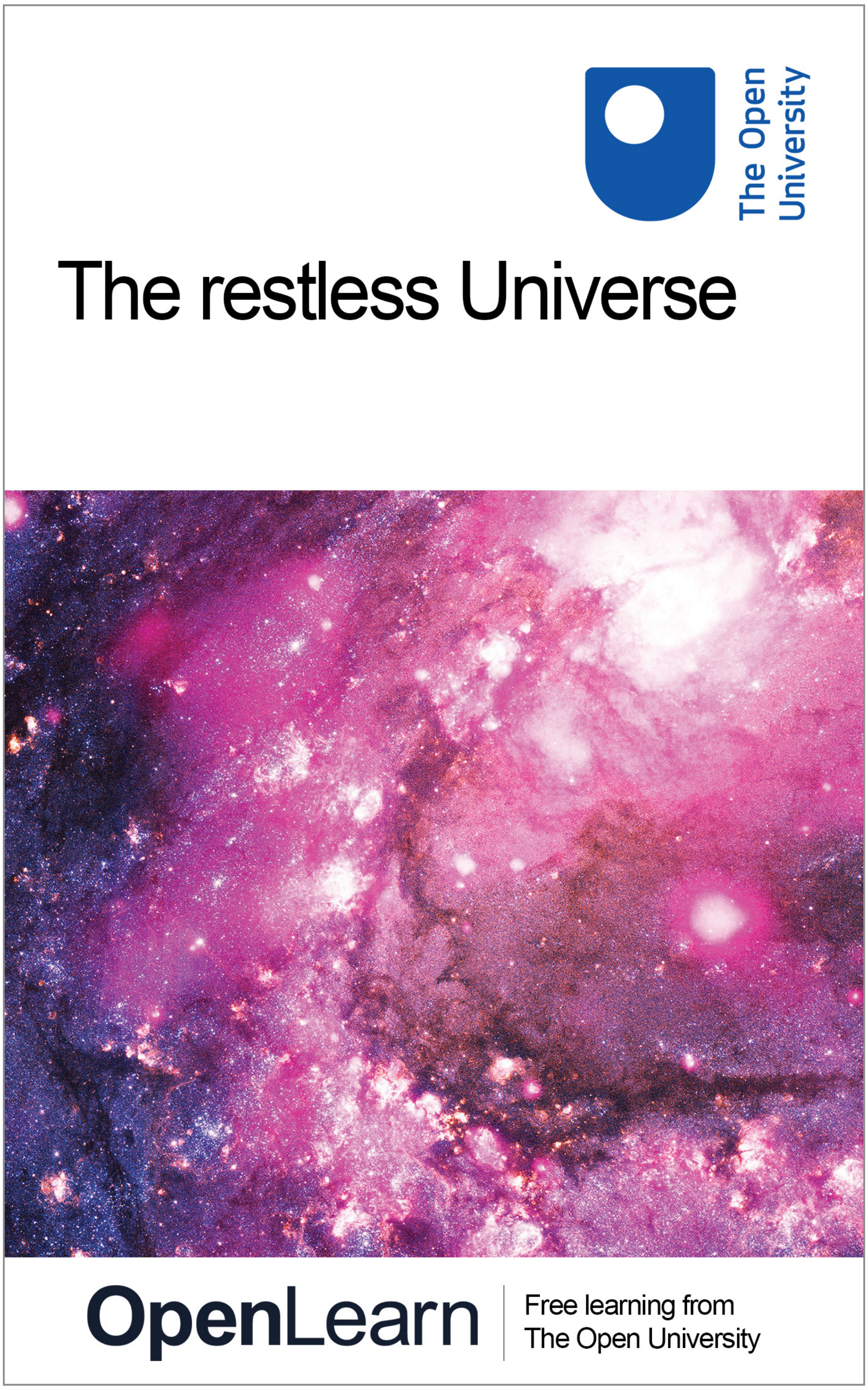
The restless Universe



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Introduction

This course offers a fascinating overview of the 'big ideas' that have shaped physics from the time of Kepler to the present day. Using little mathematics, the course surveys fundamental features of key physical theories and provides the essential context for the further study of physics.

