3 Galileo and the nature of the physical sciences

from Malcolm Longair, "Theoretical Concepts in Physics"

3.1 Introduction

There are three separate but linked stories to be told. The first concerns Galileo as natural philosopher. Unlike Tycho Brahe the observer and Kepler the mathematician, Galileo was an experimental physicist whose prime concern was understanding the laws of nature in quantitative terms, from his earliest writings to his final great treatise *Discourse and Mathematical Demonstrations concerning Two New Sciences*.

The second story is astronomical, and occupies a relatively small, but crucial, period of Galileo's career, from 1609 to 1612, during which time he made a number of fundamental astronomical discoveries which had a direct impact upon his understanding of the physics of motion.

The third story, and the most famous of all, is his trial and subsequent house arrest, which continues to be the subject of considerable controversy. The scientific aspects of his censure and subsequent trial are of the greatest interest and strike right at the heart of the nature of the physical sciences. The widespread view is to regard Galileo as the hero and the Catholic Church as the villain of the piece, a source of conservative reaction and bigoted authority. From the methodological point of view Galileo made an logical error, but the church authorities made a much more disastrous blunder, which has resonated through science and religion ever since, and which was only officially acknowledged by Pope John Paul II in the 1980s.

My reasons for devoting a whole chapter to Galileo, his science and his tribulations are that it is a story which needs to be better known and which has resonances for the way in which physics as a scientific discipline is carried out today. Galileo's intellectual integrity and scientific genius are an inspiration – more than anyone else, he created the intellectual framework for the development of physics as we know it.

3.2 Galileo as an experimental physicist

Galileo Galilei was the son of Vincenzio Galileo, a distinguished musician and musical theorist, and was born in February 1564 in Pisa. In 1587, he was appointed to the chair of mathematics at the University of Pisa, where he was not particularly popular with his colleagues. One of the main causes was Galileo's opposition to Aristotelian physics, which remained the central pillar of natural philosophy. It was apparent to Galileo that Aristotle's physics was not in accord with the way in which matter actually behaves. For example, Aristotle's assertion concerning the fall of bodies of different weights reads as follows:

> If a certain weight moves a certain distance in a certain time, a greater weight will move the same distance in a shorter time, and the proportion which the weights bear to each other the times too will bear to one another; for example, if the half weight covers the distance in x, the whole weight will cover it in $x/2$.[1]

This is just wrong, as could have been demonstrated by a simple experiment – it seems unlikely that Aristotle ever tried the experiment himself. Galileo's objection is symbolised by the story of his dropping different weights from the Leaning Tower of Pisa. If different weights are dropped through the same height, they take the same time to reach the ground if the effects of air resistance are neglected, as was known to Galileo and earlier writers.

In 1592, Galileo was appointed to the chair of mathematics at Padua, where he was to remain until 1610. It was during this period that he produced his greatest work. Initially, he was opposed to the Copernican model of the solar system but, in 1595, he began to take it seriously in order to explain the origin of the tides in the Adriatic. He observed that the tides at Venice typically rise and fall by about five feet and therefore there must be quite enormous forces to cause this huge amount of water to be raised each half-day at high tide. Galileo reasoned that if the Earth rotated on its own axis and also moved in a circular orbit about the Sun then the changes in the direction of travel of a point in the surface of the Earth would cause the sea to slosh about and so produce the effect of the tides. This is not the correct explanation for the tides, but it led Galileo to favour the Copernican picture for physical reasons.

In Galileo's printed works, the arguments are given entirely in the abstract without reference in the conventional sense to experimental evidence. Galileo's genius as a pioneer scientist is described by Stillman Drake in his remarkable book *Galileo: Pioneer Scientist* (1990).[1] Drake deciphered Galileo's unpublished notes, which are not set down in any systematic way, and convincingly demonstrated that Galileo actually carried out the experiments to which he refers in his treatises with considerable experimental skill (Fig. 3.1).

Galileo's task was enormous – he disbelieved the basis of Aristotelian physics, but had no replacement for it. In the early 1600s, he undertook experimental investigations of the laws of free fall, the motion of balls rolling down slopes and the motion of pendulums; his results clarified the concept of acceleration for the first time.

A problem with physics up to the time of Galileo was that there was no way of measuring short time intervals accurately, and so he had to use considerable ingenuity in the design of his experiments. A very nice example is his experiment to investigate how a ball accelerates down a slope. He constructed a long shallow slope of length 2 metres at an angle of only 1.7° to the horizontal and cut a grove in it down which a heavy bronze ball could roll. He placed little frets on the slope so that there would be a little click as the ball passed over each fret. He then adjusted the positions of the frets along the slope so that the clicks occurred at equal time intervals (Fig. 3.2). Drake suggests that he could have equalised the time intervals to about 1/64 of a second by singing a rhythmic tune and making the clicks occur at equal beats in the bar. In view of Galileo's father's profession, this seems quite plausible.

