Science & Education **2**: 345–362, 1993.

Newtonian in Mind but Aristotelian at Heart

MAURICE G. EBISON

Consultant in Physics, Institute of Physics, 47 Belgrave Square, London SW1X 8QX, England

ABSTRACT: This article discusses some core features of Aristotelian physics, and looks at their transformation by first Galileo, and then Newton. It shows how the Aristotelian view was rooted in commonsense, and indicates why this is the reason that such understandings prove so resistant to physics instruction. Some suggestions are made for guiding effective pedagogy.

> Moreover, mechanics is to physics what the skeleton is to the human figure – at first glance it may appear stiff, cold, and somewhat ghastly, but even after a brief study of its functions one experiences with mounting excitement the discovery of an astonishingly beautiful design, of a structure that is ingeniously complex, yet so simple as to be almost inevitable. (Gerald Holton, *Introduction to Concepts and Theories In Science*)

> Mechanics is one of the branches of physics in which the number of principles is at once very few and very rich in useful consequences. On the other hand, there are few sciences which have required so much thought – the conquest of a few axioms has taken more than 2000 years. (Rene Dugas, *A History of Mechanics*)

> Although it is unsafe to read logical necessity into particular historical developments, the special position occupied by mechanics amongst the other branches of physics and natural science must be emphasised, for it was this special position that made it the starting point of modern science. (S. Sambursky, *The Physical World of the Greeks*)

> There is, in nature, perhaps nothing older than motion, concerning which the books written by philosophers are neither few nor small; nevertheless I have discovered by experiment some properties of it which are worth knowing and which have not hitherto been either observed or demonstrated. (Galileo Galilei, *Dialogues Concerning Two New Sciences*)

> Of the intellectual hurdles which the human mind has confronted and has overcome in the last fifteen hundred years, the one which seems to me to have been the most amazing in character and the most stupendous in the scope of its consequences is the one relating to the problem of motion. (Herbert Butterfield, *The Origins of Modern Science: 1300–1800*)

> In the Beginning was Mechanics. (Max von Laue, *History of Physics*)

> I offer this work as the mathematical principles of philosophy, for the whole burden of philosophy seems to consist in this – from the phenomena of motions to investigate the forces of nature, and then from these forces to demonstrate the other phenomena. (Isaac Newton, Preface to the *Principia*)

INTRODUCTION

Mechanics, both historically and logically, represents the foundation of physics and the key topic in mechanics is the study of motion because from early times scientists have heeded the axiom:

ignorato motu, ignoratur natura.

The motion of heavenly bodies was one of the first pre-occupations of human thought in the great civilisations of Egypt and Babylon. For example, in Egypt the changing seasons were related to the rising of certain prominent stars. In Babylon the observation of eclipses played a vital role in astronomy. From the beginning of the second millenium the positions of heavenly bodies was systematically recorded and from about 600 B.C. Babylonian astronomers used the records to develop highly complex and amazingly accurate mathematical methods of describing the motions of the heavenly bodies to predict eclipses. Their methods, however, remained essentially empirical and it was left to the Greeks to begin the development of a rational structure.

Whilst the Greeks successfully developed the principles of statics those of dynamics were obscured by incorrect concepts until the end of the Middle Ages. There then followed the rapid development of dynamics in the hands of Kepler, Galileo, Descartes, and Newton and the codification of its laws by mathematicians such as Euler, Lagrange and Laplace. So successful was the process that by the end of the nineteenth century there was a general belief that the structure was complete and perfect. But this belief was shattered by the appearance of two supreme but unforeseen developments of classical mechanics – relativistic mechanics and wave mechanics.

Whilst our main concern will be almost exclusively with dynamics it is interesting to recall that Archimedes was able to construct a rational scheme for statics which became the most complete branch of ancient mathematical physics and reached a standard which was not approached in other sciences.The first of his works *On the Equilibrium of Planes* deals with the statics of rigid bodies in a way reminiscent of a geometry textbook. His second, *On Floating Bodies*, laid the foundations of hydrostatics.

GREEK DYNAMICS

Whereas Archimedes' work in statics has been of lasting value the work of the Greeks in dynamics was not anywhere near as successful. Nevertheless we need to consider it because it was based on the ideas of Aristotle, who exerted vast influence on views of the physical universe for sixty generations. No other personality in science had so deep and long-lasting effect on subsequent thought. His dynamics is the key to understanding how physics developed in the Middle Ages and thus to an understanding of the difficulties which modern science initially had to face.

ARISTOTLE ON MOTION

In his theory of motion Aristotle distinguishes three types of motion but only two of them are significant for physics. The first of these is *natural motion* which is followed by bodies under the influence of forces found within the body itself. Three forms of natural motion can be observed. There is the downward fall of heavy bodies and the upward motion of light bodies like smoke and fire. When there are no external obstacles to the motion, bodies seek their own 'natural place'. For heavy bodies this is the centre of the earth whilst for fire, for example, it is a spherical shell just below the first of the celestial spherical shells. The third type of natural motion is the rotation of heavenly bodies. This also results from internal forces but differs from the terrestrial motions in being eternal and unchangeable. The other category of motion significant for physics is *forced motion* which is the motion of an object which is *not* toward its natural place. Such motion is always caused by an external force and as the force increases the speed (note, *speed* not acceleration) of the motion increases. When the force is removed the motion must stop. This theory is in accord with our everyday experiences of shifting objects such as tables and desks across the floor.

