1 A Brief History of Space

A Primitive Model of the Universe

WE live in a world where it is difficult to extract ourselves from what might be called the collective knowledge of the human race. We are surrounded by huge information banks storing the collected thoughts of the clever people who have shaped the way we think about the world. Among these resources we can include our own education from our earliest years. In addition, we have the written word, the spoken word through television and radio, and access to the World Wide Web, which provides a view of the world through cyberspace.

As a consequence of this immersion in collective knowledge, most of us have an idea of the structure and workings of the solar system, and the universe in general, without ever having to venture beyond our armchair. It is very difficult, therefore, to put ourselves in the position of ancient man, who looked up at the sky with unsophisticated and unaided eyes, and attempted to make sense of it. If you could take this leap backward a few thousand years, and at the same time leave behind your collective knowledge, what would you make of it all? I would guess that only a minority of your friends and family would be interested anyway. Times were hard, and most of us would probably have spent the majority of our time just surviving. However, let's suppose that you were able to retain a few brain cells for things other than where your next meal was coming from. Perhaps the first obvious feature of your model of the universe would be a clear belief that the world was flat. If you look out of the window now, it does look flat, doesn't it? You wouldn't have needed to be too clever to notice that the Sun and Moon make a daily journey across the sky, from horizon to horizon in about 12 hours. If you were also a bit of an ancient astronomer, interested in the night sky, you also might have noticed that this daily journey is shared by the stars. You would have to be really observant, however, to have noticed that some of the brighter stars—what we now call the planets—wander among the fixed stars over a longer time scale.

What sort of model would you have dreamed up, as an ancient person,

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deprived of your collective knowledge? A sensible picture would be what might be called the “primitive” model—that the universe of Sun, Moon, and stars rotated about the flat Earth once every day. This flat Earth–centered model was indeed the accepted one for a long time, simply because it seems the obvious interpretation of what we see around us.

How we have moved on from this model to our current understanding of how the universe works is a well-documented but long and winding pathway through the history of science. Periodically, over time, a gifted individual has joined the journey along the pathway to challenge the accepted view. It is not the intention of this chapter to give a detailed account of this journey, but rather to look at some of the more important milestones, and to discuss some of the individuals who have made important contributions to the story.

Flat Earth to Spherical Earth

As we can see from the above, interestingly, ancient and modern civilizations can have widely different interpretations of the way things work, even though they both see the same sky. Generally, the differences occur as a consequence of the precision of observation that can be achieved using the unaided eye thousands of years ago compared to using powerful telescopes today.

The first substantive attack on our primitive model is credited to Eratosthenes, who lived in the ancient Egyptian city of Alexandria around 300 B.C. He used an astonishingly simple method, developed by a sharp intellect, to estimate the size of the spherical Earth, having first disregarded the belief that the Earth was flat. The basics of the method are illustrated in Figure 1.1a. Eratosthenes was somehow aware that at around the time of midsummer, vertical posts did not cast shadows at noon in Syene (point A), which is in a region of southern Egypt traversed by what we now call the Tropic of Cancer. However, at the same time of year and day, he could see that vertical posts in Alexandria (point B) did cast shadows. This supported the idea in his mind that the Earth was not flat, but spherical—an extraordinary leap of logic. He was also aware, using the geometry shown in Figure 1.1a, that the simple measurements of the angle a, and the distance between Alexandria and Syene, would allow him to measure the circumference of his now spherical world. The distance measurement was simple in principle, but arduous in practice, as he had to employ someone to pace out the 800 km (500 miles) or so between the two centers! His estimate of Earth’s circumference was around 40,000 km (25,000 miles), which is amazingly close to our modern estimate of 40,075 km (24,903 miles).

Eratosthenes is remembered today for his ingenuity and vision, but also because he was right. It does make you wonder, though, how many of his fellow Alexandrians believed in his claims of a spherical Earth—something a bit hard to swallow for the average man in the street at that time. In order to draw his conclusion, he needed to assume not only that Earth was spherical, but also that the Sun was a long way away from Earth so that the sunlight illuminated Earth's surface with effectively parallel rays (Fig. 1.1a). An equally good interpretation of his observation of shadow lengths at noon is illustrated in Figure 1.1b, which would probably have gone down better with

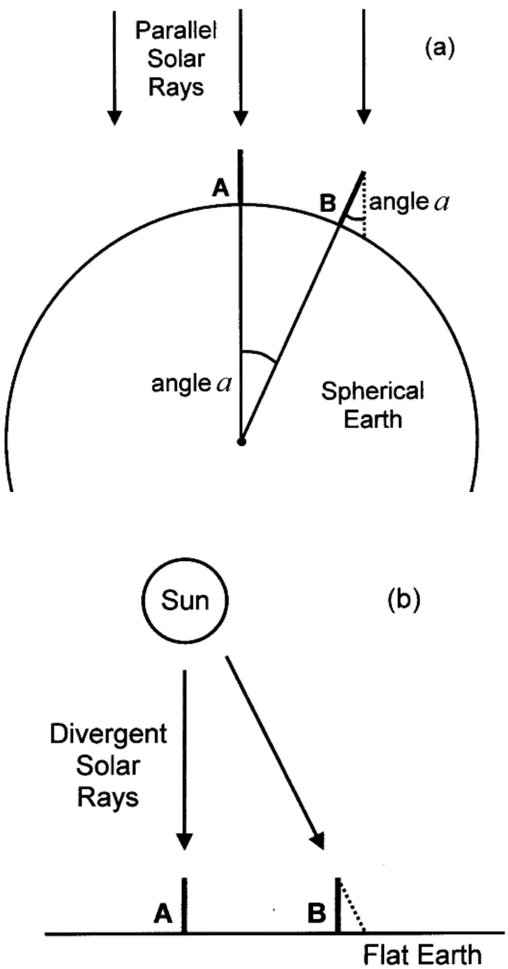

Figure 1.1: Alternative interpretations of Eratosthenes's observations of shadows cast by vertical posts at widely separated locations.

his contemporaries. If the Sun is assumed to be closer to Earth, so that the divergence of its rays is apparent, then the flat-Earth model can be saved. Over time, however, Eratosthenes was shown to be right, and the first cornerstone of our primitive model of the universe crumbled.

