser weapon emits a particle beam and not electromagnetic energy. And according to Einstein, nothing that has mass can travel at the speed of light. So as long as the Scalosian queen can move faster than the particle beam emitted by the phaser (which must propagate at a speed less than the speed of light), she could (in principle) step out of the way of the beam [12]. But the important question remains: which view of the nature of space and time—Newton’s or Einstein’s—is the better description of reality? We have more to explore.

One of the best film illustrations of Einstein’s time dilation effect is found in the opening scene of the original version of Planet of the Apes. The pilot of a space ship (played by Charlton Heston) is recording his final log entry, before placing himself into suspended animation, along with the rest of the crew, for the extended voyage. According to the chronometer, 6 months have passed since the launch from Cape Canaveral. Six months, as experienced onboard the ship, that is. The chronometer also displays the date back on Earth, which is nearly 700 years in the future, relative to the date on the ship [13]. From the information provided, it is possible to calculate the speed of the ship, according to Einstein’s equation for time dilation:
where \( t \) is the time as experienced in a frame of reference at rest (on Earth), \( t' \) is the time in the moving frame (onboard the spaceship), \( v \) is the relative speed, and \( c \) is the speed of light. The situation is illustrated in Fig. 2.2.

**Example 2.3: Relativistic Spaceflight**

Here we will use the information provided in the opening scene of Planet of the Apes to calculate the speed of the spaceship, according to Einstein’s concept of time dilation [Eq. (2.4)]. We will do this in two ways, and compare the results. First, let’s calculate the average speed of the ship over the entire trip, up to the point of the opening monolog. The ship’s chronometer displays three important pieces of information: the launch date (01-14-1972), the current time onboard the ship (07-14-1972), and the current time on Earth (03-23-2673). In Eq. (2.4), the proper time, \( t \), is the elapsed time in the rest frame of reference (on Earth). Subtracting the launch date from the current date on Earth gives approximately 702 years (including an extra day for every leap year). Meanwhile, in the moving frame of reference, the elapsed time, \( t' \), is the difference between the current time onboard the ship and the launch date, which is 6 months. We can solve Eq. (2.4) for the average speed of the ship, \( v \), first by rearranging:

\[
\sqrt{1 - v^2/c^2} = \frac{t'}{t},
\]

Then squaring both sides, we get

\[
1 - v^2/c^2 = \frac{t'^2}{t^2}.
\]

Rearranging terms again gives
Solving for $v$, we obtain

$$v = c \sqrt{1 - \frac{t^2}{c^2}}.$$ 

Finally, substituting values for the elapsed times gives the average speed of the ship:

$$v = c \sqrt{1 - \frac{(0.5y)^2}{(702y)^2}},$$

$$v = 0.999999746c.$$ 

So the average speed of the ship up to the point of the monolog is just slightly less than the speed of light. It is important to emphasize once again that according to Einstein, nothing that has mass can actually travel at the speed of light. (Only massless particles, such as photons, can travel at the speed of light.)

The camera shot of the ship’s chronometer, along with Charlton Heston’s scientific monolog, would have been plenty to satisfy just about any fan of serious science fiction. But the director (Franklin J. Schaffner) and screen writers (Michael Wilson and Rod Serling) went even further. As Charlton Heston gets ever more philosophical about human life on Earth, and his own place in the universe, we see more shots of the chronometer, showing the days passing on Earth. The rate at which time passes on Earth is roughly 3 days for every 90 s of ship time. Converting days into seconds gives

$$3 \text{ day} = 3 \times 24 \text{ h} \times 3,600 \text{ s/h} = 259,200 \text{ s of Earth time for every 90 s of ship time.}$$

We can use this information to calculate the current speed of the ship at the time of the monolog:

$$v = c \sqrt{1 - \frac{(90s)^2}{(259,200s)^2}},$$

$$v = 0.99999994c,$$

which is somewhat faster than the average speed of the ship, as calculated from the 702 years Earth time and 6 months ship time. This is direct evidence that the ship has not been traveling at a constant speed for its entire trip, but has undergone some acceleration. It’s rare for a science fiction film to treat the science at this level of detail! Unfortunately, the difference between the current speed of the ship and the average speed turns out to be rather small. This suggests that the acceleration must have occurred early in the trip, and over a very short time—probably short enough to be lethal to the passengers, unless some unexplained technology exists to protect them from the effects of enormous acceleration.

Einstein’s time dilation effect has been confirmed experimentally, by using two identical atomic clocks, initially set to the same time, one of which is flown on a trip
around the world by jet, while the other remains at rest in the airport. When the moving clock returns to the airport, it is found to be slow, relative to the clock that remained at rest, by exactly the amount predicted by Eq. (2.4), given the average speed of the jet.

**Estimation 2.3: Relativity and Passenger Jets**

Use a typical cruising speed of a conventional passenger jet (not supersonic), and the amount of time for a nonstop flight around the world, to calculate the difference in time \( t - t' \) that would result when the flight is completed, and the flying clock is compared to the clock at rest.