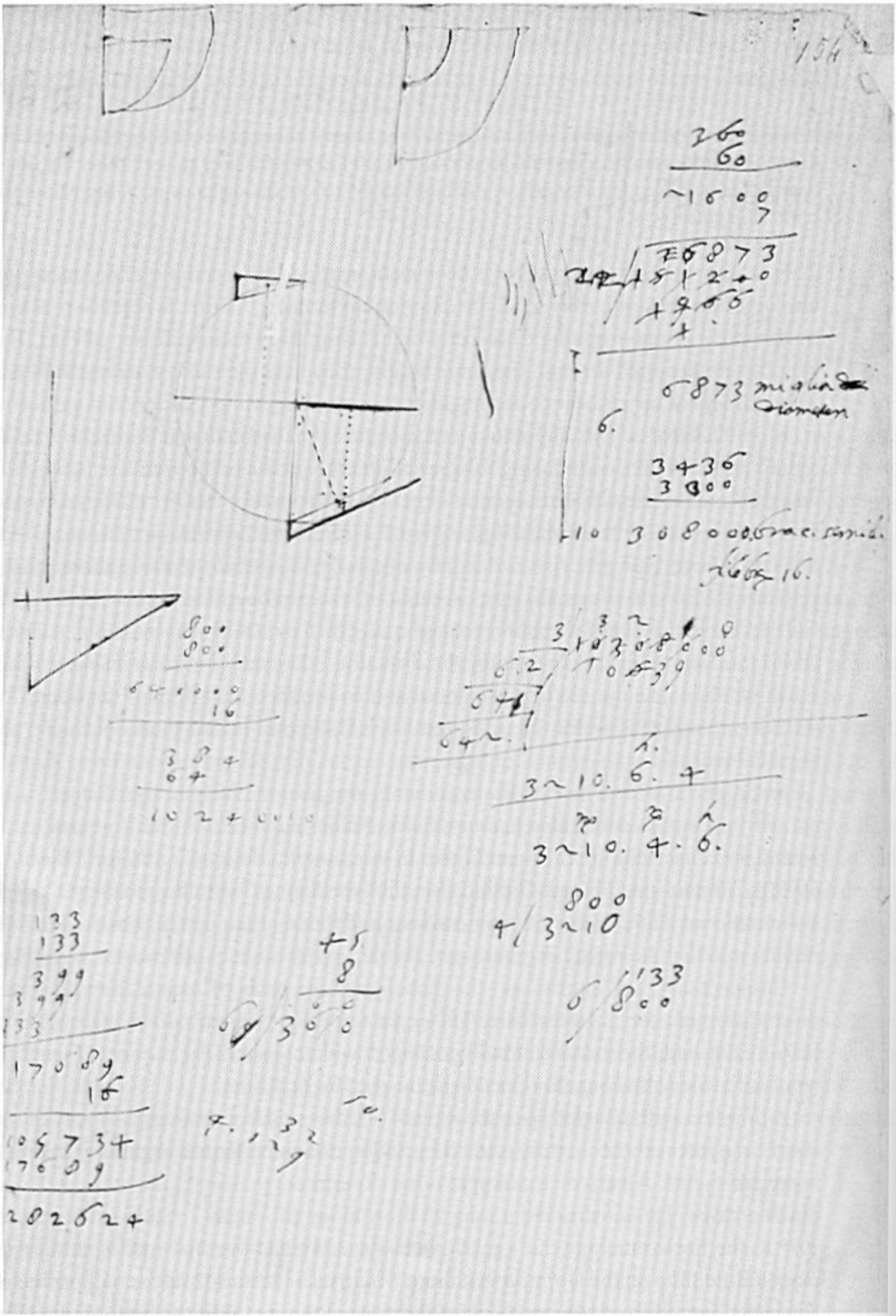

Figure 3.1: Part of Galileo's notes concerning the laws of the pendulum. (From S. Drake, 1990, *Galileo: Pioneer Scientist*, p. 19, Toronto: University of Toronto Press.)

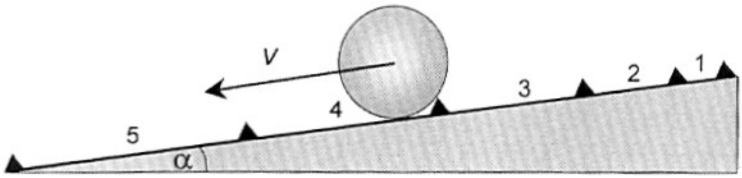

Figure 3.2: How Galileo established the law of motion under uniform acceleration. The numbers between the frets show their relative positions in order to produce a regular sequence of clicks.

By this means, he was able to measure the distance travelled as the ball rolled continuously down the slope and, by taking differences, he could work out the average speed between successive frets. He found that the speed increased as the odd numbers $1, 3, 5, 7, \ldots$ in equal time intervals.

Originally, Galileo had believed that, under constant acceleration, speed is proportional to distance travelled but, as a result of these precise experiments of 1604, he found, rather, that speed is proportional to time. He now had two relations: the first was the definition of speed, $x = vt$, and the second related speed to time under constant acceleration, $v = at$. Now, there is no algebra in Galileo's published works and the differential calculus had yet to be discovered. Suppose the speeds of a uniformly accelerated sphere are measured at times 0, 1, 2, 3, 4, 5 seconds (Fig. 3.2). Assume the sphere starts from rest at time 0. The speeds at the above times will be, say, $0, 1, 2, 3, 4, 5, \ldots$ cm s^{-1}, an acceleration of 1 cm s^{-2}. How far has the sphere travelled after 0, 1, 2, 3, 4, 5 seconds?

At zero time, no distance has been travelled. Between 0 and 1 s, the average speed is 0.5 cm s^{-1} and so the distance travelled must be 0.5 cm. In the next interval, between 1 and 2 s, the average speed is 1.5 cm s^{-1} and so the distance travelled in that interval is 1.5 cm; the total distance travelled from the position of rest is now $0.5 + 1.5 = 2$ cm. In the following interval, the average speed is 2.5 cm s^{-1}, the distance travelled is 2.5 cm and the total distance is 4.5 cm, and so on. We thus obtain a series of distances, 0, 0.5, 2, 4.5, 8, 12.5, ... cm, which can be written in cm as

$$\tfrac{1}{2}(0,\ 1,\ 4,\ 9,\ 16,\ 25, \ldots) = \tfrac{1}{2}(0,\ 1^2,\ 2^2,\ 3^2,\ 4^2,\ 5^2, \ldots). \quad (3.1)$$

This is Galileo's famous *time-squared law* for uniformly accelerated motion, expressed algebraically as

$$x = \tfrac{1}{2}at^2. \quad (3.2)$$

This result represented a revolution in thinking about the nature of accelerated motion and led directly to the Newtonian revolution.

Galileo did not stop there but went on to carry out two further brilliant experiments. He next studied the question of free fall, namely, if an object is dropped from a given height, how long does it take it to hit the ground? He used a form of water clock to measure time intervals accurately. Water was allowed to pour out of a tube at the bottom of a large vessel, kept full; the amount of water which flowed out was a measure of the time interval. By dropping objects from different heights, Galileo established that freely falling objects obey the time-squared law – in other words, when objects fall freely they experience a constant acceleration, the *acceleration due to gravity*.

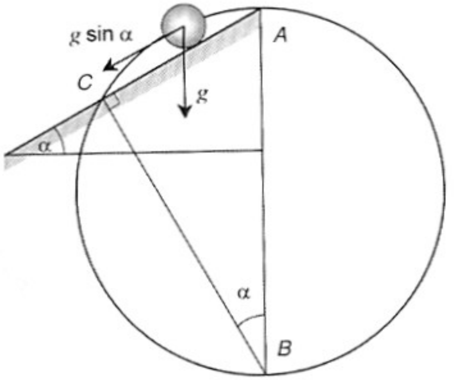

Figure 3.3: How Galileo established the theorem known by his name.