Earth-Centered to Sun-Centered Universe

The idea of an Earth-centered universe was firmly established by Claudius Ptolemaeus, known more commonly as Ptolemy, in the second century A.D. Ptolemy's universe had Eratosthenes's spherical Earth at its center, around which moved the Sun, Moon, planets, and stars. It was inconceivable that man, God's favored creation, should live anywhere other than at the center of the cosmos! Furthermore, by similar reasoning, it was supposed that these heavenly bodies, far removed from the imperfections of earthly life, should move along perfect circular paths.

However, there were problems with the model, which even the astronomers in Ptolemy's time could detect with their limited observational capabilities. The planets had been discovered centuries before—the Romans worshiped them as gods—and they could be distinguished not only by their brightness, but also by their movement across the sky relative to the fixed stars. Mars in particular appeared to challenge Ptolemy's model by moving erratically, performing loops in its motion among the stars, as shown in Figure 1.2. Ptolemy struggled to explain this behavior by introducing epicycles into his model. An *epicycle* is essentially a smaller circle around which a planet moves, which in turn is superimposed upon the larger circle representing the planet's motion about Earth. Throughout his lifetime, Ptolemy continued to tweak his model, introducing many epicycles in an attempt to fit observations.

Despite its evident weaknesses, the Earth-centered model survived for 1300 years or so, primarily because of the power and influence of the Church over this period. To challenge the notion that Earth was the center of the universe would have been considered foolhardy, a crime against God that could attract the severest penalty.

The person credited with making this challenge was Nicolaus Copernicus, a Polish Catholic cleric who was born in 1473. The main feature of Copernicus's universe was that he relegated Earth to be just one of a number of planets orbiting the Sun. At the time, this Sun-centered model was an extraordinary shift in our worldview, but Copernicus boldly swept away the old ideas, writing explicitly about the inadequacy of the previous arguments and refuting them. Copernicus waited until the year of his death, 1543,

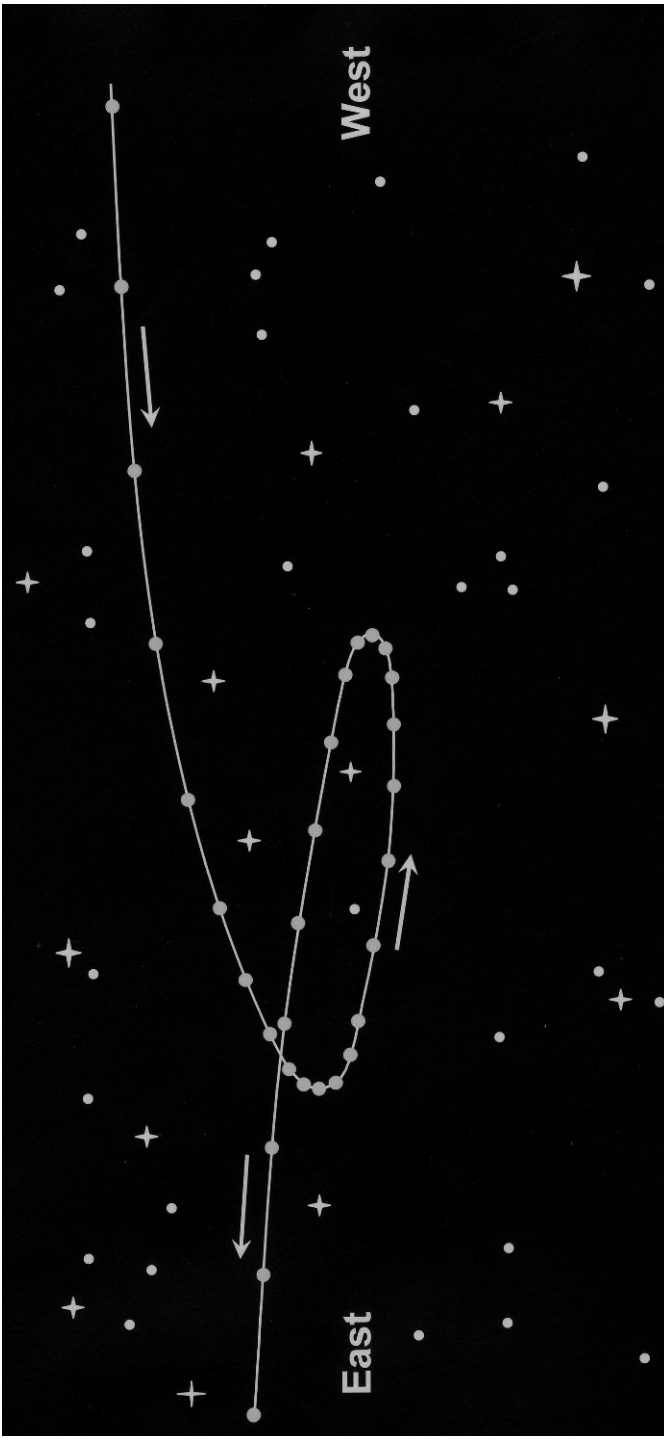

Figure 1.2: The apparent looping motion of Mars, relative to the fixed stars, as seen over a period of a few weeks.

before going public, presumably to avoid the consequences of religious persecution. Unkind contemporaries of Copernicus labeled him the "restorer" of the Sun-centered universe, in deference to Aristarchus, who held this belief around 280 B.C. However, the world was not ready for this idea in the third century B.C. Copernicus is remembered not just for establishing the idea of a Sun-centered solar system; many other related contributions secure his place in history:

- An understanding of the rising and setting of the heavenly bodies in terms of the daily rotation of the Earth.
- An explanation of the seasons due to Earth's annual journey around the Sun. Copernicus deduced that Earth's spin axis was not perpendicular to the orbit plane. Consequently, the Northern Hemisphere would be tilted toward the Sun during the Northern Hemisphere's summer, and conversely tilted away during the winter months.
- A mechanism to explain the looping motion of the planets among the fixed stars (Fig. 1.3).
- The estimation of the size of the planets' orbits in "astronomical units," and their periods (that is, the time taken to orbit the Sun). In this process, Copernicus assumed that the orbits were circular.

