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Oxford Cambridge and RSA

AS and A LEVEL

Delivery Guide

PHYSICS A

H156/H556
For first teaching in 2015

Work, energy and power

Version 2

Introduction

AS and A LEVEL
PHYSICS A

Delivery guides are designed to represent a body of knowledge about teaching a particular topic and contain:

- Content: A clear outline of the content covered by the delivery guide;
- Thinking Conceptually: Expert guidance on the key concepts involved, common difficulties students may have, approaches to teaching that can help students understand these concepts and how this topic links conceptually to other areas of the subject;
- Thinking Contextually: A range of suggested teaching activities using a variety of themes so that different activities can be selected which best suit particular classes, learning styles or teaching approaches.

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Curriculum content

Module 3: Forces and motion
The term *force* is generally used to indicate a push or a pull. It is difficult to give a proper definition for a force, but in physics we can easily describe what a force can do.

A resultant force acting on an object can accelerate the object in a specific direction. The subsequent motion of the object can be analysed using equations of motion. Several forces acting on an object can prevent the object from either moving or rotating. Forces can also change the shape of an object. There are many other things that forces can do.

In this module, learners will learn how to model the motion of objects using mathematics, understand the effect forces have on objects, learn about the important connection between force and energy, appreciate how forces cause deformation and understand the importance of Newton's laws of motion.

3.3 Work, energy and power
Words like *energy*, *power* and *work* have very precise meaning in physics. In this section the important link between work done and energy is explored. Learners have the opportunity to apply the important principle of conservation of energy to a range of situations. The analysis of energy transfers provides the opportunity for calculations of efficiency and the subsequent evaluation of issues relating to the individual and society (HSW2,5,8,9,10,11,12).

3.3.1 Work and conservation of energy
Learners should be able to demonstrate and apply their knowledge and understanding of:

(a) work done by a force; the unit joule

(b) $W = Fx \cos \theta$ for work done by a force

(c) the principle of conservation of energy

(d) energy in different forms; transfer and conservation

(e) transfer of energy is equal to work done.

3.3.2 Kinetic and potential energies
Learners should be able to demonstrate and apply their knowledge and understanding of:

(a) kinetic energy of an object; $E_k = \frac{1}{2} mv^2$

(b) gravitational potential energy of an object in a uniform gravitational field; $E_p = mgh$

(c) the exchange between gravitational potential energy and kinetic energy.

3.3.3 Power
Learners should be able to demonstrate and apply their knowledge and understanding of:

(a) power; the unit watt; $P = \frac{W}{t}$

(b) $P = Fv$

(c) efficiency of a mechanical system;

$$\text{efficiency} = \frac{\text{useful output energy}}{\text{total input energy}} \times 100\%$$

Approaches to teaching the content

What is work? What is energy? Students will think from their previous studies that they know what these terms mean, but a little gentle questioning will probably reveal that although they may be able to calculate these quantities using equations provided, and give simple definitions based on these equations, they will be much less sure about the actual concepts of work and energy themselves.

Not that they are alone in this. Even Richard Feynman acknowledged the problem of fully understanding the somewhat abstract concept of energy. Learners and teachers alike would do well to read Feynman's approach (given in the links at the end of this section) prior to starting this module, and then they should be ready to set out on their journey through work, energy and power.

Force and energy are often confused by less confident students. Force is relatively straightforward to measure (the Kinematics and Dynamics module gives more guidance on forces and their effects), but energy is not. Once work is understood as the transfer of energy, which is the key underlying concept to the whole unit, then the simple relationship $W = Fx$ can be used alongside experimental data to calculate work done. The work done by a force acting at an angle θ to the direction of motion can then be introduced, which builds upon the student's previous knowledge of resolving forces.

Students should be given the opportunity to experience energy transfers for themselves through experiments involving raising weights through use of pulleys. They can then appreciate the magnitude of the Joule through raising a 1 N weight by 1 metre, and they can gauge the energy transfers that lead to them being able to do this. This simple experiment allows students to relate other energy transfers to one that they can carry out, and increases their appreciation of the processes involved.

