Physics for non-physicists

Kate Wilson

University of New South Wales

and Australian Institute of Physics (NSW Publicity Officer)

kwilson@phys.unsw.edu.au

Introduction – Laws of Physics

Anyone studying physics tends to learn a lot of laws, principles and rules. These rules are often treated as articles of faith – things that are always obeyed and always true. In fact the laws of physics are reasonable working theories, that have been shown to work enough times, and never been shown to not-work, that we accept them as true. In fact it is impossible to prove that they are true. Any law or theory can be disproved, but it cannot be proved, that is the nature of a scientific theory.

This is not to devalue the laws and theories of physics – to say, “well, it’s just a theory, its no better than any other theory” is missing the point. Scientific theories are useful – they give us predictive power, so we can tell what’s going to happen, and they can be applied to give us technology. Many people find the quantum theory strange and unbelievable – yet all our modern technology, from transistors to computers and cellular phones is based on quantum theory.

In these lectures we will look at some of the basic laws and principles of physics, and how they can be applied. The first lecture will deal mainly with conservation principles, while the second will look at Newton’s laws and forces. The two ideas – forces and conservation – are related, and this relationship will be stressed throughout the two lectures.

Suggested Reading

“The Character of Physical Law” and “Six Easy Pieces” by Richard Feynman are both excellent and accessible books for an introduction to the nature of physics and the basic laws of physics. If you really get into, The Feynman Lectures in Physics are a good read, with a slightly different approach to a standard text book. The chapters in “Six Easy Pieces” are drawn directly from the Feynman Lectures.

Any good text book will also have a good explanation of conservation principles and forces, although some are better than others. I like Tipler’s “Physics” and Kane and Sternheim’s “Physics”. Kane and Sternheim has lots of good biological examples and Tipler puts quantum up front, and in context, rather than hiding it in the back as most other text books do.

Around the end of July the book “Workshop Tutorials for Physics” will be published. The activities in these lectures are drawn from that project. The book will be produced by a collaboration based at University of Sydney and will be available from the School of Physics there.

Lecture 1. Conservation Principles

Conservation Principles

Conservation principles are part of the basic physics toolbox used to approach a huge range of problems in physics. The conservation principles we will use here are:

- Conservation of Energy
- Conservation of Momentum
- Conservation of Charge

There are other conservation principles such as conservation of angular momentum, and some others that have been discovered as part of the development of quantum theory.

Almost anything that happens in an electronic circuit can be described using conservation of energy and conservation of charge. The way cyclones can pull roofs off houses and why planes can fly can be explained using conservation of energy. Conservation of momentum explains why gases exert pressure and why rockets fly.

Conservation of Energy

The principle of Conservation of Energy tells us that the total energy in any isolated system is constant. So what is an isolated system? An isolated system is on which no external forces are acting. Its very hard to find a genuine isolated system in real life, unless you take your isolated system to be the entire universe. But there are systems which are a reasonable approximation to isolated – ones in which there is very little or no friction. For example, cars skidding on an icy road or skiers sliding down hill. In a system like this, the total energy remains constant, although it can change forms. Energy comes in two different forms – kinetic energy and potential energy. Kinetic energy is energy associated with movement. A moving car has kinetic energy 1/2 mv^2, where m is the mass of the car and v is the velocity of the car. Thermal energy, often called heat, is also a form of kinetic energy – it is the average kinetic energy of atoms, which move and vibrate. The more kinetic energy the atoms of a substance have, the hotter that material is. Potential energy also comes in different forms, such as gravitational potential energy and electrical potential energy. In an isolated system the sum of all the different forms of energy remain constant.

In real life we usually deal with systems that are not isolated. In this case we need to take into account energy coming in and energy going out. The total energy is then the energy coming in, plus the kinetic energy plus the potential energy minus the work going out. This applies to mechanical systems including heat engines, and electrical systems.

In thermal physics, we usually call the energy coming in work, and divide the energy going out into work and heat (thermal energy). It is divided this way because heat is not generally considered very useful, and thermal physics is all about getting as much useful work out of a system as possible. The first law of thermodynamics, which states that the change in internal energy of a system is the heat or energy you put in minus the work done, is a statement of conservation of energy.

In an electric circuit, Kirchoff's loop law tells you that around loop in a circuit the sum of changes in electric potential is zero. Electric potential is potential is just potential energy per unit charge, a sort of energy density. The voltage supplied by a battery is the energy put into a circuit, and the thermal energy dissipated by a resistance is heat or energy coming out of a circuit. The energy coming in must be equal to the energy going out. Energy can be stored as potential energy in a circuit in a capacitor.

Conservation of Momentum

The principle of conservation of momentum tells us that the total momentum of all the particles in an isolated system is constant. If you consider a moving object such as a ball which has been thrown, it will have a constant momentum unless some force acts on it. Newton's first law, which says that an object at rest will remain at rest, and an object in motion will continue with constant velocity unless acted on by an external force. This is a statement of conservation of momentum – although Newton said it like this first, so we usually learn and teach it as Newton's first law, before we learn it again, or recognise it, as conservation of momentum.

Consider again a ball that has been thrown. If the ball was thrown in deep space, away from any other bodies, then it would continue in a straight line with constant momentum. However a ball thrown on Earth experiences external forces – gravity and friction (air resistance). These two forces act to change the momentum of the object.

If you consider an approximately isolated system – say a rocket ship in space – with no external forces there will be no change in momentum. To make a rocket ship work it burns fuel and ejects it out the back. If the rocket starts off with zero momentum, then the total momentum of the rocket and its contents, including fuel, continues to be zero unless an external force acts. When the fuel is ejected it has momentum away from the rocket ship. Conservation of momentum tells us that the rocket ship moves in the opposite direction so that the total momentum is still zero.

Momentum is a very useful concept – Newton defined what a force is in terms of momentum. Newton's second law, which is commonly written as $F_{\text{net}} = ma$ was originally written as $F_{\text{net}} = \mathrm{d}p/\mathrm{d}t$, the change in momentum with time. Mostly when we apply Newton's second law the mass of the object of interest is not changing, so we can just use $F_{\text{net}} = \mathrm{d}p/\mathrm{d}t = \mathrm{d}(mv)/\mathrm{d}t = m\,(\mathrm{d}v/\mathrm{d}t) = ma$.

As stated above, when we talk about the temperature of a substance, we are really talking about the average kinetic energy of the atoms that make up the substance. We measure temperature by allowing kinetic energy to be transferred to the thermometer. When we talk about pressure, we are really talking about the momentum of the particles. We measure pressure by allowing the particles to collide with and transfer momentum to the pressure meter or barometer. The greater the momentum transferred, the greater the pressure. Pressure is defined as force per unit are – $P = F/A = (\mathrm{d}p/\mathrm{d}t)/A$. Pressure can also be considered as an energy density – if you look at the units for pressure, they are the same as the units for energy divided by volume.

An aside on units:

Momentum has units of kg.m.s^{-1}. Pressure has units of (kg.m.s^{-1}) m^{-2} = kg.m^{-1}.s^{-1}, also called pascals, Pa. Energy has units of joules, J, which are the same as kg.m^{2}.s^{-2}. A useful way of trying to understand things or figure out how to solve a problem when you're not quite sure what to do, is to use the units. This is sometimes called "dimensional analysis" as units are also called dimensions. Take all the units of the things you are given, and see how they can be arranged to get the units of the thing you are trying to find – this doesn't always work, for example when there are dimensionless constants involved – but it is a very useful trick. Students are often very sloppy with units, and it is worth pointing out that knowing the units can be valuable in itself.

