OXFORD CAMBRIDGE AND RSA EXAMINATIONS
Advanced GCE

PHYSICS B (ADVANCING PHYSICS)

2865/01

Advances in Physics

JUNE 2005

ADVANCE NOTICE ARTICLE

May be opened and given to candidates upon receipt.

INSTRUCTIONS TO CANDIDATES

- Take the article away and read it through carefully. Spend some time looking up any technical terms or phrases you do not understand. You are ***not*** required to research further the particular topic described in the article.
- For the examination on 27 June 2005 you will be given a fresh copy of this article, together with a question paper. You will not be able to take your original copy into the examination with you.
- The values of standard physical constants will be given in the *Advancing Physics* Data, Formulae and Relationships booklet. Any additional data required are given in the appropriate question.

INFORMATION FOR CANDIDATES

- Questions in Section A of Paper 2865, Advances in Physics, will refer to this *Advance Notice* article, and may give additional data related to it.
- Section A will be worth about 60 marks
- Section B will consist of two questions. These will ***not*** be based on the *Advance Notice* article. Section B will be worth about 30 marks.
- Four marks are available for the quality of written communication assessed over the whole paper.

This Advance Notice consists of 8 printed pages.

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Models in Physics

Models and Metaphors

People have always used stories to try to make sense of the world about them. These range from ancient African folk tales about the Moon to Orwell's *Animal Farm*. These stories use figurative language such as metaphor to explain something new or difficult as if it were something more familiar. For example, referring to time as an ever-running stream can help people to understand difficult ideas of change and mortality.

In physics, the need to explain the unknown in terms of the known is achieved by means of a particular use of metaphor called **modelling**. A familiar example is the model of an electrical circuit as a circuit of pipes through which water is flowing (Fig. 1).