So *all* motion required a moving force, either internal or external, and the Aristotelian doctrine of inertia was a doctrine of rest. It was *motion*, not rest, that had always to be explained; the modern recognition of inertial motion as the uniform and straight line motion of a body without the action of force was completely alien to Aristotle. For him, wherever motion existed and no matter how long it had existed, a force had somehow to be introduced to account for it.

ARISTOTLE'S MODEL OF THE UNIVERSE

Aristotle incorporated his basic ideas on motion into a model of the universe. With the earth as a fixed sphere at the centre he divided his universe into a sub-lunar, or terrestrial region and a celestial region. All terrestrial matter was composed of one or more of four elements, *earth*, *water*, *air* and *fire* and each element had its natural place in the form of concentric spheres starting with earth and with successive surrounding spheres of water, air, and fire. In actual fact, the elements and bodies made up of them are constantly being shifted from their natural positions by the application of a force. An element resists displacement but once displaced it seeks to return to its natural position by the shortest possible path. So fire would tend to rise through Air and Air through Water, whereas Earth would tend to fall through both Air and Water. The actual movement of any real object would depend both on the mixture of the four elements making it up and where it was in relation to its natural place. A good deal of commonsense experience supported this view. For

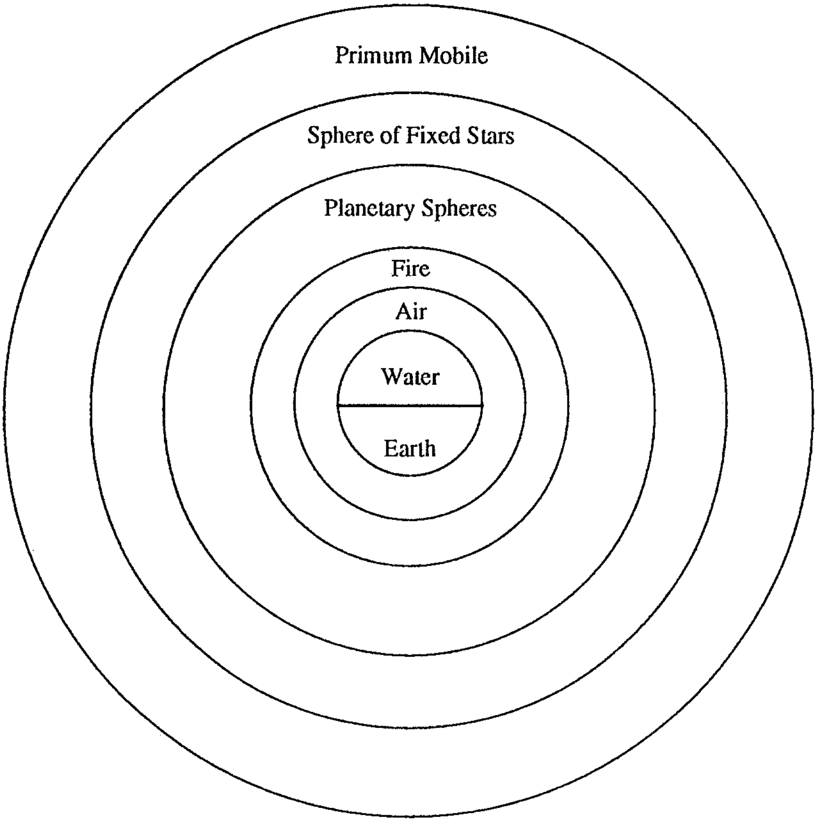


Diagram of medieval concept of world structure.

example, Water bubbles up through the Earth in springs. When sufficient fire is added to Water, by heating it, the resulting mixture of elements, which we now call steam, rises through the Air.

In the celestial region bodies, such as stars and planets, were supposed to move in a far simpler manner than objects near the Earth. The celestial bodies were believed not to contain any of the four ordinary elements but instead consisted solely of a fifth element called *ether* (in later times called the *quintessence* from *quinta essentia* the "fifth essence"). The natural motion of these bodies was neither rising nor falling, but endless revolution in circles around the centre of the universe – the centre of the earth. Celestial bodies, although moving, were thus at all times in their natural places and this set them absolutely apart from objects in the terrestrial region which moved in natural motion only when they returned to their natural places from which they had been displaced.

AREAS OF DIFFICULTY

Though the theory seemed to embrace a very wide range of phenomena there were, of course, one or two areas of difficulty. For example, if a stone is thrown it is not easy to account for its motion once it has left the hand for the stone's internal force could only make it move in its natural motion vertically downwards. It might be said, however, that the theory gained strength from the ingenuity which Aristotelians displayed in bringing the difficult cases within the general sweep of the scheme. In the case of the thrown stone the continued forward motion was explained as being due to the commotion of. the air which the initial movement of the hand had produced and this was passed from layer to neighbouring layer. In particular, the motion continued because air in front of the stone was compressed and rushed round to the back to prevent the vacuum that on no account could be allowed to form. A second difficulty was that falling bodies were seen to accelerate. This was explained by saying that they moved more jubilantly as they neared their natural place.