Conservation of charge

Charge is a fundamental property of matter, and is conserved. Charge comes in two varieties – positive and negative. The total amount of charge in the universe seems to constant, and not far from zero. Most objects are net uncharged, or neutral – they have as much positive charge in them as negative. Atoms have a positively charged nucleus, surrounded by negatively charged electrons. When you charge something up, charge is not being created, it is being moved from somewhere else. If you charge up an object, like a cat, by adding electrons, those electrons are coming from somewhere else. If the cat is becoming negative, then something else is becoming positive at the same rate.

When we talk about how atoms form bonds we often talk about filling outer electron shells and making up a full shell of 8 electrons. Students sometimes get confused when talking about electron shells in atoms, and think that a full outer shell means that the atoms has a charge of eight, or that a partially filled shell, say lithium with just a single outer shell electron, has a charge of 1. They forget that a neutral atom has the same number of protons with positive charge as it does electrons with negative charge. It is only when an electron is lost or gained – the atom is ionised – that the atom has a net charge.

For a long time it was thought that mass was also conserved, but this turned out not to be the case – mass can be converted into energy. This does not seem to be the case for charge.

Conservation of charge is useful for understanding how circuits work. Current is the flow of charge, the amount of charge (measured in coulombs, C) moving past a point in a circuit per unit time. The amount of current that flows is proportional to the (electromotive) force applied to the charges. The bigger the force, the greater the current. However to have a current, you need to have charges which are free to move. A conductor has charges which are almost entirely free to move within the conductor, while a semiconductor has partly-bound charges – they need more force to make them flow. Kirchoff's junction rule, which says that the sum of all currents coming into a junction must be equal to the sum of currents going out, is just a statement of conservation of charge. Combine that with Kirchoff's loop law, which is a statement of conservation of energy, and you can figure out what's going on in just about any circuit.

Using conservation principles: Activities

Pendulum

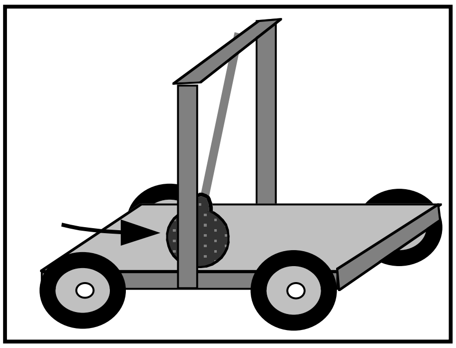
Swing the pendulum bob out and release it. At what position is the kinetic energy maximum, minimum? At what position is the potential energy maximum, minimum? Draw energy bar graphs for the pendulum at different points in its swing.

Solar panel and electric circuit

Trace the energy conversions using a flow chart and identify which ones are "useful" and which are not.
Think of a case where this "not useful" energy may be useful.
Trace energy transformations from water stored in a dam, which supplies a hydro-electric power station, to turning on an appliance at home.

Bouncing balls I

Drop two balls from the same height. Why do some balls bounce higher than others?
Can you make any of the balls bounce higher than the original height? Does this contradict conservation laws? Explain your answer.



Pendulum on Trolley

Swing the pendulum bob.
What happens to the trolley? Why does it behave like this?

Balloons

Blow up a balloon, and do *not* tie off the neck.
Now let it go. What does the balloon do?
Explain what happens in terms of conservation of momentum.

Newton's Cradle – 2 steel balls

Swing one of the balls out and release it.
What happens when it hits the other ball?
What has happened to the momentum of the first ball?
What has happened to the momentum of the second ball?
Explain how this is also consistent with Newton's third law – that for every action there is an equal and opposite reaction, which can be written as $F_{AB} = - F_{AB}$.

Newton's cradle – different balls

Examine the two sets of Newton's cradle on display. Explain the difference between the two types (one with steel balls and one with lead balls) of apparatus on display.
Can you explain the behaviour of the balls with only energy conservation or do you need conservation of momentum as well? Discuss your answer.

Bouncing balls II

Hold a little ball in contact with and directly above a big ball. Drop the balls together.
Describe what happens. Why does this happen?
Do you get the same behaviour if the big ball is above the little ball?

Blowing and lifting

How is it possible to lift a foam block off the table by blowing down a hollow tube onto it?

Two sheets of paper

What happens if you blow between two sheets of paper held approximately parallel and about 2 cm apart? Can a similar phenomenon occur as two large trucks pass each other on a highway?

Explanations of Activities

Pendulum

At the lowest point of the pendulum bob's motion, its kinetic energy is maximum and potential energy is minimum.

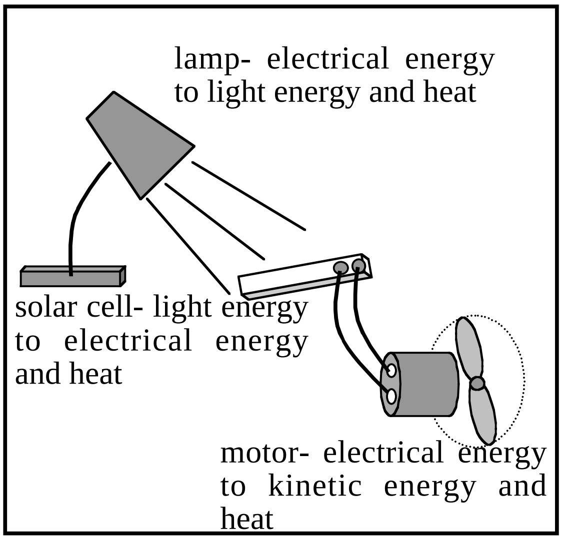
At the highest point of its motion, kinetic energy is minimum (i.e. zero) and potential energy is maximum.

Solar panels and electric circuit

Energy as light is converted to electrical energy by the solar cell which is then converted to kinetic energy by the motor. Some energy is also converted to heat, which is usually not considered useful.

Heat is useful energy when you want to heat or cook something.

Dammed water has gravitational potential energy, which is converted to kinetic energy when the dam is open. This is converted to kinetic energy of a turbine placed in the flow, which is attached to a generator. The generator turns the kinetic energy into electrical energy which is converted into light, heat, sound or mechanical energy by a home appliance.

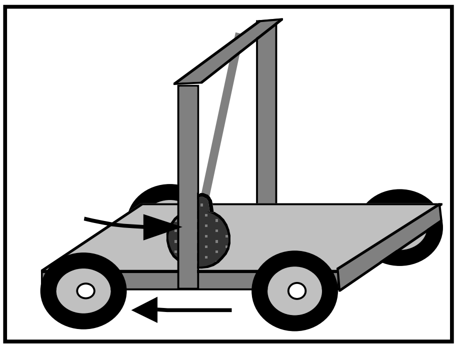


Bouncing balls I

Balls that lose less energy to non-mechanical forms rise higher than balls that lose more energy. A ball can bounce higher than the original height if we throw the balls instead of just dropping them. These balls start off with kinetic energy and gravitational potential energy instead of just gravitational potential energy.

Pendulum on Trolley

When you raise the bob and hold the base still the total momentum of the pendulum-trolley system is zero. When you release the bob it swings down, gaining momentum. In order for momentum to be conserved the trolley must move the opposite way, which it does. As the pendulum swings back and forth the trolley will roll back and forth in the opposite direction, until friction eventually stops it.



Balloons

When the balloon is released the air inside it rushes out because it is under pressure. The air comes out the neck of the balloon. For momentum to be conserved the balloon (and remaining air) must move in the opposite direction. This is what happens, and the balloon whizzes around the room, moving in the opposite direction to the air flow.

Newton's cradle – 2 steel balls

When the first ball (ball A) swings back and hits the second ball (B) it stops. The second ball swings out.