Having established these two results, he sought a relation between them. The desired relation, *Galileo's theorem*, is very beautiful. Suppose a body is dropped freely through a certain distance l, which is represented by the length AB in Fig. 3.3. Construct a circle whose diameter is AB. Now suppose the body slides without friction down an inclined plane and, for convenience, the top of the plane is placed at the point A. Galileo's theorem states that:

> The time it takes a body to slide down the slope from the point A to the point C, where the slope cuts the circle, is equal to the time it takes the body to fall freely from A to B.

In other words, the time it takes a body to fall along any *chord of a circle* is the same as the time it takes the body to fall freely down the diameter of the circle. The component of the acceleration due to gravity is $g \sin \alpha$ as the body slides down the slope; the component of acceleration perpendicular to the slope is zero (Fig. 3.3).

Now, any triangle constructed on the diameter of a circle and with its third point lying on the circle is a right-angled triangle. Therefore, we can equate angles, as shown in Fig. 3.3, from which it is apparent that AC/AB, the ratio of the distances travelled, is equal to $\sin \alpha$. Since, for equal times, the distance travelled is proportional to the acceleration, $x = \frac{1}{2}at^2$, this proves Galileo's theorem.

The next piece of genius was to recognise the relation between these deductions and the properties of swinging pendulums. As a youth, Galileo is said to have noticed that the period of the swing of a chandelier suspended in a church is independent of the *amplitude* of its swing. Galileo made use of his law of chords of a circle to explain this observation. If the pendulum is long enough, the arc AC described by the pendulum is almost exactly equal to the chord across the circle joining the extreme point of swing of the pendulum to the lowest point (Fig. 3.4). Inverting Fig. 3.3, it is therefore obvious why the period of the pendulum is independent of the amplitude of its swing – according to Galileo's theorem, the time to travel along any chord drawn to A will be the same as the time it takes the body to fall freely down twice the length of the pendulum. This is really brilliant physics.

What Galileo had achieved was to put into mathematical form the nature of acceleration under gravity. This had immediate practical application, because he could now work out the trajectories of projectiles. They travel with constant speed parallel to the ground and are accelerated by gravity in the vertical direction. For the first time, he was able to work out the parabolic paths of cannon balls and other projectiles (Fig. 3.5).

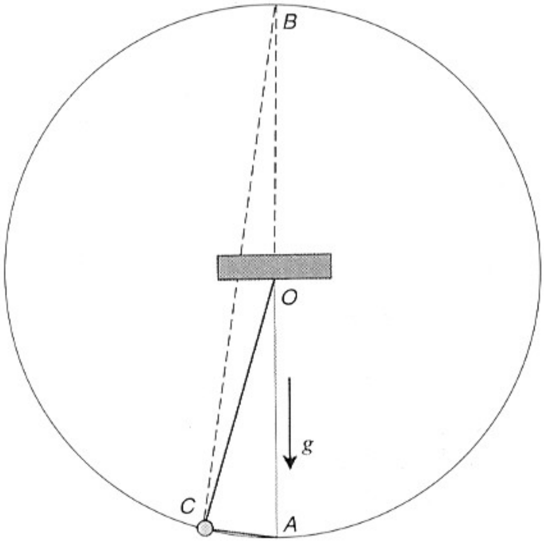

Figure 3.4: How Galileo showed that the period of a long pendulum is independent of the amplitude of the swing. Note the relation to Fig. 3.3.

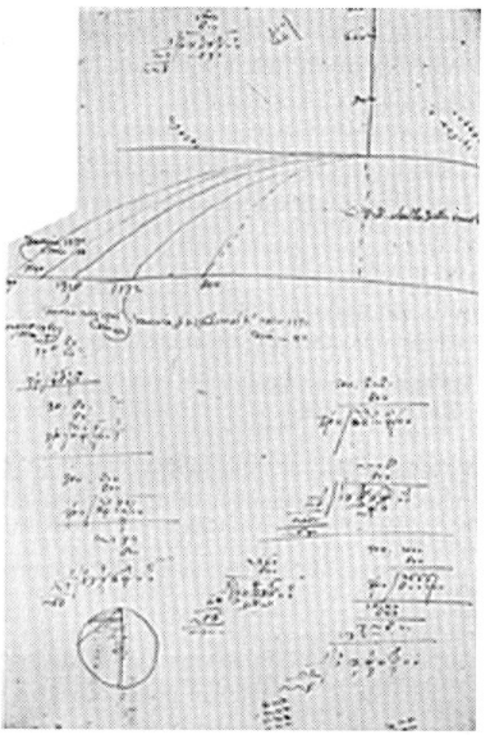

Figure 3.5: A page from Galileo's notebooks showing the trajectories of projectiles under the combination of acceleration under gravity and constant horizontal speed. (From S. Drake, 1990, *Galileo: Pioneer Scientist*, p. 107, Toronto: University of Toronto Press.)

Galileo began writing a systematic treatment of all these topics, showing how they could all be understood on the basis of the law of the constant acceleration; in 1610, in his own words, he was planning to write:

> ... three books on mechanics, two with demonstrations of its principles, and one concerning its problems; and though other men have written on the subject, what has been done is not one quarter of what I write, either in quantity or otherwise.[2]

Later he writes in the same vein:

> ... three books on local motion – an entirely new science in which no one else, ancient or modern, has discovered any of the most remarkable laws which I demonstrate to exist in both natural and violent movement; hence I may call this a new science and one discovered by me from its very foundations.[3]

The publication of these discoveries was delayed until the 1620s and 1630s. He was diverted from this task by news of the invention of the telescope. This was the beginning of his serious study of astronomy.

3.3 Galileo's telescopic discoveries

The invention of the telescope is attributed to the Dutch lens-grinder Hans Lipperhey, who in October 1608 applied to Count Maurice of Nassau for a patent for a device which could make distant objects appear closer. Galileo heard of this invention in July 1609 and set about building one for himself. By August, he had succeeded in constructing a telescope which magnified nine times, a factor three better than that patented by Lipperhey. This greatly impressed the Venetian Senate, who understood the importance of such a device for a maritime nation. Galileo was immediately given a lifetime appointment at the University of Padua at a vastly increased salary.