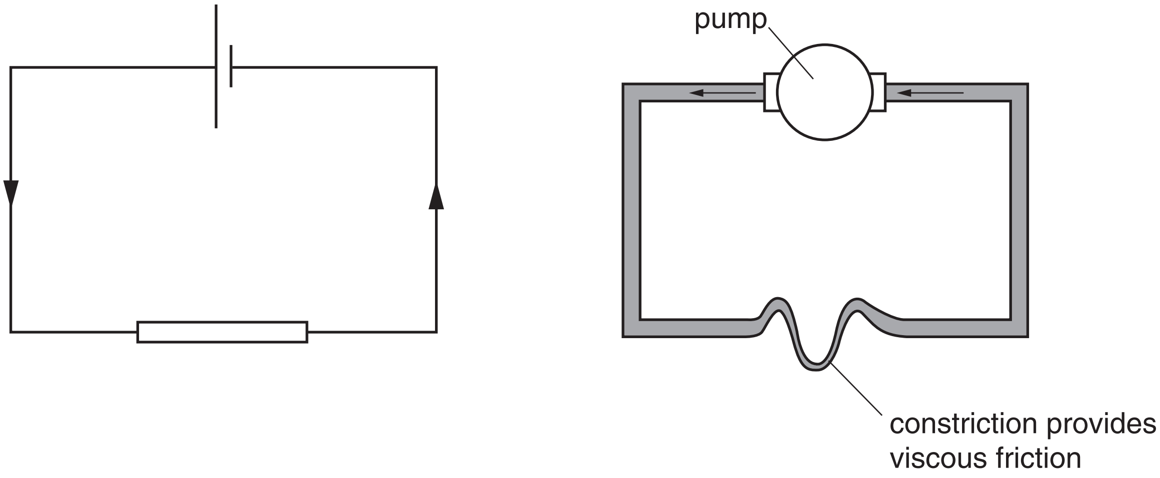


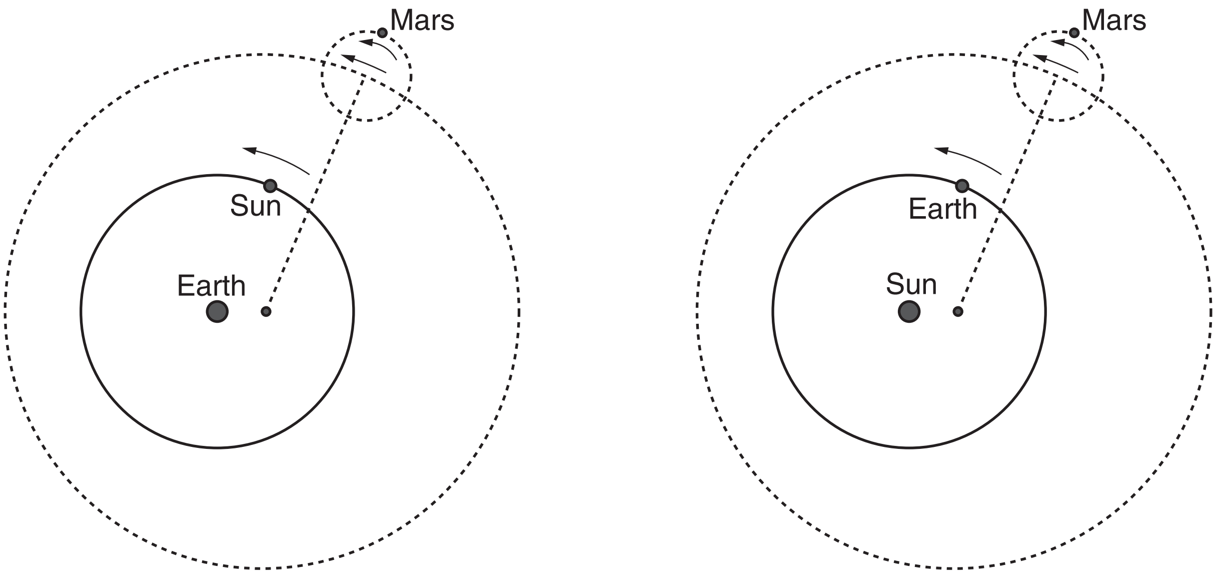
Fig. 1

This allows a difficult situation to be compared with an example which many people find more familiar. The pressure difference between the pump input and output is analogous to the potential difference between the terminals of the cell. The consequence is a flow of water, or of charge, and the rate of flow, or current, depends on how well the pipes or wires conduct. In the case of the electrical circuit above, this is justified by the presence of moving charges.

The same flow model can be used in magnetic circuits, although no actual flow takes place.

Describing the Universe

From the time of the earliest astronomers, people have tried to picture the Universe by making models to help their understanding. The Greek Ptolemy's model was one successful example. In this model, the Earth was situated at the centre with the Sun, Moon and planets orbiting it. The model fitted comfortably with people's ideas of the special place of the Earth. To allow accurate predictions of the apparent movement of the planets, Ptolemy had to introduce a complicated arrangement of circles on circles, with the main orbital circle not actually centred on the Earth (Fig. 2).
Many centuries later, Copernicus produced his model, which put the Sun at the centre of what we now call the Solar System. Unlike diagrams shown in popular science books, this was no simpler than Ptolemy's model. This was because Copernicus also was sure the orbits must be circles. He had to use Ptolemy's extra circles to produce an accurate model of the way the planets moved. However, Copernicus' model had the important difference of putting the Sun in the key position at the centre.