The last item on this list was a staggering achievement, and deserves further attention. First of all, what is an astronomical unit (AU)? In modern terms, it is the average distance between Earth and the Sun, taking into account that the distance varies a bit as the Earth orbits the Sun. Numerically

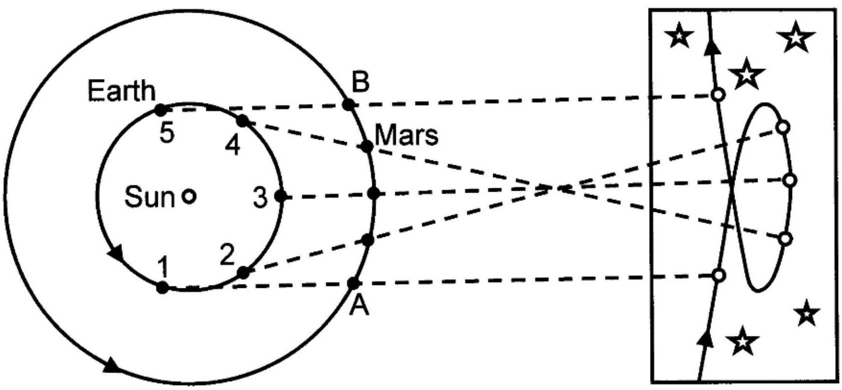

Figure 1.3: Copernicus's explanation of the apparent looping motion of Mars among the fixed stars. He assumed that Earth and Mars moved along circular orbits with different periods, so that Earth moved from point 1 to point 5 in the same time that Mars moved from point A to point B.

1 AU is around 150 million km (93 million miles). Copernicus had no way of determining this, but with careful thought he could devise ways of estimating the distance of the known planets from the Sun as multiples of the Earth-Sun distance—that is, in astronomical units. Therefore, he was able to construct the scale of the known solar system relative to the size of Earth's orbit, but its absolute size escaped him.

The explanation of his methods is a little complicated, but I hope the reader will come along for the ride! For the planets Mercury and Venus, closer to the Sun than Earth, the basics of this method are illustrated in Figure 1.4. Taking Venus as an example, Copernicus could observe its orbital motion around the Sun, as we can today, by watching its track in the sky at the time

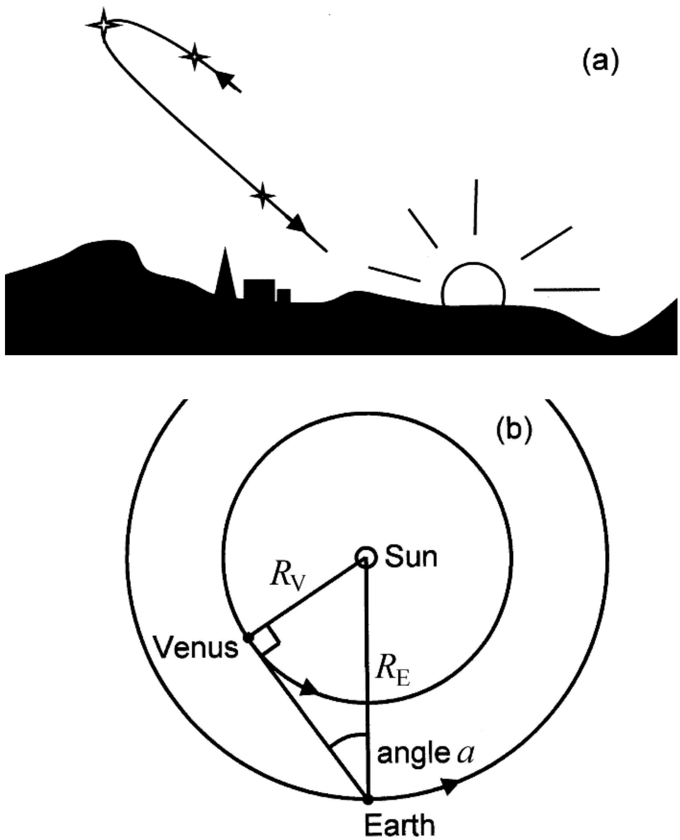

Figure 1.4: (a) The motion of Venus in the evening sky over a period of weeks, allowing the measurement of the maximum angle (angle *a*) between the planet and the Sun. (b) The orbital geometry of Earth and Venus at the time of maximum angular separation.

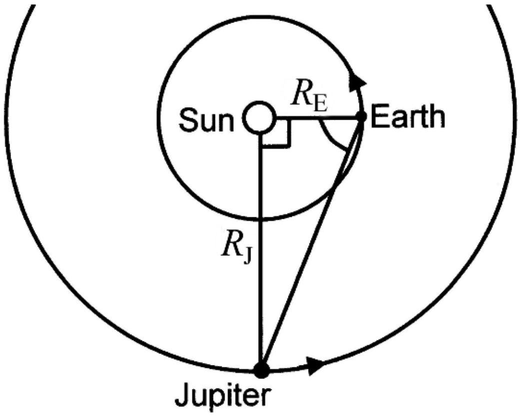

Figure 1.5: Copernicus estimated the radius R_J of Jupiter's orbit, again using 'simple' trigonometry.

of sunset over a number of weeks (Fig. 1.4a). To estimate the size of the orbit, Copernicus just needed to note the maximum angle between the Sun and the planet over this period, and he could then translate this to the orbital geometry shown in Figure 1.4b. The problem then reduces to a simple one, involving solving the lengths of the sides of a right-angled triangle using trigonometry. Most readers will have come across trigonometry in school mathematics lessons and probably will have forgotten it! However, referring to the triangle in Figure 1.4b, all that needs to be understood is that if Earth's orbit radius (R_E is 1 AU) and the maximum angle (angle a) are known, then the radius R_V of Venus's orbit can be calculated. Adopting this simple process, Copernicus found that R_V was approximately 0.7 AU, and a corresponding analysis of Mercury's motion gave its orbit radius as about 0.4 AU.

The process for estimating the orbit sizes of the outer planets known to Copernicus (Mars, Jupiter, and Saturn) was a little more involved. There are a number of ways of looking at this, but they all boil down to the same thing, and ultimately reduce again to a simple trigonometrical problem.Taking the planet Jupiter as an example, Copernicus measured the time it took for Earth to "lap" Jupiter in their respective orbits. He noted that approximately every 400 days Jupiter returned to the same position, due south in the sky at midnight. Translating this into orbital position, he realized that this happened when Earth was precisely between the Sun and Jupiter, and was about to overtake Jupiter. He then went on to deduce that a quarter of this lapping period—approximately 100 days—after this alignment, Earth would be 90 degrees ahead of Jupiter in its orbit, giving the orbital geometry shown in Figure 1.5. The measurement of the angle between the Sun and Jupiter at this time, an observation best made at sunset, completed the puzzle and allowed Copernicus to calculate the radius of Jupiter's orbit at about 5.2 AU. Similar calculations gave estimates of the radii of Mars's and Saturn's orbit, at around 1.5 AU and 9.5 AU, respectively.