By the end of 1609, he had made a number of telescopes of increasing magnifying power, culminating in a telescope with a magnifying power of 30. In January 1610, he first turned his telescopes on the skies and immediately there came a flood of remarkable discoveries. These were rapidly published in March 1610 in his *Sidereus Nuncius* or *The Sidereal Messenger*.[4] In summary, the discoveries were:

(i) the Moon is mountainous rather than a perfectly smooth sphere (Fig. 3.6(*a*));
(ii) the Milky Way consists of vast numbers of stars rather than being a uniform distribution of light (Fig. 3.6(*b*));
(iii) Jupiter has four satellites, whose motions can be followed over several complete orbits in a matter of weeks (Fig. 2.9).

The book caused a sensation throughout Europe and Galileo won immediate international fame. These discoveries demolished a number of Aristotelian precepts which had been accepted over the centuries. For example, the resolution of the Milky Way into individual stars was quite contrary to the Aristotelean view. In the satellites of Jupiter, Galileo saw a prototype for the Copernican picture of the Solar System. The immediate effect of these

(*a*)

(*b*)

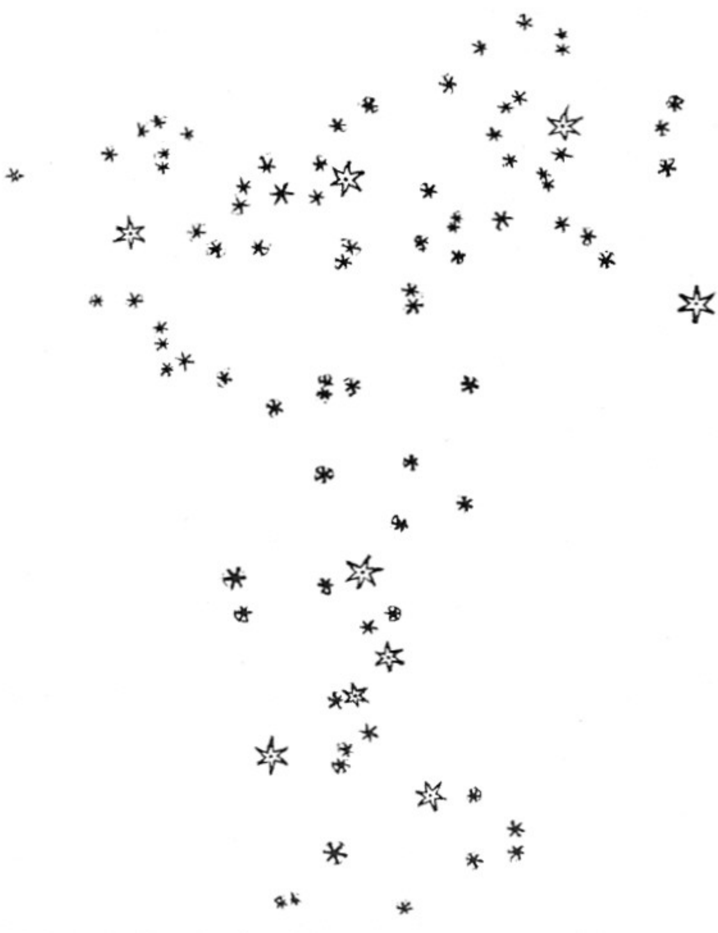

Figure 3.6: (*a*) Galileo's drawing of the Moon as observed through his telescope. (*b*) Galileo's sketch of the region of sky in the vicinity of Orion's belt, showing the resolution of the background light into faint stars. (From G. Galilei, 1610, *Sidereus Nuncius*, Venice. See also the translation by A. van Helden, 1989, Chicago: University of Chicago Press.)

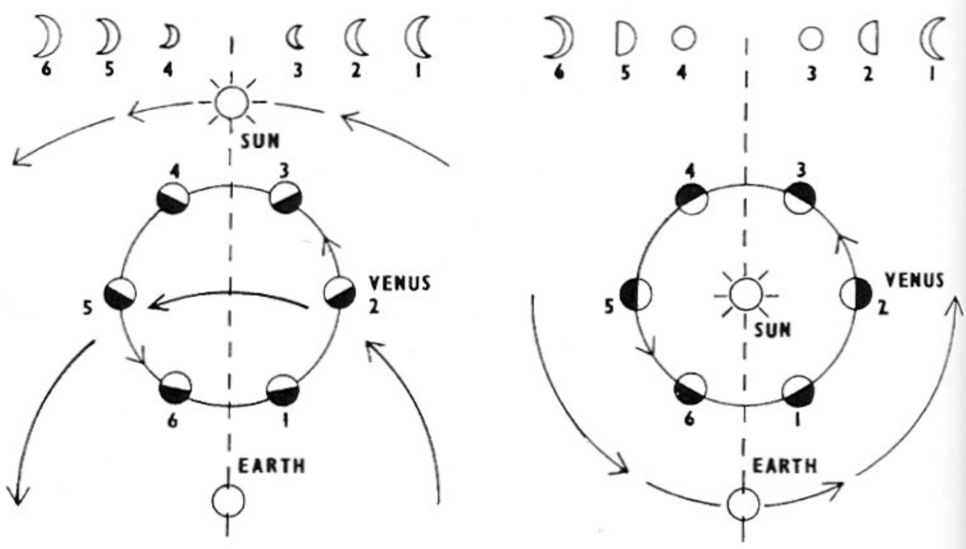

Figure 3.7: Illustrating the phases of Venus, according to the geocentric and heliocentric pictures of the structure of the Solar System. (From A. van Helden, 1989, *Sidereus Nuncius, or The Sidereal Messenger*, p. 108, Chicago: University of Chicago Press.)

discoveries was that Galileo was appointed Mathematician and Philosopher to the Grand Duke of Tuscany, Cosimo de Medici, to whom the *Sidereus Nuncius* was dedicated.

Later in 1610, he made two other crucial telescopic discoveries:

(iv) the rings of Saturn, which he took to be close satellites of the planet;
(v) the phases of the planet Venus.

This last discovery was of the greatest importance. When Venus is on the far side of its orbit with respect to the Earth, it appears circular but when it is on the same side of the Sun as the Earth, it looks like a crescent Moon. This was interpreted as evidence in favour of the Copernican picture because it is explained completely naturally if Venus and the Earth both orbit the Sun, the latter being the source of their illumination (Fig. 3.7). If, however, Venus moved on an epicycle about a circular orbit around the Earth and the Sun moved on a more distant sphere then the pattern of illumination relative to the Earth would be quite different, as illustrated in Fig. 3.7. In 1611 these great discoveries were presented by Galileo to the Pope and several cardinals, who were all favourably impressed by them. Galileo was elected to the Academia Lincei.