Ptolemy's Earth-centred model

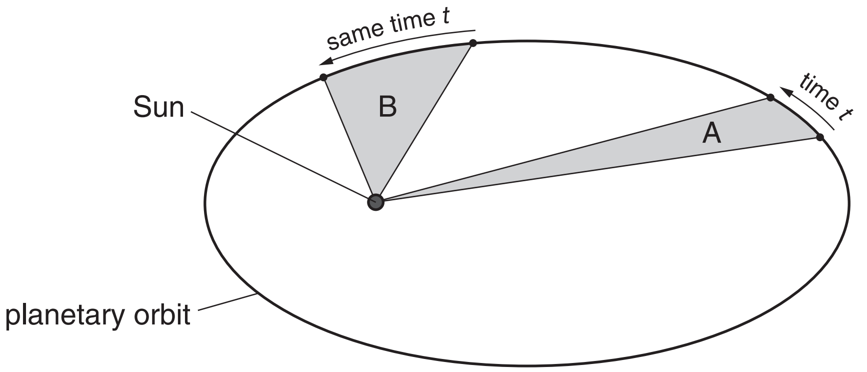
Copernicus' heliocentric model

Fig. 2

With the strong support of Galileo's observations with a telescope, the heliocentric picture soon became the accepted model. This view gained further support from a second strand of modelling that is used in physics: mathematics.

Mathematical Modelling

The mathematician Johannes Kepler analysed observations obtained by the astronomer Tycho Brahe and sought patterns in the data. He discovered that Copernicus' model of the Solar System could be improved by doing without the extra circles and offset centres. This could be achieved if the orbits were not circles, but ellipses, with the Sun at one of the two foci of the ellipse. Seeking more patterns, he discovered that the rate at which a planet moves along its elliptical path varies as shown in Fig 3.



Kepler's Second Law: the areas A and B are equal

Fig. 3

He also found that the mean orbital radius R and the orbital period T are related by the relationship $\frac{R^3}{T^2}$ = constant. The existence of mathematical relationships suggests very strongly that there is some mathematical description of the Solar System which gives rise to them. This was one of the key starting points for Isaac Newton. But it was more than just the start of modern astronomy: it was the start of systematic mathematical explanation of all phenomena.

The Triumph of Mechanics

In his great work, the *Principia*, Newton set out his Laws of Motion and stated, in his gravitational law, that all bodies in the Universe attract all other bodies, and do so with an inverse square law of force. The immediate impact of his approach, together with the new mathematical techniques he devised, changed physics for ever. In the *Principia* Newton showed how Kepler's Laws can be derived from his Laws of Motion and Gravitation, and also explained other phenomena such as tides. From this point, analytical mathematics came to be applied to all physical situations from the microscopic to the astronomic.

The gravitational law was applied to the irregular path of the newly-discovered planet Uranus, once there was enough data on its orbit. It was suggested that a planet further from the Sun was exerting a gravitational pull on Uranus, speeding it up and slowing it down at different points in its orbit. The subsequent discovery of the planet Neptune vindicated this approach, once more justifying Newton's work.

However, not all mathematical patterns are supported by the physics. A pattern discovered by the astronomers Titius and Bode predicted the orbits of the planets in the Solar System quite accurately. The pattern of numbers they found for the mean orbital radius R of a planet can be given by the equation,

$$R = 0.4 + 0.3 \times 2^n$$

where n is a whole number and R is the mean orbital radius in astronomical units (AU), where an astronomical unit is the mean radius of the Earth's orbit.