This OpenLearn course provides a sample of level 2 study in Science

Learning Outcomes

After studying this course, you should be able to:

- explain the meaning of all the emboldened terms introduced in this course
- explain what is meant by a physical world-view and describe some of the major world-views that have emerged during the evolution of physics
- describe some of the major concepts of physics, give brief biographical sketches of some of the major contributors to the development of physics and name some of the major events that have helped to shape the subject
- comment on some of the philosophical issues that are raised by the study of physics.

1 Physics and the physical world

Studying physics will change you as a person. At least it should. In studying physics you will encounter some of the deepest and most far-reaching concepts that have ever entered human consciousness. Knowledge gathered over many centuries, that has been subjected to continuous scientific scrutiny, will be presented, along with its applications. Fact will follow fact, useful theory will succeed useful theory. Amidst this rich mix of information, newcomers to physics might not always appreciate how major discoveries have radically changed our attitude to ourselves, our natural environment, and our place in the Universe. In this course we have tried to avoid intellectual overload, to ensure that you have sufficient time to appreciate the significance of each of the main ideas and applications of physics discussed. We want your exposure to physics to change you, and we want you to be consciously aware of that change.

As part of that effort, this course gives a qualitative overview of some of the 'big ideas' of physics. Presenting ideas in this way, largely shorn of detail, and without much of the evidence that supports them, should help you to see the big picture and to appreciate some of the deep links that exist between different parts of physics. But this approach also has its dangers. It may obscure the fact that physics is more than a set of ideas about the world, more than a bunch of results: physics is also a *process*, a way of investigating the world based on experiment and observation. One of the biggest of all the 'big ideas' is that claims about the physical world must ultimately be tested by experiment and observation. Maintaining contact with the real world in this way is the guiding principle behind all scientific investigations, including those carried out by physicists.

Another important function of this course is to stress that physics is a cultural enterprise. All too often physics can have the appearance of being a collection of facts, theories, laws and techniques that have somehow emerged from nowhere. This, of course, is not the case. Throughout the ages, it has been the endeavour of individual men and women that has made possible the growth of science and the advancement of physics. This course attempts to emphasise the cultural aspect of physics by providing biographical information about some great physicists of the past. The coverage is neither fair nor complete, but it should remind you that physics is a human creation. Most physicists delight in tales of the struggles, foibles and achievements of their predecessors, and many feel that their understanding of physics is enhanced by knowing something of the paths (including the dead ends) that their intellectual forbears have trodden.

Do not expect to understand everything you read in this course. On the surface, we hope that it provides a coherent and interesting survey. But the more you think about some of the issues raised, the more puzzling they may seem. If, at the end of the course, you are left with questions as well as answers, that will be an excellent starting point for further studies in physics.

A note on powers of ten and significant figures

Physics involves many quantities that may be very large or very small. When discussing such quantities it is convenient to use *powers of ten notation*. According to this notation

$$1\,000\,000 = 10^6 = \text{a million}$$
$$\frac{1}{1000} = 0.001 = 10^{-3} = \text{a thousandth.}$$

The small superscript attached to the ten is called a *power*. As illustrated by the above examples, a positive power indicates the number of zeros after the 1; a negative power indicates the number of zeros before the 1, including the zero before the decimal point.

A quantity is said to be written in *scientific notation* when its value is written as a number between 1 and 10, multiplied by 10 raised to some power, multiplied by an appropriate unit. For example, the diameter of the Earth is about 12 760 kilometres; in scientific notation this could be written 1.276×10^4 km. One advantage of scientific notation is that it allows us to indicate the precision claimed for a given quantity. Stating that the Earth's diameter is 1.276×10^4 km really only claims that the diameter is somewhere between 12 755 kilometres and 12 765 kilometres. Had we been confident that the Earth's diameter was 12 760 kilometres, to the nearest kilometre, we should have written 1.2760×10^4 km. The meaningful digits in a number are called **significant figures**. (Significant figures do not include any zeros to the left of the first non-zero digit, so 0.0025 has *two* significant figures, for example.) One advantage of writing numerical values in scientific notation is, therefore, that all the digits in the number that multiplies the power of ten are *significant* figures.

We will introduce the units in which physical quantities are generally measured. For example, time is measured in seconds, length in metres, energy in joules and electric current in amperes. A detailed understanding of these units is not needed yet, and would make a rather dull start to this course. In the few places where units appear, please skip past them if the meaning is unclear.

Many physical quantities span vast ranges of magnitude. Figures 1 and 2 use images to indicate the range of lengths and times that are of importance in physics.