**Estimation 2.4 Relativity and Fusion-Powered DeLorean**

The 1985 movie *Back to the Future* invites another simple calculation using Einstein’s time dilation equation. A fusion-powered DeLorean, with the help of something called a flux capacitor, is used as a time machine. One simply sets the chronometer to the desired date (past or future) and accelerates up to the magic speed of 88 miles/h. In the first demonstration of the time machine, the inventor, Dr. Emmett Brown, uses two stopwatches: one travels in the DeLorean, around the neck of Dr. Brown’s dog (named Einstein), and the other remains at rest in the parking lot. The stopwatches are synchronized at the start of the experiment. When the experiment is completed, the stopwatches differ by 1 min. The difference is in the right direction—the one that traveled had slowed down. But the magnitude of the difference can’t be explained just in terms of relative speed of the two reference frames [14].

Use Eq. (2.4) to calculate how fast the DeLorean had to be traveling in order for the elapsed time in the moving frame of reference to be only 1 min, while the elapsed time in the rest frame was 2 min. Alternatively, how long would the trip have had to take (in the rest frame) if the actual speed of the DeLorean had been only 88 miles/h?

**Discussion Topic 2.2**

Based on these calculations, what do you conclude about the possibility (at least in principle) of traveling into the future? If you believe it might be possible, how would it be done? Does the concept of time dilation, as expressed by Eq. (2.4), allow for the possibility of traveling into the past? Why not?

### 2.3.2 General Relativity and Distortion of Spacetime

Einstein’s General Theory of Relativity describes the distortion of spacetime in the presence of large masses, such as stars or planets. Space is stretched out and time runs more slowly, compared to regions of space that are far away from large masses. According to Einstein, the effect which we experience as gravity is simply the result of the distortion of the fabric of space in the vicinity of a large mass. Furthermore, if you are inside a closed box (one from within which you are unable
to see the outside world), you would not be able to distinguish between the effects of distorted space (gravity) and uniform acceleration. A simple experiment can be performed to illustrate this principle of equivalency relating curved spacetime and acceleration. Take a ride on an elevator and measure the apparent force on an object during the brief moments of acceleration, when the elevator begins to move and when it comes to a stop. If you did not know that the elevator was accelerating, the change in the measured force could just as easily be interpreted as a momentary change in the distortion of space, resulting in an increase or decrease in the apparent strength of the force of gravity acting on the object.

Table 2.2 shows the results of a field project conducted on a university campus, to measure the apparent change in force on an object in an elevator, during the brief moments of acceleration. An object, whose weight at rest is approximately 0.5 N, was suspended from a spring scale, with a full-scale reading of 1.00 N, and a resolution of 0.01 N. The scale reading was recorded during acceleration of the elevator under two different conditions: when the elevator is starting from rest and moving upward, and when the elevator is coming to a stop while moving downward. Measurements were taken on nine different elevators around campus. The results are expressed as a multiple of $g$, the local acceleration due to gravity.

The results in Table 2.2 indicate that the acceleration experienced in a typical passenger elevator is approximately one-tenth of the acceleration due to gravity. There appears to be a slightly larger acceleration when stopping, going downward, compared to starting and going upward, but the difference is not statistically significant. The field project could be turned into a contest to find which elevator in which department on campus gives the smoothest ride or the roughest ride. But the main point of the project is to illustrate the equivalency of acceleration and the gravitational distortion of spacetime.

This equivalency principle can be put to practical use to create artificial gravity, as illustrated in the movie 2001: A Space Odyssey. It is well known that muscles will atrophy under conditions of microgravity. In order to reduce this effect, an interplanetary spaceship might be built with a section which rotates at a constant speed. An astronaut could exercise by jogging around the inside surface of this rotating reference frame. The force required to keep objects (and astronauts) in uniform circular motion on the inside of the rotating walls would be indistinguishable from the force of gravity [15].

The effects of time dilation at high speed and distortion of spacetime near large masses are not normally thought of as having an impact on everyday life. Neither are the James Bond movies typically included in the category of science fiction.

<table>
<thead>
<tr>
<th></th>
<th>Starting, going UP</th>
<th>Stopping, going DOWN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>0.090</td>
<td>0.110</td>
</tr>
<tr>
<td>Standard deviation</td>
<td>0.039</td>
<td>0.044</td>
</tr>
</tbody>
</table>

The results are expressed as a multiple of $g$, the local acceleration due to gravity.
Nevertheless, we can use a couple of scenes from one of the more recent Bond films as a lead-in to a discussion of a very practical, everyday device, which makes use of both special relativity and general relativity. In *Tomorrow Never Dies*, a demented media mogul attempts to start a war between China and the UK by sinking a British naval vessel in the South China Sea. The crew of the ship, which had drifted off course into Chinese territorial waters, believed themselves to be in international waters, based on information from their GPS (Global Positioning Satellite) system. After repeated warnings from the Chinese, the ship was sunk, not by the Chinese MIGs, which were overflying the ship at the time, but by a self-propelled sea drill, launched from a nearby boat, equipped with stealth technology, also owned by the media mogul. Later in the movie, James Bond recovers a stolen GPS encoder, which was used to broadcast a fake GPS signal from one of the media satellites [16].

