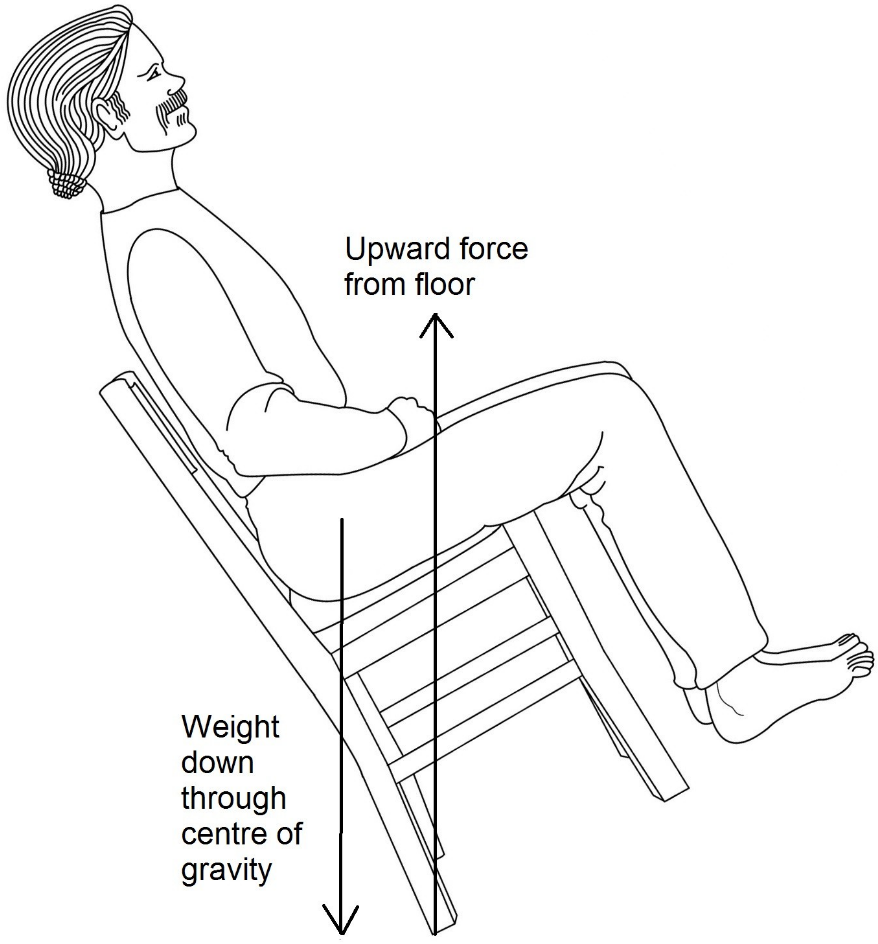
The science of model flying: Forces and inertia

Many of the ideas here will be used in future articles on structures and machines.

Forces
What is a force? This not the place to talk about the origins of force, for example the curvature of space-time resulting in the apparent force of gravity. Let's stick to the everyday meaning, namely a push or a pull. As you will see a force can change the forward movement of an object or the direction of that movement and two forces can also change its rotational movement or shape and can even break it.

Physicists like me can have a strange view of the world. As always there is a German word for it - weltanshauung or world view. If I watch someone tilting back on a chair I imagine his weight force acting down through his centre of gravity. I know that when it is further back than the pivot point of the back chair legs he will fall over backwards (Picture 1). A normal person will just enjoy the sight without thinking about it. Of course I laugh as well but know why it happened. In the same way I imagine the forces on models.



Picture 1 adapted from crazy88mma.com

Forces relevant to model flying
This would be a long list if complete. Here are some:

- The aerodynamic forces of lift and drag, the former being created by pressure.
- The mechanical forces of weight and thrust.
- The resistance or inertia of a model to acceleration or turning, which is a kind of virtual force.
- Rotational forces called torque or moment.
- The torque developed by our motors and engines.
- Glide angle, which is determined by the ratio between weight and drag forces.
- The reduced effect of a force at an angle.
- Thrust from our propellors created by accelerating air and experiencing the reaction force from it.
- Vectored thrust from jet engines allowing high manoeuvrability

Our automatic responses
When reading the practical examples in this article there is one important thing to remember. When we fly we don't think about how to move the sticks. We have trained our muscles to do what's needed without thinking. Like playing the piano, if we had to think about what to do we would be too late. So you might think, 'I don't think I do what you describe', but you do.

Mass and weight
In normal language mass and weight mean much the same. In science they are very different. The mass of something is the total of all of the atoms it is made from, that is to say the protons, neutrons, electrons and other particles that comprise atoms as described in last month's periodic table article. An object has the same mass everywhere in the universe, as far as we know.