When Johannes Met Tycho

Copernicus's work, containing a wealth of apparently irrefutable detail, put the Earth-centered universe to rest, and finally removed the constraints that had inhibited the quest to understand the solar system for over a millennium.

The next person to make progress on this quest was Johannes Kepler, who was born in Germany in 1571. As a theoretician of the first order, he brought his intellect to bear upon Copernicus's model of the solar system, and found it lacking. However, Kepler knew that precise observations of the planets' motions were required in order to expose the weaknesses of Copernicus's model and make further progress along the pathway. This need was satisfied by Kepler's chance association with Tycho Brahe, a Danish nobleman who spent much of his life and resources developing an astronomical observatory on an island off the coast of Denmark. This housed precision instruments, and Tycho compiled what was the most complete and accurate catalogue of planetary position measurements available at that time.

Johannes's brilliance as a theoretician and Tycho's observational genius complemented each other perfectly, to bring about the next revolution in understanding. However, their relationship was an uneasy one, and Tycho was reluctant to gift his life's work to a younger rival. Tycho did make his observations available to Kepler, but only in a frustratingly piecemeal manner. This impasse was finally resolved on the death of Tycho, after which Kepler was able to extract the full catalogue of measurements from Tycho's family.

Now that Kepler had accurate observations, he spent a number of years trying unsuccessfully to reconcile them with the notion that planetary orbits were circular. Looking at the orbit of Mars, he struggled for nearly a year to resolve a discrepancy between observation and theory of only 8 minutes of arc—a small angular measure of about one-quarter the diameter of the full moon. This in itself says a great deal about Kepler's integrity and honesty; clearly, it would have been easier to ignore such a small anomaly, or to regard it as an erroneous measurement. This struggle, however, led Kepler to the idea that was to be his core contribution to the understanding of the solar system—that planetary orbits were elliptical in shape. Making this step, he now found that Tycho's measurements fitted beautifully, and thereafter Kepler published his first two laws of planetary motion in 1609. His third law, to do with the relationship between the size of an orbit and its period, was also a tough one that took him a further 10 years to establish. Kepler's three laws of planetary motion are as follows (see also Figure 1.7):

Kepler 1 – The orbit of each planet is an ellipse, with the Sun at one focus.
Kepler 2 – The line joining each planet to the Sun sweeps out equal areas in equal times.
Kepler 3 – The square of the period of a planet is proportional to the cube of its mean distance from the Sun.

It is worth dwelling a few moments on Kepler's laws, to explain the jargon, and to illustrate their meaning. The first law uses the word *ellipse,* which from high school geometry could be described as egg-shaped or a squashed

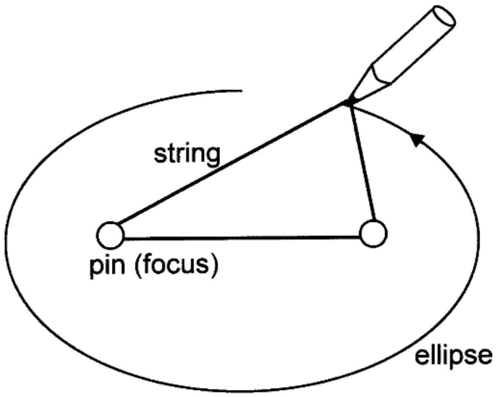

Figure 1.6: Drawing an ellipse. The ellipse's focal positions are where the pins penetrate the card.

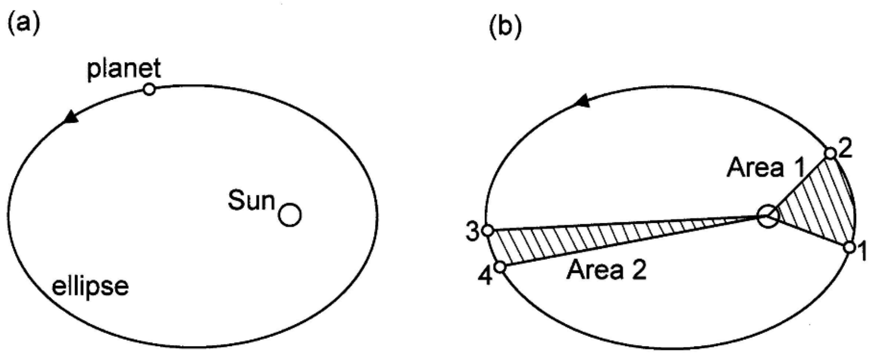

Figure 1.7: Illustrations of (a) Kepler's first law and (b) his second law.

circle. We know that to draw a circle, we use a compass. The resulting figure has one focus—the center where the point of the compass penetrates the paper. You may also have drawn an ellipse in school by pressing two pins into a piece of card, and placing a loose loop of string around the pins. Placing a pencil in the loop, and keeping the string tight, we can move the tip of the pencil over the paper to produce an ellipse, as shown in Figure 1.6. The two points where the pins penetrate are referred to as the focuses of the ellipse. From Kepler's first law (refer to Fig. 1.7a), we see that planets move along elliptical orbits, but also that the Sun is located at one of the focal positions.

Kepler's second law is a rather strange way of describing how fast a planet moves at different points on its orbit. Looking at Figure 1.7b, we can see that if a planet moves from point 1 to 2 in the same time that it takes to move from point 3 to 4, then Kepler's second law implies that the shaded areas—Area 1 and Area 2—must be equal to one another. This geometrical argument can be translated into a dynamical one, since it is easy to see that, for this to happen, the planet must move rapidly when close to the Sun, and more slowly when further away. Kepler's 17th century mind tended to think in terms of geometry, whereas a modern orbit analyst would tend to take the dynamical view.Kepler expressed his third law in terms of a word equation, and since we are trying to avoid the use of equations it is sufficient to say that planets in big orbits take longer to orbit the Sun than planets in small orbits—a fairly commonsensical notion.

Trying to summarize Kepler's activities in a few paragraphs, as we have done here, does no justice to the magnitude of his achievement in establishing the modern view of the way the planets move around the Sun. The time he took to do this does, perhaps, give a measure of the difficulty of the task. His achievement is emphasized by noting that his laws are still used today when engineers analyze the motion of spacecraft around the Sun, or indeed the orbit of a satellite around the Earth. It is also important to realize that Kepler developed his laws empirically, based purely on Tycho's catalogue of planetary measurements. He described *how* the planets moved around the Sun, but had no underlying theoretical foundation to explain *why* they moved in this way. This task was left to the intellectual giant that was Isaac Newton.

