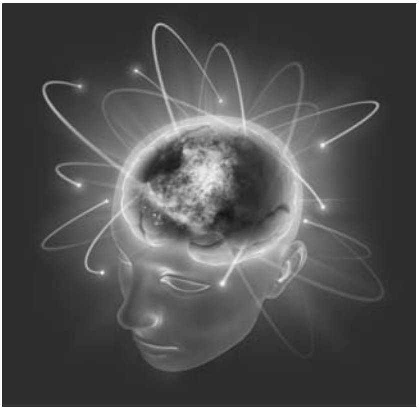
# Weaving The Universe

## Is Modern Cosmology Discovered or Invented?



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## Chapter 1

# WEAVING THE WARP

The idea that science is at least partly invented, rather than discovered, was put forward most noticeably by the great astronomer Sir Arthur Eddington (1882–1944). He was severely criticized by both philosophers and physicists. However, recent advances in quantum mechanics and relativity have supported his thesis. In fact, it is now possible to present a fresh approach to the idea that science depends not so much on experiments as on the logical fit of theories coming from the human brain. It is the aim of this book to examine the ability of the human intellect to create science — or (in short) to study mind weaving.

Weaving in the traditional sense involves setting up on a loom the basic lines which determine structure (the warp), and adding to these the orthogonal threads which yield the colour and texture of the resulting fabric (the weft or woof). Modern science is like this, insofar as it involves basic laws, to which are added interpretations, resulting in an account of a specific part of the natural world. It is currently the aim of this scientific mind weaving to produce pieces of 'fabric', for example quantum mechanics and relativity theory; and to stitch these together to form a tapestry, or grand-unified theory of physics.

This is a laudable goal. But it is by no means obvious how to achieve it, or whether it is in principle achievable at all. It is traditional to separate physics — somewhat crudely — into the theoretical and experimental approaches. However, most physicists agree that the design, construction, and operation of an experiment involve theoretical elements; and certainly, the interpretation of the data from an experiment is mathematical and mind-based in nature. Eddington himself worked with observations in his former years, but later came to the view that physics (and science in general) is an intellectual exercise (Figure 1.1). We now have far more information at our disposal than did Eddington. So it is not surprising that some of our conclusions will differ from his. To present the modern argument for the mind as the seat of science, we have divided the material in a pragmatic fashion: Chapter 1 deals with the warp of scientific theory, while Chapter 7 deals with the weft of interpretation. The intervening Chapters 2–6 present the accepted elements of physics, though the presentation may be somewhat novel. This sandwich mode — philosophy in two slices of bread with the meat of physics between — is designed to present our arguments in the most efficient manner. Efficiency, at least in physics, is formalized by the philosophical statement called Ockham's razor. This is really an application of convenience or common sense insofar as it means that we introduce the least number of hypotheses necessary to solve a given problem. It is also widely used to choose between several viable theories for an observation, by taking the most simple.

**Figure 1.1.** Eddington, who was the Plumian Professor of Astronomy at Cambridge, came to believe that much of science is the product of the human mind.

A concept related to simplicity, which is much used in the quantitative sciences, is that of the minimum. We form a quantity which is typical of the system, and find the conditions under which it has its least value. The conditions found this way usually correspond to laws of nature. We need to understand this method before proceeding, and choose to illustrate it by two wide-ranging applications, one to the motion of a test particle and one to the laws which govern matter.

Measuring the distance between two points A and B in a given type of 'space' is arguably the most basic operation in physics, and was formalized by Euler, Fermat and others. On a flat, two-dimensional surface like the page of this book, there are an infinite number of paths connecting A and B. But one is special, namely that which makes the distance a minimum, giving a straight line (Figure 1.2). This is elementary; but already we see that a certain degree of subjectivity has entered our considerations, in that the concept of simplicity is based in the human mind. Particles which are not acted on by external forces travel on straight lines. It is worth consideration that physics would be unworkably complicated without this stricture. We may not, however, be able to measure the total distance between A and B, and only have access to a small element of it, say $ds$. Then we imagine that we can form the total distance, or interval, by integrating. If we vary the interval between A and B, keeping these points fixed, we can find the minimum. Technically, the mathematiccal problem involved here gives the extremum, but we conventionally disregard the maximum and choose the minimum (again, this is a subjective choice). The definition of a straight line then takes the symbolic form $\delta\left[\int ds\right] = 0$. This also gives the shortest (or 'straightest') path when the surface under consideration is not flat, but curved. There is also no restriction as to the number of dimensions of the 'space' involved, so the noted formula can be