Momentum is conserved, so the change in momentum of ball A must be equal in magnitude and opposite in direction to the change in momentum of ball B. We can write this as $\Delta p_A = - \Delta p_{B.}$

We also know that $\vec{\mathbf{F}} = \frac{d\vec{p}}{dt}$, so as the momentum changes of the two balls are equal in magnitude and opposite in sign, the forces acting on them must also be equal in magnitude and opposite in sign. This is equivalent to Newton's third law which states that the force exerted by ball A on ball B must be equal and opposite to the force exerted by ball B on ball A, $F_{AB} = - F_{AB}$.

Newton's cradle – different balls

Steel balls have almost elastic collisions, in which both kinetic energy and momentum are conserved. The lead balls have inelastic collisions in which only momentum is conserved.

Both energy and momentum conservation are needed to explain the behaviour of the balls. Energy conservation is needed to account for the KE of the ball at the time of impact. The collisions obey conservation of momentum.

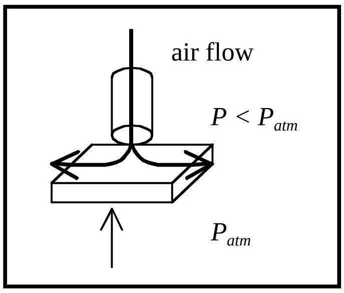
Bouncing balls II

The small ball held over the big ball bounces off higher as some momentum is transferred from the big ball to the small ball, increasing its velocity. Momentum has been conserved during the collision and the change in momentum of the small ball is large.

If the balls are switched around the momentum is still conserved, but the transfer of momentum from the small to the big ball makes little difference to the big ball's velocity due to its large mass.

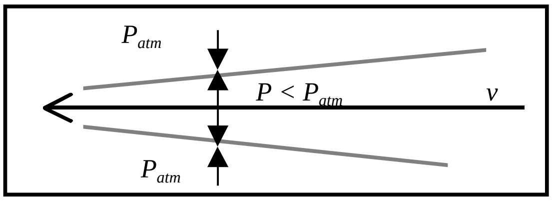
Blowing and lifting

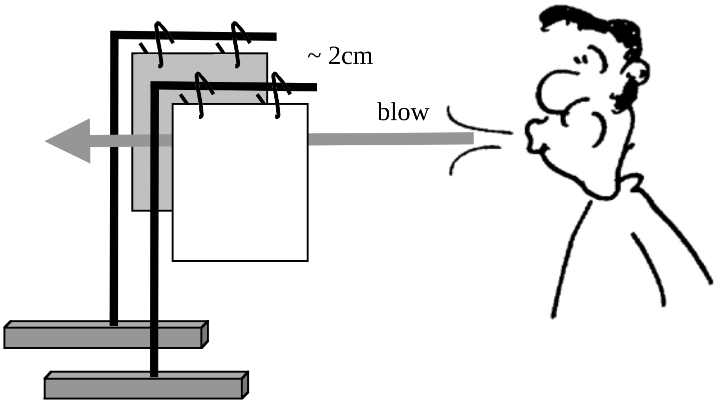
As air rushes through the narrow gap it speeds up and the pressure drops. There is atmospheric pressure under the polystyrene so the pressure difference results in a force up, equal and opposite to the weight of the polystyrene.



Two sheets of paper

There is reduced pressure between the sheets of paper and they move inwards. Other examples are passing vehicles and the lower end of a shower curtain curling towards the water.





Conservation principles – some practice questions for students

1. You throw a ball vertically into the air and catch it when it returns. Answer questions **a** and **b** first by ignoring air resistance, and then taking it into account.

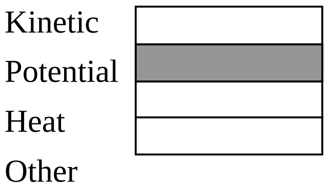
a. What happens to the ball’s kinetic energy during the flight?

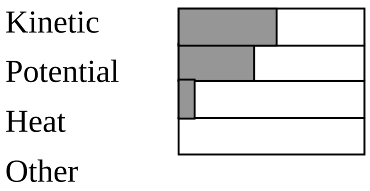
b. What happens to the total energy of the ball?

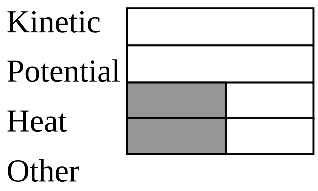
c. What happens to the energy of the ball as you catch it and it comes to rest?

d. Why is it easier (and less painful) to catch a ball while moving your hands backwards?

2. Draw a set of diagrams for a situation which could be described by the following energy bar graphs **or** make up your own scenario and draw appropriate energy bar graphs (be creative!!)







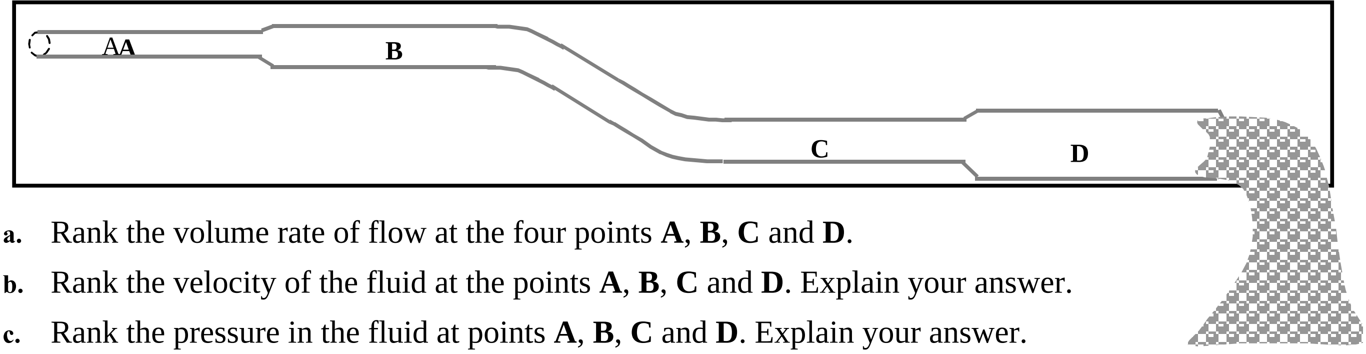
3. Astronauts use a strong line to attach themselves to the outside of a space craft when they go outside. Draw a diagram showing what happens when an astronaut pulls on the line to get back to the space craft. How does the momentum of the astronaut change? How does the momentum of the space craft change? What about the astronaut and space craft combined?

4. A group of students are designing a roller coaster. They want to be able to make it go faster along a straight, frictionless length of track. Brent suggests putting some water in the bottom half of the carriage and a plug in the bottom, which can be removed. His theory is that when the plug is removed the carriage will speed up. Rebecca tells him not to be silly, the carriage will slow down. Julia doesn’t think it will make any difference, but lets them go ahead and try it just to prove her point. Who is right and why?

5. Why is it easier and less painful to catch a fast moving ball by moving your hand back with the ball, rather than keeping your hand still?

6. Rebecca is helping Brent study for a test on circuit theory. Brent is having trouble remembering Kirchoff’s rules. Kirchoff’s rule for junctions states that the total currents going into a junction must be equal to the total currents coming out of a junction. Kirchoff’s rule for loops says that the sum of all the potential changes around a loop must be zero. Rebecca tells him that these things are pretty obvious, and are really just statements of conservation of charge and conservation of energy. How can Rebecca justify this claim? (Hint: the potential difference (or voltage) between two points is the difference in potential energy per unit charge at those points.)

