Module 3 Forces & Motion

Unit 3 Work, Energy & Power

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).

Module 2 – Foundations of physics

2.1 Physical quantities and units
2.2 Making measurements and analysing data
2.3 Nature of quantities

Module 3 – Forces and motion

3.1 Motion
3.2 Forces in action
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3.4 Materials
3.5 Newton's laws of motion and momentum

Module 4 – Electrons, waves and photons

4.1 Charge and current
4.2 Energy, power and resistance
4.3 Electrical circuits
4.4 Waves
4.5 Quantum physics

3.3 Work, Energy & Power

- 3.3.1 Work & Conservation of Energy
- 3.3.2 Kinetic & Potential Energies
- 3.3.3 Power

3.3.1 Work & Conservation of energies

3.3.1 Work and conservation of energy

	Learning outcomes
	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.

This is really hard work, or is it?

Work

- Work = force (F) x distance moved in the direction of the force (x)

- A scalar quantity
  - Obtained by multiplying two vectors.
  - Work has no direction

- SI unit is the Joule (J)

  One joule = one newton metre

Examples of Work

- Picking up a pen =

  $0.2\text{N} \times 0.1\text{m} = 0.02\text{J}$

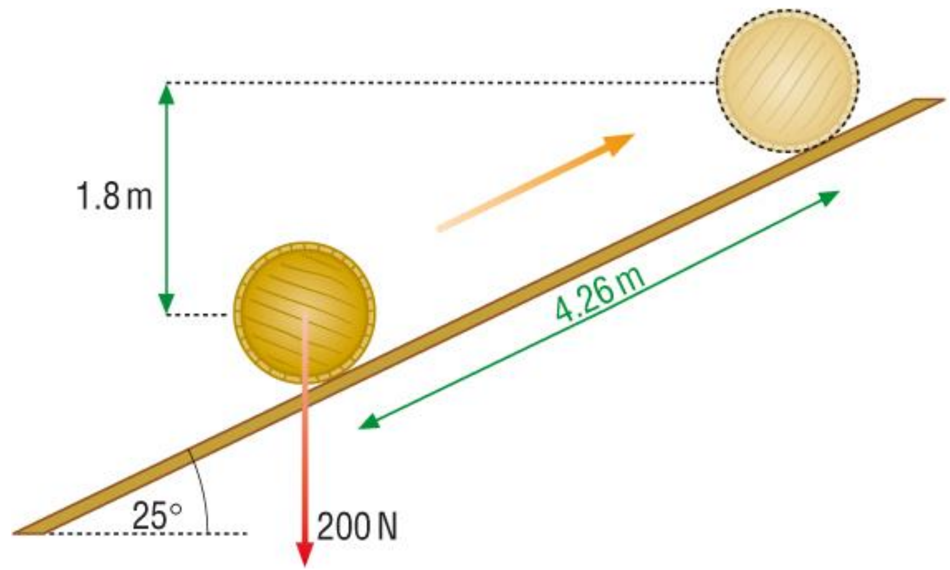
- Lifting a 20.39kg barrel to a height of 1.8m =

  $20.39\text{kg} \times 9.81 \times 1.8\text{m} = 360\text{J}$

These calculations all imply movement at a constant speed in the direction they are pushed. In reality, this does not always happen.

Forces at an angle to direction

- Lifting the barrel is easier if you push it up a ramp.
- The work done against gravity will always be 360J.
  - But it can be calculated in two ways:



Vertically upwards:
Work = 200N x 1.8m = 360J

Up the ramp:
Work = 200N x 4.26m x cos65 = 360J

So we have two formulae for work

- Work = Fx
- Work = Fxcosθ

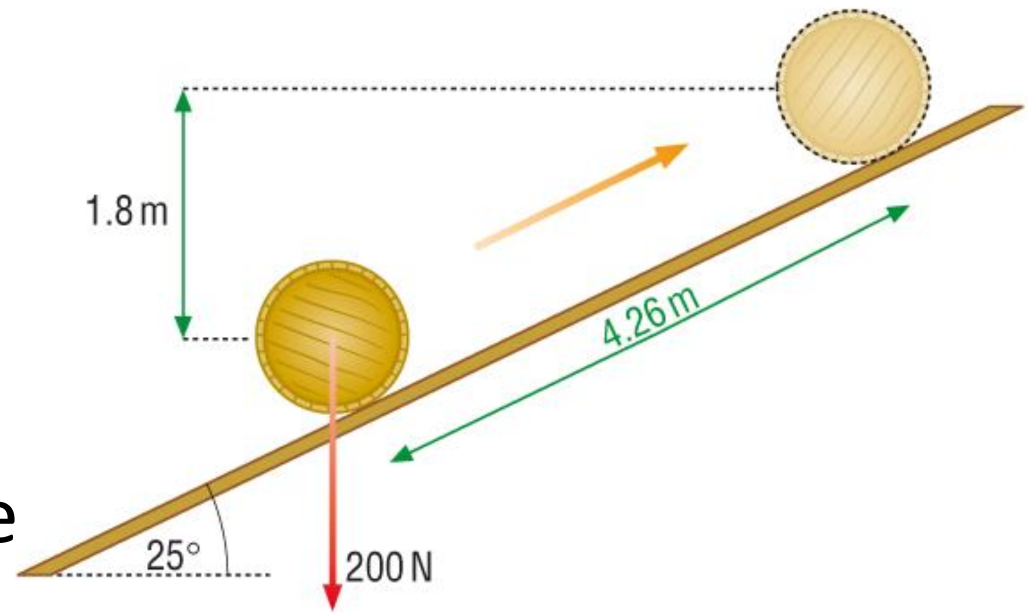
F = Force

x = Distance travelled

θ = Angle between force and direction of travel

What force would be used to push the barrel up the ramp?

- We know the total work done is 360J.
- If the distance moved is 4.26m the force in this direction must be 360/4.26=84.5N



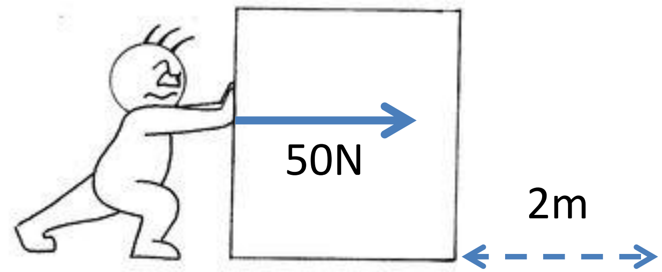
Forces at right angles

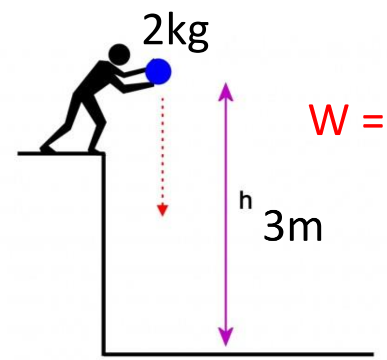
- If the force is at right angles to the direction of travel then no work is being done ($\cos 90 = 0$).

- So no work is being done **against gravity** when you push a car along a horizontal road.
  - You need to specify what work is being done.

Work and Energy

- **Work done = Energy transferred**
  - The work done on a box being pushed along the floor is transferred to thermal energy of the box and the floor.
  - The work done by gravity on a falling object is transferred to kinetic energy.
  - The work done against the force of gravity as an object is lifted is transferred to gravitational potential energy.





Is energy always conserved?