3.4 The trial of Galileo – the heart of the matter

Before recounting the events which led up to Galileo's appearance before the Inquisition and his conviction for the second most serious crime in the papal system of justice, let us summarise briefly some of the different facets of the debate between the Ptolemaeans, the

Copernicans and the church authorities; Finocchiaro provides an excellent summary in his documentary history *The Galileo Affair* (1989).[5] The established laws of physics remained in essence Aristotelian and only a few adventurous spirits doubted the basic correctness of the Ptolemaic system. There were problems with the Copernican picture and so Galileo *had* to become involved in these issues because they undermined his new-found understanding of the laws of motion.

3.4.1 The issues

The physical issues centred on these questions. First, does the Earth rotate on its axis with respect to the fixed stars? Second, do the Earth and the planets orbit the Sun? Specifically, is the Earth in motion? This latter concept was referred to as the *geokinetic hypothesis*. Finocchiaro summarises the pre-Galilean objections to this hypothesis under five headings.

(i) *The deception of the senses*. None of our senses gives us any evidence that the Earth is moving in an orbit about the Sun. If this were a fact of nature, surely it would be of such importance that our senses would make us aware of it.

(ii) *Astronomical problems*. First, the heavenly bodies were believed to be composed of different forms of matter from the material of the Earth. Second, Venus should show phases similar to the Moon if it were in orbit about the Sun. Third, if the Earth moved, why didn't the stars exhibit parallaxes?

(iii) *Physical arguments*. These were largely based upon Aristotelian physics and we have encountered some of them already.

(a) If the Earth moves, falling bodies should not fall vertically. Many counter-examples could be given – rain falls vertically, objects thrown vertically upwards fall straight down again, and so on. This was in contrast to the trajectory of an object dropped from the top of a ship's mast when a ship is in motion. In this case, the object does not fall vertically downwards, with respect to an observer on the shore.

(b) Projectiles fired in the direction of rotation of the Earth and in the opposite direction would have different trajectories. No such difference had been observed.

(c) Objects placed on a rotating potter's wheel are flung off if they are not held down. This was called the *extruding power of whirling*, what is now known as the *centrifugal force*. The same phenomenon should occur if the Earth is in a state of rotation, but we are not flung off the surface of the Earth.

(d) Next, there were purely philosophical arguments. Two forms of motion, uniform motion in a straight line and uniform circular motion, were thought to be the only 'natural' motions which objects could have. Objects must either fall in a straight line to the centre of the Universe or be in a state of uniform circular motion. We have already discussed the question whether objects fall towards the centre of the Earth or towards the Sun. Furthermore, according to Aristotelian physics, a simple body could have only one natural motion. But, according to Copernicus, objects dropped on Earth have *three* motions – downward motion under free fall, motion due to the rotation of the Earth on its axis and motion in a circular orbit about the Sun.

(e) Finally, if Aristotelian physics was to be rejected, what was there to replace it? The Copernicans had to provide a better theory and none was available.

(iv) *The Authority of the Bible*. There are no absolutely unambiguous statements in the Bible that assert that the Earth is stationary at the centre of the Universe. According to Finocchiaro, the most relevant statements[6] are as follows:

(a) Psalm 104:5. 'O Lord my God . . . who laid the foundations of the Earth, that it should not be removed forever.'
(b) Ecclesiastes 1:5. 'The Sun also riseth, and the Sun goeth down, and hasteth to the place where he ariseth.'
(c) Joshua 10:12,13. 'Then spake Joshua to the Lord in the day when the Lord delivered up the Amorites before the children of Israel, and he said in the sight of Israel, "Sun, stand thou still upon Gibeon; and thou, Moon, in the valley of Ajalon." And the Sun stood still, and the Moon stayed, until the people had avenged themselves upon their enemies.'

These are rather oblique references and it is intriguing that the Protestants were much more virulently anti-Copernican than the Catholics because of their belief in the literal truth of the Bible. The Catholic theologians took a more sophisticated and flexible interpretation of holy writ. However, the concept that the Earth is stationary at the centre of the Universe had also been the conclusion of the Church Fathers – the saints, theologians and churchmen who codified Christianity. To quote Finocchiaro,

> The argument claimed that all Church Fathers were unanimous in interpreting relevant Biblical passages . . . in accordance with the geostatic view; therefore the geostatic system is binding on all believers, and to claim otherwise (as Copernicus did) is heretical.[7]

(v) The most interesting argument from our perspective concerns the *hypothetical nature of Copernican theory*. It strikes at the very heart of the nature of the natural sciences. The crucial point is how we express statements concerning the success of the Copernican model. A correct statement is: '*If* the Earth rotates on its axis and moves in a circular orbit about the Sun, and if the other planets also orbit the Sun, *then* we can describe simply and elegantly the observed motions of the Sun, Moon and planets on the celestial sphere.' What we *cannot* do logically is to reverse the argument and state that *because* the planetary motions are explained simply and elegantly by the Copernican hypothesis *therefore* the Earth must rotate and move in a circular orbit about the Sun. This is an elementary error of logic, because there might well be quite different reasons why the Copernican model was successful. The key point is the difference between *induction* and *deduction*. Owen Gingerich[8] gives a pleasant example. A *deductive* sequence of arguments might run:

(a) If it is raining, the streets are wet.
(b) It is raining.
(c) Therefore, the streets are wet.

There is no problem here. But, now reverse (b) and (c) and we get into trouble.

(a) If it is raining, the streets are wet.
(b) The streets are wet.
(c) Therefore, it is raining.

This second line of reasoning is obviously false since the streets could be the streets of Venice, or could have been newly washed. In other words, you cannot prove anything about the absolute truth of statements in this way. This type of reasoning, in which we attempt to find general laws from specific pieces of evidence is called *induction*. All the physical sciences are to a greater or lesser extent based on induction, and so physical laws necessarily have a provisional, hypothetical nature. This was seen as in marked contrast to the absolute certainty of God's word as contained in the holy scriptures and its interpretation as dogma by the Church Fathers. According to Owen Gingerich,[8] this was the issue of substance which led to the trial and censure of Galileo – the juxtaposition of the hypothetical world picture of Copernicus with the truth as revealed in the Bible.