7. Water flows through the pipe shown below from left to right.



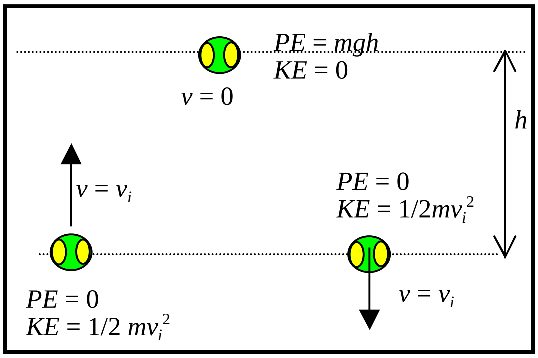
a. Rank the volume rate of flow at the four points **A**, **B**, **C** and **D**.

b. Rank the velocity of the fluid at the points **A**, **B**, **C** and **D**. Explain your answer.

c. Rank the pressure in the fluid at points **A**, **B**, **C** and **D**. Explain your answer.

Solutions to Practice questions

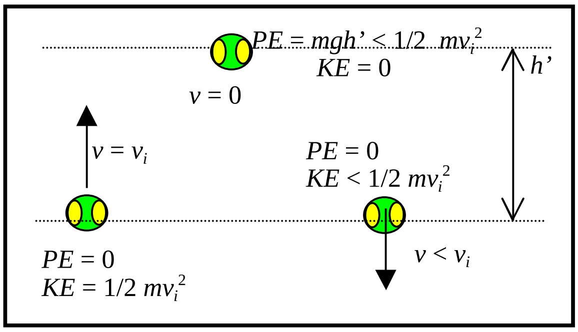
1. a. and b. With no air resistance:



The ball has an initial velocity, v_i, and kinetic energy $KE_i = 1/2\ mv_i^2$. It also has an initial height $h_i = 0$ and potential energy $PE_i = mgh_i = 0$. As the ball goes up, its kinetic energy decreases and is zero at a height of h, its gravitational potential energy increases and is maximum at h. The reverse happens on the way down, such that the total energy of the ball is constant, i.e. at every instant $PE + KE =$ total energy.

Or, in terms of work rather than potential energy, there is no change in kinetic energy of the ball between the initial and final positions thus the total work is zero. During the flight the work done by weight on the way up is $W=-mgh$ and on the way down is $W = mgh$.

a. and b. With air resistance:



As the ball goes up, there is work done by air resistance, so the ball's its kinetic energy decreases and is zero at a height h' which is less than h. On the way down again there is work done by air resistance. Consequently the final kinetic energy is less than the initial kinetic energy, i.e. final speed is less than initial speed. The total energy of the ball-earth system is $PE + KE + W_{\text{air resistance}}$.

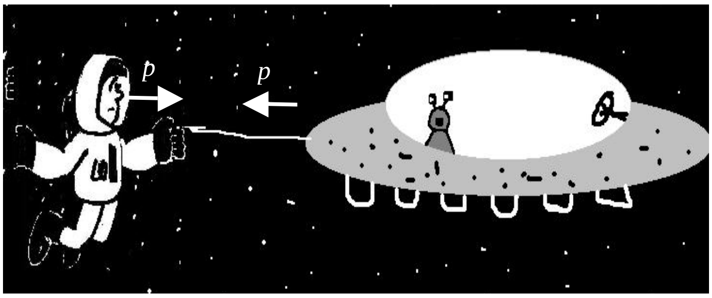
Total energy is constant but the ball has mechanical energy when caught. Some of its energy has been converted into heat due to work done by air resistance.

c. The energy is converted into heat, sound and motion of the muscles in your hand.

d. Your hand must do work on the ball to change it's kinetic energy from $1/2\ mv^2$ to 0. The work done is given by the force times the distance, so if you increase the distance over which your hand applies the force to stop the ball, the force required is less. If the force on the ball by your hand is less then the force by the ball on your hand will also be less.

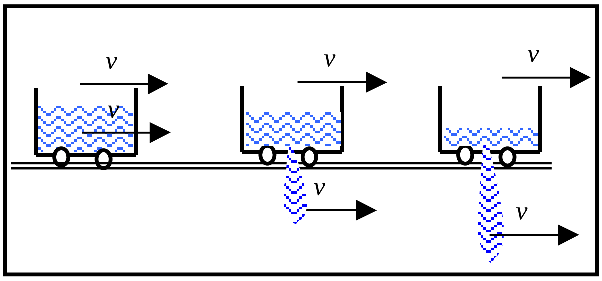
2. One possible scenario is someone sliding down a hill with potential energy being converted to kinetic energy and heat due to friction, and hitting a tree at the bottom, the collision converting the kinetic energy into heat and sound. There are a virtually infinite number of possible scenarios!

3. Astronauts use a strong line to attach themselves to the space craft when they go outside. When an astronaut pulls on the line to get back to the space craft they move towards the space ship and it moves towards them. They apply a force to the ship, via the rope. The ship applies a reaction force, equal in magnitude but opposite in direction, to the astronaut.



The rate of change of momentum is equal to the net force applied, and so assuming no other forces the change in momentum of the space ship is equal to that of the astronaut, and they move towards each other. As no external forces are acting the total change in momentum is zero. Note that the mass of the ship is much larger than the astronaut's mass, hence the astronaut accelerates rapidly towards the ship, while the ship accelerates only slowly towards the astronaut.

4. Julia is correct. Pulling the plug will not change the speed of the roller-coaster. Consider the roller-coaster plus water as the system. As the water falls it does not apply a force to the roller-coaster, and there are no external forces acting in the horizontal direction, so the speed does not change. The water will flow out with horizontal velocity the same as that of the roller-coaster, and fall with vertical acceleration *g*.

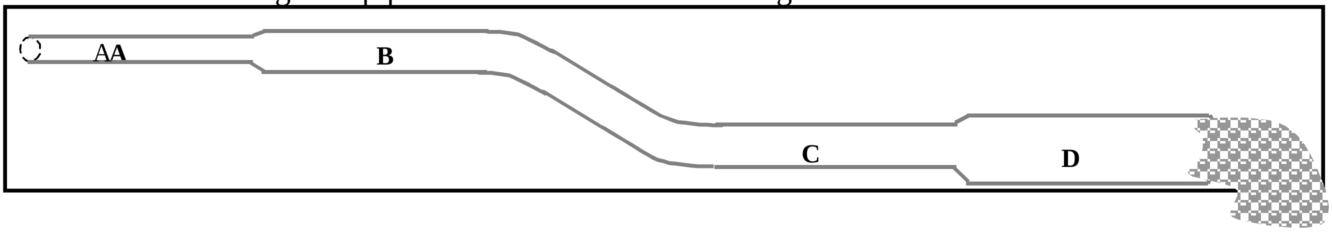


5. Your hand must do work on the ball to change its kinetic energy from 1/2 mv^2 to 0. The work done is given by the force times the distance, so if you increase the distance over which your hand applies the force to stop the ball, the force required is less. If the force on the ball by your hand is less then the force by the ball on your hand will also be less.

6. Kirchoff's rule for junctions states that the total currents going into a junction must be equal to the total currents coming out of a junction. This is a statement of conservation of charge, as current is just a flow of charge. Charge must be conserved, so whatever flows into a junction must flow out again. If it didn't come out again, or if more came out than went in, then charge is either being created or destroyed.

As an electron flows around a loop it loses potential energy as it goes through resistances (there is a potential drop), and it gains energy when it passes through a source of *emf* (electromotive force). When it gets back to the same point it must have the same potential energy as when it was there before, just like if you walk down a hill and back up again you have the gravitational potential energy as before. Hence the total changes in potential energy must equal zero around the loop, and as potential is just potential energy per unit charge, the sum of the changes in potential must also equal zero, which is what Kirchoff's loop law says.