Energy

- Energy = the stored ability to do work.
  - Scalar quantity, the SI unit is the joule, J

- Energy can take different forms:
  - Kinetic Energy (where movement is taking place)
    - Moving objects
    - Sound

  - Potential Energy (in regions where electric, magnetic, gravitational or nuclear forces exist)
    - Chemical
    - Electrical
    - Electromagnetic
    - Gravitational
    - Internal (heat)
    - Nuclear

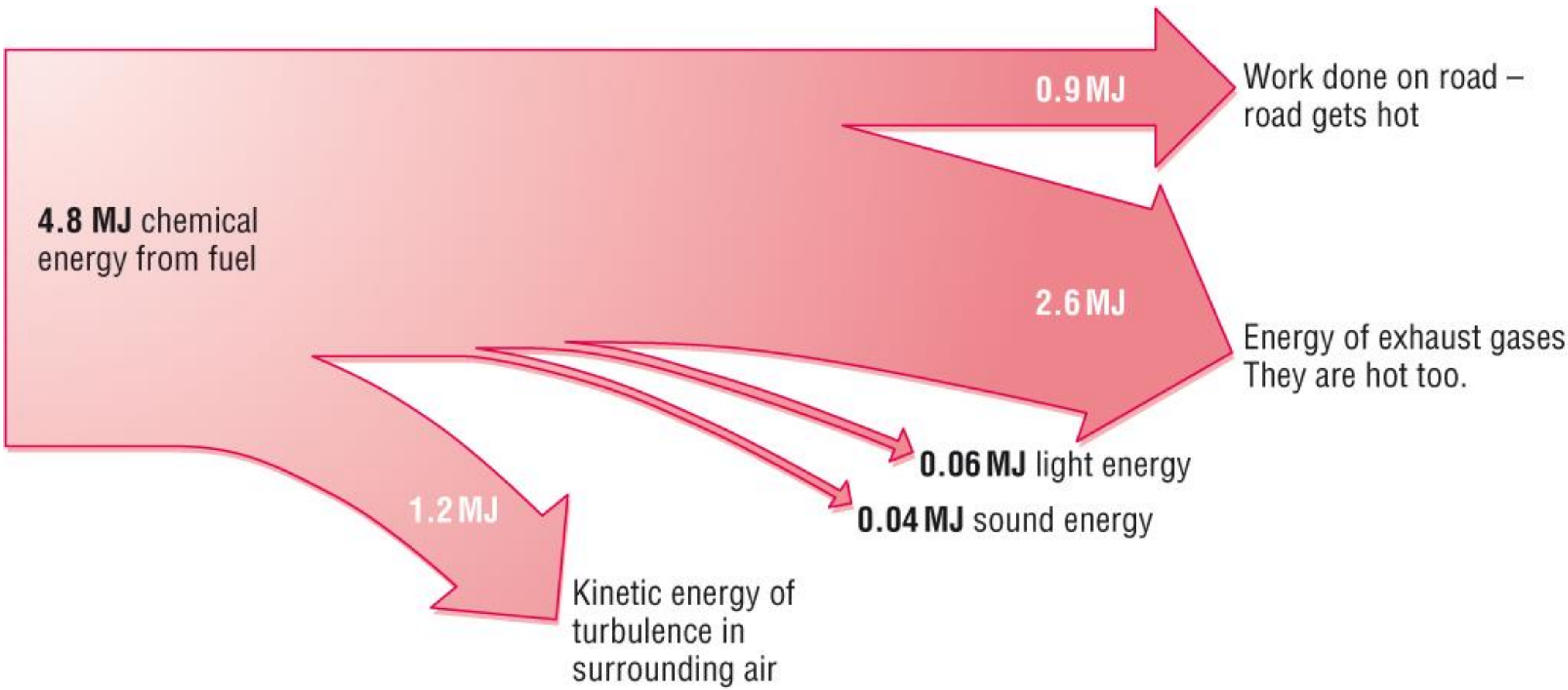
Conservation of Energy

- **In any closed system, energy cannot be created or destroyed but can be transferred from one form into another.**

- A Sankey diagram can be used to show these conversions diagrammatically.