3.4.2 *The Galileo affair*

Prior to his great telescopic discoveries of 1610–11, Galileo was at best a cautious Copernican, but it gradually became apparent to him that his new understanding of the nature of motion eliminated the *physical* and *astronomical problems* listed under (ii) and (iii) above. The new evidence was consistent with the Copernican model; specifically, there are mountains on the Moon, just as there are on Earth, suggesting that the Earth and the Moon are similar bodies and the phases of Venus are exactly as would expected according to the Copernican picture. Thus, the physical and astronomical objections to Copernicanism could be discarded, leaving only the logical and theological problems to be debated.

As the evidence began to accumulate in favour of Copernicanism, conservative scientists and philosophers had to rely more and more upon the theological, philosophical and logical arguments. In December 1613, the Grand Duchess Dowager Christina asked Castelli, one of Galileo's friends and colleagues, about the religious objections to the motion of the Earth. Castelli responded to the satisfaction of both the Duchess and Galileo, but Galileo felt the need to set out the arguments in more detail. He suggested that there were three fatal flaws in the theological argument. To quote Finocchiaro:

> First, it attempts to prove a conclusion [the Earth's rest] on the basis of a premise [the Bible's commitment to the geostatic system] which can only be ascertained with a knowledge of that conclusion in the first place . . . the business of Biblical interpretation is dependent on physical investigation, and to base a controversial physical conclusion on the Bible is to put the cart before the horse. Second, the Biblical objection is a *non sequitur*, since the Bible is an authority only in matters of faith and morals, not in scientific questions . . . Finally, it is questionable whether the Earth's motion really contradicts the Bible.[9]

This letter to the Grand Duchess Christina circulated privately and came into the hands of the conservatives. Sermons were delivered attacking the heliocentric picture and accusing its proponents of heresy. In March 1615, the Dominican friar Tommaso Caccini, who had already preached against Galileo, laid a formal charge of *suspicion of heresy* against Galileo before the Roman Inquisition. This charge was less severe than that of *formal heresy*, but was still a serious one. The Inquisition manual stated that, 'Suspects of heresy are those who occasionally utter propositions that offend the listeners . . . Those who keep, write, read, or give others to read books forbidden in the Index . . .' Further, there were two types of suspicion of heresy, *vehement* and *slight* suspicion of heresy, the former being considerably more serious than the latter. Once an accusation was made, there was a formal procedure which had to be followed.

Galileo responded by seeking the support of his friends and patrons and circulated three long essays privately. One of these repeated the arguments concerning the validity of the theological arguments and became known as *Galileo's letter to the Grand Duchess Christina*; the revised version was expanded from eight to forty pages. By good fortune, a Neapolitan friar, Paolo Antonio Foscarini, published a book in the same year arguing in detail that a moving Earth was compatible with the Bible. In December 1615, after a delay due to illness, Galileo himself went to Rome to clear his name and to prevent Copernicanism being condemned.

So far as Cardinal Roberto Bellarmine, the leading Catholic theologian of the day, was concerned, the main problem concerned the hypothetical nature of the Copernican picture. Here are his words, written on 12 April 1615 to Foscarini, after the *Letter to Christina* was circulating in Rome.

> . . . it seems to me that Your Paternity [Foscarini] and Mr Galileo are proceeding prudently by limiting yourselves to speaking suppositionally* and not absolutely, as I have always believed that Copernicus spoke. For there is no danger in saying that, by *assuming* the earth moves and the sun stands still, one saves all the appearances better than by postulating eccentrics and epicycles is to speak well; and that is sufficient for the mathematicians. However, it is different to want to affirm that in reality the Sun is at the centre of the world and only turns on itself without moving from east to west, and the Earth is in the third heaven and revolves with great speed around the Sun; this is a very dangerous thing, likely not only to irritate all scholastic philosophers and theologians, but also to harm the Holy Faith by rendering Holy Scripture false.[10]

Behind these remarks is a perfectly valid criticism of Galileo's support for the Copernican picture. It is not correct to state, as Galileo did, that the observation of the phases of Venus proves that the Copernican picture is necessarily correct; for example, in Tycho's cosmology, in which the planets orbit the Sun but the Sun together with the planets orbit the Earth (Fig. 2.7), exactly the same phases of Venus would be observed as in the Copernican picture. According to Gingerich, this was Galileo's crucial logical error. Strictly speaking, he could only make a hypothetical statement.

The findings of the Inquisition were favourable to Galileo personally – he was acquitted of the charge of suspicion of heresy. However, the Inquisition also asked a committee of 11 consultants for an opinion on the status of Copernicanism. On 16 February 1616, it reported unanimously that Copernicanism was philosophically and scientifically untenable and theologically heretical. This erroneous judgement was the prime cause of the subsequent condemnation of Galileo. It seems that the Inquisition had misgivings about this outcome because it issued no formal condemnation. Instead, it issued two milder instructions. First, Galileo was given a private warning by Cardinal Bellarmine to stop defending the Copernican world picture. Exactly what was said is a matter of controversy, but Bellarmine reported back to the Inquisition that the warning had been issued and that Galileo had accepted it.

* This word is often translated *hypothetically*.

The second result was a public decree by the Congregation of the Index. First, it reaffirmed that the doctrine of the Earth's motion was heretical; second, Foscarini's book was condemned and prohibited by being placed on the Index; third, Copernicus's *De Revolutionibus* was suspended until a few offending passages were amended; fourth, all similar books were subject to the same prohibition.

Rumours circulated that Galileo had been tried and condemned by the Inquisition and, to counteract these, Bellarmine issued a brief statement to the effect that Galileo had neither been tried nor condemned, but that he had been informed of the Decree of Index and instructed not to hold or defend the Copernican picture. Although he had been personally exonerated, the result was a defeat for Galileo.

3.5 The trial of Galileo

For the next seven years, Galileo kept a low profile and complied with the Papal instruction. In 1623, Gregory XV died and his successor, Cardinal Maffeo Barbarini, was elected Pope Urban VIII. He was Florentine and took a more relaxed view of the interpretation of the scriptures than his predecessor. An admirer of Galileo, he adopted the position that Copernicanism could be discussed hypothetically and might well prove to be of great value in making astronomical predictions. Galileo had six conversations with Urban VIII in Spring 1624 and came to the conclusion that Copernicanism could be discussed, provided that it was only considered hypothetically.