Weight is the pull on an object from another object. It depends on how many kilograms each object is (m_1 and m_2) and how far apart they are (d). In maths it is:
F is proportional to $m_1 m_2 / d^2$
To find F in newton you multiply by the gravitational constant G (6.674×10^{-11}).
$F = G m_1 m_2 / d^2$

As I wrote that I thought, 'You've never done the sums for the earth.' The earth isn't uniformly dense so it won't come out exactly right. Anyway here goes:
$m_1 = 1$ kg
$m_2 = 5.9722 \times 10^{24}$ kg (mass of the earth)
$G = 6.674 \times 10^{-11}$
$d = 6.36 \times 10^6$ km (average radius of the earth)
$W = 6.674 \times 10^{-11} \times 5.9722 \times 10^{24} / (6.36 \times 10^6)^2$
Adding up the powers of ten (-11 +24 -6 -6) gives 10^1
Multiplying and dividing the rest: 6.674 x 5.9722 / (6.36 x 6.36) = 0.98539
Wow!
In other words 9.85 or 10 in our practical approximation. The difference from the average measured value of 9.81 is no doubt due to the increasing density of the earth with depth.

Our own weight is the result of the earth's gravity. It is less in some places than others. It gets less as we move away from the earth. It is more near the poles because the earth is slightly flattened and we are nearer the earth's centre. In space it appears to be zero because we are pulled equally in all directions by the rest of the universe. On the moon we weigh less because the moon has less mass and pulls us less despite its smaller radius. If we are orbitting the earth we are in free fall so appear weightless. To describe someone as over-weight is meaningless scientifically. Take a person to the moon and he or she weighs less. On Neptune much more. In space nothing. To a scientist the correct term is ‘too massive.’

Massive is a word that is often abused usually by being taken to mean large. Poor old English is taking a battering at the moment. Exponential growth is now taken to mean rapidly increasing. What it really means is increasing at an increasing rate. Though our savings increase exponentially with compound interest, with current interest rates that is very slow, though that appears to be changing. Another abused word is decimate, which now means destroy almost completely. In fact it was the opposite - a method used by Roman commanders to discipline a rebellious legion. The soldiers were lined up and every tenth man in the row was killed with a sword ‘to encourage the others.’ No point in killing all your soldiers for mutiny, just a tenth. No-one seems to question the use of ‘deci’.

Higgs space and dark matter

Our ideas about mass are developing very rapidly. Some physicists are now suggesting that space should be called Higgs Space. Aye aye boson! One suggested that we think of space as like a snow field, which is an analogy or model that was new to me. Though made of snow flakes, viewed from a distance it looks smooth. If we ski we move at top speed without friction. This is like how light and other very low mass waves/particles move at the speed of light. If we put on snow shoes we find it more difficult to move. Which is like a small mass. With only boots on, movement is much more difficult. This is a larger mass with a lot of inertia. Space fights back. If we whack two heavy particles together in an accelerator sometimes they cause a part of the Higgs space to fly out, the famous Higgs Boson. Watch that exciting space. This might mean all of the forces including gravity are finally explained in one thing. Or not.

In a BBC radio science programme (not ‘show’. Yuk!) in April 2024 another fascinating idea about mass and energy was suggested. Stupidly I didn’t note the programme. The subject was the idea of nucleation, where vapours condense or crystallise around a particle or nucleus. If there is no nucleus then no such effect will occur, even when a vapour or liquid is below the relevant temperature. The physicist suggested that this might account for dark matter and energy. She explained how solid mass in the form of atoms started to form not long after the big bang. However most of the mass in the universe cannot be seen. She suggested that perhaps the universe was still in the process of crystallising. After all why should it have finished? I thought, at last here is a sensible explanation of why there should be dark matter. Yet another useful analogy.

Mass and weight are different in another way. Mass is just there. It just has quantity or magnitude. It does not act in any direction. Scientists call that a scalar quantity. Other examples are temperature and energy. Weight pulls in a particular direction. So it has two dimensions, magnitude and direction. That makes it a vector quantity. Another everyday confusion is to use kilogram for both mass and weight. Normally it doesn’t matter much but to be clear what we are talking about we should use the newton (N) as the unit for force. To give an idea of how big it is, near the earth a kilogram weighs about 10 N so a medium apple is one newton. Bearing in mind Isaac’s malic inspiration it’s a nice touch isn’t it? In old units mass would be pound and force would be poundal, with one pound near the earth weighing about 32 poundals. This multiplier is given the symbol g or and called the acceleration due to gravity. A falling mass accelerates at 10 m s^{-2} or 32 ft $s^{-2.}$

The equation for weight W is W = mg (g is approximately 10 as we calculated above)

Now to look at what types of force there are and what they can do.

Static forces

Forces on a fixed structure, such a house or a bridge, must balance or the structure would move. These are called static forces. For a large structure standing on the ground upward forces must act together to balance its weight. Such structures are usually made of many component parts each of which carries part of the load. Some parts are vertical, some at an angle and some horizontal. The last won't carry weight but will hold together other components that do.

Even in pre-university physics, students learn how to calculate the forces in each part of a structure. Exactly the same analysis can be done in our model aircraft as you will see in a future article on structures.