7. Water flows through the pipe shown below from left to right.



a. Water is incompressible, and as there is no water either entering or leaving between points A and D the volume flow rate must be same at all points, just as current must be the same at all points along an arm of an electrical circuit. This is called the principle of continuity – $A \times v$ = constant.

b. As the water flows from **A** to **B** the area increases, hence to maintain continuity v must decrease, therefore $v_{\mathbf{A}} > v_{\mathbf{B}}$. As the water then flows downhill to point **C** it will gain energy, however the area has not changed so we know, because of continuity, that the velocity has not changed, $v_{\mathbf{B}} = v_{\mathbf{C}}$. When the water flows from **C** to **D** the area increases again, so the velocity will decrease again, $v_{\mathbf{C}} > v_{\mathbf{D}}$. The ranking is therefore $v_{\mathbf{A}} > v_{\mathbf{B}} = v_{\mathbf{C}} > v_{\mathbf{D}}$.

c. When the water flows from **A** to **B** there is no change in gravitational potential energy, however the velocity has decreased which means that the kinetic energy of the water has decreased. By conservation of energy we know that if kinetic energy decreases, some other form of energy must increase. If we look at Bernoulli's equation, $\rho gh + 1/2\, \rho v^2 + P$ = constant, (which is a statement of conservation of energy density), we can see that the pressure must have increased, $P_{\mathbf{B}} > P_{\mathbf{A}}$. When the water flows downhill from **B** to **C** it loses gravitational potential energy, but the velocity and hence kinetic energy does not change. The pressure must again increase in going from **B** to **C**, $P_{\mathbf{C}} > P_{\mathbf{B}}$. Finally, as the water flows from **C** to **D** the velocity decreases again and the pressure must once more increase, $P_{\mathbf{D}} > P_{\mathbf{C}}$. So the final pressure ranking will be $P_{\mathbf{A}} < P_{\mathbf{B}} < P_{\mathbf{C}} < P_{\mathbf{D}}$.

Lecture 2: Forces and Newton’s Laws

Newton’s Laws

We have already discussed Newton’s first law – an object at rest will remain at rest, and an object in motion will continue with constant velocity unless acted on by an external force. This is a statement of conservation of momentum – unless you apply an external, net force, the momentum of the system is conserved. It is always possible to define your system such that there is no net external force (an isolated system), although this may mean defining your system as the whole universe. Often it is enough to define your system as a collection of objects that are interacting with each other, but nothing external. In this case the total momentum is conserved, while the objects may change their velocity, the average velocity of the system as a whole remains constant. This means that the centre of mass of an isolated system has a constant momentum.

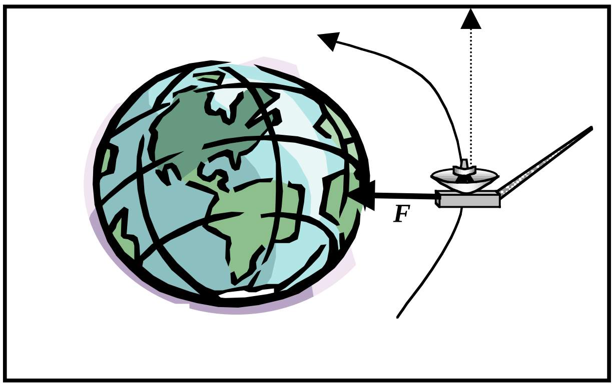
Newton quantitatively defined force with his second law – $F_{\text{net}} = ma$ (or $F_{\text{net}} = \mathrm{d}p/\mathrm{d}t$). This tells us that the bigger the force, the greater the acceleration, but that the bigger the mass, the smaller the acceleration for a given force. It is important to remember that both force and acceleration are vectors – and that the *net* force is always in the same direction as the acceleration.

When an object, such a car, is stationary, a force must be applied to the car to make it move. Once it is in motion, it will continue with constant velocity unless a force is applied to it. This seems to contrary to our common understanding – if we didn’t have to apply a force to keep the car moving, why does it slow and stop if we take our foot off the accelerator? Of course there is a force acting to slow down the car – friction. The car is rolling, and momentum is lost due to friction acting between the wheels and axles, and air resistance acting on the car body. All the petrol that you burn while driving at a constant speed goes to overcome the forces of friction acting to slow down the car.

There is a relationship between force and energy – the amount of energy transferred to an object (or taken from it) by a force acting on the object is the force times the displacement of the object in the direction of the applied force. This is usually called work, and written $W = F.d = Fd\cos\theta$ where d is the displacement and θ is the angle between the displacement vector and the force. In the simple case of a single force acting on a body initially at rest the displacement will be in the same direction as the force, so the energy transferred (or the work done) is just $W = Fd$. When a net force acts on an object it does work on it, which results in a change in the objects kinetic energy, the change in kinetic energy is the work done.

This is not to say that the force is always acting in the direction of displacement, or the direction of velocity. It quite frequently isn’t. But the net force is always acting in the direction of acceleration. A car that is slowing down due to friction does so because it experiences a net force. The direction of this force is opposite to the direction of displacement. This means that the force does negative work, and decreases the car’s velocity and its kinetic energy.

What happens when a force acts in a direction perpendicular to the direction of motion? This is what happens in circular motion, for example the orbit of a satellite around the Earth. The satellite is held in orbit by the force of gravity. If there was no gravitational force the satellite would simply fly off at a tangent.



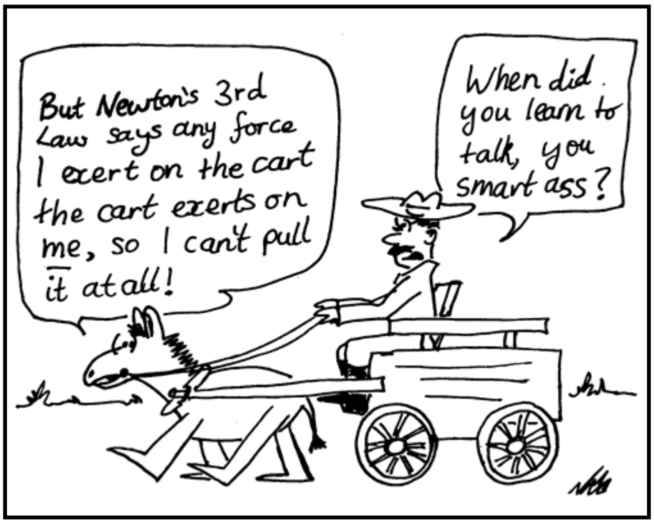
The direction of the gravitational force acting on the satellite is directly in towards the Earth, which is at right angles towards the path of the satellite. This force causes an acceleration, and the acceleration is in the same direction as the force – towards the Earth. But the force is at right angles to the path, and hence no work is done on the satellite. This makes sense when you consider work as the change in kinetic energy, the satellite has not changed speed (but it has changed velocity), so there is no change in kinetic energy, and no work is done.

The solid curved path is the path taken by the satellite. The dotted straight line shows the path if there were no inwardly directed (centripetal) force.

Newton's third law says that for every force there is an equal and opposite force, often stated as *for every action there is an equal and opposite reaction*. This is written as $F_{AB} = - F_{BA}$, where F_{AB} is the force acting on object B due to object A, and F_{BA} is the force acting on object A due to object B. In the case of one body exerting a force on a second body, this means that the second body exerts an equal force on the first body, but in the opposite direction. The really important thing to remember here is that the forces act on *different* bodies. If we go back to the way Newton wrote his second law – $F_{\text{net}} = \mathrm{d}p/\mathrm{d}t$, we can see that Newton's third law is telling us that whatever the change in momentum of A is, the change in momentum of B is equal and opposite – i.e. the net change in momentum is zero and total momentum is conserved.