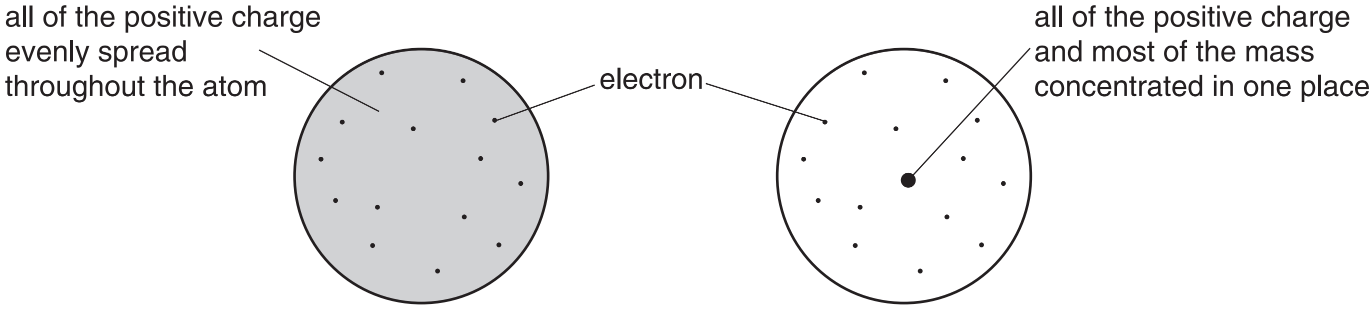
Although the Titius-Bode Law seemed promising for a while, it was eventually discredited. This is a good example of the requirements of a mathematical model: it must give valid predictions, and it must have a plausible theoretical basis. Newtonian mechanics gave a strong, rational explanation for Kepler's Laws, but the Titius-Bode 'Law' had no such theoretical basis.

Atoms, Electrons and Nuclei

In 1897, J J Thomson succeeded in removing electrons from matter, and so showed that the atom was not the smallest possible particle. As electrons are negatively charged, unlike the matter from which they had been removed, the model of the atom as an indivisible, uniform sphere had to be modified.

Thomson's suggestion was a simple one: if an atom contains a certain number of these negative electrons, then it must possess an equal quantity of positive charge. As he had no way of knowing how this might be distributed, nor where the electrons in an atom may be found, he made the simplest possible modification to the model of an atom as a solid sphere. He suggested that the atoms were positively charged, with the positive charge spread uniformly through them, and with the negative electrons studded through the atom like currants in a bun (Fig. 4).

In a very few years, the discovery of radioactivity, particularly the emission of positive alpha particles, discredited Thomson’s model. The famous experiment of Geiger, Marsden and Rutherford, where very few alpha particles rebounded from thin gold foil but most emerged undeflected, indicated clearly that gold atoms could not really contain Thomson’s smeared-out positive charge. The positive charge must be concentrated in a small, massive region, while most of the atom was effectively empty. For reasons of symmetry, it was assumed that this small region, soon to be named the nucleus, was in the centre.



Thomson’s model

Rutherford’s model

Fig. 4

The Rutherford model, being so similar to the hard-won heliocentric model of the Solar System, quickly absorbed features of that model. Electrons became planets orbiting the nuclear Sun.

After Chadwick identified the mysterious radiation emitted when an alpha particle strikes a beryllium nucleus as the neutron, the model of the nucleus became a cluster of protons and neutrons, rather like a blackberry. This model of the nucleus has been successful, and continues to be so, despite the establishment of the finer structure of nucleons in terms of quarks.

The simplified model of the atom satisfied some aspects of chemistry, but its shortcomings were obvious from the start. Orbiting electrons are accelerating charged particles, and so should be radiating energy, making the atom unstable. This clearly does not happen, or matter could not exist. A more profound quantum model of the atom is necessary, with the electron positions not so clearly defined as the position of the planets around the Sun. Unfortunately, this model is hard to visualise, so the popular planetary picture has already lasted for nearly a century past the time at which it was seen to be clearly inadequate.

Mathematical modelling with computers

Newton’s formal mathematics is perfect for working out the orbit of the Moon, or of Halley’s comet, but it becomes difficult to apply in complex situations. To model the evolution of the Solar System, for example, you must apply Newton’s Laws to thousands upon thousands of moving bodies. With the development of computers in the second half of the twentieth century, new approaches have become possible.