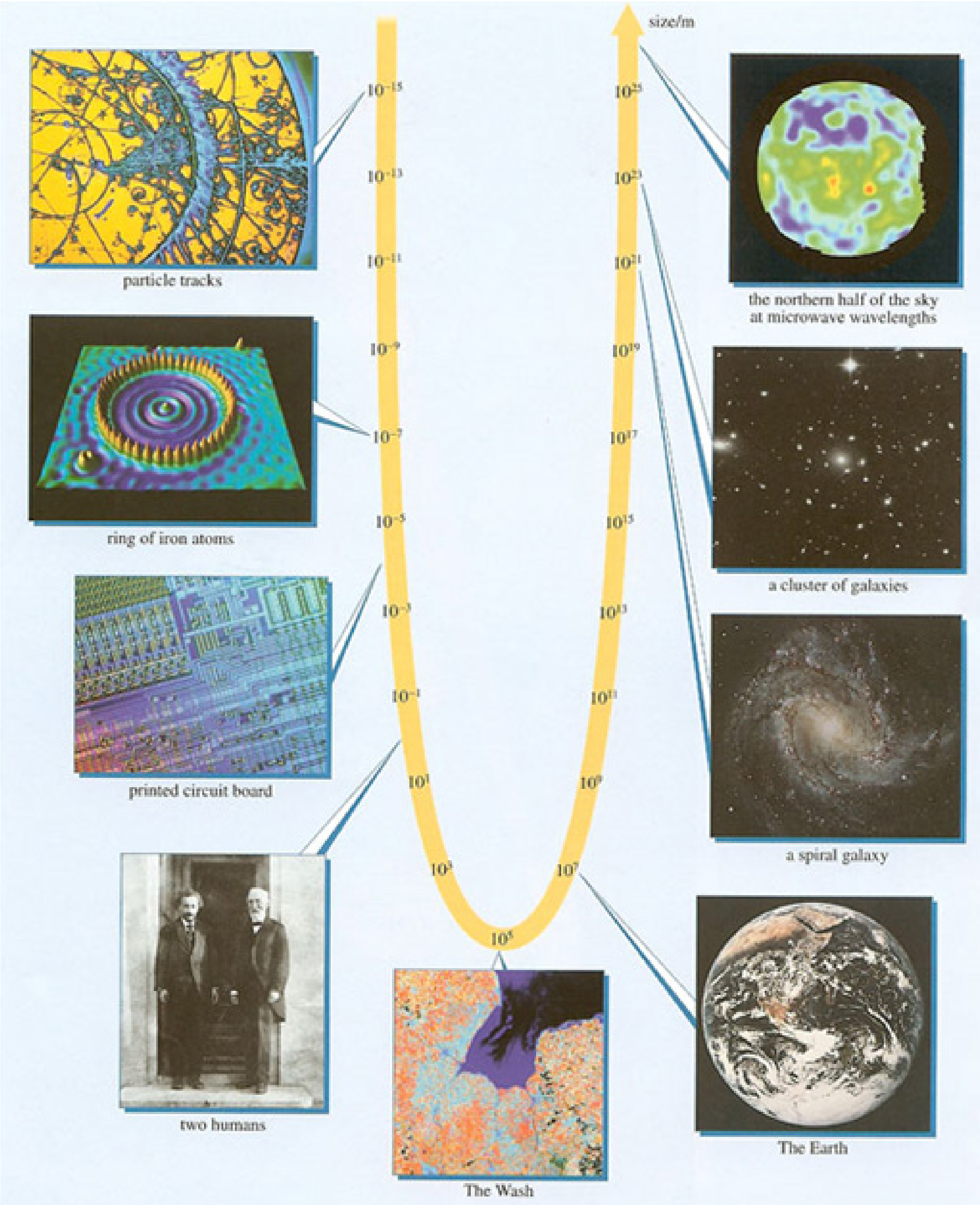

Figure 1 Snapshots of the Universe at a selection of length scales from the smallest to the largest scale