Many students find Newton's third law difficult to apply, even though they can recite it easily.

A typical question is how can a horse pull a cart if the cart exerts an equal and opposite force on the horse. The answer is simple. The force that the horse exerts on the cart causes the cart to accelerate. The force acting on the horse due to the cart may cause the horse to accelerate in the other direction – but this has no effect on the motion of the cart (unless they collide). So the cart is accelerated forward. If the horse is to accelerate forward there must be a net forward force acting on the horse, which means there must be another force acting on the horse greater than the force applied by the cart. This other force is the frictional force of the ground on the horse's hooves.



Have you ever tried to push a heavy piece of furniture along the floor and found your feet sliding out from you instead? This is because the force of friction between your feet and the floor is smaller than the force that the piece of furniture is exerting on you (which from Newton's third law is equal in size but opposite in direction to the force that you are exerting on the furniture). We often think of friction as a nuisance, something that wastes energy. But without friction we wouldn't even be able to walk – our feet would just slide out from under us and we wouldn't go anywhere.

When we walk, we move forwards because the ground exerts a frictional force on us. The only way to start moving, or change velocity, is for an external force to act on us – we cannot change our own state of motion. To be able to move about we are constantly applying Newton's third law – we push on the ground, it pushes back on us, and it is this force of the ground on us that moves us forwards.

Sometimes forces are described as conservative or non-conservative forces. Conservative forces are those that completely convert potential energy into kinetic energy or vice versa. Non-conservative forces convert potential energy or kinetic energy into thermal energy – in particular frictional forces. Thermal energy is a form of kinetic energy – it is the kinetic energy due to movement of all the particles in an object or substance. The sort of bulk kinetic energy we usually talk about, where a whole object is moving with a given velocity, can be completely converted into thermal energy. But thermal energy cannot be completely converted back into potential energy or kinetic energy. Hence frictional forces are called non-conservative – even though the total energy is still conserved, it's just not all available to use anymore. This is what the concept of entropy is really about – while energy is conserved, whenever friction acts some of that energy is "lost" to thermal energy. Entropy is a measure of the disorder of a system – when all the particles move together with the same kinetic energy this is a very ordered system. When they all have their own random kinetic energy this is a very disordered system, with a higher entropy. Entropy may decrease locally, but overall, the entropy of the universe is always increasing.

The four forces

There are only four known forces, and in fact it now seems that there are only really three. These are the gravitational force, the electromagnetic force and the strong and weak nuclear forces, although there is now evidence that the electromagnetic force and the weak nuclear force are aspects of the same force.

The Gravitational Force

The gravitational force is the force that acts between all bodies with mass. It has the form $F_G = \frac{Gm_1m_2}{r^2}$. The force is proportional to the masses of the bodies and inversely proportional to the square of the distance between the bodies. The constant G is the universal gravitational constant. It is possible to derive Kepler's laws, which describe the behaviour of orbiting bodies, such as the planets around the sun or satellites around the Earth, from Newton's law of gravitation.

Gravity is responsible for the "weight force" that we feel on Earth. If we plug the numbers into the gravitational force we find that on the surface of the Earth, which has a mass of 6×10^{24} kg and a radius of 6 400 km, the force is equal to $F = m \times 9.8\ \text{m.s}^2$. Using Newton's second law, F = ma, we can see that the acceleration of an object on or very close to the surface of the Earth is $9.8\ \text{m.s}^2$.

The Electromagnetic Force

The electromagnetic force is the force that acts between electrically charged bodies and magnetic bodies. Apart from gravitational forces, virtually all the forces that we experience are electromagnetic in nature. The forces that bind atoms together are electromagnetic in nature, and frictional forces and contact forces are also electromagnetic. We know from Rutherford's experiments bombarding atoms with alpha particles that atoms are mostly space. So why is it that you can rest your hand on the desk, or push the buttons on a keyboard, without your fingers going through? This is because the electrons in the atoms of your fingers interact with the electrons in other matter, preventing them from simply all joining together or flowing through each other.

One aspect of the electromagnetic force is the Coulomb force - $F_E = -\frac{kq_1q_2}{r^2}$. This force acts between charged objects at rest. You have probably noticed that this force looks very similar to the gravitational force. It is proportional to the product of the charges, and inversely proportional to the square of the distance between them. There are a couple of differences – this force is repulsive for similarly charged objects, and gravity is always attractive. Mass only comes in one type – charge comes in two – positive and negative.

A charge has an electric field associated with it – which is just a way of describing force at a distance. The field is the force that would act on a positive test charge at a given point. When a charge moves its electric field moves with it. A moving charge creates a magnetic field. A moving magnetic field, such as that due to a moving bar magnet, creates an electric field. This is a beautiful symmetry – a changing electric field creates a magnetic field, and vice versa. It is also incredibly useful, apart from solar energy, all our electricity supplies are based on this effect.

A generator uses a changing magnetic field in a coil of wire, by moving either magnets or the coil, to produce an electric field. This electric field supplies a force (an electromotive force) on the electrons in the wire coil, which makes them move – a current. A generator converts kinetic energy into electrical potential energy. We can also do it the other way around – a motor converts electrical energy into kinetic energy using the opposite process.

The Nuclear Forces

Apart from hydrogen, which has only one proton, all nuclei are made up of multiple protons and neutrons. Protons are positively charged and hence should repel each other. Yet most natural nuclei are stable. If the only forces acting were the gravitational force and the electromagnetic force, nuclei would fly apart because the attractive gravitational force is much weaker than the repulsive Coulomb force. Hence there must be another force acting, which is strong enough over small distances to keep the nuclei together – this is called the strong nuclear force. It does not obey a $1/r^2$ rule, like the electromagnetic and gravitational forces, but drops off much faster.

Using Newton's laws: Activities

Newton's Cradle (2 balls)

Swing one ball out and release it.
Draw a diagram showing the forces acting on the balls.
Is there an action-reaction pair here? If so, what is it?

Constant velocity

Pull a trolley along a flat surface with a spring balance.
What does the spring balance indicate?
Set the ramp so that the trolley rolls down freely.
Pull the trolley up the ramp with constant velocity. This is not easy and may take several attempts.
What is the reading on the spring balance now? Is it what you expect it to be?
Is this reading different to that when pulling the trolley on a flat surface with constant velocity?
How can you tell if frictional forces are significant?

Boxes on a Trolley

Several boxes of the same size, shape and material are packed so that they have different weights.
These are placed on a stationary trolley.
If the trolley is accelerated, which, if any, box will you expect to slip off the trolley first? Why?
Do the masses of the boxes affect the falling and slipping in the situations described above?

Block on a rough variable ramp

For a particular angle, is the force needed to keep a block stationary on the ramp larger, smaller or the same for a rough surfaced ramp in comparison to a smooth surfaced ramp. Why?
Draw a free body diagram for the block.
Adjust the angle of inclination and note when the box begins to slide.
How will this angle be different for a smooth ramp?

Falling objects and terminal velocity

Hold a piece of paper horizontally and drop it. What happens?
What happens if you hold it vertically and then drop it?
Now crumple a piece of paper up into a ball and drop it.
Explain your observations.

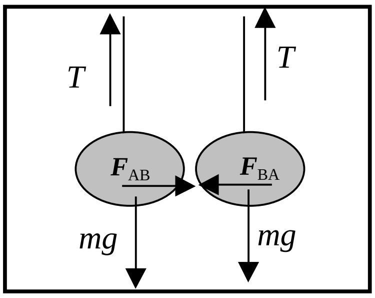
Electromagnetic Induction – 2 coils of wire and a magnet

If a magnet is moved into and out of a closed loop of wire, a current is induced in the loop of wire.
How do the direction and magnitude of the current depend on the motion of the magnet?
What happens if the magnet is reversed?
What happens if the loop is moved and the magnet is stationary?
Will a similar phenomena be observed if a current carrying coil of wire moves relative to a loop of wire?