Sankey Diagrams

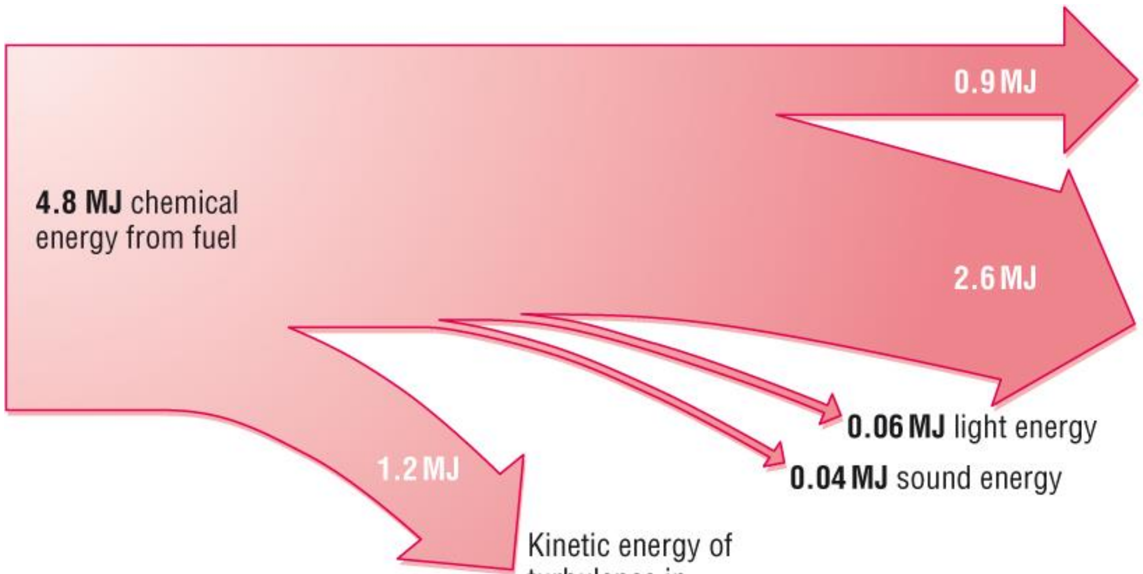
- A car travelling at constant velocity at night.



Figures are per minute

Why is there no energy being converted to kinetic energy of the car?

- The car is moving at a constant velocity



3.3.1 Work & Conservation of energies (review)

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3.3.2 Kinetic & Potential Energies

3.3.2 Kinetic and potential energies

Learning outcomes

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.

What energy transfers occur when an object is dropped?

Gravitational Potential Energy

- Gravitational Potential Energy (E_p)is gained by an object as it is raised vertically and lost when it is lowered.
  - The amount of energy transferred is dependent on the mass of the object and the height raised/lowered.
- Work (done against gravity) = Force x Distance
  - So energy gained (E_p) = Force x Height
    - E_p = Weight x Height
    - E_p = Mass x g x Height
    - **E_p = mgh**

Kinetic Energy

- The kinetic energy (E_k)of a moving object equals the work it can do as a result of its motion.

$$E_k = \frac{mv^2}{2}$$

- Kinetic energy can do work against a stopping force, heating a set of brake pads for example.

$$E_k = \frac{mv^2}{2} = Work = Fs$$

Deriving E_k

Deriving $E_k = \frac{1}{2}mv^2$

You can derive the equation for KE by using ideas developed in this book already.

Figure 2 shows a constant force F acting on an object of mass m. The object is initially at rest. The acceleration of the object is a. After a distance s it has a speed v.

The distance s travelled by the object can be determined from the equation of motion $v^2 = u^2 + 2as$.

$$s = \frac{v^2 - u^2}{2a} = \frac{v^2}{2a} \qquad (u = 0)$$

The work done by the force is entirely transferred to the KE of the object. Therefore

$$\text{work done} = E_k = Fs$$

The force F is given by $F = ma$. Therefore

$$E_k = ma \times s = ma \times \frac{v^2}{2a}$$

$$\therefore E_k = \frac{1}{2}mv^2$$

(where $\therefore$ denotes *therefore*).