"On the Shoulders of Giants . . ."

Newton was born on Christmas Day 1642, just 23 years after Kepler had published the last of his three laws—and what a gift to the world! Newton has been described in clichéd terms by numerous biographers: "the foremost scientific intellect of all time"; "the father of modern science"; and so on. However, when applied to Newton, these glowing epithets are arguably fully justified. Newton made major contributions to many areas of scientific activity, including optics and light, mathematics, dynamics, gravitation, and theoretical astronomy. He himself, however, summarized his contribution to science by stating, "If I have been able to see further, it was only because I stood on the shoulders of giants," referring to some of those giants discussed in the preceding sections of this chapter.

Newton's quest to understand the world began with his undergraduate career at Trinity College, Cambridge University, at the age of 18. However, his time at Cambridge was interrupted in the summer of 1665, when the university was closed down by an outbreak of plague. Newton then returned to his birthplace, the isolated village of Woolsthorpe in Lincolnshire, where in an amazingly productive period of 2 years he revolutionized science.

In summary, during this period he devised his law of gravitation and his laws of motion. Combining these, he was able to formulate the equations that governed the motion of the planets around the Sun. He then realized that these equations could not be solved using the methods then available. However, he was not a person to let such a small detail inhibit his efforts, and so he set about inventing a new branch of mathematics, called calculus, to remove the barrier. All of these accomplishments have had a lasting impact upon science and engineering to the present day, and any one of them would be considered a major intellectual achievement. For them all to have come from one individual in such a short period of time is extraordinary.

It is worth pausing a few moments to consider in more detail each of the steps that comprised Newton's achievement. Perhaps the thing most people associate with Newton is his law of gravitation, along with the story of the mythical apple that is supposed to have fallen on his head and given spontaneous birth to the idea. It is likely, however, that the formulation of his understanding of gravity took a little more time and effort. The formal statement of Newton's law of gravitation is given below, and as can be seen it is expressed once again as what might be called a word equation:

> **Newton's Law of Universal Gravitation** – the force of gravity between two bodies is directly proportional to the product of their masses, and inversely proportional to the square of their distance apart.

However, it can be easily understood in simple terms. The phrase "directly proportional to the product of their masses" simply means that the force of gravity between two large objects—say two planets, or two stars—is large, and indeed will govern the way these celestial bodies move with respect to each other. On the other hand, the force of gravity between two small objects will be tiny. For example, if you place a couple of balls on a pool table, you expect them to remain firmly attached to the surface, since they are attracted to the large mass which is the Earth beneath the table. It is only the structural strength of the table that is preventing them from responding to the force by whizzing off toward Earth's center. At the same time, we do not expect them to move across the table toward each other, since the force of gravity between them is so small as to be effectively zero. The game of pool would be somewhat different if it were otherwise!

The way the force of gravity varies with distance, as described above, is sometimes referred to as the *inverse square law.* This describes how the force between two bodies diminishes as they move further apart. If you think of two objects a particular distance apart—strictly this distance is measured between their centers—then the force of gravity between them will have a particular strength. When we move them apart so that the distance between them is doubled, the inverse square law says that the force is one fourth of what it was before. To get this, we take 2 from "twice the distance," square it to give 4, and then take the inverse to give us the one fourth. In the same way, we can move the bodies 10 times further apart, and the same argument tells us that the force of gravity is reduced by a factor of $^1/_{100}$.

There is some debate among scientific historians about how Newton settled upon the inverse square law for gravitation. Some believe he was influenced by his studies of the way light behaved; he discovered by experiment that the intensity of light falling upon a surface decreased in proportion to the inverse square of the distance between the source of light and the surface. However, more likely he proposed the inverse square law since it was consistent with Kepler's third law of planetary motion, which can be shown by the use of some simple mathematics that can be done literally on the back of an envelope.

Coming back to Newton's apple, we can explore some of Newton's thinking during his brief but prolific period of exile in the Lincolnshire countryside. Having thought about his law of gravitation in a universal context, Newton's observation of the fall of an apple from a tree engendered universal questions in his mind such as, Why doesn't the moon also fall to the ground? To answer this one, we can compare the motion of the apple with that of the moon.

Taking the apple first, when it is released from the tree it responds to the force of gravity by accelerating toward the ground. It starts from rest up in the branches of the tree and builds up speed until impact with the ground. If we were able somehow to measure this impact speed and the time of fall, we would be able to calculate its acceleration. For example, if the height of the tree was such that the apple took 1 second to hit the ground, we would find that its impact speed was about 10 meters per second (32 feet per second). In this case, the distance fallen can be estimated as about 5 meters (16 feet)—quite a tall apple tree. If the ground were not in the way, the apple would continue to accelerate toward Earth's center, gaining 10 meters per second in speed for every second of the fall. This acceleration due to gravity at Earth's surface of 10 meters per second per second is usually expressed as 10 m/sec/sec or 10 m/sec^2 (32 feet/sec^2).

Newton was the first to realize that the moon must also respond to the force of gravity in the same way. However, the moon is around 60 times more distant from Earth's center than his apple. Applying his law of gravitation, he estimated that the acceleration of the moon toward the Earth will be much less than that of the apple by a factor of $^1/_{3600}$—that is, the inverse of 60 squared. In its distant orbit then, the moon will fall toward Earth with an acceleration of approximately 10/3600 meters per second per second, or about 3 millimeters/sec^2 ($^1/_{100}$ feet/sec^2). With this small acceleration downward, it is easy to estimate that in 1 second the moon falls a small distance toward Earth of about 1.5 millimeters—much less than the 5 meters fallen by the apple. However, it is instructive to consider what happens to the moon's motion during the period of a minute, as then the numbers are a little easier to grasp. Because of the coincidence that the moon is 60 times further away from Earth's center than the apple, and that there are 60 seconds in a minute, the mathematics tell us that the moon falls the same distance in 1 minute as the apple falls in 1 second—about 5 m. However, at the same time the moon has a relatively high speed along its orbit so that in 60 seconds it moves horizontally approximately 61,100 meters (200,500 feet). Figure 1.8 shows that the combination of these horizontal and vertical motions result in the near-circular orbital path that we observe, so that although the moon does actually fall continually toward Earth, fortunately it never reaches the ground!

To understand the motion of bodies, such as the apple and the moon, in this way, Newton had to devise not only his universal law of gravitation, but also his three laws of motion, which are stated as follows:

Newton 1 – A body will continue in a state of rest, or of uniform speed in a straight line, unless compelled to change this state by forces acting upon it.