The GPS system depends crucially on accurate timekeeping. As bizarre it may seem, the gravitational distortion of spacetime is a real effect, which must be taken into account, along with the time dilation effect of Special Relativity, in order to make the GPS system work properly. Clocks on the satellites in orbit are moving faster than clocks on the surface of the Earth and thus will run more slowly by about one part in ten billion, due to the time dilation effect of Special Relativity [Eq. (2.4)]. But the clocks in orbit are also farther away from the spacetime-stretching gravitational field of the Earth. Clocks that are closer to a large mass will run more slowly, according to Eq. (2.5):

$$t_r = t_\infty \sqrt{1 - \frac{2Gm}{rc^2}},$$

where $G$ is the universal gravitational constant, $m$ is the mass of the object creating the gravitational field, $r$ is the distance from the center of the massive object, and $c$ is the speed of light. The subscripts $r$ and $\infty$ are the time as measured at a distance $r$ from the gravitational source and the time measured far from any source of gravitational distortion, respectively. The time-dilating effect of General Relativity makes the clocks that are on the surface of the Earth run slower by about five parts in ten billion, compared to clocks in orbit (farther from the center of the Earth). These two time-dilating effects (gravitation and relative speed) are in the opposite direction and are of different magnitudes. Both must be taken into account, in order to make accurate positioning calculations.

**Discussion Topic 2.3**

The question remains, is the scenario in *Tomorrow Never Dies* plausible? Could a fake GPS signal be broadcast by a media satellite, orbiting near a real GPS satellite, in such a way as to confuse a naval vessel, and send it off course? Discuss what else might have to happen, in addition to broadcasting the fake signal, in order for this to work.
2.3.3 Gravitational Waves

The opening scene of Star Trek VI: The Undiscovered Country provides an illustration of a prediction of General Relativity, which has yet to be confirmed experimentally. The catastrophic explosion of the Klingon moon, Praxis, creates a shockwave through space, which rocks the starship Excelsior [17]. We have already considered the distortion of spacetime due to the presence of a large mass, which results in the experience of the force of gravity. But suppose something catastrophic happens to a large mass, such as the explosion of Praxis, or many orders of magnitude larger, the explosion of a supernova? Could this cause a wave of distorted spacetime, which might propagate outward and be felt (or measured) at a large distance away? The research effort known as LIGO (Laser Interferometer Gravitational-Wave Observatory) seeks evidence of gravitational waves by measuring a minute shift in position of the laser-reflecting mirrors in its roughly 4-km long arms [18].

The experiment hopes to detect the sort of transient disturbances, which might result from the merger of a neutron star with a black hole, as well as the more subtle, but periodic effects produced by a wobbling, asymmetric pulsar. You can join the search for gravitational waves by downloading software from Einstein@home and donating idle time on your home computer to analysis of the data [19].

2.3.4 Faster Than Light, But Not Faster Than Light

As we have already seen, one of Einstein’s major contributions to our understanding of space and time is the constancy of the speed of light in all reference frames, and the notion that nothing can travel faster than light in a vacuum. In September of 2011 the CERN research center, near Geneva, Switzerland, announced that neutrinos produced at the Large Hadron Collider seemed to have traveled to a detector in Gran Sasso, near Rome, Italy, faster than light. Details were provided in a report for Reuters by Robert Evans [20]. If this had proved to be true, it would have meant another major revolution in thinking about space and time. Proposed explanations for the anomalous results included support for a theory of quantum gravity [21]. Even the writers of TV’s The Big Bang Theory were quick to pick up on the potentially earthshaking news. Only 6 weeks after the public announcement, in the opening scene of the 11/3/2011 episode “The Isolation Permutation,” Dr. Sheldon Cooper proposed the following topic for discussion: “Faster-than-light particles from CERN: paradigm-shifting discovery, or another Swiss export, as full of holes as their cheese?” [22]. It wasn’t until several months later that the definitive explanation was found. In the end the effect was attributed to a faulty connection between a GPS receiver and a computer [23].

So it would seem that a fundamental principle of physics is upheld, after all. Nothing can travel faster than the speed of light in a vacuum. At least not with respect to one’s local surroundings. But are there any loopholes in this law of
Nature? Is it possible, for example, by some trick of General Relativity, to distort the fabric of spacetime, and create a traveling wave, which one could ride, like a surfer riding a water wave? Could such a wave be made to travel through the galaxy faster than light, while the wave rider would not have to travel very fast at all, with respect to the wave, itself? The writers of *Star Trek*, supported by at least one respectable physicist, would say yes! Warp drive, a most clever and essential piece of *Star Trek* technology, is what enables travel from one star system to another in a short time, without the complications of time dilation. Without warp drive, it would not be possible for the starship Enterprise to engage in its mission of exploration. But how does it work, and is it even remotely plausible? Lawrence Krauss devotes an entire chapter in *The Physics of Star Trek* to the details [24]. A brief summary of the basic concept will suffice here.