Now it is important to appreciate that the Aristotelian teaching on motion had great psychological strength. There was a very close interlocking of observations and explanations which covered, without too much difficulty, an immense range of cases which were accessible to observations at that time. In addition, the theory of motion was further buttressed by being a part of a much wider system that was an intellectual *tour de force* in its logical coherence. It is not surprising, therefore, that it proved extremely difficult for the human mind to escape from its grip.

SHOULD ARISTOTLE HAVE ANTICIPATED NEWTON?

It is bordering on the absurd to suggest that if only Aristotle had looked at things more closely he would have beaten Newton by some two thousand years in putting forward the modern view of inertial motion that bodies continue in a state of rest or in motion along a straight line unless acted upon by an external force. It is in fact extremely difficult to escape from the Aristotelian scheme by observation alone. For example, it is sometimes suggested that modern science started when Galileo observed experimentally that two bodies of unequal weight released from the top of the Leaning Tower of Pisa, struck the ground at exactly the same time. Aside from the point that it is unlikely that this particular experiment was ever performed by Galileo, the fact is that in the everyday world some heavy bodies do fall faster than some lighter ones.

It was natural for Aristotelians to focus on bodies failing through a resistive medium such as air or water for this is the kind of motion that we commonly observe. The resistance of the medium could explain in qualitative terms why, for example, a leaf falls more slowly than a boulder. Aristotelians would have considered unresisted motion as an unrealistic abstraction. Indeed Aristotle himself did explicitly argue that in a vacuum, where the resistance to motion would be zero, *all* bodies would move with the same speed and he took this as a piece of evidence that a vacuum could not exist.

Aristotle and his successors did not observe less than, say, Galileo; rather they viewed things from a different stand-point and this was not because they were less intelligent but simply because the rather more quantitative approach of Galileo was irrelevant to their world-view. For them it was not sufficient that a theory should merely describe and predict the facts of observation; it must, above all, give them meaning in a much wider sense by showing the facts to be consistent with and part of a complete philosophical system. To the Aristotelian of the late sixteenth century the theory based upon elements and natural motion was *philosophically* true, clear and certain, precisely because it was part of a satisfying overall scheme which reached across many fields of study. In his view the theory could not be abandoned simply because the detailed motion of two weights dropped from a tower appeared not to be in accord with the scheme which was so much grander than an insignificant artificial 'experiment'.

THE NEED FOR A TRANSPOSITION WITHIN THE MIND

What was needed was a transposition within the mind of the observer; in real life we simply do not have perfectly smooth spheres moving on perfectly smooth horizontal planes nor do we see ordinary objects continuing forever in rectilinear motion in empty space. The real genius of Galileo, of course, was that it occurred to him *to imagine* such objects as geometrical entities moving in an ideal world. His important contribution to physics, in the first instance at least, was not in producing fresh observations or new evidence but rather in convincing people that a transposition within the mind was needed. This is always a supremely difficult task because no mental activity is harder than being asked to handle the same set of data within a completely different framework. Yet it is also a supremely important task because science is much more than lots of facts fitted into a pre-determined pattern. It involves the attempt to fashion a system which will relate and order these facts.

GALILEO CRITICISES ARISTOTLE

Although the Aristotelian system was subject, of course, to a good deal of critical analysis over the years with regard to certain details it was, by and large, the system that Galileo was taught at the University of Pisa. Indeed he started his scientific career in the way that was customary at that time, by annotating Aristotle's *De Caelo*. Nevertheless, he was not long in causing a scandal by performing experiments on the motion of terrestrial objects. Reasoning from the results of these experiments, he was able to point out errors and misconceptions in the Aristotelian ideas on motion, particularly in the free fall of objects, in projectile motion and in the concepts of 'natural' and 'violent' motion themselves and in so doing he laid the basis for modern kinematics.

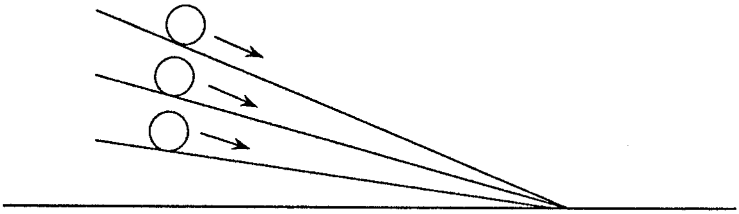
THE IMPORTANCE OF ANALYSIS

Another feature of the genius of Galileo was that he realised that an experimental result had to be very carefully analysed if it was to form the basis for a theory – a casual first glance was not enough. So if different bodies are released simultaneously to fall freely from the top of a tower and do *not* arrive at exactly the same instant at the bottom, this on careful consideration turns out to be far less significant than the fact that they *very nearly* do arrive at the same instant. In a vacuum the times of fall *would* be equal. A focus on this conception is fruitful because it regards the failure of precisely simultaneous arrivals as a *minor* discrepancy instead of a *major* fact requiring explanation in terms of resisted motion and it marks a fundamentally different viewpoint from that of the Aristotelians. In Galileo's time, of course, a vacuum was an unattainable idealisation but Galileo showed that an analysis arising from this idealisation was capable of giving a new and more fruitful understanding of the real world. In examining Galileo's attitude to experiments Gerald Holton reminds us of the old quip:

> Science has grown almost more by what it has learned to ignore than by what it has had to take into account

THE SEARCH FOR UNDERLYING SIMPLICITY

Galileo's theory is more useful than Aristotle's to the progress of physics *not* so much because it represents observational experience more perfectly but rather because it reaches behind any superficial regularity shown by the senses to a underlying but hidden aspect of the way in which the world works. This is a recurring theme in science – the need to search behind the immediate confusion of appearances for an underlying simplicity expressible in mathematical laws. In this particular work of Galileo it was easier to counteract the Aristotelian hypothesis that speed of fall is proportional to weight by reasoning in a thought experiment than by performing extensive experiments which at that time would not have been wholly convincing. It would have been futile to expect to get to the correct result by using the observational methods and the technical equipment then



For each angle, the acceleration was found to be constant.

available. Instead, everything depended on Galileo's ability to 'think away' the air and its effects on free fall.

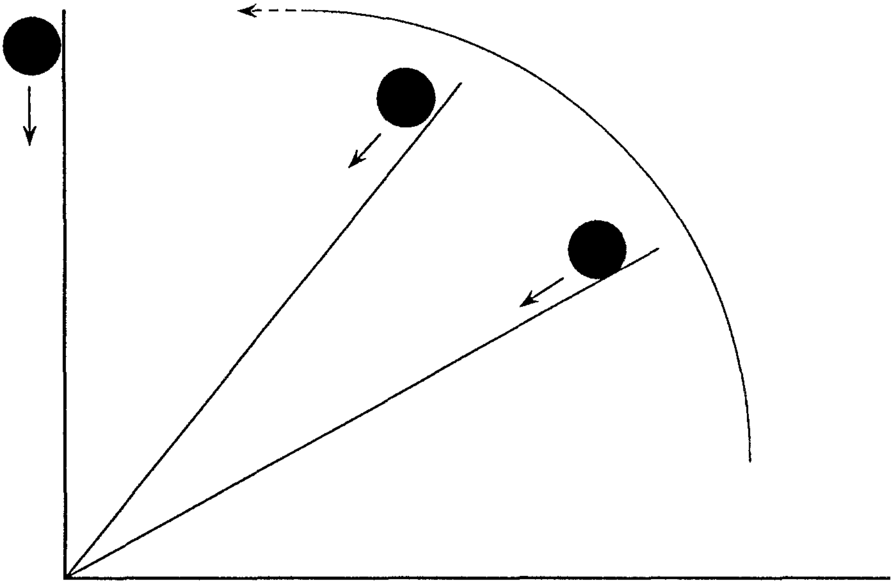
RIGOROUS TREATMENT OF MOTION

In dealing with the motion of freely falling bodies Galileo had a larger overall plan in mind. This was to produce a rigorous, mathematical and general treatment of the motion of objects. He begins by making two distinct suggestions. The first is that 'uniform acceleration' is to be defined as equal changes in speed Δv in equal *times* Δt. Now Galileo knew from his early struggles with the concept of acceleration that it was far from obvious that this is the *only* possible definition. He could have chosen equal speed changes Δv in equal *distances* Δs. The choice simply turned on which definition turned out to be the more *useful* in describing real, observable motions in nature. The second suggestion is that bodies actually *do* fall with uniform acceleration. This was a pure hypothesis from which he deduced some consequences which could be tested experimentally. This was not easy because with the instruments available to him at that time it was not possible to perform the tests on freely falling bodies *directly*. Galileo therefore argued that his hypothesis would be confirmed it it were to be successful in describing another kind of motion related to free fall – the rolling of a ball down an inclined plane.

GALILEO AND INCLINED PLANES

A ball was rolled down a grooved plank lined with smooth parchment and held at different inclinations. The timing was done with a simple water clock. Of course, even in these diluted gravity experiments it was not possible to test *directly* whether $\Delta v/\Delta t$ is constant, because this needed direct measurements of instantaneous velocities. By an ingenious argument Galileo was able to show that *for uniformly accelerated motion from rest the distance travelled is proportional to the square of the time.* This was the result obtained from the experiments.

By extrapolation (often very dangerous!) from the small angle inclina-



Galileo's extrapolation.

tions to steeper and steeper ones up to ninety degrees Galileo argued that in *vertical* fall bodies would move with uniform acceleration.