Figure 2 *Gaining kinetic energy*

1. Use the equation for E_k to derive the SI base units for kinetic energy.
2. Derive an equation for E_k in terms of speed v, weight W of an object, and acceleration of free fall g.

Measuring g

- Use a card, some plasticine, a light gate and a ruler to measure g.

What else can we do with these equations?

- We can prove Galileo right when he suggested that objects fall at the same rate regardless of mass.
  - A falling object loses GPE and gains KE as it accelerates towards the ground.
  - The amount of KE gained equals the GPE lost.

Mass cancels from both sides

V is therefore independent of mass

$$mgh = \frac{mv^2}{2} \qquad 2gh = v^2 \qquad v = \sqrt{2gh}$$

Anything else?

$$\Delta E_k = \frac{mv^2}{2} = Fs = \text{Work Done}$$

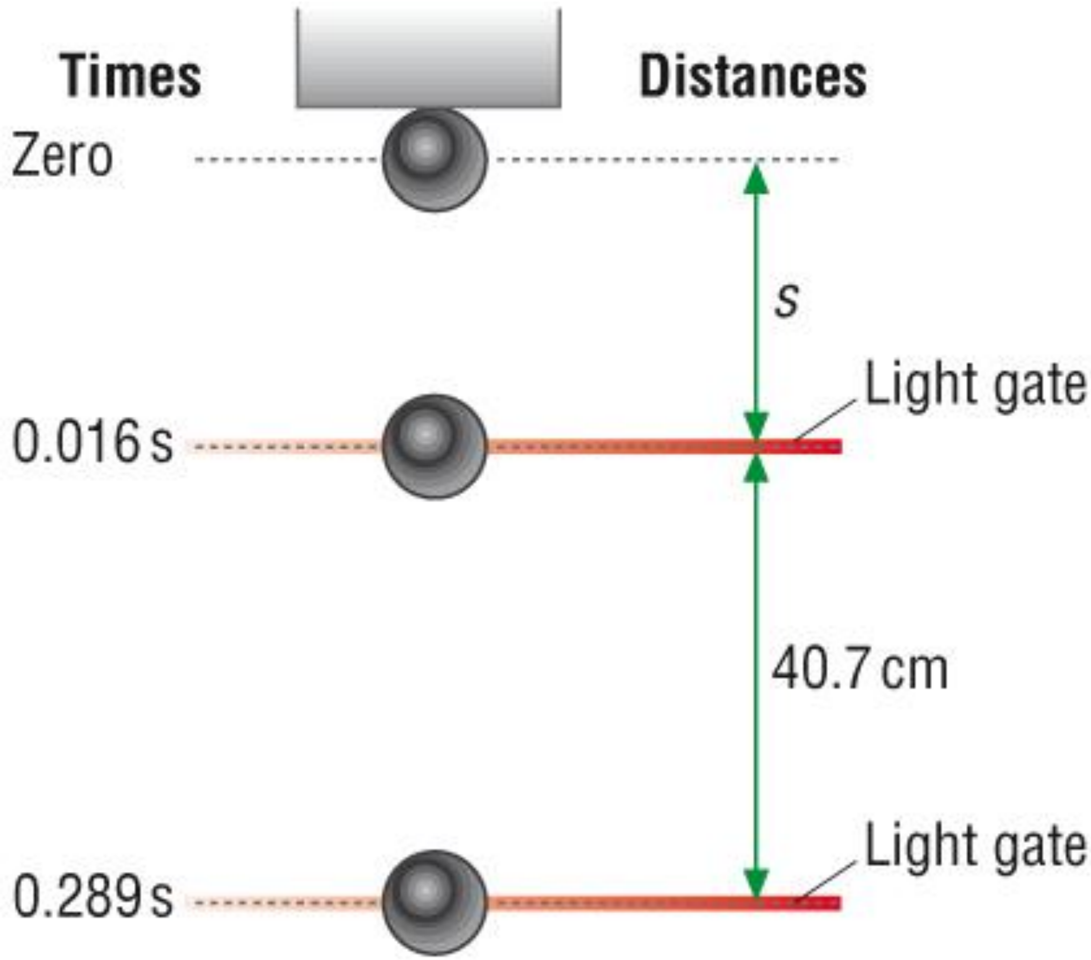
- This explains why the braking distance of a car (work done by the brakes) is proportional to its initial speed.