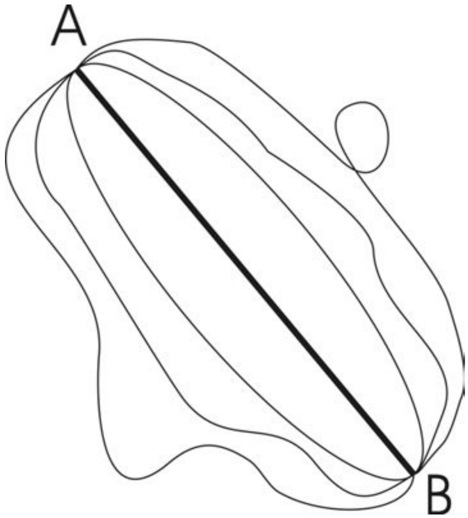

**Figure 1.2.** Between two points A and B there are an infinite number of curved lines, but a unique straight and shortest one.

applied to the four-dimensional space or manifold of relativity. The paths of particles travelling in the manifold are called geodesics. This word reminds us that on the curved 2D surface of the Earth, the geodesics are great circles, which define the most economical routes for travelling by airplanes when A and B denote cities. The crucial thing is that the Fermat principle can be applied to a manifold with any number of dimensions that is flat or curved, and serves to pick out a unique path from the infinitude that are possible. The principle can be applied in many situations, and was used especially to study the propagation of light, not only through empty, ordinary 3D space but also through the refractive 'space' provided by substances such as glass. In another context, sociologists have spent considerable effort trying to explain why most people value the truth above other forms of statement in everyday discourse. From the perspective of the Fermat principle, the answer is obvious: there are an infinite number of possible lies for a special and unique truth.

Matter is usually thought of as some kind of material which occupies a certain volume of ordinary 3D space and may evolve with time. In the above, we looked at the motion of a particle between two points in what we intrinsically assumed to be empty space. To handle the problem of matter, we could redo the analysis to take into account its effects on the motion of a test particle. However, we can actually go much farther than this, if we apply a more complicated version of the Fermat rule to the matter itself. That is, we can pick out rules for the matter's own behaviour by asking that it obey certain rules of minimality. The technique involved is called the calculus of variations. It was first used in the present context by Hilbert, who confirmed the importance of a quantity suspected as a 'catch-all' description of matter by Einstein.

General relativity is based on the insight by Einstein that the properties of matter in space and time are equivalent to the geometrical properties of 4D spacetime. This is a startling idea, beautiful in conception and successful in application. It is sometimes explained by the statement that matter curves spacetime, so by studying the mathematics of the latter we can work out the physics of the former. This statement is true as far as it goes. But what Einstein really showed was that matter and geometry are essentially the same thing. Ergo, if we wish to understand the laws of matter, we have to find a way to isolate preferred forms of the geometry.

This is where the calculus of variations comes in. There is a quantity in the geometry of curved spaces which is known as the Ricci scalar $R$. As a scalar, it is a simple thing, depending only on the location in space and time. (It lacks the directional properties of a vector, or the more complicated properties associated with the indices of a tensor.) Geometrically, it can be thought of as measuring the (inverse square of the) radius of curvature. Physically, it can be thought of roughly as measuring the energy density at a point in spacetime. Let the 'true' (corrected for curvature) volume element of a localized portion of spacetime be denoted $dV$. Then by analogy with our previous application of the Fermat rule, we can imagine that we integrate over the volume, take the variation, and set it to zero to get the minimum: $\delta\left[\int RdV\right]=0$. The result identifies a quantity called the Einstein tensor, which is the basis of the gravitational field as it is described by general relativity.