Dynamic forces

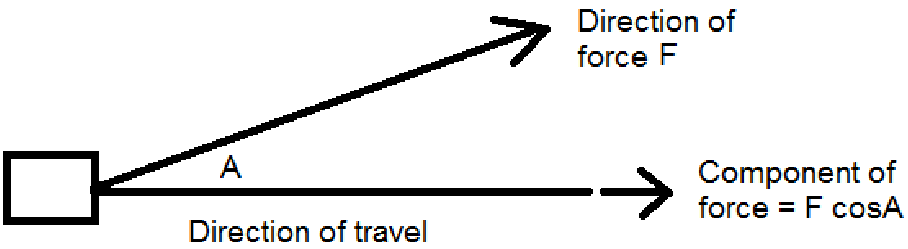
These cause change in motion. Newton's first law of motion tells us that a mass continues in a straight line at constant speed unless a force acts on it. We will need to understand that when we consider a glider flying downhill at constant speed.

Forces at an angle

One idea we need now is resolution of forces. Force is a vector quantity meaning it has both size (magnitude) and direction. We know intuitively that we get the best effect if we push or pull something exactly in the direction it is free to move. A force at an angle has less effect. Resolution means finding the effect of a vector, such as force, at an angle.

Look at Picture 2.

It shows us an object that is pulled by a force at an angle A to its direction of travel. The effect of the force is called a component and is equal to F cosA. If A is zero degrees then cosA is 1 and the whole force will move the object. If A is 90 degrees then cosA is zero and the object won't feel any forward force.



Picture 2 Peter Scott

Here is a table of the effect of angle on a force:

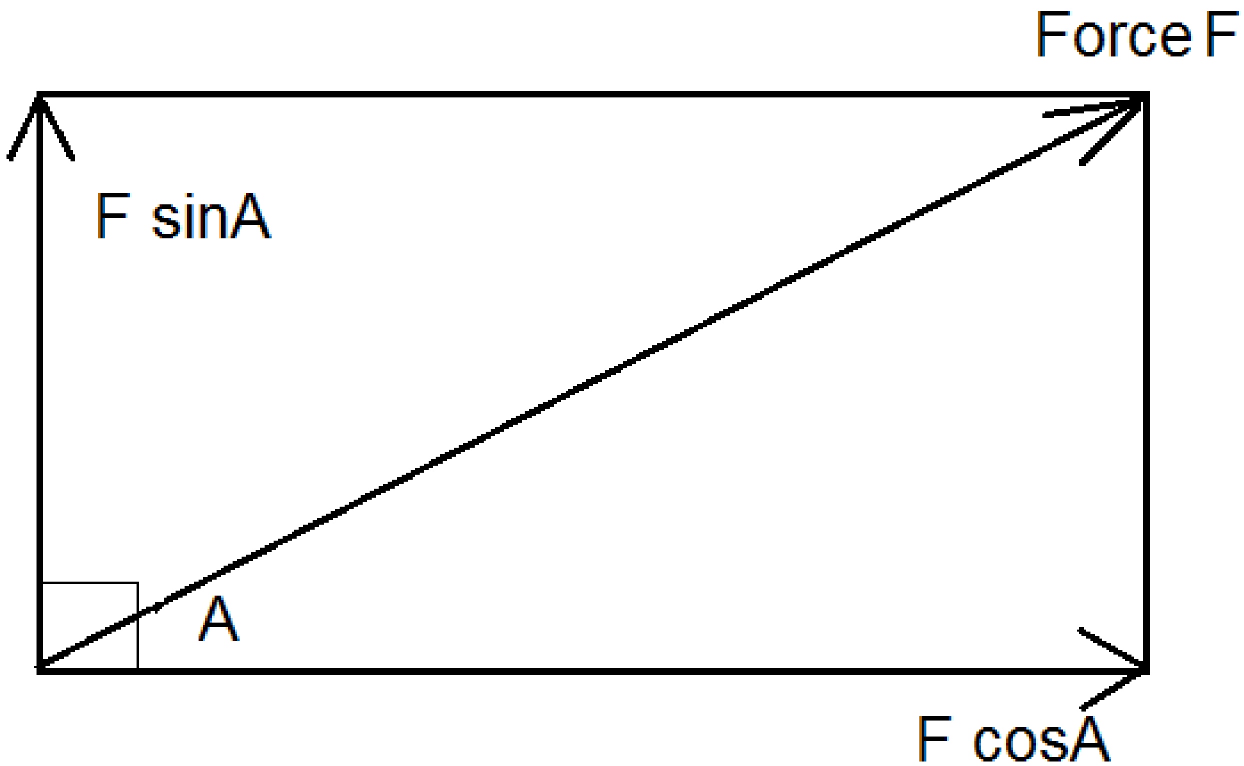
Degrees	% of force (approx)
0	100
10	98
20	94
30	87
45	71
60	50
75	26
90	0

As you see it takes large angles to make much difference.

Why is is cosA?

It’s due to the dreaded trigonometry. Wake up at the back there!

The theory is shown in the rectangle in Picture 3, that models the example above. There are two right-angled triangles. The applied force F is the diagonal hypotenuse.



Picture 3 Peter Scott

We can calculate the sizes of the vertical and horizontal forces from trigonometry on the lower triangle. Adjacent is the side next to the angle. Opposite is the side furthest from the angle.