The engines of a starship create a warp field—a wavelike distortion of space, in which the space behind the ship is made to stretch out, and the space in front of the ship is compressed. The starship rides along on this wave of distorted space, like a surfer on a wave of water. How to create such a wave of distorted space involves a clever combination of special and general relativity. We have already seen that the GPS system simply would not work properly without taking into account the effects of both special relativity and general relativity. The time dilation effect experienced by the satellites in orbit, as well as the distortion of the fabric of spacetime by the Earth’s gravity, must be included in the calculations, in order to achieve accurate positioning. But warp drive actually makes use of both special relativity and general relativity in order to function. One of the ideas of Special Relativity is the equivalency of matter and energy, according to Einstein’s equation

\[ E = mc^2. \]  

(2.6)

A basic idea of General Relativity is that space is significantly distorted by the presence of large amounts of matter and energy. In principle, any desired distortion of space can be achieved by the appropriate configuration of matter and energy. Perhaps even more remarkable is that the concept of warp drive is not limited to the minds of the writers of science fiction. At least one serious physicist has explored the possibility in mathematical detail and has even published in a respected scientific journal. In a five-page letter to the editor of the journal Classical and Quantum Gravity, Miguel Alcubierre has shown that “within the framework of general relativity and without the introduction of wormholes, it is possible to modify a spacetime in a way that allows a spaceship to travel with an arbitrarily large speed” [25]. Thus, *Star Trek*’s warp drive is a bit of science fiction which seems to be possible, in principle, but simply beyond our technological capability.

A particularly imaginative episode of *Star Trek: The Next Generation* raises questions about the effect of modern technology on the environment. *Force of Nature* takes the concept of spacetime as a four-dimensional fabric very literally and asks whether or not the distorting effects of warp drive might ultimately be bad for the fabric of spacetime. Might it be possible, by overuse of warp engines, to create a rift in the fabric of spacetime, much like overstressing a piece of physical
material? If so, what might be the consequences? Like any environmental issue, the problem is highly complex and interdisciplinary. Scientific investigation, sometimes delayed by bureaucracy, is necessary to determine the cause. The solution is a delicate balance of politics, economics, and environmental stewardship [26].

2.4 Stephen Hawking, Black Holes, Wormholes, and Quantum Gravity

The third of Cmdr. Data’s trio of famous physicists is Stephen Hawking, who until recently held the Lucasian Chair of Mathematics at Cambridge University (a position previously held by Sir Isaac Newton) [27]. Hawking has devoted much time to the study of solutions to Einstein’s equations of general relativity, including black holes and wormholes. His major contribution to our understanding of space and time has to do with the fact that a black hole is enormously massive and creates huge distortions of the fabric of spacetime over exceedingly small distances. Einstein’s general relativity works well when dealing with very large massive objects, but fails completely at the small (subatomic) scale. Quantum mechanics, on the other hand, has been very successful at describing physics at the subatomic level, but is completely incompatible with Einstein’s description of gravity. The need for a quantum theory of gravity arises because the sharp distortion of spacetime near the center of a black hole occurs over subatomic distances. Hawking and many others are searching for a theory which will successfully describe gravity at the quantum scale.

2.4.1 Black Holes

The term black hole was first introduced into the scientific literature by physicist John Wheeler, in the same year that a similar-sounding term was introduced into popular culture by the original series of Star Trek. In the episode Tomorrow is Yesterday (original air date: 26 January 1967), the Enterprise is caught in the gravitational field of what Captain Kirk refers to as a black star [28]. In the process of breaking away, the ship and crew are sent back into the past (the situation to which Kirk later referred in the motion picture Star Trek IV: The Voyage Home, when said that they had done it before). It is not clear in this case whether the writers of Star Trek have influenced the language of science, or if they were somehow anticipating a technical term that was yet to be published. Although Wheeler is often credited with having coined the term black hole, he insists that he did not invent it, but simply popularized it. In his memoirs, published in 1998, he gives the exact date and location of the talk in which he first used the term: 29 December 1967, at a Sigma Xi-Phi Beta Kappa lecture at the New York Hilton hotel. But he credits an unknown member of the audience at a
previous talk, which he gave in the fall of 1967, at NASA’s Goddard Institute for
Space Studies in New York, for proposing the term, as a simpler way of referring to a
“gravitationally completely collapsed object” [29].

One way of describing a black hole is to say that it is a singularity in density: a
finite amount of mass in an infinitesimally small volume of space. A black hole can be formed when a star of sufficient mass reaches the end of its life, and collapses under its own gravity. The resulting concentration of mass distorts the fabric of spacetime to such an extent that anything which approaches close enough to a black hole will never escape. The distance of safe approach is known as the event horizon. Beyond the event horizon, not even light can escape. Our own solar system will never suffer this fate, since the minimum mass required for a star to collapse into a black hole is roughly three or four times the mass of our Sun. But black holes can be created on a much smaller scale in high-energy particle collisions. This effect led to considerable public outcry about the safety of particle accelerators, and the wisdom of conducting research in high energy physics.