The full theory, following Einstein, involves equating this geometrical tensor to the physical one which encodes familiar properties of matter such as the density and pressure. This material object is called the energy-momentum tensor (see Chapter 5 for a discussion of the properties of matter and tensors). In this way, general relativity gives a geometrical description of matter.

The approach outlined above can easily be extended to 'spaces' with more than the 4 dimensions of spacetime. In fact, there is nothing in the approach which restricts the number of dimensions of the manifold (see Chapter 3 for a discussion of the physical and mathematical aspects of dimensions). And we will see later that the extension of general relativity to $N = 5$ dimensions has the neat property of amalgamating the expressions for the $N = 4$ Einstein and energy-momentum tensors. By counting, the number of field equations for an ND theory of the type we are discussing is $N(N+1)/2$. These can be solved to obtain the allowed physics. (A more detailed account of the number and nature of ND field equations is given in Chapter 5.) In the 4D spacetime of general relativity, there are 10 relations, which are Einstein's field equations. Numerous exact solutions of these equations are known, and a compendium is due to Kramer et al. (1980). In the simplest extension of general relativity to the 5D manifold of space-time-matter theory and membrane theory, there are 15 relations, which express the most basic kind of unified field theory. Many exact solutions of these more difficult equations are known, and a compendium is due to Wesson (2007). At this stage, the reader may be feeling slightly stunned by the escalation involved in going from the motion of a test particle to the laws of gravitating matter. Take heart! We have, in a couple of pages, managed to write down a protocol for describing much of the physical world as it is currently understood. We have succeeded in reducing multiple infinities of possibility to a relatively few likelihoods.

The audacity of the human mind is truly remarkable. However, in contemplating the achievements of physics, we should not lose sight of the fact that its equations and associated paraphernalia are the manifestations of a kind of academic instinct. There is a parallel between the researcher in theoretical physics and the composer of classical music. The latter learns technique developed over several centuries, including the language of the stave and the technical properties of the musical instruments that make up an orchestra. Equipped with this learning, it is possible to write a symphony that is deep in technical quality, agreeable to the ear, and (hopefully) makes contact with those human feelings which are difficult to put into words but nonetheless vital. Connections between physics and music range from the incidental to the near profound (Halpern 2000, 2004). Einstein, of course, gained solace from playing the violin; and Feyman let out his energy by beating the bongo drums. Sir Fred Hoyle developed a theory of time by using classical music as a backdrop, and wrote a space-based opera. Sir James Jeans, who was a contemporary of Sir Arthur Eddington, even went so far as to propose that God must be both a mathematician and a musician. We will return to some of these topics later (see Chapters 4 and 5; also Halpern and Wesson 2006; Eddington 1928, 1939; and Hoyle 1966, 1994). Here we note that theoretical physics — like classical music or fine art — does not merely represent a job, but is a calling.

Cosmologists are an especially dedicated bunch. It is unknown how many professional cosmologists there are in the world, but they are probably no more numerous than brain surgeons. This in an age when popular coverage of the universe, particularly by television, gives the impression that it is easily understood. In this regard, it is instructive to look at some hard numbers. Today, a typical university will offer classes in astrophysics from first to fourth year which reveal a kind of pyramid structure. The enrolment in a first-year survey course on astronomy may typically be about 250. The following second-year class, which is frequently on the solar system, may have a student number of 70–100. By third year, when the subject is again restricted to a subfield such as stars or galaxies, the enrolment is down to about 30. The typical university will round out its educational offerings with a fourth-year course specifically on extragalactic astrophysics or cosmology, where it is fortunate if the attendance is 12. The student who survives the whole curriculum will indeed end up with a broad knowledge of the subject — which is after all what the word "cosmology" means. But the progressive cuts in enrolment, from hundreds to a dozen or so, tells us that the subject matter is not easy. This is partly because the dosage of mathematics increases as the educational process moves forward. In fact, the average television viewer of a show about the universe would likely be dismayed to discover that by the end of the study route for a B.Sc., the subject being taught is close to applied mathematics. The difference between astronomy and cosmology is akin to the difference between botany and genetics: one is mainly descriptive while the other is largely analytical.