Horizontally:
Cosine = adjacent / hypotenuse
So adjacent = cosine x hypotenuse or F cosA
In the above case this is the component that speeds up the object

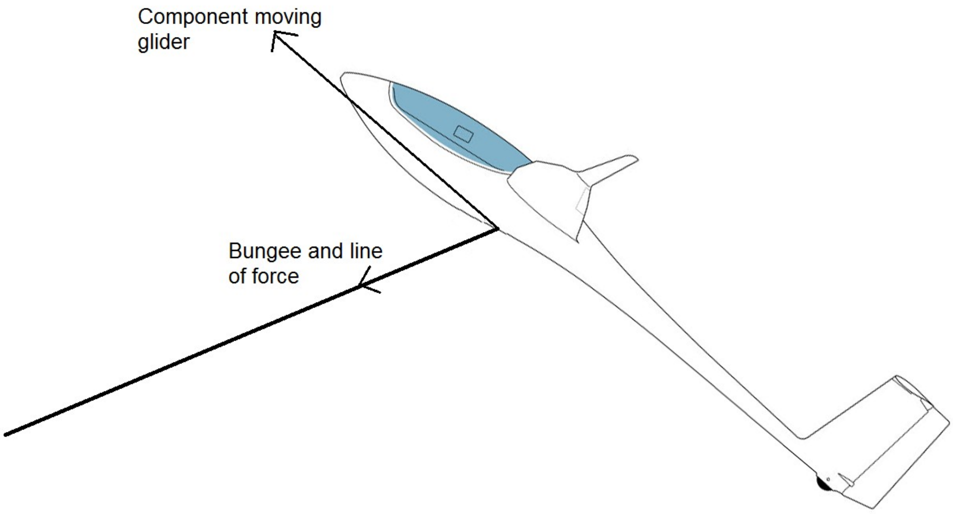
Vertically:
Sine = opposite / hypotenuse
So opposite = cosine x hypotenuse or F sinA
In the above this component that has no efffect on the object

The two partial forces are called components. You could also find them by doing a scale drawing.

Practical examples

Bungee (hi-start) or winch

As you release the model the bungee angle is virtually zero so acceleration is rapid. Immediately the nose goes up the angle increases dramatically as does the drag. We are all familiar with the stick work needed to maintain both climb and forward speed. Some web pictures show the bungee at right angles to the model in the climb, unlike Picture 4. We now know that this cannot produce any forward force. Only if nearly overhead and ready to drop the line, could a prevailing wind provide airspeed and lift.



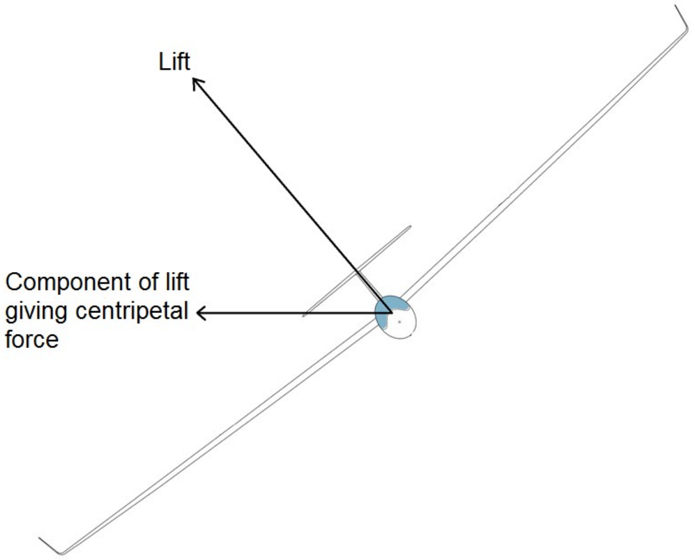
Picture 4 Peter Scott

Knife edge

This is a manoeuvre that is for the power model. Here we effectively alter the thrust line so there is a component of thrust upwards. Whilst it is true that there might be a small lift force from the fin or a flattish fuselage, it is mostly the change in thrust line that maintains height as you can see from the right-most image in Picture 5.

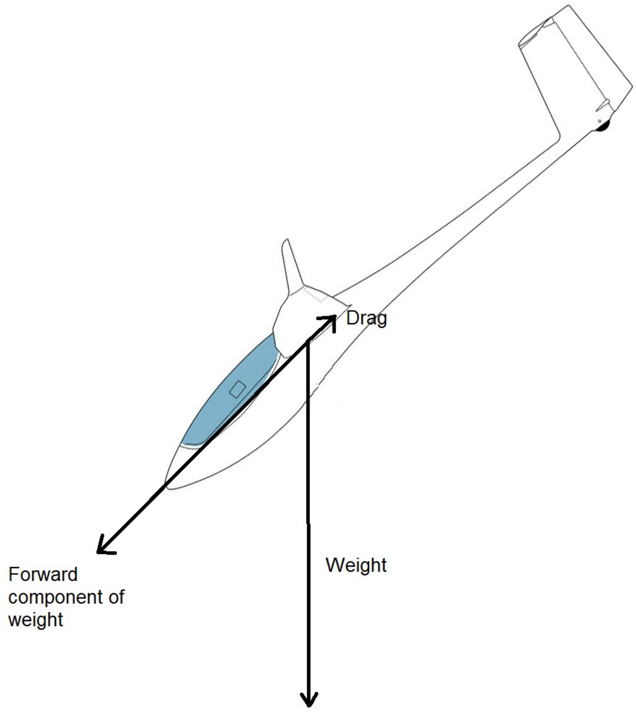
Picture 5
From flyrc.com

Circling
When a model banks and turns due to ailerons there is component of lift that acts towards the centre of the turning circle as shown in Picture 6. This force pushes the model sideways. The steeper the bank the greater is the percentage of the lift pushing sideways. There is now a smaller lift component to hold the model up so we instinctively apply up elevator so the model doesn't lose height.