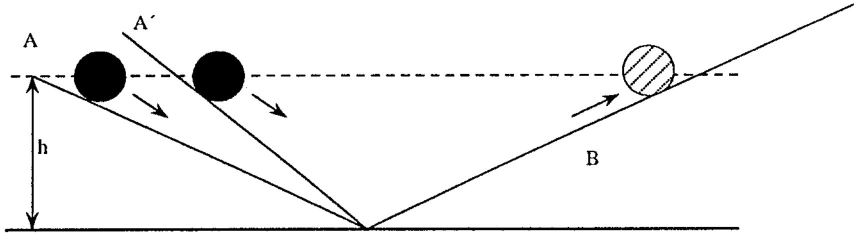
It is not difficult, of course, to criticise Galileo's argument. For example, if the runway is tilted more and more towards the vertical, the ball will start to slip as well as roll and the simple theoretical relationship will no longer hold.

It is not clear whether Galileo actually did all the experiments himself or whether he was quoting from the work of earlier investigators. In any case, by the very nature of the experiments the measurements were very approximate. This did not worry Galileo since he was *already* convinced that he knew the correct law.

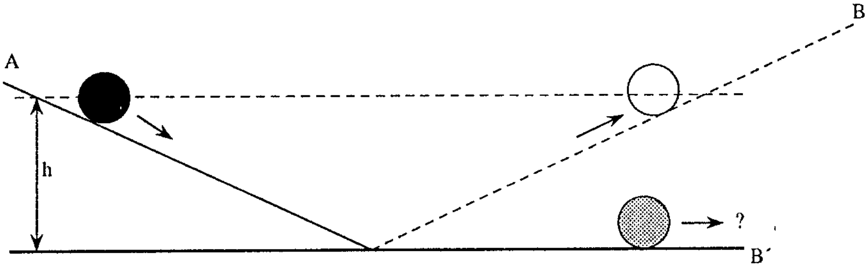
Galileo went on to *guess* that if a ball rolls down an incline, A, and up another connected incline, B, it will roll up to the original height and this would be true for another initial incline, A′, of the *same* vertical height, *h* (see diagram on next page).

Friction, of course, prevented a satisfactory demonstration of this idea but Galileo used a judicious mixture of experiment and thinking – he had a genius for making intuitive guesses on the basis of approximate experimental results.

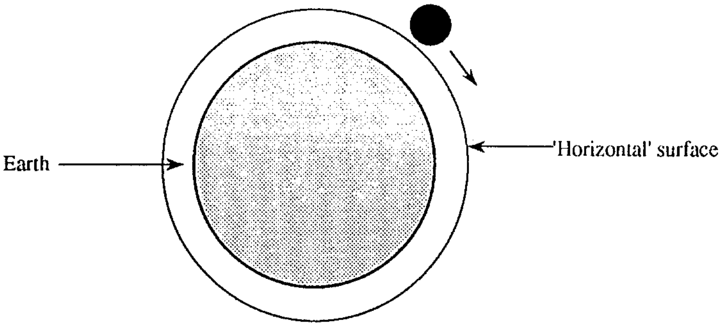
One interesting further development occurred to Galileo. He asked himself what would happen if slope B was made more and more shallow until in the extreme case it was horizontal (B′). In that case, Galileo argued, the ball would continue along the horizontal surface for ever. Now at first sight this idea might appear to contain the essence of Newton's



Galileo's guess on 'ideal' downhill-uphill motion.



Galileo's thought experiment.



Galileo's 'horizontal' plane.

First Law of Motion. But it was only the first step towards a full understanding of the concept of inertia because for Galileo a horizontal plane was one for which every point was equidistant from the centre of the Earth, that is, it was a kind of spherical shell parallel to the Earth's surface.

So the perpetual *circular* motion of celestial bodies which dominated Greek thought still governed Galileo's world picture. For him circular motion was *the* natural motion which did not need to be explained.

THE PROBLEM OF INERTIAL MOTION

In fact the problem of inertial motion only became manageable when men could be induced to change their fundamental view of *space*. The modern view of inertial motion as applying to a body moving perpetually in a straight line to infinity in the absence of external forces is not one that could arise from experiment. It depends on a certain knack of looking at things. First, to see bodies as being, for this purpose, purely geometrical, that is, the motion as being independent of the nature of the body. Secondly, to see the space through which the bodies are moving as being empty and neutral. For Aristotelians both ideas would have seemed utterly inconceivable. As we have seen, the motion of bodies was dependent upon their nature and also certain directions in space had to be regarded in a preferential way in the sense that certain parts of the universe exerted special attractive forces. Galileo escaped from the first of these constraining concepts but was unable to escape from the second by reaching a full realisation of completely empty, utterly directionless and neutral, Euclidean space.

The concept of inertial motion is not just a detail of a world-picture – it is one of the essential foundations of a system. The change from the Aristotelian idea of inertial motion probably represents *the* most important element in the transition from ancient and medieval science to classical science. There can be no doubt that this tremendous change was largely initiated by Galileo but it needed Newton to set the seal finally by his systematisation of mechanics.