Winnowing of the student population continues, moreover, at the postgraduate level. It typically takes two years in North America to complete an M.Sc. degree. And it is only towards the end of this (and then only for those at an academically strong institution) that the student has the opportunity to work on new material. However, the number of professional jobs in theoretical astrophysics or cosmology is so low that a minimum qualification for one is not an M.Sc. but a Ph.D. The latter is a particularly time-consuming project. It is not surprising that many gifted students abandon the quest at this stage, in favour of money/stability/family, rather than spend another segment of their life on something as esoteric as the big bang. There is a wide variation in the time that people spend on acquiring a doctoral degree. It lies for most able scholars in the range 4–8 years. Not only is this a significant chunk out of anybody's life; but it is also a period that for many is fraught with problems to do with research, arguments with supervisors and other academics, and the frustrating lack of cash. Wait a second, though. The course is not yet complete for the majority, even on completion of the Ph.D. degree. The paucity of jobs is such that most researchers will find themselves doing at least one post-doctoral two-year stint at a university, analogous to the internship at hospitals required of medical physicians. Enough! By age 32–35 typically, the scholar who is gifted enough and stubborn enough will finally obtain a position as a professional cosmologist.

The preceding account is conservative, number-wise. It deserves to be more widely appreciated than is apparently the case. Biblically, we are informed that "three score and ten" is about as much life as the average person can expect; and while modern medicine may enhance this somewhat, it is still true that most people's mental faculties are circumscribed by age 70. It is a sobering realization that for the typical cosmologist, half of his or her life is over before access to a regular pay cheque.

Why then do people aspire to become cosmologists? We can answer this superficially by repeating that it is not so much a job as a calling. However, a deeper insight can be gained by shifting the question to related fields. Why does the aspiring composer hope to emulate Beethoven, who when largely deaf managed to write his monumental ninth symphony? Or, going in another direction: Why does the young chess player try to emulate the brilliant gambits of the masters, like Bobby Fischer, Garry Kasparov and Boris Spassky? Above, we have remarked on the parallels between science and subjects in the arts, such as music. In fact, several leading cosmologists have likened their subject to some vast and intricate game of cosmic chess (Halpern and Wesson 2006). It is in a consideration of other subjects that we find an answer (at least partially) to the question of why some people are driven to study science and especially theoretical physics. Research in science means doing something new, and if it happens to have some relationship to the real world then so much the better.

Doing something new is usually satisfying — and even intoxicating — for the achiever. However, in science we have to be careful concerning what we mean by "new".

To the majority of scientists, doing something new means discovering an aspect of the natural world that was previously hidden from human appreciation, though the data are assumed to exist independent of the inquirer, who is like an explorer uncovering the plan of some concealed city of knowledge. This view is so traditional among scientists that we do not need to mention the names of those who have and still hold it.

To a few scientists who follow Sir Arthur Eddington, doing something new means using the power of the intellect to create fresh insights, whose development is mainly guided by the need for new knowledge to fit consistently with old and accepted knowledge. This view is rare, but puts science in the same class of human cultural achievements as (say) classical music and fine art.

In the last chapter of this book, we will argue in favour of the second opinion over the first. The detailed grounds for this will be outlined in Chapters 2–6, where it will become apparent that many recent advances in quantum theory and relativity bear the stamps of being invented rather than discovered. Theoretical physics, in particular, now bears a close relationship to human practices usually described as arts, such as composing a symphony, creating a painting or writing a poem. Eddington was the first person of stature to propose the view that science is at least partly subjective, and it was put forth mainly in two volumes by him of a philosophical type (Eddington 1928, 1939). This view was met with something like respectful puzzlement by some physicists (Whittaker 1951, Dingle 1954). And it was met with outright hostility by several philosophers (Stebbing 1937, Nerlich 1967). However, a modern reading of the opinions of the latter shows that their criticism was mainly directed at how things were stated rather than the meaning of the statement; and today Eddington's views meet with more respect (Leslie 2001, Price and French 2004). If there is still a divide between science and the arts, it is narrower now than at any point in history.

Einstein, whose general theory of relativity was presented to the English-speaking world by Eddington, said that imagination is more important than knowledge (Figure 1.3). Everybody agrees that

**Figure 1.3.** Einstein, who spent his later years at Princeton, believed that the mind's powers of imagination are superior to its ability to store data.

imagination is an essential feature in the arts, and it is instructive to see how it figures in science.