Picture 6 Peter Scott

Dive angle
A glider is always diving. That's where its energy comes from. Mostly the dive angle is small, being just enough to overcome drag so Newton's first law tells us it won't change in speed. Hopefully the air it is diving through is moving upwards. When we want to gain speed we go into a steeper dive as in Picture 7. This increases the forward component of weight. The surplus of forward force over drag now accelerates the model.

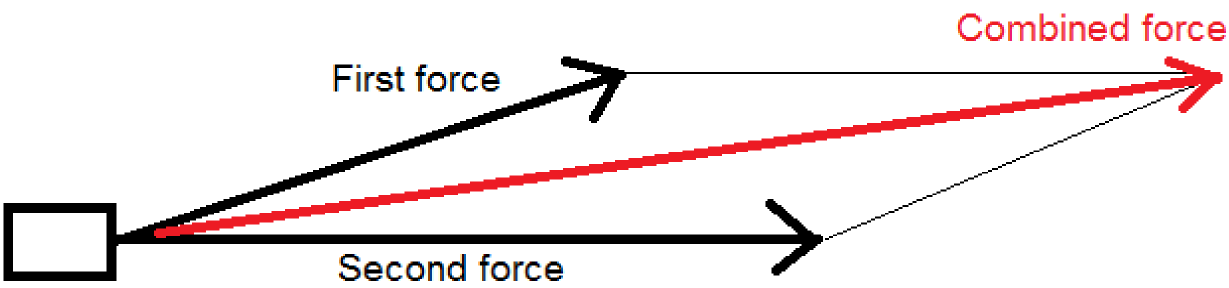


Picture 7 Peter Scott

Combining forces

Look at Picture 8, which is a variation of the diagram in Picture 3. In this case the object is free to move in any direction and instead of splitting the force into two components it is being pulled by two forces. However they are not at right angles to each other, though they could be. Instead of a rectangle we draw a parallelogram. The two components in black act together to produce a resultant combined force shown in red.

If we draw the two to scale, e.g. 10 mm : 10N, as the sides of a parallelogram enclosing the angle between them, the corner to corner line gives the magnitude and direction of the combined resultant force. You can find the length and angle of this line either by calculation or by scaling off the drawing



Picture 8 Peter Scott

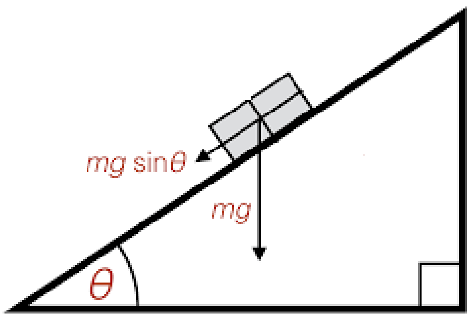
Practical examples of resultant forces

Slope traverse
An example would be a glider traversing a slope. As well as the forward motion due to weight there would be a wind force into the slope. When traversing, the model would move towards the slope and we correct that, without having to think about it, with rudder or aileron.

Bungee or hi-start in a side wind
No you wouldn't normally bungee with a side wind. However some flying sites only have two launch directions, mine being an example. The wind is NEVER exactly along the runway and the surrounding fields are cropped not grass.

Buddy box training
I do a fair bit of that. The most common takeovers are when the model is getting too far downwind because the trainee pilot has not got the experience to correct for the wind. A close second is the problem with sidewinds when landing as, for safety, the instructor must not allow the model to get overhead nor to drift off the runway.

Forces on a slope
Look at Picture 9. The weight of the block is mass times gravity (mg). Remember that near the earth g is about 10 which is why one kg weighs 10 N. The component of mg down the slope is the weight multiplied by the sine of the slope's angle, hence mg sinθ. We will use this idea in an experiment later.



Picture 9
Adapted from quora.com

Importance to us?
A slope, also called an inclined plane, is used in many simple machines such as a wedge and a screw thread. These will be covered in a future article. And of course a glider flying down its glide angle is another example. The above equation mg sinθ applies here too, though in this case it is equal and opposite to the drag. A high performance glider might have a glide angle of 2º, roughly 1:30. The forward component of weight and the drag will be about 3.5% of its weight.

Change of motion
A single force can a cause of change in velocity (speed and/or direction) though there is a second reactive force from the object called inertia. More about that later. The relevant

equation for motion is Newton's Second Law, F = ma. Notice the similarity with F = mg. Go on, you work it out. The clue is 'acceleration due to gravity'.