The Large Hadron Collider (LHC) at CERN, near Geneva, Switzerland, is the largest particle accelerator in the world. Straddling the border between France and Switzerland, the main accelerator ring of the LHC is 16.7 miles in circumference and is designed primarily to collide high-energy protons. We will consider the LHC and its research objectives in more detail in the next chapter. Before the LHC was scheduled to be turned on for the first time in September, 2008, there was widespread concern over the possibility that a black hole would be created. People feared that a black hole would suck in all the matter around it and destroy the world. Among the more tongue-in-cheek responses was the painting of a landmark fence on the campus of Carnegie Mellon University, by some of our students, in commemoration of the scheduled start-up of the LHC, on 10 September 2008 (Fig. 2.3). The words on the fence include a famous song lyric “It’s the end of the world, as we know it, and I feel fine.”

The public fear and misperception of the LHC may have been fueled, in part, by a sci-fi movie, released just a few years earlier. The 2005 movie, The Black Hole, depicts the devastation that results when a black hole is created at a fictitious particle research facility near St. Louis, Missouri [30]. The proposed solution to the problem is more typical of sci-fi movies of the 1950s, than the early twenty-first century: full nuclear strike! Unfortunately for the people of St. Louis, and for the rest of the world, this is a completely counterproductive proposal. If you throw
more matter and energy, of whatever form, into a black hole, you are not likely to blow it up. You’ll just make it bigger.

So the question remains, is it possible for a high-energy particle accelerator to create a black hole? And if so, what is the best thing to do about it? The answer to the first question is yes! Microscopic black holes are, indeed, created in high-energy collisions, of the sort that happen all the time in the Earth’s upper atmosphere. High-energy protons from supernova explosions race through the galaxy. When one of these particles collides with matter in the Earth’s ionosphere, the result can be a microscopic black hole—a singularity of density. But thanks to the research of Stephen Hawking, we understand that such microscopic black holes do not last long enough to accrete enough additional mass to cause the kind of devastation depicted in the movie *The Black Hole*. This effect, first described in a 1974 paper by Hawking, now bears his name: Hawking radiation [31]. So the answer to the second question is just leave them alone, and they will evaporate.

After a number of technical difficulties, the LHC has been operating successfully for many months, gathering enormous amounts of data, which will help to answer some fundamental questions about the structure of the universe. We will take up some of these questions later in this book. The good news is that so far no black holes have been observed eating France or Switzerland. For those who are interested in more details about the connection between black holes and particle accelerators, the press office at CERN have addressed the issue and the concerns very thoroughly on their web site [32].

The concept of an event horizon can be formalized with reference to Eq. (2.5) (gravitational time dilation). The quantity $\frac{2Gm}{c^2}$ in Eq. (2.5) has dimensions of length and is known as the Schwarzschild radius:

$$r_s = \frac{2Gm}{c^2}. \tag{2.7}$$

It is possible for an object to have such a large mass that its Schwarzschild radius is larger than its physical radius. Anything that approaches the object closer than the Schwarzschild radius (or event horizon) can never escape. Thus, a black hole need not be infinitely dense. It just has to have a sufficiently large mass to create an event horizon at a radius greater than its physical radius.

The 2009 movie *Star Trek* treats black holes in a way that has absolutely no basis in reality, but will provide a good lead-in to our next section on *wormholes*. Director J.J. Abrams creates an alternate universe scenario, touched off by a catastrophic accident. A star within the territory of the *Romulan Empire* is about to become a supernova and (so we are told) threatens to destroy the galaxy. The proposed solution is to create a black hole inside the star and stop the supernova from expanding. Unfortunately, the plan is executed too late to prevent the destruction of *Romulus*, the home planet of the *Romulans*. But what does occur changes the course of history, or rather transports the audience into an alternate universe, in which the flow of history is completely different from the one that generations of *Star Trek* fans knew [33]. Two ships, one piloted by Spock, the *Vulcan* who was attempting to stop the supernova, and another piloted by Nero, a *Romulan* miner, get caught in the gravitational field of the
black hole and are pulled in. First the Romulan ship and then the Vulcan ship go through the black hole and end up in the past. Their subsequent actions change the course of history.

As brilliant as this movie is, from an entertainment perspective, this scenario could never occur. Based on our understanding of the properties of black holes, both ships would be destroyed by the extreme distortion of the fabric of spacetime. Spock and Nero would die, and history would continue to unfold undisturbed.

2.4.2 The Multiverse Hypothesis

In the spirit of science fiction, we will take this opportunity to depart from the realm of science into the realm of pure speculation. The miraculous passage of Spock and Nero through the black hole, which we have just discussed from a scientific perspective, resulted in what has been referred to as an alternate universe—a different playing out of events from the one that we are used to. For example, in the universe that we knew, James T. Kirk was the captain of the U.S.S. Enterprise. In the alternate universe of the 2009 Star Trek movie, Spock is the captain, and Kirk is marooned on a desolate planet for mutiny. The question might arise, did Spock and Nero go back in time in their own universe and change the flow of history, or did they pass into a completely different parallel universe? There are theories of the so-called multiverse, that is to say, multiple parallel universes, in which reality plays out differently in each one. But there is no possibility of communication between any two of them—they are causally disconnected from one another. Nothing that happens in our universe can have any effect on similar events occurring in another universe, and vice versa. So this does not present a plausible explanation for the events in the movie. By the same token, since there is no possibility of information exchange between these hypothetical parallel universes, there is also no way to know whether or not they exist. The multiverse hypothesis can never be tested experimentally.