That an act of the human mind is involved in science is evident even at the simple level of Newtonian mechanics. Let us reconsider the case of motion in a straight line (see above). Then Newton's laws tell us that the distance $s$ that a particle travels in time $t$ is give by $s = vt$, where $v$ is the velocity. This elementary relation already presumes that the natural state of an object is to continue in motion.

This may not have been obvious to the common person in the England of Newton's age, when a road was likely to be a muddy track in which a cart would come to rest unless encouraged to move by the force of horses or oxen. The state of continuous motion implied by the noted relation is more akin to that displayed by a ball rolling on a smooth table top. But even in the latter situation, friction brings the moving object eventually to rest. Thus the most basic law of motion we possess actually involves a somewhat counter-intuitive choice. We now admit that it is basically correct, given data on particles moving in vacuum tubes or satellites orbiting in space. However, the law involves a visualization of a state that is not common in everyday life, to which it is reconciled only by the invention of a countervailing force that we call friction. That is, Newton's laws involve an element of human insight which is close to what we call imagination.

The law $s = vt$ noted above can more instructively be written as $v \equiv s / t$, which defines the velocity. Here $s$ and $t$ are examples of what in basic physics are called extrinsic measures, while $v$ is an example of an intrinsic measure. Extrinsic measures are those whose values are divided when we divide the amount of the quantity under consideration. They include distance, time and mass. Intrinsic measures, by comparison, retain their values when we divide the amount of the quantity under consideration. Examples are density, pressure and temperature. The distinction between these classes is often overlooked in advanced physics, such as general relativity. But it is still present, because extrinsic measures are usually employed as the independent variables in a problem, while intrinsic measures are usually employed as the dependent variables. The distinction is present, for example, in Einstein's field equations for the behaviour of matter in a gravitational field. There the coordinates are frequently labelled $x$, $y$, $z$ and $t$ for space and time; while the properties of matter are commonly taken to be $\rho$, $p$, $T$ for density, pressure and temperature. The object of the exercise, in solving Einstein's equations, is to obtain the intrinsic measures as functions of the extrinsic ones. This is what we mean by a solution, say for the density of the galaxies $\rho = \rho(t)$ as a function of time since the big bang. At a basic level, the equations of physics are set up by making a choice between intrinsic and extrinsic measures, and this choice is essentially subjective.

Dimensional homogeneity is another property of the equations of physics which is often taken for granted but is basically subjective. We will discuss the meaning of dimensions in detail in Chapter 3. Here we note that it is universal in physics to categorize quantities in terms of the base dimensions, which for mechanics are denoted $M$, $L$, $T$ for mass, length and time. Thus the velocity $v \equiv s/t$ discussed above necessarily has the physical dimensions of $LT^{-1}$. Similarly, the density $\rho$ necessarily has the physical dimensions of $ML^{-3}$. Other quantities have more complicated dimensions. But the dimensional content of the terms in an equation of physics is always the same, meaning dimensional homogeneity. This property was at one time seen as puzzling, but is now recognized as an elementary application of group theory (Bridgman 1922, Wesson 1992). Also, since all the terms in an equation have the same physical dimensions, we can divide through by this and obtain an equivalent equation in which all the terms are dimensionless (i.e., they are pure numbers). Such quantities have the useful attribute of retaining their numerical size under changes of units, which are merely man-made standards for measuring things like mass, length and time. Also, the dimensionless quantities of real-world physics can be brought into correspondence with the numbers of abstract mathematics. This connection can in principle be used in reverse, and Eddington especially argued that much of physics might in principle be deducible from number theory. A less ambitious usage of the dimensionless quantities of physics is to reformulate the Cosmological Principle, so that it means not merely that the universe should "look the same" to all observers, but have physically-constructed dimensionless parameters which are measured to be the same by all observers (Wesson 1978). But however we use the dimensional homogeneity of the equations of science, it should be recalled that the assignment of physical dimensions to quantities is essentially subjective.