Change of shape

Two forces can cause a change of shape. An example is a bungee launch (hi-start). The peg in the ground pulls at one end of the bungee and the launch person pulls on the ring or model at the other end. The result is that the bungee changes shape. It gets longer and thinner. Moving a force is called work and takes energy. Energy (work done) is force times distance. The further you walk with the model the more energy you store in the bungee and the higher the model should be lifted unless you make a mess of controlling the climb.

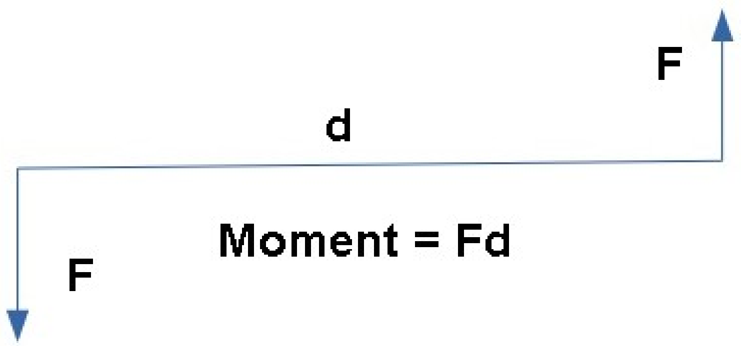
To calculate change of shape we need to know how bendy the object is, called elasticity. The simplest equation here is Hooke's Law, that describes the extension of a springy object with increasing load. So extension is proportional to force or one of two opposing force to be exact.

Hooke's Law: Extension = Force / stiffness

Hooke also said that if you stretch it beyond a certain point called the elastic limit some of the stretch will be permanent. The molecules have been rearranged. That's why when you let a balloon down it doesn't go back to its original size.

Rotation

Two equal and opposite forces cancel each other if they are in line. They can cause rotation if they are not in line, that is if there is a distance between their lines of action. We call this turning effect torque or moment of force. Torque is found by multiplying one force by the perpendicular separation (Picture 10).

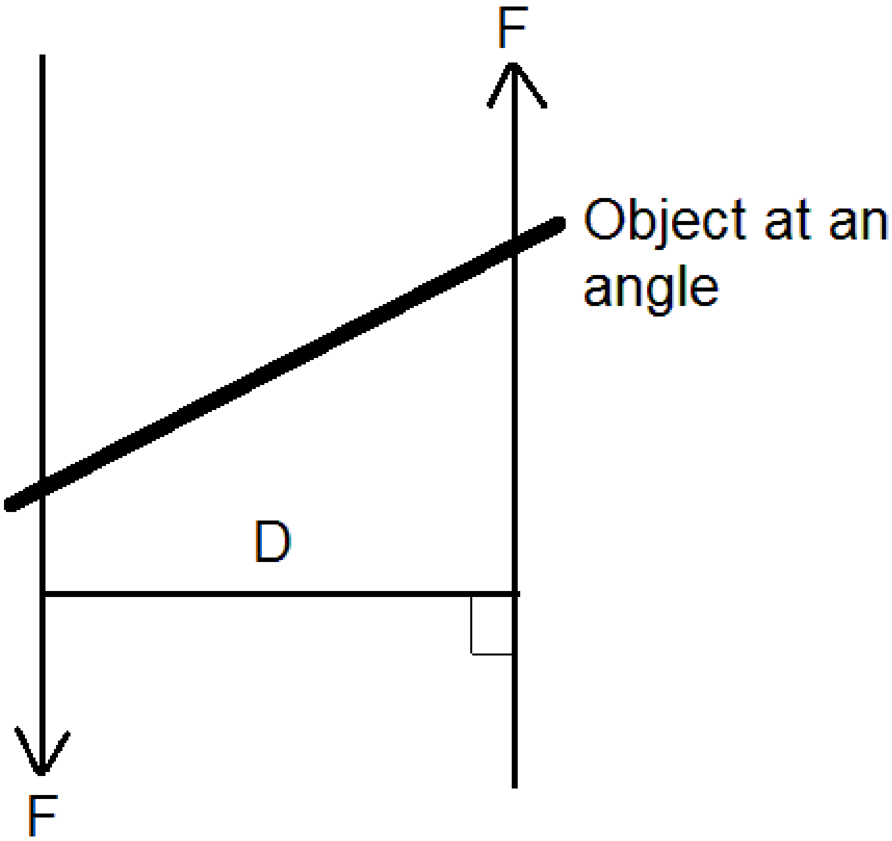


Picture 10 Peter Scott

When the second force is well separated from the first we usually call it a moment rather than torque.