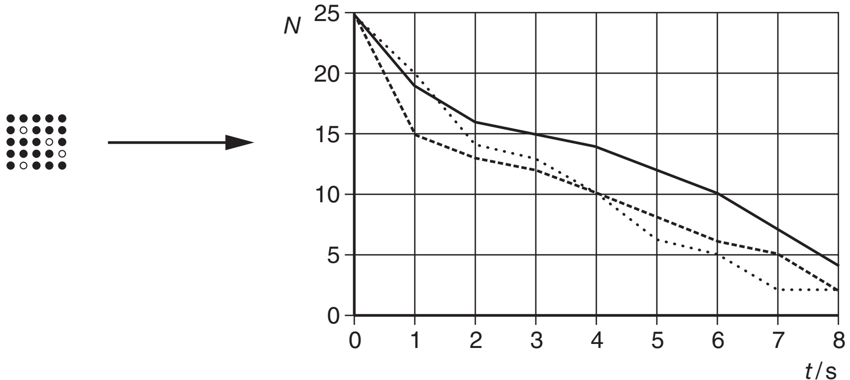
One approach uses numerical methods to predict how different equations, possibly interacting, produce changes in a system. Changes in the variables of the system are calculated independently at regular intervals. The values of those variables are then reset at the end of each interval, and the way in which the system changes can be monitored.

Another approach uses computer 'objects' which obey sets of defined rules. Governed by these rules, the system of computer objects evolves over time.
As an example of their use, see how these two quite different methods of computer modelling can be applied to the example of radioactive decay.

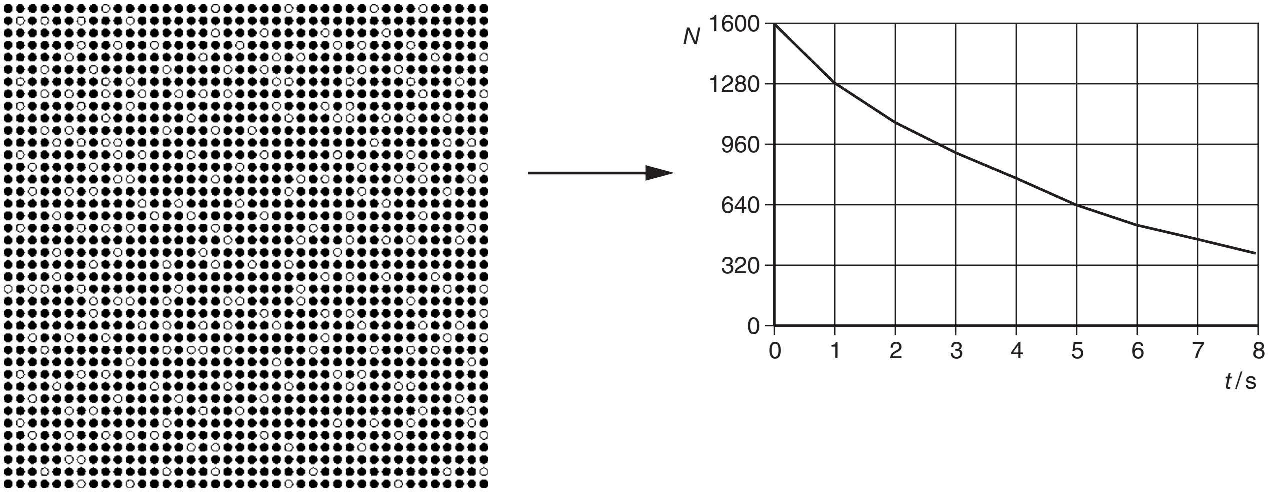
Radioactive decay

A numerical model would calculate precisely, for a particular initial number of nuclei N, how many would be expected to decay in a particular time interval Δt, using the equation $\frac{\Delta N}{\Delta t} = -\lambda N$. The number decaying, ΔN, is then subtracted from the original number of nuclei to give a new number N, and the process repeated. In the alternative approach, each computer 'nucleus' is given the same probability of decay, but the decays are allowed to happen at random, as if each nucleus in the model were throwing dice to find if it were allowed to decay or not.

An example of the second method is illustrated in Fig. 5, where two different sized collections of computer objects, simulating nuclei, are decaying at random with the same probability of decay. Time does not flow uniformly, but in jumps of equal duration, with each computer nucleus 'throwing its dice' once in each interval.