A critic might respond to the contents of the previous paragraphs by asking: "If you think that the equations of physics are subjective in nature, or at least partly the result of human imagination, then why do you trust them? Are not the equations of physics just a kind of distillation of common sense?"

This critic is mostly right in what he says, but probably wrong in why he says it. A person is justified in believing in the equations of physics, and these do mainly agree with common sense, but only as ideals that have to be qualified in application to real life. (For example, we can believe in Newton's laws of motion, but only when these are modified by the inclusion of friction.) It is wrong to believe that the laws of physics are sacrosanct. Certainly, they are not edicts of the kind found in the Bible. The average, practising scientist is not like the religious zealot who is dedicated to scripture. (There are a few scientific zealots, but their views are distrusted by the majority.) Rather, science has strength because its practioners are willing to take periodic looks at its foundations and ask if they are sound. And a good theoretician, in any field of science, must be willing to abandon a line of research if it proves invalid.

The amount of time and energy invested in producing a typical research paper is often underestimated by the non-scientist. The starting point of a new project is frequently an idea, which may be of a technical kind in an experimental area or of a more philosophical kind if the researcher is in a theoretical area. Today, most ideas are actually developed by more than one individual, and include graduate students, colleagues and sometimes technical personnel. Of the order of a hundred people may be involved in large projects, like mapping the human genome, searching for elementary particles or carrying out an astronomical survey. It is a non-trivial job to keep everybody 'in the loop' for months or years, and to coordinate their activities so that the research progresses in the most productive manner. Eventually, when the results are at hand, these are written up in a paper. The task of writing a paper is detested by many scientists. In large groups, the designated scribe is sometimes rewarded by first place in the list of authors. Otherwise, the general rule is that the authors' names appear alphabetically. A departure from this usually means that one researcher has made an exceptionally large contribution; but it may also indicate that a supervisor is pre-empting the work of graduate students or others with a lower place on the academic ladder. Such abuses happen, as do misuses of the refereeing process. The latter consists in sending the paper to one or more anonymous peers by the editor of the journal to which it is submitted. Though it is not common, there have been cases where the unknown referee has usurped the results in an article, while delaying an official response to it. The refereeing process is the most contentious part of the obstacle course through which the author has to steer a paper if it is to be published by a regular, hard-copy journal. Not surprisingly, some scientists prefer to short-cut the system, by sending the article to an electronic website. There, it can be read by all. However, this 'democratization' of science also brings with it many papers that are badly written, have poor logic or are just plain wrong. Many of the articles on websites will — after revision in accordance with readers' comments — be ultimately sent to regular journals. Assuming that the journal referees eventually recommend publication of the paper, the editor will send it to the printer. To avoid typesetting or software errors, the printer will usually send a preliminary copy or proof of the article to the first-listed author. When this is returned with corrections as needed, the paper is finally printed. It will be available to the general populace, either in a library or via an electronic version of the journal. Given the rigmarole of the publishing business, it is hardly surprising that from writing a draft to the appearance of the final version, a paper is typically delayed by six months to a year. In fast-moving areas of science such as genetics and cosmology, research results can be obsolescent before the public learns about them.

Despite the time and effort involved in publishing a scientific paper, more are being produced now than ever before. In the century from 1900 to 2000, research went from being the occasional occupation of the intellectual to being the staple of the modestly-educated person. Science has become an industry. And like other things which are mass-produced, the question arises of quantity versus quality. Although there is a wide variation, a productive researcher might be responsible for a couple of hundred papers during a career. However, a perusal of the journals today shows a host of articles which add an increment of insight to a hypothesis or a decimal point to a numerical result, but a dearth of papers which have a genuinely new idea or an original calculation. This is particularly the case in medicine and physics. In fact, the contents pages of most scientific journals have become so nit-pickingly technical as to be indecipherable to the average person. This may mark the demise of common sense as the basis for science. For why the outcome of some scientific calculation may be consistent with other knowledge or agree with experiment, it cannot be considered "common sense" in the true meaning of that phrase if it cannot be understood by the average or common man/woman. In a way, the credibility of science is threatened by its own cleverness.