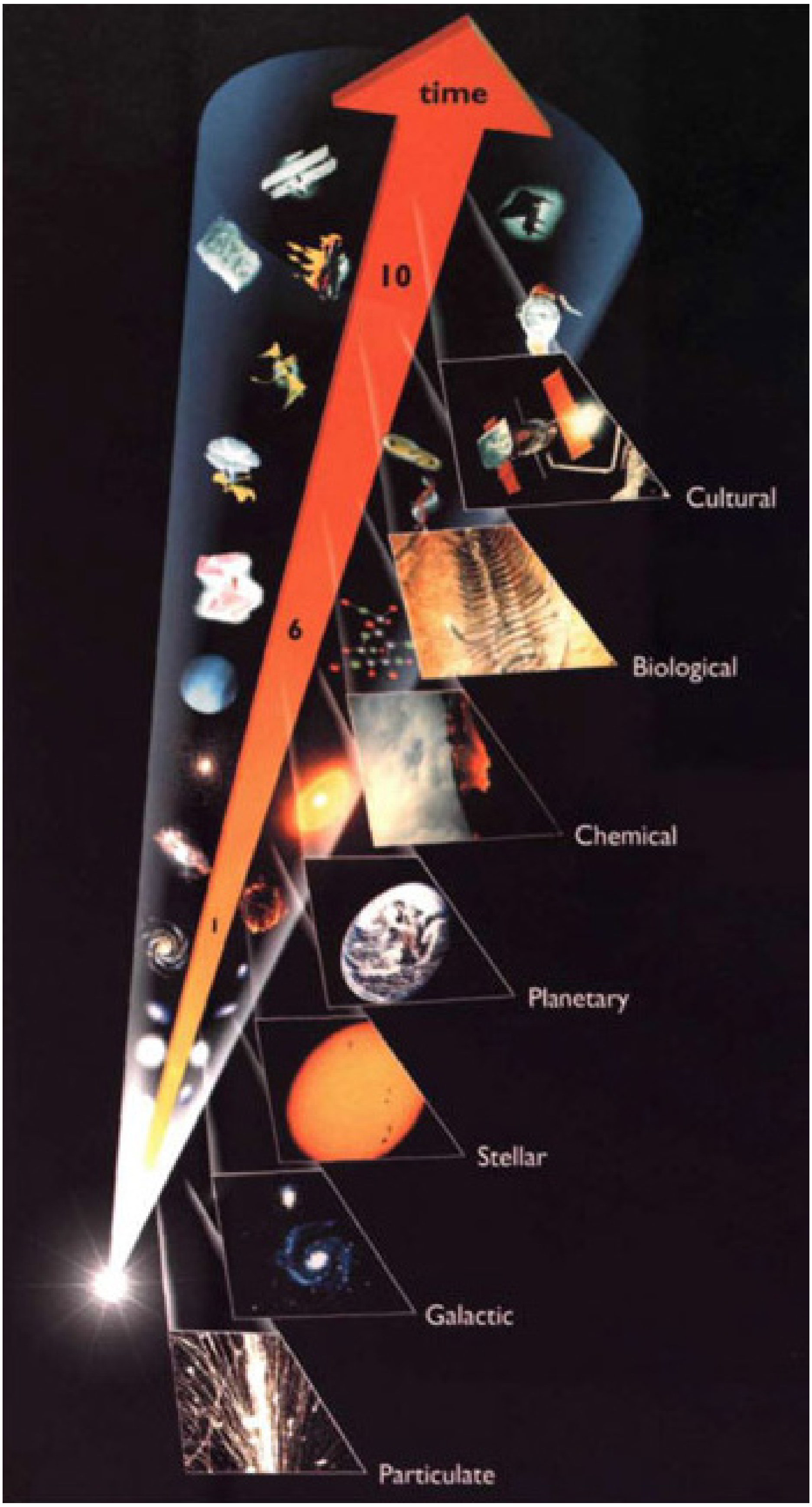

Figure 2 A range of time scales of relevance to the Universe. Time is measured in billions of years since the Big Bang. The evolution of the Universe is marked by the onset of various ages: from the appearance of particles and galaxies to the emergence of life and

intelligence.

2 World-views

2.1 The lawful Universe

2.1.1 Science and regularity

> 'Our experience shows that only a small part of the physical Universe needs to be studied in order to elucidate its underlying themes and patterns of behaviour. At root this is what it means for there to exist laws of Nature, and it is why they are invaluable to us. They may allow an understanding of the whole Universe to be built up from the study of small selected parts of it.”
>
> John D. Barrow (1988), The World Within the World, Oxford.