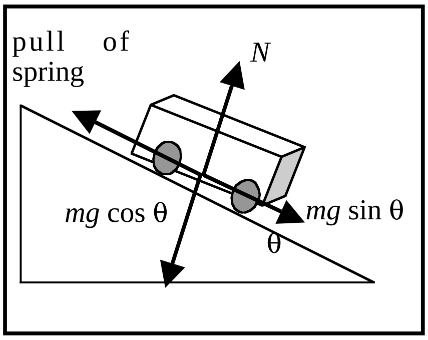
Magnetic braking II – magnets in pipes

Drop the magnet down the pipes.
Why do magnets take longer falling down a copper pipe than free falling?
What is happening in the copper pipe with the slit?

Explanations of activities

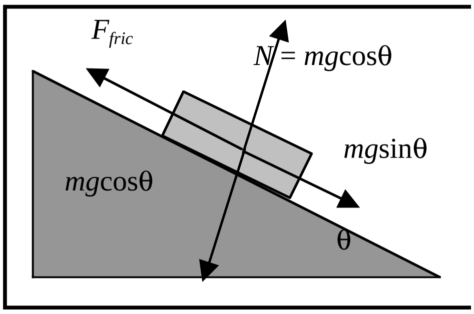


Newton's Cradle (2 balls)
When one ball is held out and released it swings back, hitting the second ball and causing it to swing out. The action reaction pair is the force of all A on ball B and the force of ball B on ball A, F_{AB} and F_{BA}.



Constant velocity
On a flat surface the net force acting to give a constant velocity is zero. Hence at constant velocity the spring balance will read close to zero. On a flat surface we need just enough force to oppose frictional forces To pull a trolley up a ramp at constant speed we need to apply a constant force of $mg\sin\theta$ so that the net force is zero. N balances the component of mg perpendicular to N, which is $mg\cos\theta$, so the pull must be equal to the component of gravity $mg\sin\theta$.

Boxes on a trolley
All boxes slip off together. If the trolley is accelerated forwards the boxes slip backwards, and if it is decelerated the boxes slip forwards. The rougher the surfaces, the harder it is for slipping to occur, i.e. slipping occurs at a greater acceleration. The acceleration of the truck and μ, the coefficient of friction between the trolley and the box, determine if the box slips or not. The mass of the boxes doesn't affect their slipping.



Block on a rough variable ramp
Consider forces up and down the inclined plane. Just before slipping the forces up the ramp (frictional forces) must be equal to the forces down the ramp (component of weight), so

$F_{fric} = \mu mg\cos\theta = mg\sin\theta$ and $\mu = \tan\theta$
If the F_{fric} is greater (a rough surface), the angle for slipping is larger. A smoother ramp gives a smaller angle for slipping.

Falling objects and terminal velocity
Air resistance varies with the surface area pushing against the air. A flat sheet of paper held out flat and dropped has a large area in the direction of movement and hence falls slowly and tends to glide around on the way. A sheet of paper dropped vertically falls much faster as it experiences less air resistance. A crumpled sheet falls at an intermediate rate. Note that in the absence of air they would all fall and accelerate at the same rate.

Electromagnetic Induction – 2 coils of wire and a magnet
A current carrying coil of wire has a magnetic field so there will be an induced current in a closed loop of wire that is moving relative to a current carrying coil. The direction of the current depends on the motion of the magnet relative to the loop and changes when the magnet is reversed. The magnitude of the current depends on the speed of the motion, number of turns of wire and the 'angle' between the loop and the magnet. It doesn't matter whether the coil or the magnet is moved, only the relative motion of the two is important.

Magnetic braking II – magnets in pipes

The movement of the magnet creates currents in the copper pipe, which produce magnetic fields, which act to oppose the motion which causes them, slowing the fall of the magnet. The plastic pipe is an insulator, no current is created and hence the magnet is not braked. In the pipe with the slit there are still currents produced in vertical loops, but not around the pipe as the slit prevents this. So the fall is slowed, but not as much as in the complete pipe.

Some practice questions for students

1. When high jumpers or pole vaulters land they have a mattress or other soft surface to land on, so that they are not injured.

a. How does the mattress prevent injury? Explain your answer in terms of acceleration and forces.

b. Draw a sketch of a high jumper just before he lands, as he starts to sink in to the mattress and when he has come to rest. Show the direction of motion at each position.

c. Draw arrows representing the direction and magnitudes of all the forces acting on the high jumper at each position.

d. Sketch a graph of the high jumper's acceleration over time as he lands.

e. Sketch a graph of the magnitude of the normal (contact) force acting on the high jumper over time.

2. Can a car, with a zero net force, roll down a hill? Explain your answer.
Why would a car rolling down a hill slow down, without the driver using the brakes?

3. If air resistance didn't increase with increasing speed, would sky divers ever reach a terminal velocity? Hint: draw force diagrams at less then terminal velocity and at terminal velocity.

4. A passenger sitting in the rear of a bus claims that he was injured when the driver slammed on the brakes causing a suitcase to come flying toward the passenger from the front of the bus.

Can this occur when the bus is initially travelling forward or travelling backwards?

Include free-body diagrams for each situation in your answer.

5. A box is placed on the back of a truck and the truck drives away (forwards). The coefficient of friction between the surface of the truck and the box is μ.

a. Draw a sketch showing the box on the truck.

Add each piece of information, from the questions below, to your sketch.

b. What is the direction of motion of the box relative to the ground?

c. Under what circumstances will the box not move away with the truck?

d. Identify each force, including frictional force, acting on the box.

e. What is the direction of the net force acting on the box?

f. What is the direction of acceleration of the box?

g. What force causes the acceleration of the box?

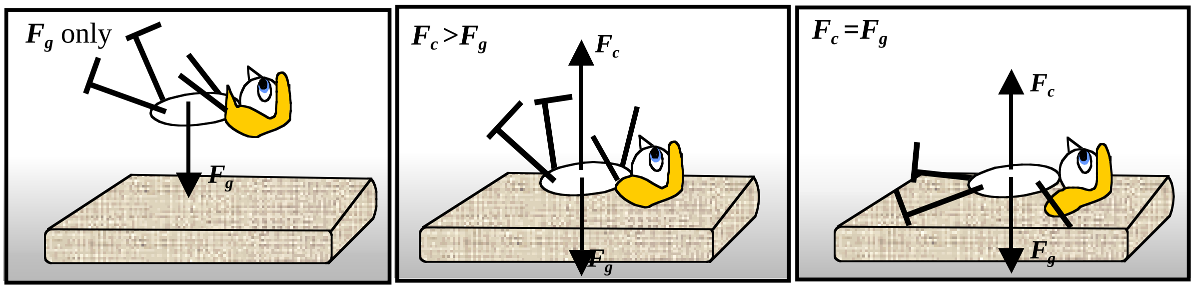
6. In a simple model of the helium atom, two electrons (each of charge = -*e)* orbit a nucleus consisting of two protons (charge = +2*e*) and two neutrons (charge = 0). Is the magnitude of the force exerted on the nucleus by one of the two electrons less than the force exerted on the electron by the nucleus? Explain your answer.

Solutions to practice questions

1. When high jumpers or pole-vaulters land they have a mattress or other soft surface to land on, so that they are not injured.