KINEMATICS AND DYNAMICS

Because of the success with which Galileo had investigated many special topics in mechanics and had developed effective schemes for saying *how* objects move (kinematics), Newton was able to turn his attention to the question of *why* objects move as they do (dynamics). In one sense, of course 'why' questions are extremely difficult [impossible (?)] to answer. This has been neatly put by Feynman:

> What makes planets go round the sun? At the time of Kepler some people answered this problem by saying that there were angels behind them beating their wings and pushing the planets around an orbit . . .
> The answer is not far from the truth. The only difference is that angels sit in a different direction and their wings push inwards
>
> (*The Character of Physical Law*)

NEWTON'S METHODS

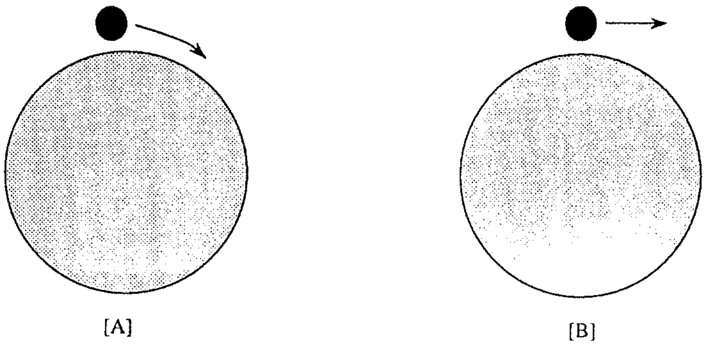
It is not in the deeply metaphysical sense that we talk about Newton tackling 'why' questions but rather to emphasise that what lay at the heart of his approach was not so much how objects move *per se* but what causes them to move in the way that they do. In his work on mechanics Newton adopts a consistent method governed by a number of rules:

1. To assume as few causes as possible in explaining a particular phenomenon.
2. To relate as completely as possible analogous effects to the same cause.
3. To extend to all bodies the properties on which it is possible to make experiments.
4. To consider every proposition obtained by induction from observed phenomena to be valid until a new phenomenon is observed which contradicts or limits the proposition.

Essentially the task that faced Newton was to systematise a mass of accumulated knowledge that still had a fragmentary and confused character. It has been suggested that in mechanics Newton faced the same sort of problem as Pascal in hydrostatics who by the enunciation of a single universal principle (the equality of pressure in every direction at a point in a liquid) succeeded in systematizing a whole branch of science. But clearly Newton's problem in mechanics was very much more difficult due to the much greater generality of the subject.

As we have seen, scientists had from early times speculated about motion under the influence of internal or external forces. In order to do this it was necessary, of course, to employ specialist terms. Now one of the perennial difficulties faced by physics is that, more than any other branch of science, it uses terms which also occur in everyday language. This can give a quite spurious feeling of confidence in the clarity of the meaning to be attached to terms (just think of the difference in the meanings of words such as *velocity*, *power* and *energy* nowadays when they are used strictly in physics or more loosely in ordinary speech). Commonly used words such as *gravity*, *force*, *resistance*, *tendencies*, *impetus*, *quantity of motion* and so on were used in the early speculations about motion and these turned out to be insufficiently sharply defined to be useful in scientific discussions.

So one of Newton's important tasks was to attempt to introduce some sort of order in the chaos of terms. Perhaps the best method would have been to make a completely clean break and use an entirely new set of terms not drawn from common usage. However, this is never easy because any reformer or revolutionary who wishes to reorganise a system has nevertheless been brought up within it and cannot help being influenced by its terms and its concepts. No one is ever radical enough in reformation, tending to preserve the more familiar things which are often precisely those which most need reconstruction. Particularly in the case of terminol-



inertial motion for Galileo [A] and Newton [B].

ogy, the worst possible confusion arises when old terms are used for new ideas.

It could be said that in one sense Newton did not have the ideal scientific personality to succeed *completely* in this particular task. He had a rare mind of great creative brilliance which was able to formulate original and elegant proofs over a vast range of topics but it was not well suited to the patient work required to axiomatise a subject and sometimes his writings lacked the careful definition of terms. Nevertheless, his axiomatic system did provide the very thing that had always been lacking previously in ancient mechanics and in this way he laid down a firm foundation for future developments. Furthermore, it is important to appreciate that axiomatization, whilst vital in laying foundations, is only one aspect of the contribution that a genius can make to the development of his subject. The efficacy of the *methods* which he develops, which can be represented as the building of the superstructure, need also to be considered. In this area there can be no doubting Newton's universal genius.

NEWTON'S LAWS OF MOTION

Newton's scheme for dynamics is essentially summed up in his three laws of motion. In the First Law we finally arrive at a satisfactory *qualitative* understanding of inertia (the tendency of a object to maintain its state of rest or uniform motion in a straight line) as a basic inherent property of all objects.

It is a completely general law which emphasises that a single scheme is applicable to motion *anywhere* in the universe. It is the very first occasion in the history of physics when *no* distinction is made between the terrestrial and celestial domains.

In his Second Law we finally reach the explanation of acceleration and a *quantitative* relationship between inertia and force. [It is interesting to remember that Newton did *not* express this as $F = ma = m(\mathrm{d}v/\mathrm{d}t)$ but essentially in the form $F\Delta t = m\Delta v$, that is, he spoke of "change of 'motion'" (= momentum) and related this to the value of force × time].