Feynman's description of the conservation of energy is key to the next part of the unit. The Principle of Conservation of Energy is not easy to directly verify in the laboratory, since measurement and summation of all the non-useful energy transfers is not a simple process. However, students could use Feynman's blocks analogy to develop their understanding of energy transfers.

Transfers between gravitational potential energy and kinetic energy are the classic way of introducing transfer of energy, although other energy transfers (such as from electrical energy to other forms) can be considered in the laboratory, and devices such as model internal combustion engines and steam turbine models can be used to show transfer of chemical potential energy into kinetic energy, through several intermediate steps. The derivation of the expressions for gravitational potential energy (= mgh) and kinetic energy (= $\frac{1}{2}mv^2$) is important, as is the understanding of the difference between momentum and kinetic energy – learners at lower levels often confuse the two.

Transfer of energy is such a fundamental concept to the devices used in our modern society, and proper study of this unit will open the eyes of the student to the energy transfers happening around them all the time. Power is an often misunderstood and misused term outside of the Physics laboratory, but its proper definition as the rate of energy transfer should allay such misconceptions, and students should then be able to understand the difference between work done (in Joules) and power (in Watts).

Just a little mathematical knowledge of velocity = displacement / time is required to see that the very first equation in this section, $W = Fx$, can be used to derive $P = Fv$, where v is simply the velocity of the object under consideration.

How efficient are energy transfers? Whilst energy may be conserved in a closed system, not all the energy transfers are useful – something that will be readily appreciated by the student in any experiment where work is done, and the expression of efficiency (as a ratio or as a percentage) is key to the understanding of the utility of any process where energy is transferred.

Common misconceptions or difficulties students may have

Students may confuse force with energy – it is important that the difference is made clear at the outset. A force may act on an object but no work is done if the object does not move – this can be a difficult concept at first, but once it is accepted then the learner can proceed with confidence.

Conservation of energy always applies in a closed system, and this may cause a problem or two on first meeting. However, a full consideration of the likely energy transfers in any process should address any concerns, and Feynman's introduction to Conservation of Energy is an excellent preparatory activity for any student studying this concept.

The difference between kinetic energy and momentum has caused many learners problems, and given the common origin of the two terms (the work-energy theorem) this is not altogether surprising.

Understanding the change in the kinetic energy of an object as the work done by a net force on an object is important, and the same theorem can be used to express the net force acting on an object as being equal to the rate of change of momentum of the object.

However, momentum can be understood as a measure of the force required to decelerate an object, whereas kinetic energy can be understood as the maximum work that an object can do when it interacts with other objects and ends up stationary.

Gravitational potential energy (GPE) is encountered at a lower level of study, and it should not cause major difficulties. However, the key concept in transfer of GPE is change in height, not just height above a defined zero level, and this can catch out the unwary.

Power as rate of energy transfer should not cause too many issues with learners, but the calculation of efficiency (and expression of it as a percentage as well as a ratio) has been the source of many slips in the past, leading to significant contraventions of the Law of Conservation of Energy in calculations. Care should be taken to ensure that percentages can be calculated properly, and the number of significant figures in any answers should also be appropriate.

Conceptual links to other areas of the specification

Work done as a transfer of energy is a key concept in the study of electrical circuits, and the unit of power in an electrical circuit (p.d. × current) should be equated to the unit of power in a mechanical system (P = energy / time, or $P = Fv$). Efficiency is a key concept in the understanding of transformers.

Conservation of energy is a fundamental concept in Physics. Apart from this section, this principle can also apply to electromagnetic induction (Lenz's Law), to inelastic and elastic collisions of objects, to the deformation of materials such as springs (such as in Unit 3.4), to the energy stored in capacitors, to thermal physics and thermodynamics, to simple nuclear decay processes and to studies of sub-atomic interactions in particle physics – a principle that holds true on a scale running from the very smallest particles to the very largest stars.

Learner Activity 1
Energy

An excellent preparation to the concept of energy as something tangible that can be transferred whilst being conserved is contained within chapter 4 of 'Six Easy Pieces', Richard P. Feynman, Penguin, London, 1998, which is also at www.feynmanlectures.caltech.edu/I_04.html

and www.youtube.com/watch?v=qMd4KOI6LF0.

Another source worth consulting as an introduction to the use of proper terminology is https://spark.iop.org/energy-common-knowledge-hard-concept.