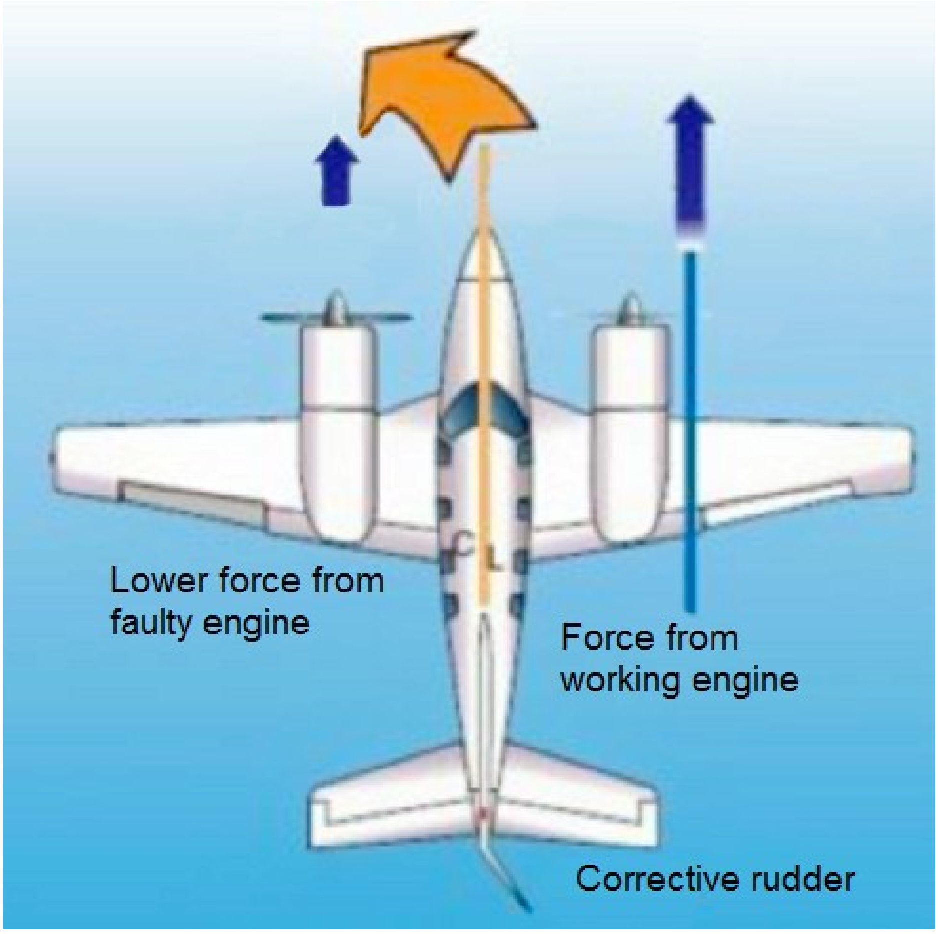
The unit of torque or moment has two parts, a force and a vertical distance apart. Units of measurement that have more than one component are called derived units. In the case of torque the derived unit is metre newton (mN). Actually in a text book you will see this written Nm. I dislike this as it can be confused with work done which is force times distance (Nm). However I give in as it's the accepted way and mN can mean millinewton. In old units this will be foot-pounds or more correctly foot-poundals, where there are 32 poundals of force acting on a pound mass near the earth.

Things are a little more complicated when the two forces are at an angle to the thing they are rotating. Here we have to find their perpendicular separation D not how far apart they are on the object. As shown in Picture 11 Torque = F x D



Picture 11
Peter Scott

Another complication is when one accelerating force is larger than the other. What happens in the case in Picture 12 showing a twin engine aircraft where one engine is running poorly and producing less thrust? The forces will rotate the aircraft with a torque based on the difference in the forces. Yaw would result from the difference in moments of the two thrusts about the centre line CL, so needing rudder correction. At the same time the aircraft will move or accelerate based on the sum of the forces.

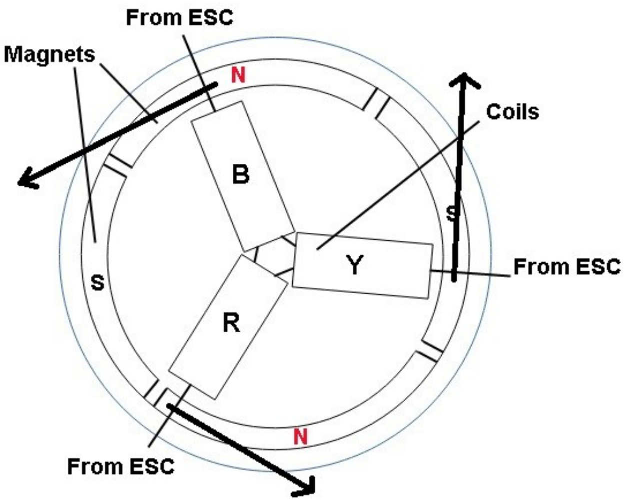


Picture 12
Adapted from esquoracom

Examples of torque in model aircraft

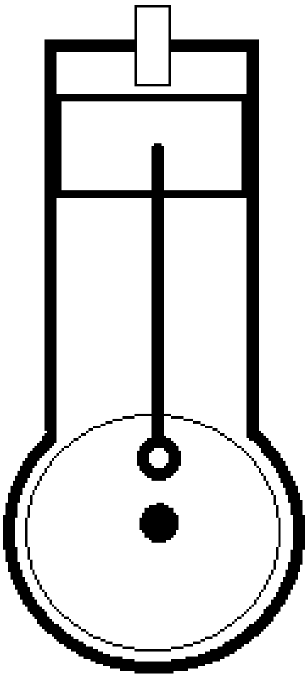
Rotational effect of a motor and an engine
Looking at the geometries of IC engines and electric motors you can clearly see why the latter are smoother running.