This does not (nor should it!) prevent the writers of science fiction from having fun with the concept. A brilliant illustration of the most extreme version of the multiverse hypothesis is the Parallels episode of Star Trek: The Next Generation [34]. In the opening scene Lt. Worf is returning to the U.S.S. Enterprise from a Klingon bat’leth tournament, having won champion standing. But his sense of pride in his victory is tempered with a sense of dread, as he anticipates his fellow crewmembers might be planning a surprise birthday party for him. As the episode unfolds Worf begins to suspect that things are not as they ought to be. Details of his surroundings change. Relationships with crewmembers are different. Even interplanetary political situations are not the way he knew them. He finds himself shifting from one quantum reality to another. Toward the end of the episode, multiple quantum realities begin to converge at the same place. As Cmdr. Data observes, “Everything that can happen does happen.”
In his book *The Hidden Reality*, physicist and acclaimed author Brian Greene distinguishes nine variations on the multiverse theme, which differ markedly both in terms of the overall makeup of the landscape and in terms of the nature of the individual member universes [35]. And not all variants of the multiverse hypothesis should be dismissed as mere flights of fancy. Our observable universe is finite. That is to say, we are only able to see out as far as light could have traveled to us, since the beginning of the universe. There is no reason (at the moment) to believe that the universe does not extend beyond our visual horizon and that there might be other regions of this hypothetically bigger universe. But again, since there is no way for us to receive information from these hypothetical other regions, we have no way of knowing what they might be like. The conditions might be similar to our known universe, or very different [36].

### 2.4.3 Wormholes

Since Spock and Nero could not have passed through a black hole and lived to tell about it, nor could they have passed into a different parallel universe, by way of a black hole, is there some other way in which the events of the movie might have taken place? This brings us into another dimension of theoretical physics, which presents a whole new set of possibilities, as well as complications.

When the astronomer Carl Sagan was writing his novel, *Contact*, about the search for extraterrestrial intelligence (a topic which we will take up in Chap. 5) he needed a way for his main character to travel enormous distances through the galaxy in a short time. He initially made the same mistake that was made in the new Star Trek movie: he used a black hole as the means of transportation. But he had the foresight to consult with Kip Thorne, a physicist who specializes in general relativity, for some advice. In Sagan’s own words, Thorne replied to his inquiry with “... pages of tightly reasoned equations, which was more than I had expected.” He recommended that Sagan use a wormhole, instead of a black hole [37].

A wormhole, simply put, is a shortcut through space. Within the framework of Einstein’s general relativity, it is theoretically possible to distort space in such a way that you could travel from Pittsburgh to London as quickly as you could step through a doorway. But an unfortunate property of wormholes is that they are unstable. There is no known way of keeping a wormhole open long enough for it to be useful. For this, at least for the time being, we need to rely on the imaginations of the science fiction writers.

In *Contact*, a coded message from an alien civilization includes the plans to construct a giant machine, which will open a wormhole to another part of the galaxy. How this machine does what it does is never explained in the movie, but it may involve the creation of some kind of exotic matter, with negative energy, in order to keep the wormhole from collapsing [38].
Discussion Topic 2.4
The *Time Travel* episode of the PBS *NOVA* series includes the suggestion that a stable wormhole (if it could exist) could also be turned into a time machine, simply by taking one mouth of the wormhole on a round trip, at relativistic speed. As we have already discovered, time would slow down for the moving mouth of the wormhole, according to Eq. (2.4). But once the moving mouth of the wormhole returns to the point of departure, will the wormhole really be able to take a person into a different time, or has the moving mouth simply aged more slowly than the mouth of the wormhole that remained at rest (like Charlton Heston in *Planet of the Apes*)? Is this proposal as simple as it seems?

If spacetime really is a single four-dimensional fabric, there is no reason, in principle, why a wormhole might not connect different times, as well as different places. The concept of a wormhole time machine is taken up in the movie *Timeline*, in which an interdisciplinary team of researchers are able to travel back in time to 1357, in the midst of the 100-Years War [39].

Even more speculative is the portable wormhole opener, used by the *Paladins*, in *Jumper* [40]. If the imagination allows for the giant wormhole-creating machine in *Contact*, could this same technology then be miniaturized down to the scale of a suitcase? The question of miniaturization will come up again in the next two chapters, as we consider such technologies as lasers and portable data storage devices.