For those interested in the development of the science of heat and energy transfer, a history of caloric' and energy (in the form of heat) as a fluid can be found at https://spark.iop.org/cannons-steam-engines-and-caloric.

Learner Activity 2
Force and energy

An understanding of the difference between force and energy can be developed by using the resource at https://spark.iop.org/solving-problems-force-or-energy

Learner Activity 3
Trolley collisions

Energy transfers can be observed and measured using simple trolley experiments (for example https://spark.iop.org/trolley-collisions), or by inversion experiments of tubes containing lead shot – the rise in temperature of the lead shot is relatively easy to measure (for example, http://www.physics.usyd.edu.au/super/therm/tpteacher/demos/shottube.html).

Learner Activity 4
Conservation of energy

The Principle of Conservation of Energy is a key concept to many areas of Physics, and there are many experiments to demonstrate it. Examples include https://spark.iop.org/investigating-energy-transfers-pendulum and www.education.com/science-fair/article/pendulum-physics-teacher-ming-dynasty/.

There are many excellent simulations at the Phet website from the University of Colorado (http://phet.colorado.edu) which enable students to experiment with unusual rollercoaster designs without risking harm to themselves and others.

Learner Activity 5
Energy Transfers

Transfer of gravitational potential energy into kinetic energy can be demonstrated with equipment involving a falling mass (for example, https://spark.iop.org/trolley-and-falling-mass) and through moving objects (for example https://spark.iop.org/episode-216-energy-changes) , and a simple derivation of the equation for kinetic energy based on the work-energy theorem can be found at http://www.dummies.com/how-to/content/how-to-calculate-the-kinetic-energy-of-an-object.html.

The transfer of electrical energy into gravitational potential energy (via intermediate steps) can be investigated by experiments such as the one at https://spark.iop.org/using-electric-motor-raise-load.

Learner Activity 6
Power

Power as rate of transfer of energy can be investigated using several experiments described at https://spark.iop.org/collections/power, which extends the concept of power from mechanical to electrical systems. Mechanical power can also be investigated using experiments and calculations at https://spark.iop.org/episode-218-mechanical-power.

Learner Activity 7
Efficiency

The efficiency of mechanical systems can be investigated using Galileo's pin and pendulum (https://spark.iop.org/galileos-pin-and-pendulum).

Thinking contextually

Activities

In order for the student to gain a full and proper understanding of the material covered in this Module, it is important that they have a good and firm grasp of the basic terminology of work, energy and power. Once this is complete, students can set out on their journey through the Work, Energy and Power areas described in the Specification.

The sequence in this section is intended to steadily build the students' knowledge and skills in the areas described, so that they may confidently move on to the next section.

The sequence given in the Specification is a logical order of teaching – it is important that the central idea of work done as energy transferred is firmly established before kinetic and potential energies, and the concept of power, are introduced. Power as the product of force and velocity can be derived from the basic definitions of power and work done. Efficiency is a rich area for contextual learning, and offers plenty of project-based activities that will enable students to relate their knowledge to everyday situations around them.

Learner Activity 1
Definition of quantities and units
The topic can start with students becoming familiar with the terminology of energy, energy transfer and power. An exercise in matching quantities and units is given in **Learner Resource 1**. Students must become confident and proficient in handling prefixes and multiples of units, and an example exercise in the correct use of prefixes, along with the magnitude of quantities, is given in **Learner Resource 2**.

Learner Activity 2
Work and conservation of energy
The topic can start with students considering the work done by a force, and appreciating the magnitude of the joule, eg https://spark.iop.org/shift-joule, and https://spark.iop.org/episode-214-work-done-force. Useful analogies of transfer of energy are given at https://spark.iop.org/work-done-force.

Learner Activity 3
Raising a load on a ramp
The work done by a force, where the direction of the force and the direction of movement are not co-linear, can be seen using the context of raising a load up a ramp (eg https://spark.iop.org/sites/default/files/media/documents/episode-214-1-work-done-in-raising-a-weight-using-a-ramp.doc).