Even professional scientists distrust things which appear to be too clever or abstract. There are many physicists who believe implicitly in

Newton's laws (and indeed trust their lives to them every day when driving home), but are uneasy about Einstein's laws. Yet the two sets are supposed to be connected by a secure line of reasoning. To compress the argument: Newton's laws of motion plus gravity need to be modified by the introduction of the invariable speed of light (special relativity), and the separate labels of space and time need to be joined into a manifold (spacetime) which is moreover curved by matter (general relativity), so that the force of gravity becomes the curvature of an imaginary surface. This statement is a condensation of what takes a couple of hundred pages to write out in detail. But whether in short form or long form, there are many people with a professional training in physics who will agree with the starting point but distrust the conclusion. The majority of these are not, by the way, 'cranks'. The latter are those who decline to listen to any argument which gainsays their own narrow viewpoint. By contrast, many reasonably open-minded folk find it difficult to follow the train of thought which, in effect, goes from a bouncing soccer ball to a singular black hole. For many people, common sense is lost somewhere along the way.

The concept of common sense is, in fact, a slippery one. Opinions about what is 'obvious' differ from person to person; and even if there is consensus about what is sensible at some point in history, it will more often than not change with time. In pre-Copernican days, it was apparently 'obvious' to most people that the Sun went around the Earth; but today an individual holding such an opinion would be called an idiot or a lunatic.

We should, however, be careful not to use the follies of history to give the impression that our ancestors were uniformly stupid. For example, it is frequently implied that scientists and philosophers of the past believed that the Earth was flat. This is incorrect. Our ancestors had the opportunity throughout prehistory to observe the phases of the Moon, which are the semicircular shapes produced when sunlight strikes a spherical body. Even though the physics may not have been clear to the average cave dweller, the fact of the circular shape must have been obvious. There are indications from archaeology that the original Indian inhabitants of North America could also see the phases of the planet Venus. This is not so surprising, when we recall that their eyes were more acute than those of the modern urbanite, who is more accustomed to seeing a street light than a planet. It is also reported that a man with sharp eyes, keeping watch from the top of a mast on a ship at sea, could detect the curvature of the horizon. Plato, in the pre-Christian era, wrote about the circle and the heavens. And of course the history of humankind is punctuated by observations of eclipses, when the Sun's disk is cut by the circular shape of the Moon, or when the circle of the Earth's shadow is cast onto its face. So, we realize on reflection that our forebears were not all card-carrying members of the flat-Earth society. In the modern Monty Python movie *The Meaning of Life*, the story of men's silly beliefs begins with a galleon that sails over the edge of the world into oblivion. But that is where the idea belongs: in fantasy. People in the past had their own versions of common sense, which while we may not endorse them today were nevertheless reasonable by ancient standards. Our ancestors were not morons. It is just that views of what is sensible have changed through time.

Do we really expect that the science of today will also be the accepted norm a hundred years hence? Almost certainly not. Assuming it does not defeat itself by trivial complexity (see above), science appears to have an open future. In this regard, it is like the arts, where there is always a new vogue in waiting. Indeed, science could probably only be halted by some significant sociological shift. This might be of the catastrophic variety, where society as a whole would be frozen by some natural or man-made calamity, maybe associated with global warming. Or it could be of the insidious variety, where society decides that new science is not desirable, such as might happen if experiments become too expensive or have potentially negative consequences. The Large Hadron Collider, which was completed in the fall of 2008, provides an example in the latter class (Figure 1.4). Its cost was around 10 billion dollars, which is comparable to the gross domestic product of a small country; and its high-energy collisions were feared by some, who argued that they could lead to the spawning of tiny black holes, which might eat up the Earth! However, while it is possible to imagine scenarios whereby the progress of science is halted on the experimental/observational front, it is unlikely that it can be stopped on the theoretical front. Indeed, many people think of “science” as shorthand for the spirit of inquiry and the urge to understand which separates humans from animals.

**Figure 1.4.** The large Hadron Collider is an expensive gadget which may be one of the last flings of experimental science.