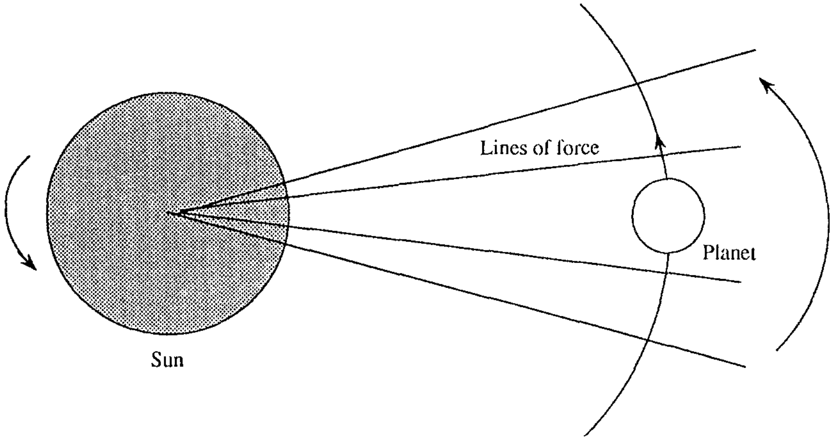
Newton's Third Law was highly original and it completed his general treatment of the concept of force by explaining that *every* force has its mirror image twin. A consequence of this law is that a solitary particle can by itself neither exert nor experience any force. Forces arise *only* from the interaction of two entities. We may elect to call one force 'action' and the other 'reaction' but the naming is arbitrary. They are related in the same way as credit and debit: the one is impossible without the other. Action and reaction are equal in magnitude but opposite in direction. Any causal connection we introduce is artificial. Most important of all is that they happen respectively to *two different entities*.

THE WORK OF KEPLER

We must look briefly at Newton's contribution to the theory of gravity. By the end of the sixteenth century there were two problems concerned with the motion of celestial bodies that were becoming more and more acute. Basically these problems were:

> What force keeps celestial bodies in motion?
> How are celestial bodies held in their orbits?

The old view that both questions could be satisfactorily answered by attaching the celestial bodies to large crystalline spheres was increasingly being regarded as suspect. We cannot deal even in outline with all the contributions made prior to Newton but mention must be made of the great astronomer Kepler. He confined his suggestions on gravity to the solar system since he regarded the fixed stars as being so different from terrestrial bodies that they had no gravity. He knew nothing of the modern idea of inertia and suggested that the planets needed a force to push them round their orbits. This force reached out from the sun and moved round with the sun's rotation so sweeping the planet along like a broom sweeps a pebble along a road. The essential feature was the *rotation* of the sun. If the sun did not rotate on its axis, he said, the earth would not revolve round it and similarly if the earth did not rotate on its axis, the moon in turn would not revolve round the earth. Kepler does not suggest an inverse-square law, for his force did not radiate in *all* directions but streamed out from the sun only along the plane of the planet's orbit. In a sense the force had to 'know' where to find its object and this was one of the objections often made to the idea of attraction across empty space.



Kepler's gravitational theory for the solar system. This is perhaps a classical example of a reasonable answer to questions which have been expressed in the wrong way.

NEWTON AND GRAVITATION

Newton's superb contribution to the answering of both of the above questions was made only after a remarkable and protracted intellectual struggle.This was the Law of Universal Gravitation derived essentially by asking the question in the right way, namely, what prevents the planet from moving in a straight line?

One of Newton's aims when developing his gravitational theory was to put forward an alternative to the vortex theory used by Descartes who had produced a world-system by starting with only matter and motion and working deductively. This world-system was very attractive to many scientists and continued to be so for many years. There can be no doubt that Newton owed a considerable intellectual debt to Descartes which unfortunately he never publicly acknowledged. Newton showed mathematically that the vortices could not sensibly account for the observed motion of planets or comets and that if space was indeed composed of matter dense enough to push planets along their paths by the whirling of vortices then it would also act as a resistive medium which would slow down all movements in the universe. By using the idea of action at a distance Newton at one stroke destroyed two grand Aristotelian principles – first, the view that a vacuum was impossible and second, the view that objects could only influence one another if they actually touched. Newton's theory did not gain immediate and complete acceptance being severely criticised, for example, by Huygens and Leibnitz. But eventually it triumphed and in retrospect it can be seen as one of the great culminating points in the history of thought.

So in outline we have traced a gradually evolving pattern with brilliant individual contributions from great scientists such as Aristotle, Kepler, Galileo, Descartes and Newton. The process may be likened to the building up of a jigsaw from pieces which can interlock to produce a recognisable picture if properly fitted together by someone of sufficient talent. For mechanics that someone was Newton but he did recognise the debt that he owed his predecessors when he said that if he had seen further than others

> It is by standing upon the shoulders of Giants.