Science, it is widely agreed, originated from two main sources. One was the need to develop practical knowledge and to pass it from generation to generation. The other was a more spiritual concern with the nature and origin of the world. Common to both of these well-springs of science was an appreciation of the regularity of Nature. The way to build an arch that would not fall down today was to build it in much the same way as an arch that had not fallen down yesterday. The way to predict the waxing and waning of the Moon this month was to assume that it would follow much the same course as the waxing and waning that had been observed last month and the month before.

The observation of regularity in Nature allows *predictions* to be made concerning the future course of particular events. In many primitive societies these regularities were ascribed to the activities of gods or other mystical spirits. However, gradually, over a long period of time, there emerged the notion that the behaviour of the world was guided by a set of *natural laws* that were themselves regular, in the sense that identical situations could be expected to have identical outcomes.

One of the first scientists to make frequent use of the concept of a law of Nature, in the sense that we now use that term, was the Franciscan friar and scholar Roger Bacon (c. 1214-1292). Bacon is traditionally credited with the invention of the magnifying glass, but he is best remembered as an effective advocate of the *scientific method* and a follower of the maxim 'Cease to be ruled by dogmas and authorities; look at the world!' He lived at a time when the commonly accepted view of the world was fundamentally religious, and the Catholic church to which he belonged was coming to embrace the authority of the ancient Greek philosopher Aristotle on matters pertaining to physics and astronomy. Bacon's independence of mind brought him into conflict with the church, and he suffered fifteen years of imprisonment for heresy. Nonetheless, he helped to prepare the way for those who, irrespective of their own religious beliefs, insisted that the scientific investigation of Nature should be rooted in experiment and conducted on a purely rational basis, without reference to dogmatic authority.

Figure 3 Roger Bacon

Laws of Nature are now a central part of science. Carefully defined concepts, often expressed in mathematical terms, are related by natural laws which are themselves often expressed in a mathematical form. Just what those laws are is a central concern of physicists, who see their branch of science as the one most directly concerned with discovering and applying the fundamental laws of Nature. Improvements in our knowledge of natural laws have repeatedly led to a broadening and a deepening of our understanding of the physical world and hence to a change in the scientific world-view.

However, the fundamental requirement that the laws should be rational and rooted in experiment has survived all changes to the detailed content of those laws.

2.1.2 Mathematics and quantification

Roger Bacon once said 'Mathematics is the door and the key to the sciences'. This statement aptly summarises the role of mathematics in science, particularly in physics, and it is not hard to see why.

Much of physics is concerned with things that can be measured and quantified, that is, expressed as numbers, multiplied by an appropriate unit of measurement such as a metre or a second. It is natural to turn to mathematics to try to reveal patterns underlying such measured data. This is more than a matter of arithmetic. By Roger Bacon's time the basic ideas of *algebra* had been developed, mainly by Arabic mathematicians and astronomers. The idea of *representing* a quantity by a symbol, such as x or t is extremely powerful because it allows us to express general relationships in a very compact way. For example, in the equation

$$h = \frac{1}{2}gt^2, \qquad (1.1)$$

the symbol h represents the height fallen by an object that has been dropped from rest, the symbol t represents the time the object has been falling, and g is a constant with a known value (g = 9.81 metres per second per second). Equation 1.1 encapsulates a wealth of information about falling objects, information that is precise and useful. The tools of algebra allow us to go further. For example, the above equation can be rearranged to read

$$t = \sqrt{\frac{2h}{g}}, \qquad (1.2)$$

so now, if we know the height fallen by an object, we can work out how long it has taken to fall.

Mathematics provides a natural medium for rational argument. Given an equation that relates various quantities, the rules of mathematics allow that equation to be re-expressed in a number of different but logically equivalent ways, all of which are valid if the original equation was valid. Given two equations, mathematical reasoning allows them to be combined to produce new equations which are again valid if the original equations were valid. Long chains of reasoning can be put together in this way, all of which are guaranteed to be correct provided that the starting points are correct and no mathematical rules are transgressed. Quite often these arguments are so long and detailed that it would be impossible to follow them in ordinary language, even if it were possible to express them at all.

Mathematics has been an immensely effective part of the scientist's toolkit throughout history. It was the increased use of mathematics in the sixteenth and seventeenth centuries, in the hands of individuals such as Galileo Galilei (1564-1642) and Isaac Newton (1642-1727), that opened a new era of physics and marked one of the greatest flowerings of science. Galileo and Newton, it should be noted, were both, at key times in their careers, professors of mathematics. In both cases they brought mathematical precision and rigour to the study of science, and in Newton's case made major breakthroughs in mathematics in the process. The types of mathematics used in physics are extremely varied. Practically every branch of mathematics that has developed over the centuries has been used within physics. Sometimes physics has provided direct inspiration for new mathematical concepts, sometimes abstract mathematical theories have found completely unexpected uses in physics, years after their introduction as products of pure thought.