Eddington was a quiet champion of the power of the human mind, a belief he shared with that of his contemporary Einstein. The latter is, of course, recognized as the paramount thinker, especially in regard to the foundation of the special and general theories of relativity. Later, we will examine these accounts in some detail. But for now, all we need to know is that the special theory describes events as affected by velocities; while the general theory extends to accelerations and forces, notably that of gravity (and by implication, masses). However, while the effects of relativity are now well understood, it is still a question of controversy as to whether Einstein discovered or invented it. Specifically, it is unclear whether or not Einstein was aware of the results of the Michelson–Morley experiment (see Chapter 7). This is commonly regarded as the breakthrough observation, which showed the invariance of the speed of light, and the non-existence of the medium (aether) which was supposed to support electromagnetic waves. The question of whether Einstein was aware of experiments that supported his theory of relativity is not only of interest to historians of science. For the larger question — of whether science is discovered or invented — goes to the heart of the subject, affecting both its contents and how we carry it out. On this question, Eddington (1928, 1939) wrote at length and with remarkable insight. He was of the opinion that science is largely invented.

The allegory of the fisherman and his net is one which is often quoted as illustrating Eddington's views. The fisherman has a net with a certain mesh dimension, and on retrieving his catch he notices that all of the fish have a minimum size, a rule he (wrongly) attributes to the sea and its contents, whereas it is actually a property of his net. Eddington applied this and other allegories to the sciences, arguing that they are at least partly subjective in nature. His philosophical views have sometimes been misinterpreted, and he certainly did not believe that the world is created inside our own heads, like the solipsist. But while he admitted the existence of an external world, he was convinced that our interpretation of it is necessarily conditioned by the biological and mental traits which attach to us being human. It is in this context that we should understand his much-quoted statement: "To put the conclusion crudely — the stuff of the world is mind-stuff."

In the following chapters, the aim is to inquire how far this provocative statement holds up in the context of modern science. There have assuredly been great changes in the mathematical sciences since Eddington's time, notably in quantum mechanics and cosmology (Bell 2004, Wesson 2007). It is now widely accepted that the physical sciences, at least in regard to how they are discussed, contain a cultural element (Shapin 2009). The biological sciences, also, have undergone a vast development (though Eddington was sympathetic to these, arguing that there is less interpretation intervening between the thing being observed and the person doing the observing). In the following five chapters we will concentrate on the 'hard' sciences. It is already clear that if Eddington's allegory of the fisherman's net is to be applied today, we will have to replace his single net by a suite of them — with the mesh sizes and shapes necessary to 'catch' the quantities of modern science. Our account will be quite concrete: we will, for example, ask just what is meant by things like the density and pressure of matter, which are used glibly by the physicist but whose origin we need to pin down. In this inquiry, we will perforce need to employ the occasional equation. But for the non-mathematically inclined, these should be regarded as shorthand for wordy statements, somewhat in the way a cartoon is used to convey the essence of a political argument. For more complicated equations — like Einstein's for general relativity — they can be regarded as paintings in a gallery, to be viewed and registered by the mind, before it moves on to consider other things. (Every equation is in any case accompanied by an explanation in words, as accurate as can be achieved by that medium.) Talking of works of art, we will frequently run across parallels between these and the products of science. We will also draw comparisons with music and literature, and briefly investigate that most thorny of subjects, the overlap (or lack of it) between science and religion. For science is an integral part of the culture of the modern world, and it is legitimate to ask how it relates to the more intuitive aspects of human thought.

In the present chapter, we have given an account of the warp of science. This means the basic laws and structure of it, as presently understood by the majority of scientists. In the following five chapters, we will sort through the material which is to be added to the warp, identifying the components of the scientific weft. This process is intricate and fascinating. The weaver who aims to produce a garment on a loom can set up the warp from any basic material, but the colour and texture of what he creates depends on picking through balls of wool or cotton for the weft, a process which involves choice. (Our scientific weft will be examined in the last chapter.) Likewise, the scientist who aims to give a complete theory of some natural phenomenon is faced throughout by issues of choice. In the case of a great scientist like Einstein, it is as if he set out single-handedly to weave the Bayeux Tapestry. We need to inquire how such things are achieved.

We particularly need to inquire about the issue to which Eddington drew attention: between the external world and the scientific account of it, there is a marvellous but poorly-understood filtering device, namely the human mind.

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