Newton 2 – The rate of change of momentum of a body is proportional to the force acting upon it, and is in the same direction as the force.

Newton 3 – To every action there is an equal and opposite reaction.

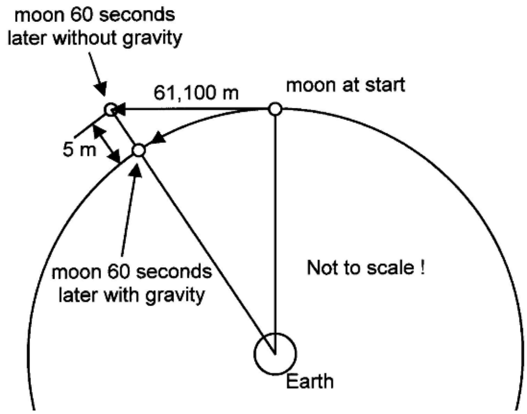

Figure 1.8: Newton applied his universal law of gravitation to the Moon, as well as to his apple, to show how the Moon orbits Earth.

It is important to note that these laws, written in the form of words here, have their most powerful manifestation when expressed in mathematics. They revolutionized 17th century science, and indeed still dominate engineering science today. Newton's contribution is summed up by noting that 21st century engineers still use the mathematical expression of these laws to design buildings, bridges, cars, airplanes, and indeed spacecraft. I would love to stand with Isaac Newton at the end of a modern airport runway as a jumbo jet is taking off, and tell him that he is responsible for this apparently impossible apparition of 350 metric tonnes of predominately metal soaring into the sky—an amazing legacy!

In terms of our understanding of the solar system, Newton's revolution came about when he combined his law of gravitation with his laws of motion to produce equations that described the motion of the planets around the Sun. As described earlier, the solutions of these equations were obtained only after Newton had devised a new branch of mathematics. But once this was done, Newton rediscovered Kepler's three laws of planetary motion in his mathematics, thus giving a theoretical basis to Kepler's empirical work completed almost half a century before. However, Newton found not only Kepler's work in his new formulism but lots more. His mathematics were saying that objects moving in a gravity field, for example, a planet moving around the Sun, or a spacecraft moving around a planet, were not confined to elliptical paths. The shape of the path of such an object could also be that of a circle, a parabola, or a hyperbola. Most people are familiar with circles and ellipses, but what about the parabolic and hyperbolic shapes? These four shapes are referred to as conic sections,

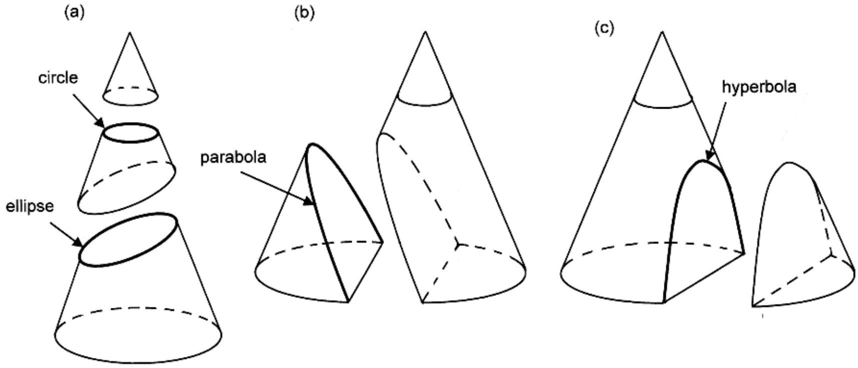

Figure 1.9: The shapes of orbital trajectories can be obtained by slicing a cone.

because you can get them by sectioning, or slicing, a cone as illustrated in Figures 1.9 and 1.10.

In Figure 1.9a, we can see that if we slice the cone horizontally we get a circle, and if we slice it slightly obliquely we get an ellipse. Another trajectory shape is obtained by slicing the cone in such a way that the plane of the slice is parallel to the side of the cone, as in Figure 1.9b. In this case we get a parabola. The parabolic trajectory is not a closed one—as are the circle and ellipse—so we have to imagine that the cone is infinitely big, and not truncated at the base as illustrated. An example of an object on a parabolic trajectory is a comet that falls with initially zero speed from infinity—or effectively from a great distance—and is swung around the Sun and ends up heading back to the same place, arriving again at infinity with zero speed. Perhaps this type of trajectory can best be describes as a celestial U-turn.

The final trajectory shape that Newton found in his mathematics is the hyperbola, which is obtained by slicing our cone vertically, as shown in Figure 1.9c. This trajectory is again an open one, stretching to infinity, so we have to imagine that our cone is very large. An example of this type of orbit is a spacecraft swinging by a planet. The spacecraft approaches from great distance, initially traveling at constant speed relative to the planet in a straight line, as the gravitational influence of the planet is tiny. However, as the spacecraft closes in, the gravitational force increases and the trajectory is deflected. The gravity of the planet swings the spacecraft's path around so that the vehicle leaves the planet in a new direction, traveling in a straight path again at the same planet-relative speed once it has reached great distance. As we will see later in Chapter 4, this type of swing-by trajectory is commonly used by engineers designing interplanetary spacecraft missions. The hyperbola is distinguished from the parabola by the deflection angle; in a parabolic trajectory the object is deflected by 180 degrees by its encounter