Galileo returned to Florence and immediately set about writing the *Dialogue on the Two Chief World Systems, Ptolemaic and Copernican*. He believed he had made every effort to comply with the wishes of the censors. The preface was written jointly by Galileo and the censors and, after some delay, the great treatise was published in 1632. Galileo wrote the book in the form of a dialogue between three speakers, Simplicio defending the traditional Aristotelian and Ptolemaic positions, Salviati defending the Copernican position and Sagredo an uncommitted observer and man of the world. Consistently, Galileo argued that the purpose was not to make judgements, but to pass on information and enlightenment. The book was published with full papal authority.

The Two Chief World Systems was well received in scientific circles, but very soon complaints and rumours began to circulate in Rome. A document dated February 1616, almost certainly a fabrication, was found in which Galileo was specifically forbidden from discussing Copernicanism in any form. By now, Cardinal Bellarmine had been dead 11 years. In fact, in his book Galileo had not treated the Copernican model hypothetically at all, but rather as a fact of nature – Salviati is Galileo speaking his own mind. The Copernican system was portrayed in a much more favourable light than the Ptolemaic picture, contradicting Urban VIII's conditions for discussion of the two systems of the world.

The pope was forced to take action – papal authority was being undermined at a time when the Counter-reformation and the reassertion of that authority were paramount political considerations. Galileo, now 68 years old and in poor health, was ordered to come to Rome under the threat of arrest. The result of the trial was a foregone conclusion. In the end, Galileo pleaded guilty to a lesser charge on the basis that, if he had violated the conditions imposed

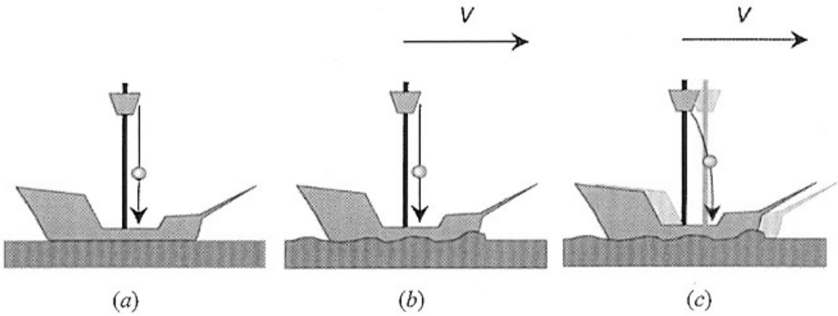

Figure 3.8: (*a*) Dropping an object from the top of a mast in a ship that is stationary in the frame of reference S. (*b*) Dropping an object from the top of a mast in a moving ship, viewed in the frame of reference S' of the ship. (*c*) Dropping an object from the top of a mast in a moving ship, as observed from the frame of reference S. The ship moves to the lighter grey position during the time the object falls.

upon him in 1616, he had done so inadvertently. The pope insisted upon interrogation under the formal threat of torture. On 22 June 1633, he was found guilty of 'vehement suspicion of heresy' and was forced to make a public abjuration, the proceedings being recorded in the Book of Decrees.

I do not hold this opinion of Copernicus, and I have not held it after being ordered by injunction to abandon it. For the rest, here I am in your hands; do as you please.[11]

Galileo eventually returned to Florence where he remained under house arrest for the rest of his life – he died in Arcetri on 9 January 1642.

With indomitable spirit, Galileo set about writing his greatest work, *Discourses and Mathematical Demonstrations on Two New Sciences Pertaining to Mechanics and to Local Motion*, normally known as simply *Two New Sciences*. In this treatise, he brought together the understanding of the physical world which he had gained over a lifetime. The fundamental insights concern the second new science – the analysis of motion.

3.6 Galilean relativity

The ideas expounded in *Two New Sciences* had been in his mind since 1608. One of them is what is now called *Galilean relativity*. Relativity is often thought of as something invented by Einstein in 1905, but this does not do justice to Galileo's great achievement. Suppose an experiment is carried out on the shore and then on a ship moving at a constant speed. If the effect of air resistance is neglected, is there any difference in the outcome of any experiment? Galileo answers firmly, 'No, there is not.'

The relativity of motion is vividly illustrated as mentioned earlier, by dropping an object from the top of a ship's mast (Fig. 3.8). If the ship is stationary, the object falls vertically downwards. Now suppose the ship is moving. If the object is again dropped from the

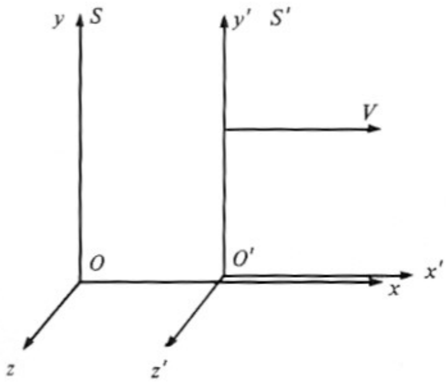

Figure 3.9: Illustrating two Cartesian frames of reference moving at relative velocity v in the direction of the positive x-axis in 'standard configuration'.

top of the mast, it again falls vertically downwards according to an observer on the ship. However, a stationary observer sitting on the shore notes that, relative to the shore, the path is curved (Fig. 3.8(c)). The reason is that, relative to the shore, the object has two separate components to its motion – vertical acceleration downwards due to gravity and uniform horizontal motion due to the motion of the ship.

This leads naturally to the concept of *frames of reference*. When the position of some object in three-dimensional space is measured, we can locate it by its coordinates in some rectangular coordinate system (Fig. 3.9). The point P has coordinates x, y, z in this stationary frame of reference, which we will call S. Now, suppose the ship moves along the positive x-axis at some speed v. We can set up another rectangular frame of reference S' on the ship, in which the coordinates of the point P are x', y', z'. It is now straightforward to relate the coordinates in these two frames of reference. If the object is stationary in the frame S then x is a constant but the value of x' changes as $x' = x - vt$, where t is the time, assuming that the origins of the two frames of reference are coincident at $t = 0$. The values of y and y' remain the same in S and S', as do z and z'. Also, time is the same in the two frames of reference. We have derived a set of relations between the coordinates of objects in the frames S and S':

$$\begin{aligned} x' &= x - vt, \\ y' &= y, \\ z' &= z, \\ t' &= t. \end{aligned} \tag{3.3}$$

These are known as the *Galilean transformations* between the frames S and S'. Frames of reference which move at constant relative speed to one another are called inertial frames of reference. Galileo's great insight can be summarised by stating that *the laws of physics are the same in every inertial frame of reference.* As a corollary of this insight, Galileo was the first to establish the *law of composition of velocities* – if a body has components of velocity in two different directions then the motion of the body can be found by adding together the separate effects of these motions. This was how he showed that the trajectories of cannon-balls and missiles are parabolae (Fig. 3.5).