First simulation



Second simulation

Fig. 5

In Fig. 5, the first simulation uses 25 'nuclei', and each has a one in five chance of decaying each second. The calculations are done each second, and the resulting graph is not very reproducible: three separate runs of the model are shown on the graph. The second simulation uses 1600 'nuclei', each having, as before, a one in five chance of decaying each second. Using a larger number of computer objects produces a much smoother graph, giving a half-life much closer to the predicted value of 3.5 s, with subsequent runs of the model giving curves very close to the one shown. However, modifications of this sort can only happen at the cost of extra time in computing.

Weather forecasting

Computer simulations really come into their own in complex situations such as weather forecasting. The weather forecast seen on television relies on the Unified Model run by the Meteorogical Office. This model attempts to include all factors which can affect the weather: the incoming and outgoing radiation, the way the air moves, the way clouds form and rain falls, etc. These models calculate how all these different parts of the climate system interact, and how the feedback processes work. The developments in weather forecasting over the last decade have come about by improvements in the resolution of the models used.

As in the radioactive example above, the time intervals for calculation are made as small as possible to allow for smooth changes. Space is another variable which is divided into ‘chunks’ or cells, with the assumption that everything within a cell is uniform for the entire time interval. The resolution of the Unified Model has been improved by dividing the surface of the Earth into small squares about 11 km across (Fig. 6), and the atmosphere above is divided into about 20 layers. Even the tiny English county of Rutland has the atmosphere above it divided into dozens of separate cells.

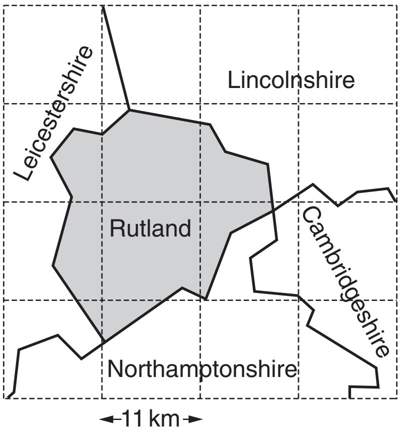


Fig. 6

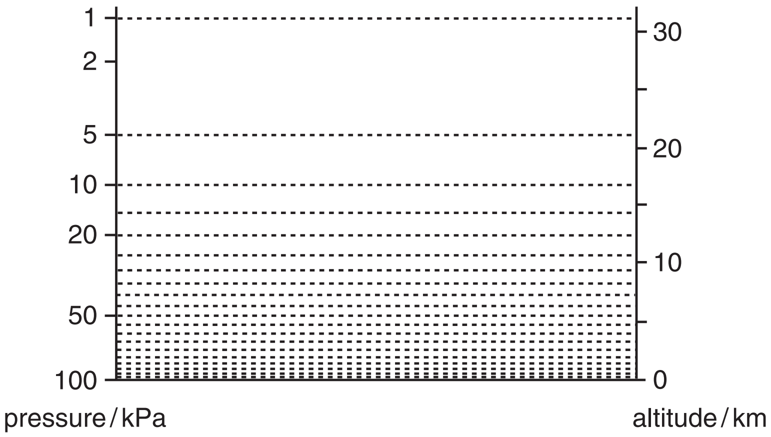


Fig. 7

The atmospheric cells are not equal in volume. The layers into which the atmosphere is divided become larger as you move away from the surface of the Earth (Fig. 7), because the density of the air decreases with height. This is reasonable, because the reduced mass of moving air in the upper atmosphere will have less effect on circulation patterns than the denser layers lower down.

The huge number of separate calculations needed within each time interval makes great demands on computing power, but the development of supercomputers has meant that the computing power available to meteorologists in recent years has greatly increased: that is why weather forecasts are now very much more accurate.

End of Article