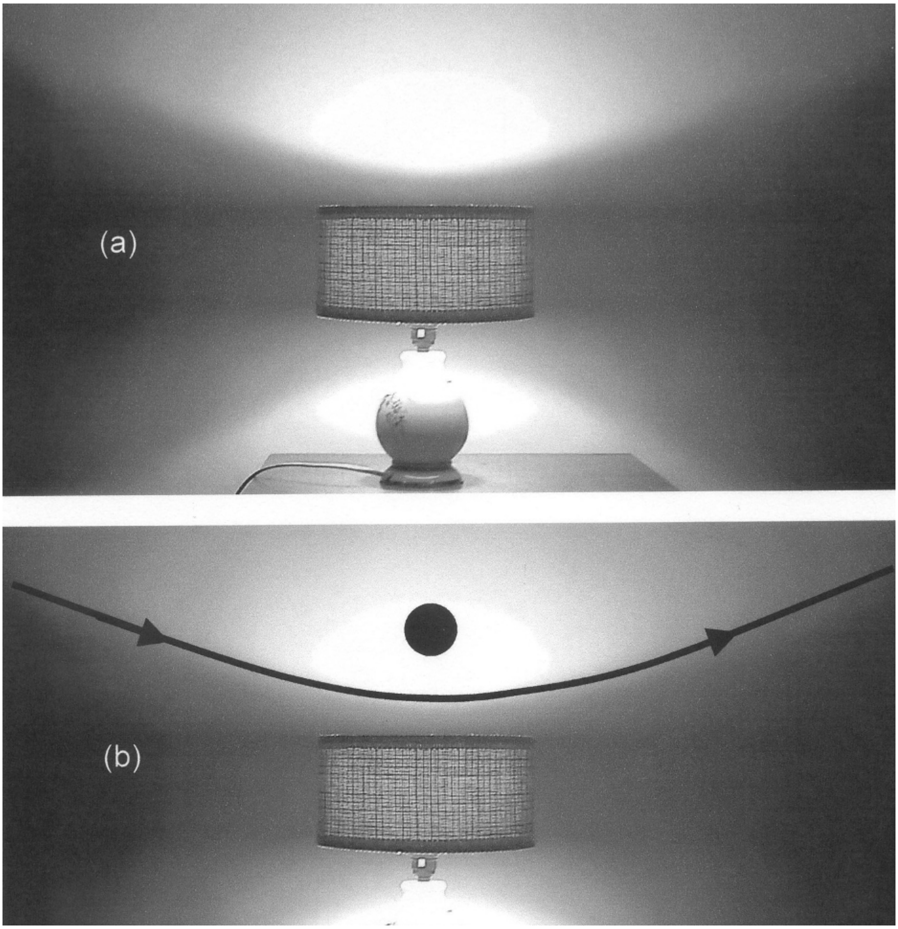

Figure 1.10: The light cast by a table lamp shows the hyperbola-shaped, swing-by trajectory of a spacecraft.

with the planet, whereas the hyperbolic trajectory is deflected by an amount less than this.

Surprisingly, the hyperbola is also a fairly common sight in everyday life. All you need is a lamp with a circular shade, which projects a cone of light both upward and downward, producing a circle of light on the ceiling above and on the table below. If, however, the lamp is placed next to a wall, then the cone of light is effectively sliced vertically, as in Figure 1.9c, to produce the shape of a hyperbolic trajectory on the wall. A photograph of such a shape is shown in Figure 1.10a, and how it relates to the orbital trajectory is shown in Figure 1.10b. If you find yourself on a dinner date in a restaurant with this common type of wall lighting, you could use your knowledge of celestial mechanics to break the ice. (On the other hand, your guest may just think that you are a rather sad person who needs to get out more!)

Newton himself thought of his scientific investigations as a small contribution toward revealing the fundamental laws of the universe that were “written” by God, its designer. Thinking about his discoveries in this context, it *is* rather strange that we live in a universe where the shapes of gravitational trajectories are related to slices of a cone!

The final episode in this story of Newton’s achievement is also surprising. Having “solved the universe” in this way, Newton then failed to communicate his work to anyone! Meanwhile, unknown to him, contemporary scientists—principally Robert Hooke and Edmund Halley (of Halley’s Comet fame)—were struggling with the problem of planetary motion in the coffee houses of London. Finally in 1684, Halley visited Newton in Cambridge, hoping to gain some insight into the riddle. When Halley posed the question about the shape of gravitational trajectories about the Sun, Newton revealed that he had already solved the problem, but had characteristically misplaced it. It was ultimately Halley who encouraged Newton to write his landmark work, the *Philosophiae Naturalis Principia Mathematica*, requiring 2 years of hard work to complete. In this rather circuitous manner, Newton was finally recognized as being one of the greatest scientific thinkers of all time.

The only other individual described is this way is perhaps Albert Einstein, whose scientific genius was unleashed upon the world at the beginning of the 20th century.

What Did Einstein Do for Us?

Einstein’s contribution was fundamental and profound, a revolution in the way we think about the physics of motion, and in particular the motion of bodies in a gravitational field. This revolution began with the publication of Einstein’s *special theory of relativity* in 1905, when Newtonian physics was well established, and most scientists believed their understanding of the physical laws of nature was complete. After all, newtonian physics had reigned supreme for something like 220 years! This blow to the scientific establishment was all the harder to take, as Einstein’s interest in physics was a hobby at the time; his job was that of a patent clerk in an office in Berne. However, his new physics took the scientific community by storm.

A cornerstone of Einstein’s work was an appreciation that the arena in which all physical events take place is a four-dimensional world called *space-time*. In other words, to describe the location of a physical event—for example, the impact of an apple on the ground—we need four numbers, three defining its position in space, and another giving the time. In Newton's physics the three-dimensional spatial world and time were considered to be independent and absolute. However, in Einstein's theory, space and time are inseparably interwoven, and the place and time defining an event are not absolute but depend on the state of motion of the observer. This rather strange notion led to the uncomfortable idea that Newton's physics was incorrect; however, the differences between Newton's and Einstein's descriptions of the world manifested themselves only when things moved at very high speeds, that is, speeds near the speed of light of 300,000 km per second (186,000 miles per second).

Einstein's revolution was not complete, however, as in 1916 he published his theory of gravitation—the *general theory of relativity.* The journey from the special theory to the general was not an easy one, and Einstein struggled with the physics and, in particular, the mathematics required to formulate his gravitational theory. Indeed, the mathematics required to describe his theory of gravity were so complex that it was claimed that few people in the world actually understood it when first published. Fortunately, the principles of the theory can be explained in relatively simple terms.

Einstein's description of the way planets moved around the Sun is completely different from Newton's view. In Einstein's theory, the four-dimension world of space-time is not just a background reference system against which the locations and timings of physical events are recorded, but rather it becomes a dynamic entity, playing a central role in the way things move in a gravity field. The underlying principle of Einstein's general theory is that massive objects, like the Sun, distort the geometry of space-time. This is the famous *warped space*, which has become so familiar to us all, courtesy of popular science-fiction epics like *Star Trek*. However, although we have heard a lot about it in sci-fi stories, nevertheless an appreciation of what a curved four-dimensional space-time continuum means is very difficult to grasp, even for those equipped to understand the mathematics! Einstein's basic idea of motion in a gravity field is that objects move in such a way as to take a path that gives the shortest distance between two points. Clearly in our everyday experience, the path defining the shortest distance between two points is a straight line. But then, in our everyday experience, we do not often come across warped space!