Learner Activity 4
The Principle of Conservation of Energy
The Principle of Conservation of Energy is a concept that underpins Physics at many levels, and a grasp of it is crucial for success at any level of study. It can be introduced through discussion and calculation (eg https://spark.iop.org/episode-217-conservation-energy), and experiment (eg http://www.schoolphysics.co.uk/age14-16/Mechanics/Forces%20in%20motion/), along with experiment collections at https://spark.iop.org/collections/law-conservation-energy).

Learner Activity 5
Energy stores and transfers
Energy stores and transfers are first introduced at Key Stage 3 level, but students requiring a refresher could use the experiments at https://spark.iop.org/collections/introducing-energy. The transfer of energy between different stores is a fundamental concept underpinning just about every physical, chemical and biological process, and experiments such as https://spark.iop.org/jobs-needing-food-or-fuel serve to reinforce the universal contexts of energy in its different manifestations.

Learner Activity 6
Kinetic and potential energy
Kinetic energy can be understood in the context of transport systems, eg https://spark.iop.org/episode-217-conservation-energy, and in stopping vehicles (eg https://spark.iop.org/episode-216-energy-changes). Gravitational potential energy can be seen in context by relating work done by an object in raising a mass (eg https://spark.iop.org/episode-214-work-done-force), and the exchange between GPE and KE (and back again) is easily demonstrated using pendulum experiments (eg https://spark.iop.org/investigating-energy-transfers-pendulum).

Learner Activity 7
Power
Power as the rate of energy transfer can be learned in the context of measuring and comparing the power of lamps and motors (eg https://spark.iop.org/collections/power), which links this module to other modules involving the study of electrical quantities. The mechanical power of a student can be measured using relatively simple experiments, such as https://spark.iop.org/collections/power#student-power, which allow the student to appreciate the size of the Watt. Power = force × velocity can be derived from the definitions of power and work done, and can be seen in context in activities such as those described at https://spark.iop.org/episode-218-mechanical-power.

Learner Activity 8
Efficiency
The idea of "wasted" energy needs to be treated carefully, eg https://spark.iop.org/power-and-energy, and students should be encouraged to identify less useful energy transfers in a number of processes. The efficiency of familiar processes could be studied to put the idea into context (eg http://www.schoolphysics.co.uk/age14-16/Mechanics/Forces%20in%20motion/), and more able students could be invited to consider the thermodynamics of simple heat engines (eg http://www.schoolphysics.co.uk/age16-19/Thermal%20physics/Thermodynamics/text/Heat_engine_efficiency/index.html).

The problem of increasing the efficiency of energy transfer processes, particularly given the use of finite resources, is a key issue in society, and students could examine this in the context of better lubricants for engines (eg www.youtube.com/watch?v=mmmcj53TNic) and increasing the efficiency of insulation in buildings (eg http://www.energysavingtrust.org.uk/domestic/) – there is plenty of scope for project-based tasks on the topic of efficiency, which would enable students to link their knowledge with the wider world around them.

Quantities and units

Match the quantity and unit

Work done	Joules, J
Distance	Joules, J
Energy transferred	Metres, m
Mass	Joules, J
Weight	Kilograms, kg
Power	Newtons, N
Velocity	Watts, W
Force	Metres per second, $m\,s^{-1}$
Kinetic energy	Newtons, N
Gravitational potential energy	Joules, J

Learner Resource 2

Powers of ten and prefixes

Match the measured quantity in the left-hand column with the correct statement in the centre column and the type of quantity in the right-hand column

Zero work	0 J	Work done in holding an object in the air without moving it
100 Joules per second	100 W	Mean total energy output per second of typical student at rest
1 Joule	1 J	Work done in moving an object by 1 metre with a force of 1 Newton
7 000 kW	7×10^6 W	Calculated maximum power output of Top Fuel dragster engine
0.7 kW	700 W	Maximum short-term power output of sprint cyclist
13.7 kJ	1.37×10^4 J	Gravitational potential energy of 70 kg human at height of 20 m above ground
630 kW	6.3×10^5 W	Approximate maximum power output of Formula 1 car
1 eV	1.6×10^{-19} J	Amount of energy transferred to electron when it is moved across a potential difference of 1 V
1650 MW	1.65×10^9 W	Maximum output of Dinorwig pumped storage power station
0.99	99%	Efficiency of typical electrical transformer

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