$$\Delta E_p = mg\Delta h$$

- As objects fall, GPE is lost.
  - Where does it go?
    - Transferred to E_k.
    - Dissipated as thermal energy.

Worked example

- Calculate:
  - g (acceleration due to gravity).
  - loss of GPE between the light gates.
  - KE of the ball as it passes second light gate.



Mass of ball = 5.38g

3.3.2 Kinetic & Potential Energies (review)

3.3.2 Kinetic and potential energies

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3.3.3 Power

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Learning outcomes

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;

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

Watt is the unit of Power?/!

Watt is the unit of Power?

Power = the rate at which work is done.

Power = Work Done/Time Taken

$$P = \frac{W}{t}$$

- Power is measured in joules per second, or watts (W).

- Power can also be seen as the rate of energy transfer.

$$P = \frac{E}{t}$$

Watt is Horsepower?

- Power can be applied to all energy transfers (eg the rate at which we climb a ladder, or push a trolley in Tescos).
- Humans would do well to transfer energy at a rate of 70W over a long period.

- Horsepower is a measure still used today.
  - 1 Horsepower is equivalent to 746W

How powerful are you?

- If a 50kg person runs up a 3.0m (vertical height) flight of stairs in 6.5s, what is the rate of work done against gravity?

$$P = \frac{W}{t} = \frac{E_p}{t} = \frac{mgh}{t}$$

P = 50 x 9.81 x 3.0 / 6.5 = 230W

- Watt is your power? Who is the most powerful in the class? Find out using the stairwell.

Ideal Height v Mass for men

Weight																				
Height			Small Frame						Medium Frame						Large Frame					
(ft)	(in)	(cm)	(lbs)		(lbs)	(kg)		(kg)	(lbs)		(lbs)	(kg)		(kg)	(lbs)		(lbs)	(kg)		(kg)
5	2	158	128	-	134	58	-	61	131	-	141	59	-	64	138	-	150	63	-	68
5	3	160	130	-	136	59	-	62	133	-	143	60	-	65	140	-	153	64	-	69
5	4	163	132	-	138	60	-	63	135	-	145	61	-	66	142	-	156	64	-	71
5	5	165	134	-	140	61	-	64	137	-	148	62	-	67	144	-	160	65	-	73
5	6	168	136	-	142	62	-	64	139	-	151	63	-	68	146	-	164	66	-	74
5	7	170	138	-	145	63	-	66	142	-	154	64	-	70	149	-	168	68	-	76
5	8	173	140	-	148	64	-	67	145	-	157	66	-	71	152	-	172	69	-	78
5	9	175	142	-	151	64	-	68	148	-	160	67	-	73	155	-	176	70	-	80
5	10	178	144	-	154	65	-	70	151	-	163	68	-	74	158	-	180	72	-	82
5	11	180	146	-	157	66	-	71	154	-	166	70	-	75	161	-	184	73	-	83
6	0	183	149	-	160	68	-	73	157	-	170	71	-	77	164	-	188	74	-	85
6	1	186	152	-	164	69	-	74	160	-	174	73	-	79	168	-	192	76	-	87
6	2	188	155	-	168	70	-	76	164	-	178	74	-	81	172	-	197	78	-	89
6	3	191	158	-	172	72	-	78	167	-	182	76	-	83	176	-	202	80	-	92
6	4	193	162	-	176	73	-	80	171	-	187	78	-	85	181	-	207	82	-	94