However, there is one everyday example of determining the shortest distance between two points in a curved space—that is, the efficient global routing of aircraft. For example, what is the shortest distance between London and Sydney in the curved two-dimensional space we call Earth's surface? If we take a map and just draw a straight line between London and Sydney (the broken line in Figure 1.11), we find that this is not the shortest route. The shortest route can be found by stretching a piece of string on a globe, holding down the ends over London and Sydney. If you then plot this route on a map (the continuous line in Figure 1.11), you will find that the shortest route is curved. A quick experiment with a globe and a piece of string will help you to check this.

Returning to Einstein's gravity, as we said above, the influence of the massive Sun is to produce curvature in the fabric of space-time surrounding it. Straight lines in this space are no longer straight, but curve along the contours of the warped space produced by the Sun. The resulting orbital trajectories are effectively those found by Kepler and Newton. Given this, the reader might ask why Einstein's complex theory of gravity is needed, when Newton does a perfectly good job already. The answer is that Einstein's theory goes further, and predicts additional effects that are particularly conspicuous in very intense gravitational fields. A good example of this is the bending of light as it passes the Sun, an experimentally confirmed effect that is not predicted at all by Newton's theory. In our everyday experience, a beam of light is perhaps the best way of defining a straight line. However, in

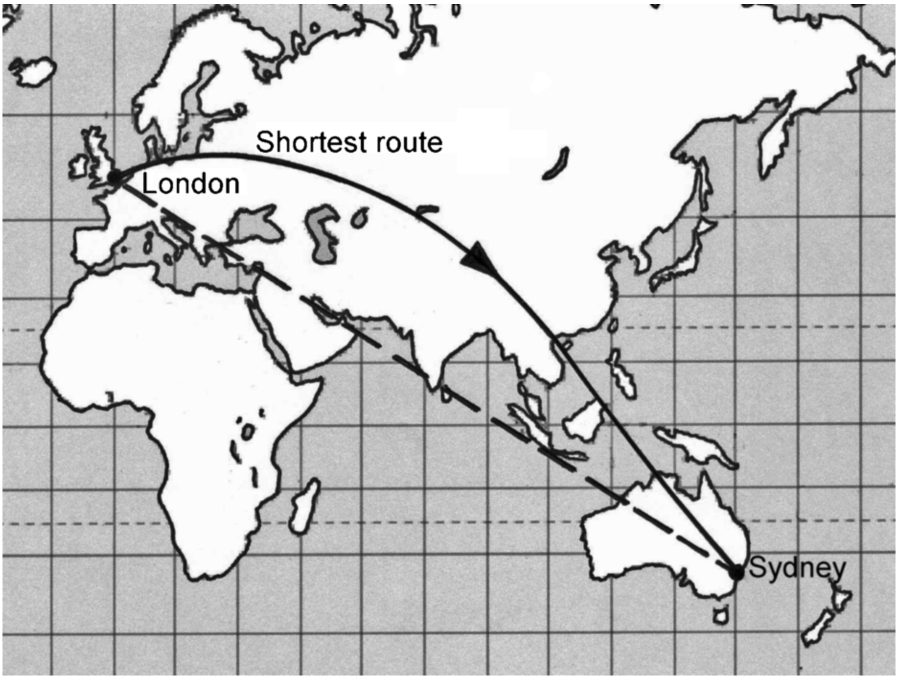

Figure 1.11: In the curved two-dimensional space of Earth's surface, the shortest distance is not a straight line.

the warped space surrounding the Sun, the path of the light is deflected (very slightly) in response to the curvature of space-time. Another curious feature of Einstein's general theory is that when space-time is curved by the presence of a massive object, not only are the spatial dimensions curved, but the time dimension is as well; we are presented with the bizarre notion that clocks run at different rates depending on how close they are to the object!

Clearly Einstein's achievements are pertinent to our story, but we should return to the question in the title of this section: What did Einstein do for us? Well, if the "us" refers to spacecraft design engineers, the honest answer is "not a lot!" The spacecraft missions achieved in the first half century or so of the Space Age involve space vehicles that have not achieved very high speeds, compared to the speed of light. Similarly our activities have effectively been confined to the region of space near the Sun, where very intense gravitational fields are not encountered. As a consequence, the more exotic effects of Einstein's theory do not manifest themselves, and we are left with the rather surprising conclusion that modern spacecraft engineers still use 300-year-old Newtonian theory.

There is, however, one clear example where Einstein's relativity theory does make an essential contribution to the design of a spacecraft. The U.S. Department of Defense operates a space system called Navstar Global Positioning System (GPS), which is used as a navigational aid for all branches of the U.S. armed forces. However, a lot of people reading this may have used GPS for leisure purposes—hiking, sailing, or flying—or for in-car navigation. The space system comprises a constellation of 24 satellites in near-circular orbits at heights of around 20,500 km (12,700 miles). If you have an appropriate receiver on the ground, the system will provide information about your location accurate to about 10 meters in each of the three spatial dimensions. To do this, however, each satellite must carry an atomic clock, which needs to be accurate—to about one second in every 30,000 years or so! To do the necessary calculations to find your position on the ground, your receiver must also have a clock. Fortunately, this clock need not be quite so sophisticated (or expensive!) as the satellite clocks, but it should record the passage of time at the same rate as the orbiting clock, during the short period when the receiver is doing its calculations to estimate where you are. However, the receiver clock on the ground is a lot closer to the gravitational mass of Earth than the satellite clock, and therefore Einstein said the ground clock will run slower than the orbiting clock. Over the period of a day, the combined effects of Einstein's theory cause an accumulated error of around 38 microseconds (38 millionths of a second) difference between the orbiting and ground clocks. Although this sounds small, when translated into a navigational error it amounts to about

10 km. After a day your in-car navigation system might be indicating that you are in the wrong town!

When the first experimental GPS satellite was launched, some engineers were skeptical about the importance of the Einstein effects, but soon realized that time warping is a reality. To overcome this problem in the current spacecraft design, the satellite clocks are manufactured with an appropriate offset in the clock rate built in.

How we have come to understand space is a rather intriguing story, and what I have presented here is an abbreviated and personal view of something that could have a whole book devoted to it. In summary, perhaps one of the most surprising conclusions to be drawn from this discussion is that modern spacecraft engineers still predominantly use Newtonian theory to design spacecraft, and to design the orbits they travel to achieve a particular destination. We will take this notion forward in subsequent chapters, where the way spacecraft are designed is discussed in more detail.