Despite its power, physics students often find the extensive use of mathematics troublesome and some think of mathematics as providing a barrier to understanding. Do not let this happen to you. From the outset, you should regard mathematics as a friend rather than a foe. As the course progresses, you may meet some mathematical ideas that are new to you, or you may need to improve your ability to use methods you have met before. These are not distractions from trying to understand physics, but are the tools needed to make that understanding possible. It is only through using mathematics that a secure understanding can be achieved. When you see an equation, welcome its concision and clarity and try to 'read' the equation just as you would the large number of words it replaces. Learn to get beneath the squiggles and the equals sign and to understand the quantitative assertion that is being made.

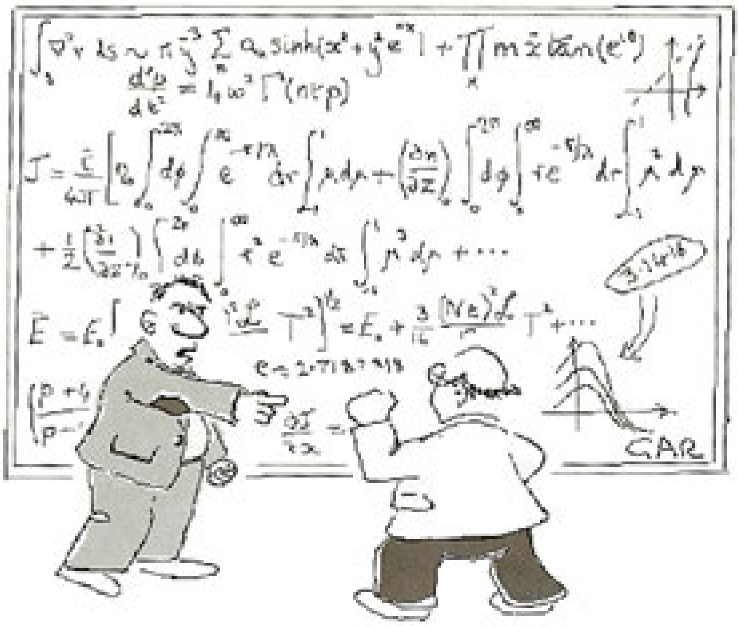

Figure 4 “I see through your squiggles.”

Later, you will see how graphs can be used to visualise an equation and how consideration of special cases and trends can help unpack its meaning.

Question 1

When Jesuits first visited China they spoke about the 'laws of science'. The Chinese thought this was a ridiculous notion: people could be persuaded to obey the laws of the Emperor, but sticks and stones have no intelligence so it is absurd to think of them as 'obeying laws'. How would you respond to this?

Answer

The Chinese were perhaps right, but their complaint is more about language than substance. When we talk about a system obeying a scientific law, we do not mean that the system has understood the law and is consciously following it. We just mean that the behaviour of the system follows a pattern that is predictable, and that someone has discovered and announced this pattern as a scientific law.

2.2 The clockwork Universe

2.2.1 Mechanics and determinism

It is probably fair to say that no single individual has had a greater influence on the scientific view of the world than Isaac Newton. The main reason for Newton's prominence was his own intrinsic genius, but another important factor was the particular state of knowledge when he was, in his own phrase, 'in the prime of my age for invention'.

In 1543, a century before Newton's birth. Nicolaus Copernicus launched a scientific revolution by rejecting the prevailing Earth-centred view of the Universe in favour of a **heliocentric** view in which the Earth moved round the Sun. By removing the Earth, and with it humankind, from the centre of creation, Copernicus had set the scene for a number of confrontations between the Catholic church and some of its more independently minded followers. The most famous of these must surely have been Galileo, who was summoned to appear before the Inquisition in 1633, on a charge of heresy, for supporting Copernicus' ideas. As a result Galileo was 'shown the instruments of torture', and invited to renounce his declared opinion that the Earth moves around the Sun. This he did, though tradition has it that at the end of his renunciation he muttered '*Eppur si muove*' ('And yet it moves').