2.5 Other Time Travel Scenarios

As we have already seen in our discussion of special relativity, Einstein’s time dilation equation allows for the possibility of time travel into the future. All you have to do is make a round-trip at relativistic speed, and you will find yourself far in the future without having aged very much, as Charlton Heston did in *Planet of the Apes*. But this does not allow for time travel into the past. Are there any other possibilities, within the framework of physics as we know it, which might enable someone to travel backward in time?

In *Star Trek IV: The Voyage Home*, science and technology are used to solve a fundamentally human problem. A giant probe of enormous power and unknown origin approaches Earth, disabling starships as it goes. It takes up orbit around the planet and begins to vaporize the oceans. Analysis of the transmission from the probe leads to the conclusion that it is attempting to make contact with humpback whales. But there is a serious problem: it is the twenty-third century, and humpback whales had been hunted to extinction at some time in the twenty-first century. The only solution to the problem: travel back in time to Earth in the twentieth century, find some humpback whales, bring them forward in time to the twenty-third century to appease the probe, and save the Earth from certain destruction [41]. The movie is tremendously entertaining and does an admirable job of portraying interdisciplinary collaboration to solve a complex problem. As we shall discover in a later chapter, some of the science and technology
are actually plausible. Unfortunately, the time travel scenario, upon which the entire plan depends for success, is not. It involves what is described as a slingshot around the Sun, in order to pick up enough speed to go into “time warp.” The slingshot effect is a real technique used by NASA to change the direction of space probes, in order to explore the solar system more efficiently, but not to send them back into the past. As we have already seen, taking a round-trip at high speed is a plausible way of traveling into the future. But speed alone does not enable travel into the past. The absolute limit on speed is the speed of light. In principle, according to Eq. (2.4), time can be made to run arbitrarily slowly, by going arbitrarily close to the speed of light. But the time interval, as perceived in the moving frame of reference, can never be negative. A different mechanism must be invoked, other than the time dilation of Special Relativity, in order to travel back into the past. Can General Relativity be of any help here? We know that the mass of the Sun stretches the fabric of spacetime and that clocks close to the surface of the Sun will run more slowly, compared to clocks far from the Sun. But just as the time dilation effect of Special Relativity can never enable a clock to run backwards, so the stretching of time by a large mass, according to General Relativity, goes only in one direction. Is there any plausible explanation for time travel, as portrayed in *Star Trek IV*? One scenario, proposed by Kurt Gödel, involves traveling through a universe in which the fabric of spacetime is spinning. According to the best observational data, the universe in which we actually live is expanding, but not spinning. So this proposal is purely hypothetical. But suppose that the fabric of spacetime in the vicinity of a huge spinning mass, such as a star, could be dragged along with the rotation of the mass. What then? If the effect occurs at all, it would likely require much more mass than the mass of our Sun to make it noticeable.

Einstein’s equations of general relativity allow for a curious situation known as a closed timelike curve. Like the concept of spinning space, this scenario was also first explored by Kurt Gödel. In principle, an object could follow a trajectory through spacetime and return to its starting point, not just in terms of its spatial coordinates, but in time, as well. An object trapped on a closed timelike curve would repeat the same set of events over and over again. This possibility formed the basis for the *Cause and Effect* episode of *Star Trek: The Next Generation*. The scriptwriters call the phenomenon a temporal causality loop, but the idea is the same. Members of the crew of the Enterprise begin to get feelings of déjà vu. While playing poker, they seem to know which cards are going to be dealt next. Doctor Crusher knows who is about to walk into sickbay, and so forth. Eventually they put the pieces together and figure out that the Enterprise seems to be stuck in a loop in time and destined to repeat the same catastrophic event over and over again [42].

A temporal causality loop, or properly, a closed time-like curve, is something, which, for the moment, at least, remains in the realm of the imagination of science fiction writers and theoretical physicists. But if it were possible to create such a loop through spacetime, could one then travel back in time and change the events of the past? In *Cause and Effect*, the crew of the Enterprise eventually figure out how to send a message to themselves, which they could pick up in the next cycle of the loop, and avoid the repeating catastrophe.
If it is possible to change one small event in the past, what other ripples in history would be created as a result? These ideas are explored in movies such as *The Butterfly Effect* and *Donnie Darko* [43, 44]. But according to physicist Igor Novikov, time travel into the past, if it is possible, must be constrained to follow what he calls the principle of self-consistency. As recounted in the PBS NOVA episode, *Time Travel*, Novikov was inspired to explore the possibilities of time travel by colleague Kip Thorne, and his willingness to help Carl Sagan with the scientific foundation of his novel CONTACT. Novikov suggests that time travel can only work without violating causality. That is to say, no event of the past can be changed in any way that would affect events in the future [37]. This opens the possibility of yet another Star Trek time travel scenario. In the *Trials and Tribbleations* episode of *Star Trek: Deep Space 9*, members of the crew have traveled roughly 75 years into the past and are witnessing the events of an episode of the original series of *Star Trek (The Trouble with Tribbles)*. While taking every precaution not to do anything that might alter the flow of history, Dr. Bashir finds himself contemplating the possibility that he might be his own great grandfather [45]. Igor Novikov may be on to something significant about the nature of space and time. If his self-consistency principle is correct, then time travelers into the past would be as helpless to alter the flow of history as we would be helpless to defy the law of gravity. This would rule out the scenario in Primer, in which two engineers accidentally invent a time machine and proceed to use their discovery for personal profit. Day by day they invest in the stock market, based on the foreknowledge they have gained, thanks to their ability to travel in time [46].