Ideal Height v Mass for women

Weight																				
Height			Small Frame						Medium Frame						Large Frame					
(ft)	(in)	(cm)	(lbs)		(lbs)	(kg)		(kg)	(lbs)		(lbs)	(kg)		(kg)	(lbs)		(lbs)	(kg)		(kg)
4	10	147	102	-	111	46	-	50	109	-	121	49	-	55	118	-	131	54	-	59
4	11	150	103	-	113	47	-	51	111	-	123	50	-	56	120	-	134	54	-	61
5	0	153	104	-	115	47	-	52	113	-	126	51	-	57	122	-	137	55	-	62
5	1	155	106	-	118	48	-	54	115	-	129	52	-	59	125	-	140	57	-	64
5	2	158	108	-	121	49	-	55	118	-	132	54	-	60	128	-	143	58	-	65
5	3	160	111	-	124	50	-	56	121	-	135	55	-	61	131	-	147	59	-	67
5	4	163	114	-	127	52	-	58	124	-	138	56	-	63	134	-	151	61	-	68
5	5	165	117	-	130	53	-	59	127	-	141	58	-	64	137	-	155	62	-	70
5	6	168	120	-	133	54	-	60	130	-	144	59	-	65	140	-	159	64	-	72
5	7	170	123	-	136	56	-	62	133	-	147	60	-	67	143	-	163	65	-	74
5	8	173	126	-	139	57	-	63	136	-	150	62	-	68	146	-	167	66	-	76
5	9	175	129	-	142	59	-	64	139	-	153	63	-	69	149	-	170	68	-	77
5	10	178	132	-	145	60	-	66	142	-	156	64	-	71	152	-	173	69	-	78
5	11	180	135	-	148	61	-	67	145	-	159	66	-	72	155	-	176	70	-	80
6	0	183	138	-	151	63	-	68	148	-	162	67	-	73	158	-	179	72	-	81

Watt is the power of a falling object?

When an object is moving at constant velocity against friction

- Eg. Terminal velocity of a falling object.
- Eg. A car driven at constant speed on the M1.
- Eg. Michael Phelps swimming 100m.

- The resultant force on the object is zero (constant speed).
- The work done by the forward force (weight, thrust) is therefore work done against friction.

When an object is moving at constant velocity against friction

- We can calculate the power developed by the forward force:
  - The constant force against constant friction moves the object a distance (x) in a time (t).
  - Work done = Force x Distance.

$$P = \frac{W}{t} = \frac{Fx}{t}$$

But speed is x/t, so..

$$P = Fv$$

$$P = Fv$$

- This equation can be used for any object moving at a constant velocity against friction.

- What is the power developed by an object moving at constant velocity in deep space?

How can we calculate efficiency?

Efficiency

- A measure of how much useful energy is transferred in a system compared to unwanted energy.

- $$\text{Efficiency} = \frac{\text{Useful output energy}}{\text{total input energy}} \times 100\%$$

Efficiency is always less than 100%

- In any energy transfer there will always be some energy “lost” to the environment.

Device	Energy input	Energy output	Typical efficiency (%)
electric motor	electrical	kinetic/potential	85
solar cell	light	electrical	10
rechargeable battery	electrical	electrical	30
electric radiator	electrical	internal	100
power station	nuclear	electrical	40
car (petrol)	chemical	kinetic/potential	45
car (diesel)	chemical	kinetic/potential	55
steam engine	chemical	kinetic/potential	8

Table 1 Examples of common devices for which efficiency is important

Erm, is this right?

This will produce light so no, it’s not.