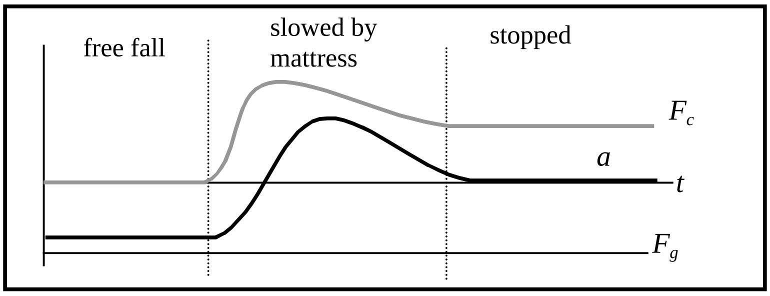
a. The forces acting on the high jumpers or pole-vaulters from contact with the ground can cause injury. Using a mattress increases the time of contact and so for a given change in velocity the deceleration is less. The magnitude of the contact force will be reduced thus reducing the chance of injury.

b. and **c,** see diagrams below. Initially the only force is gravity, acting down. Once the jumper touches the mattress it accelerates her upwards, providing a force greater than gravity to slow him down. As he slows, this force decreases until there is no net force acting and he is stationary, having come to a rest on the mattress.



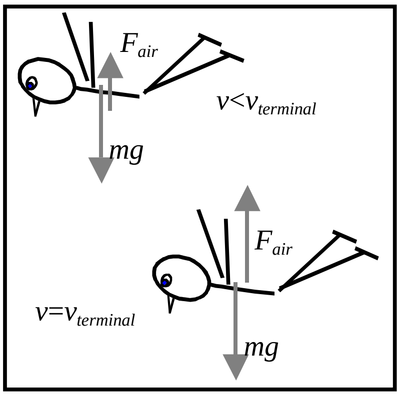
d. and **e,** see graph opposite.

Note that the acceleration is proportional to the net force, $F_g + F_c$.



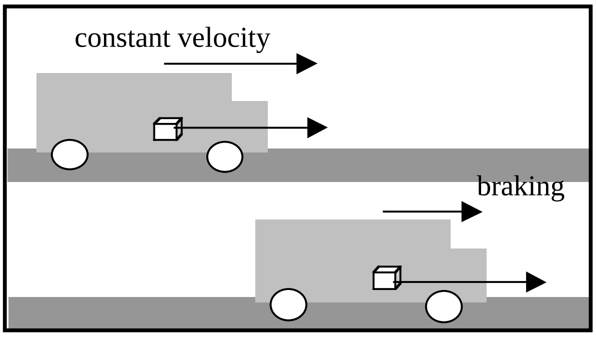
2. If a car is stationary then it will not move unless there is a net force acting on it. If it is already rolling it will continue to do so at the same rate unless a net force acts. If a car is rolling down a hill at a high enough speed that the air resistance acting on the car is greater than the component of gravity in the direction the car is rolling, then the car will have a net force acting on it to slow it down. You probably haven't noticed this unless you do a highway driving, and tend to coast down hills. Try it next time you do a long drive or are coming down a not very steep hill.

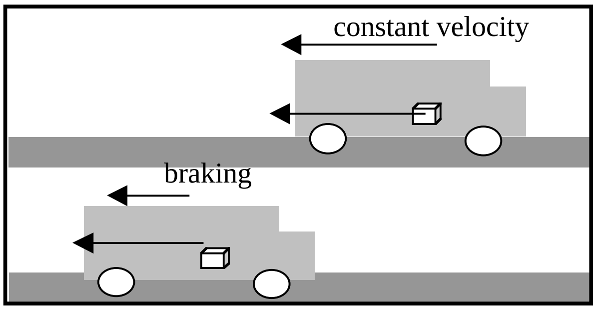
3. See diagram opposite. At terminal velocity $F_{air} = mg$. If air resistance didn't increase with increasing speed, sky divers would never reach a terminal velocity. They would continue to accelerate, and the heights from which they could jump would be limited by this.

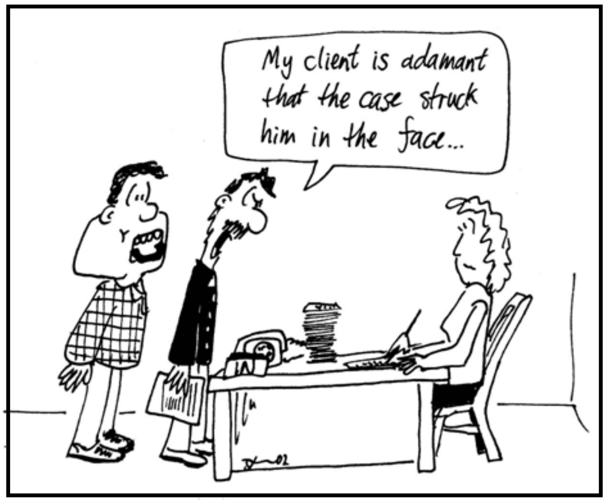


4. The case will only go backwards if the bus is accelerating forwards. A suitcase cannot fly backwards if the bus is moving forwards at constant speed or braking. If there is not enough friction to slow the case along with the bus then as the bus slows the case will continue to move forwards. At constant speed there is no net force on the bus or case, and the case will not move relative to the bus. Hence the passenger's claim cannot be true if the bus was going forwards and braking.

A suitcase may fly towards the rear if a reversing bus decelerates. When the driver slams on the brakes the suitcase will continue to move backward, unless the force of friction between the case and the bus is enough to accelerate it along with the bus.







5. Box on a truck.

a. See diagram opposite.

b. The box (the system) will move along with the truck, which is to the left unless the truck is reversing.

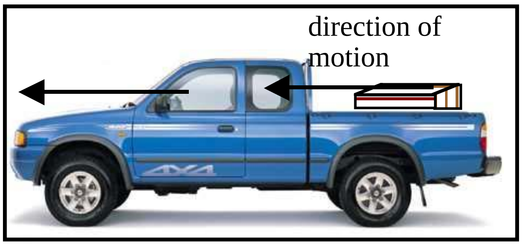
c. If the tray and box are very smooth the box will slide off as the truck moves away, i.e. if there is not enough friction.

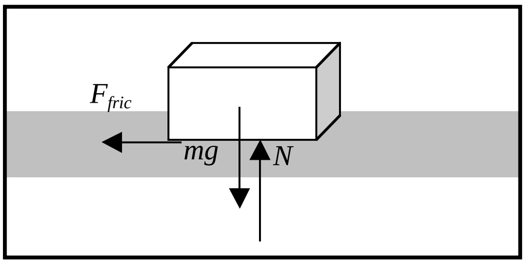
d. The forces acting on the system (the box) are the weight force, mg, the normal force, N, and the frictional force of the truck's tray on the box.

e. The net force is the frictional force, which is to the left. The box is accelerating to the left, hence the net force **must** be to the left.

f. The acceleration is in the direction of the net force.

g. The only force acting in the horizontal direction is friction, this is the force which accelerates the box





6. Coulomb's law for electrostatics: $F_E = -\frac{kq_1q_2}{r^2}$.

The force on one electron in the helium atom due to the nucleus is $F = -\frac{kq_1q_2}{r^2} = -\frac{k(-e)(2e)}{r^2}$, where r is the distance from the nucleus to the electron, $-e$ is the charge on the electron and $+2e$ is the charge of the nucleus due to the two protons it contains.

The force on that one electron due to the nucleus is $F = -\frac{k(-e)(2e)}{r^2}$, which is *exactly the same* as the force on the nucleus due to that electron, not less. Note that this is also the case for the gravitational force. The force on the Earth due to the gravitational attraction of a thrown tennis ball is the same as the force on the ball due to the Earth. These are action reaction pairs, and Newton's third law tells us that they must experience equal and opposite forces.