In *Two New Sciences* Galileo described his discoveries concerning the nature of constant acceleration, the motion of pendulums and free fall under gravity. Finally, he stated his *law of inertia*, which asserts that a body moves at a constant velocity unless some impulse or force causes it to change that velocity – notice that it is now velocity rather than just speed which is constant, because the direction of motion does not change in the absence of forces. This is sometimes referred to as the *conservation of motion* – in the absence of forces, the separate components of the velocity remain unaltered. The word *inertia* is used here in the sense that it is a property of the body which resists change of motion. This law will become Newton's first law of motion. It can be appreciated why the Earth's motion caused Galileo no problems. Because of his understanding of Galilean relativity, he realised that the laws of physics would be the same whether the Earth were stationary or moving at a constant speed.

3.7 Reflections

We cannot leave this study without reflecting on the methodological and philosophical implications of the Galileo case. There is no question now that the Church made an error in condemning the new physics of Copernicus and Galileo. It was a further 350 years before Pope John Paul II admitted that an error had been made. In November 1979 on the occasion of the centenary of the birth of Albert Einstein, John Paul II stated that Galileo '. . . had to suffer a great deal – we cannot conceal the fact – at the hands of men and organisms of the Church.' He went on to assert that '. . . in this affair the agreements between religion and science are more numerous and above all more important than the incomprehensions which led to the bitter and painful conflict that continued in the course of the following centuries.'

For scientists, the central issue is the nature of scientific knowledge and the concept of truth in the physical sciences. Part of Cardinal Bellarmine's argument is correct. What Copernicus had achieved was a model that was much more elegant and economical for understanding the motions of the Sun, Moon and planets than the Ptolemaic picture, but in what sense was it the truth? If one were to put in enough effort, a Ptolemaic model of the Solar System could be created today which would replicate exactly the motions of the planets on the sky, but it would be of enormous complexity and provide little insight into the underlying physics which describes their motions. The value of the new model was not only that it provided a vastly improved framework for understanding the observed motions of the celestial bodies but also that, in the hands of Newton, it was to become the avenue for obtaining a very much deeper understanding of the laws of motion in general, leading to the unification of celestial physics, the laws of motion and the law of gravity. A scientifically satisfactory model has the capability not only of accounting economically for a large number of disparate observational and experimental phenomena but also of being extendable to make quantitative predictions about apparently unrelated phenomena.

Notice that I use the word *model* in describing this process rather than asserting that it is in any sense *truth*. Galileo's enormous achievement was to realise that the models to describe nature could be put on a rigorous mathematical basis. In one of his most famous remarks, he stated in his treatise *Il Saggiatore* (*The Assayer*) of 1624:

> Philosophy is written in this very great book which always lies before our eyes (I mean the Universe), but one cannot understand it unless one first learns to understand the language and recognise the characters in which it is written. It is written in mathematical language and the characters are triangles, circles and other geometrical figures; without these means it is humanly impossible to understand a word of it; without these there is only clueless scrabbling around in a dark labyrinth.[12]

This is often abbreviated to the statement that

> The Book of Nature is written in mathematical characters.

This was the great achievement of the Galilean revolution. The apparently elementary facts established by Galileo required an extraordinary degree of imaginative abstraction. Matter does not obey the apparently simple laws of Galileo – there is always friction, experiments can only be carried out with limited accuracy and often do not work. It needs deep insight and imagination to sweep away the unnecessary baggage and appreciate the basic simplicity in the way matter behaves. The modern approach to science is no more than the formalisation of the process begun by Galileo. It has been called the *hypothetico-deductive method*, whereby hypotheses are made and consequences deduced logically from them. A model is acceptable so long as it does not run significantly counter to the way matter is observed to behave. But models are only valid within well-defined regions of parameter space. Profesionals become very attached to them and the remarks by Dirac and Douglas Gough quoted in Chapter 1 describe the need to be satisfied with approximate theories and the 'pain' experienced on being forced to give up a cherished prejudice.

It is rare nowadays for religious dogma to impede progress in the physical sciences. However, *scientific prejudice* and *dogma* are the common currency of scientific debate. There is nothing particularly disturbing about this so long as we recognise what is going on. A scientific prejudice becomes embodied in a model, which provides a framework for carrying forward the debate and for suggesting experiments and calculations which can provide tests of the self-consistency of the model. We will find many examples throughout this book where the 'authorities' and 'received wisdom' were barriers to scientific progress. It takes a great deal of intellectual courage and perseverance to stand up to what is normally an overwhelming weight of conservative opinion. It is not just whimsy that leads us to use pontifical language to describe some of the bandwagons which can dominate areas of enquiry in the physical sciences. In extreme cases, through scientific patronage scientific dogma has attained an authority to the exclusion of alternative approaches. One of the most disastrous examples was the Lysenko affair in the USSR shortly after the Second World War, where Communist political philosophy strongly impacted the biological sciences, resulting in a catastrophe for these sciences in the Soviet Union.

Let me give two topical examples. It is intriguing how the idea of *inflation* during the very early stages of expansion of the Universe has attained the status of 'received dogma' among certain sections of the cosmological community. There are good reasons why this idea should be taken seriously, as will be discussed in Chapter 19. There is, however, no direct experimental evidence for the actual physics which could cause the inflationary expansion of the early Universe. Indeed, a common procedure is to work backwards and 'derive' the physics of inflation from the need to account for the features of the Universe as we observe it today. Then, theories of particle physics need to be found which can account for these forces. There is the obvious danger of ending up with bootstrapped self-consistency without any independent experimental check of the theory. Maybe this is the best one can do, but some of us will maintain a healthy scepticism until there are more independent arguments which support the conjecture of inflation.

The same methodology has occurred in the theory of elementary particles with the development of string theory. The creation of self-consistent quantum field theories involving one-dimensional objects rather than point particles has been a quite remarkable achievement. The latest versions of these theories involve the quantisation of gravity as an essential ingredient. Yet, they have not resulted in predictions which can be tested experimentally. Nonetheless, this is the area into which many of the most distinguished theorists have transferred all their efforts. It is taken as an article of faith that this is the most promising way of tackling these problems, despite the fact that it might well prove very difficult to find any experimental or observational tests of the theory in the foreseeable future.

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