### 2.6 Exploration Topics

**Exp-2.1: Black Holes, Black Stars, and Naked Singularities**

Why has it been so difficult to observe a black hole directly?

What new techniques are being developed to enable direct observation of a black hole?

What are the differences between a black hole and a black star?

How would an observer be able to distinguish between a black hole and a black star?

In what ways are naked singularities similar to black holes?

What are the observable differences between black holes and naked singularities?

If naked singularities exist in space, what could be learned by observing them?

References

Exp-2.2: Wormholes and Time Travel
Watch the PBS NOVA episode, “Time Travel”, which proposes that a wormhole might be used as a time machine. Based on your understanding of special relativity and time dilation, write an argument either for or against this proposed mechanism for time travel.

Exp-2.3: Improving the GPS System
What important physics principles are essential for an effective GPS system? Why might there be a need to improve the current system?

References

Exp-2.4: The Multiverse Hypothesis
Briefly describe the difference between a Level 1 multiverse and a Level 2 multiverse.
What is the fundamental problem with all multiverse theories, which prevents any of their claims from ever being directly tested or verified?

Reference

References


Changing Perspectives Through History

3. Although using Data’s poker game as a springboard for discussing the nature of space and time should be obvious to any physicist, who is also a fan of science fiction, Lawrence Krauss
deserves the credit for being the first (to my knowledge) to make such a connection in print. I am indebted to him for his brilliant and entertaining book *The Physics of Star Trek* (Basic Books, 1995), which served, in part, as the inspiration for the course, upon which the present work is based.

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**Newton’s Laws**

9. *Independence Day* (Roland Emmerich, 20th Century Fox 1996). Giant spaceships descend upon earth and proceed to destroy the major cities with death rays. But are death rays really needed? Data presented in the film, on mass and dimensions of the ships, enable calculation of the pressure underneath the ship [DVD scenes 1 (July 2), 2 (data on mother ship: diameter 550 km, mass \(\frac{1}{4}\) mass of moon), 4 (mother ship collides w/satellite), 8 (deployment of attack ships, roughly disk-shaped, 15 miles wide), 24 (death ray used on several major US cities), 27 (conventional air strike), 40 (nuclear attack)]

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**Einstein and Relativity**

18. LIGO, [http://www.ligo.caltech.edu/](http://www.ligo.caltech.edu/)

Black Holes and Worm Holes

28. Star Trek (The Original Series) – Tomorrow is Yesterday (Written by D.C. Fontana, Directed by Michael O’Herlihy, Paramount 1967). The Enterprise and her crew are sent back into the past, after breaking away from the gravitational field of a black star [DVD, Time Travel Fan Collective, Disc 1, opening scene]
30. The Black Hole (Tibor Takacs, Equity Pictures (made for television) 2005). A particle accelerator creates a black hole, which begins to eat St. Louis [DVD scenes 9 and 10]
33. Star Trek (J.J. Abrams, Paramount 2009). Black hole, time travel [old Spock’s account: DVD toward the end of scene 9] [young Spock’s hypothetical explanation: DVD toward end of scene 8]

The Multiverse Hypothesis

34. Star Trek: The Next Generation – Parallels (Written by Brandon Braga, Directed by Robert Wiemer, Paramount 1993). An extreme illustration of the multiverse hypothesis: everything that can happen does happen [DVD season 7 disc 3, opening scene + scene 2, or full episode]
37. NOVA: Time Travel (Judith Bunting, BBC/WGBH 1999). Including interviews with Carl Sagan and Kip Thorne, the episode proposes using a wormhole as a time machine [VHS tape, use the first half hour through billiard balls causality]
38. Contact (Robert Zemeckis, Warner Brothers 1997). Wormhole [DVD scenes 32, 33]
40. *Jumper* (Doug Liman, 20th Century Fox 2008). Humans with the unusual ability to create wormholes, and jump spontaneously from one place on Earth to another, are hunted down by others who hate them because of their ability. The hunters use portable devices to keep the wormhole open, enabling them to follow the jumpers [DVD scenes 19, 20]

**Other Time Travel Scenarios**

41. *Star Trek IV: The Voyage Home* (Leonard Nimoy, Paramount 1986). Time travel by “sling-shot” around the Sun at warp speed: is this possible, even in principle, in the kind of universe in which we live? [DVD scenes 5, 6]

42. *Star Trek: The Next Generation, Cause and Effect* (Jonathan Frakes, Paramount 1992). Temporal causality loop (closed, timelike curve) [DVD season 5 disc 5, opening scene, then skip to scenes 4 and 5]


46. *Primer* (Shane Carruth, THINKFilm 2004). Time travel [DVD scene 7]
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