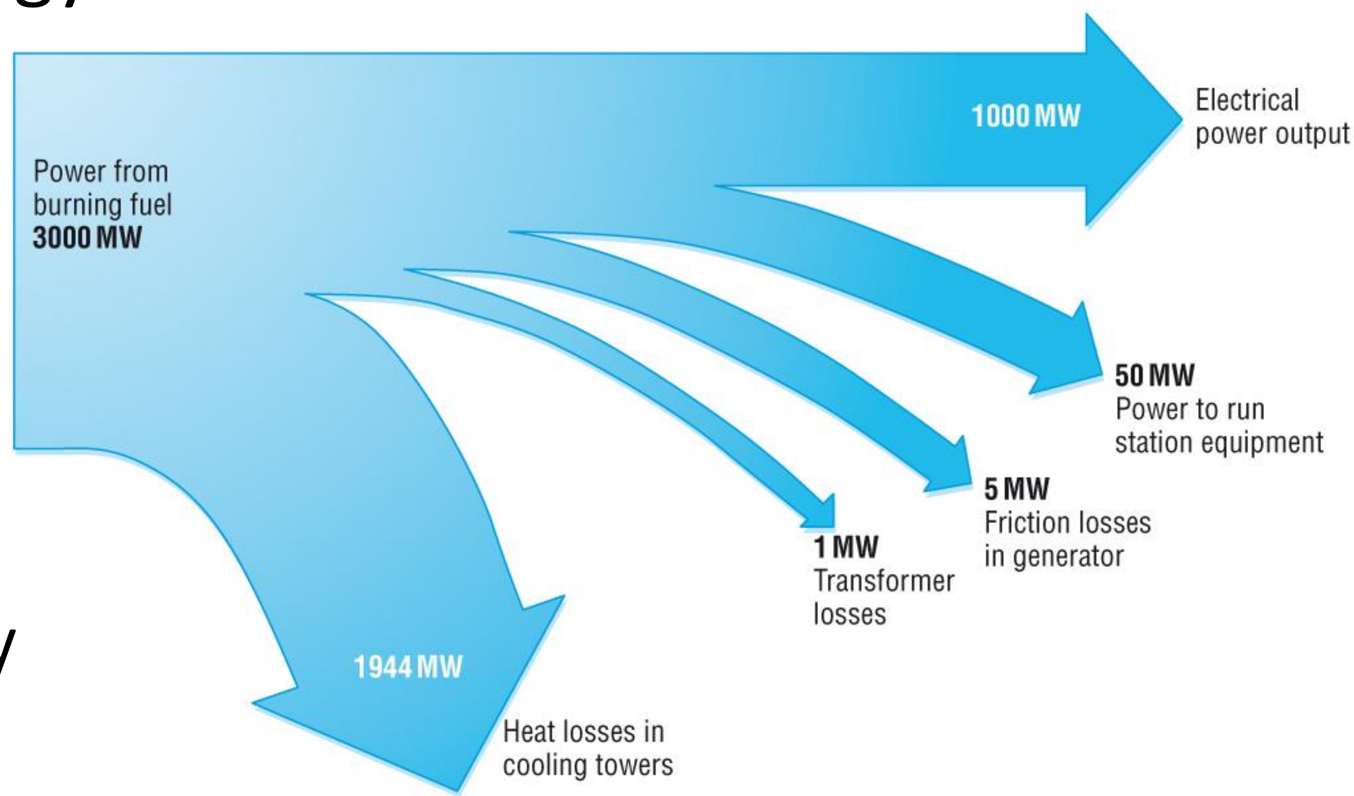
Which transfers are most efficient?

- Transfers involving nice, ordered systems like electrical energy converting to a disordered heat energy will be easy to achieve and so be the most efficient.

- Transfers going the other way round (eg generating electricity from heat) are more difficult and so less efficient.

Sankey diagrams can be used to represent the energy changes

- This one is expressed in terms of power rather than energy...



What is the efficiency of this electricity generator?

3.3.3 Power (review)

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