IMPLICATIONS FOR TEACHING

What lessons does this historical development of mechanics hold for our teaching of the subject? I would like to suggest the following:

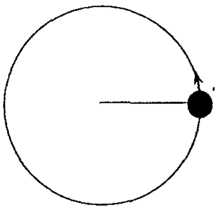
1. *We need to remember that Aristotelian ideas have a deep-rooted appeal*

We need to be aware that students bring to their study of physics a collection of proto-concepts formed from early commonsense experiences. Very commonly held pre-conceptions include the idea that continuing motion implies the presence of a force in the direction of the motion and that changes in the speed of an object can be accounted for by a force that either 'dies out' or 'builds up'. Consider, for example, a box being pulled across a horizontal floor with a steady speed in a straight line. The Newtonian commentator would suggest that the effort being applied by the person pulling the box is only to equalise and cancel the frictional force between box and floor. The Aristotelian, on the other hand, would explain that since the natural state of the box is rest, a force has to be supplied to the box in order to keep it in uniform motion. There is. of course, no dispute about the experimentally observed facts but rather a difference in viewpoint and it is important for teachers to appreciate that the Aristotelian view in this case, as in many other contexts, is closer to common-sense opinion. Since friction is never altogether absent in the everyday world and indeed is often a very real hindrance in moving objects, it is natural that people develop early on in their lives the intuitive idea that a force is necessary 'to keep an object moving'.. It is instructive to try problems similar to the ones below on students, even those who have studied a good deal of physics.

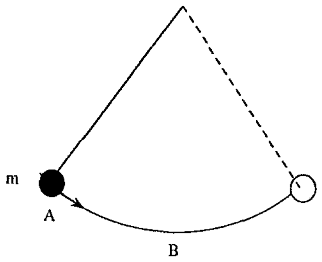
2. *The definition of terms is vitally important*

Returning to the example of the box being pulled across the floor, it is clear that the two observers are using the word *force* in two quite different senses. The Aristotelian uses intuitive ideas and seeks to define force as 'the cause of continued motion'. The Newtonian attempts to turn away from the human-centered viewpoint by considering the *net* force acting

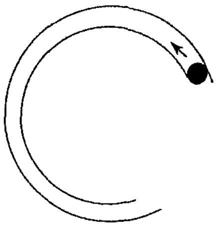
Use arrows to represent the forces acting on this block at rest of table.



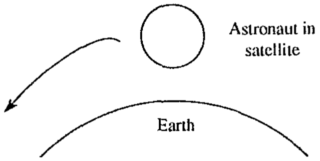
Stone being whirled in a horizontal circle. Draw the initial trajectory if the string is cut.



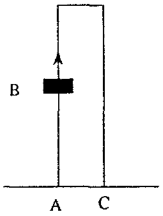
Show total force at A and at B.



Horizontal curved tube. What trajectory does the ball follow on leaving the tube?



Any forces on astronaut?



Coin tossed from A to be caught at C. Force when at B?

on the object (taking into account the *vector* nature of forces). But this is not a natural thing to do until a good deal of experience convinces you that this viewpoint is, in practice, much the more fruitful.

Furthermore, when dealing with the definition of terms we do well to remember how abstract are some of the concepts we use in physics. If we recall the difficulty that Galileo, a superb physicist, had in dealing with acceleration we may have more patience with our students.

3. *It is important to ask the right question*

If we recall the example of Kepler and Newton the vital necessity of framing questions in the right way (preferably in a way that facilitates the obtaining of an answer!) is made abundantly clear. So many other similar examples arise in the history of physics that there is no need to labour the point.

CONCLUSION

There can be little doubt that Aristotelian concepts do have a strong hold on the way in which we think. Kuhn in his book The Copernican Revolution writes as follows:

> Aristotle was able to express in an abstract and consistent manner many spontaneous perceptions of the universe that had existed for centuries before he gave them a logical verbal rationale . . . the opinions of children, of the members of primitive tribes, and of many non-western peoples do parallel his with surprising frequency.

And *all* of us still talk about the sun rising in the morning!

REFERENCES

Blanpied, W.: 1969, *Physics: Its Structure and Evolution*, Blaisdell, Waltham, Massachusetts.
Butterfield, H.: 1965, *The Origins of Modern Science*, Bell & Sons, London.
Casper, M. & Noer, R.J.: 1972, *Revolutions in Physics*, Norton, New York.
Cooper, L.N.: 1968, *An Introduction to the Meaning and Structure of Physics*, Harper & Row, New York.
Dicks, D.R.: 1970, *Early Greek Astronomy to Aristotle*, Thames & Hudson, London.
Dijksterhuis, E.J.: 1961, *The Mechanization of the World Picture*, Clarendon Press, Oxford.
Dugas, R.: 1957, *A History of Mechanics*, Routledge & Kegan Paul, London.
Goldberg, S.: 1984, *Understanding Relativity*, Clarendon Press, Oxford.
Holton, G. & Brush, S.G.: 1973, *Introduction to Concepts and Theories in Physical Science*, Addison-Wesley, Reading, Massachusetts.
Kuhn, T.S.: 1957, *The Copernican Revolution*, Harvard University Press, Cambridge, Massachusetts.
Pedersen, O. & Pihl, M.: 1974, *Early, Physics and Astronomy*, Macdonald, London.
Sambursky, S.: 1956, *The Physical World of the Greeks*, Routledge & Kegan Paul, London.