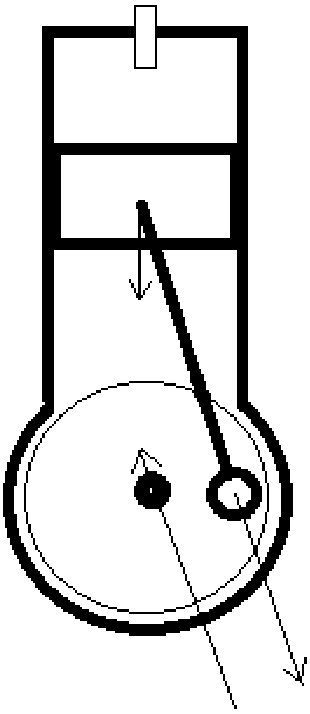
Remember this diagram of an outrunner motor (Picture 13)? I have added dark arrows to show the force from each coil. Notice that they are at a tangent to the motor case. In a practical motor layout with many coils they will also be pretty constant and the case will act as a fly wheel anyway.



Picture 13 Peter Scott

On the other hand in Pictures 14 and 15 is an internal combustion (IC) engine. The piston moves up and down and the crankshaft rotates. The connecting rod and circular crank web, which was a brilliant Victorian invention, turns the linear motion into rotation, but the force it exerts varies with the angle of the conn rod. So not only are the piston and conn rod continuously reversing direction but the torque produced varies from zero to a maximum. Also the power stroke is only for half the time for a two-stroke engine and a quarter for a four-stroke.





Picture 14 Picture 15 Peter Scott

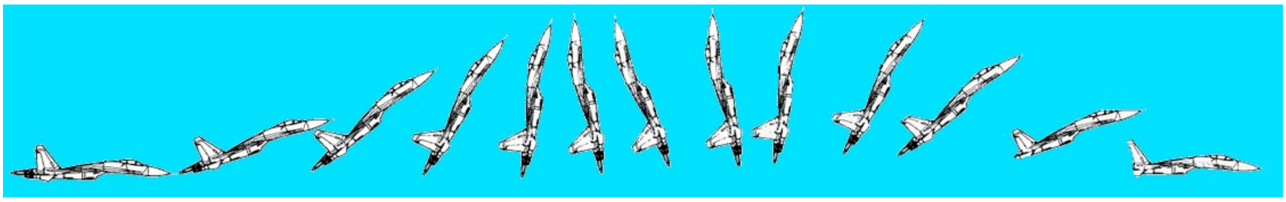
Picture 14 on the left shows the piston at top dead centre. The force down the connecting rod is exactly opposed by the push back from the pin on the crankshaft. There is therefore no torque. In Picture 15 on the right the crankshaft has rotated a bit, initially because its momentum carries it over. There is now a perpendicular distance between the forces from the conn rod and the crankshaft's centre and there is therefore torque. However the connecting rod is at an angle to the piston's force so the component of the force down the conn rod is smaller. You can see that as the engine rotates the torque will vary wildly during the power stroke from a maximum a little before Picture 15 to zero as in Picture 14.

Another inefficiency is that some of the energy generated is used in the compression stroke to squeeze the fuel and air mixture ready for it to catch fire next time. This is one reason why internal combustion engines typically turn about 25 to 30% of the energy in the fuel into useful energy. For electric motors this is around 90%. The reciprocating engine and crank was a brilliant design but things are even better now. I must remember when next at the field not to turn my back on the fellow club members who love their noisy IC engines. 'No, we haven't seen him around today.' 'What spade?'

When at university I attended a lecture on automobile engineering. You won't believe it but then I was a bit of a smart-arse. Foolishly the lecturer invited questions at the end. I said, 'Most of a modern car is ancient technology. When do you think there will be a major advance in car design?' Silence. I had in mind Rudolf Diesel (1858 – 1913), Nicolaus Otto (1832 - 1891) and Earle S. MacPherson (1891 – 1960), who would easily recognise the diesel and petrol (gas) engines and the suspension strut used in 'modern' cars. Coil springs were invented in 1906 and independent suspension in 1922. Well of course we now know the answer to my question - 'When?' It's now. We now have smooth electric motors and electronically controlled suspension. In the nineteen-sixties NSU had a go at a petrol rotary engine, called epitrichoidal, or less fortunately Wankel, but it wore out quickly, as an aquaintance of mine found out to his cost. 20 000 miles between rebuilds! However it was very smooth and powerful and other car companies have tried it since including Mazda and Chevrolet. If only the batteries were better, and the prices of the cars more sensible, I would love an electric car.

Vectored thrust

A fellow club member has ducted fan scale models that are always a joy to watch. One special treat is his Sukhoi Su35 Flanker with vectored thrust. He has mastered the cobra manoeuvre in which the nose is forced upwards to beyond the vertical followed by falling forwards imitating a striking cobra as you see in Picture 16. When Mark is in the air we give him the sky and all just watch. Once the thrust is vectored to create a moment about the neutral point it pushes the nose up. There is only a small component of it left to push the model forward. The cobra has be entered with plenty of speed.



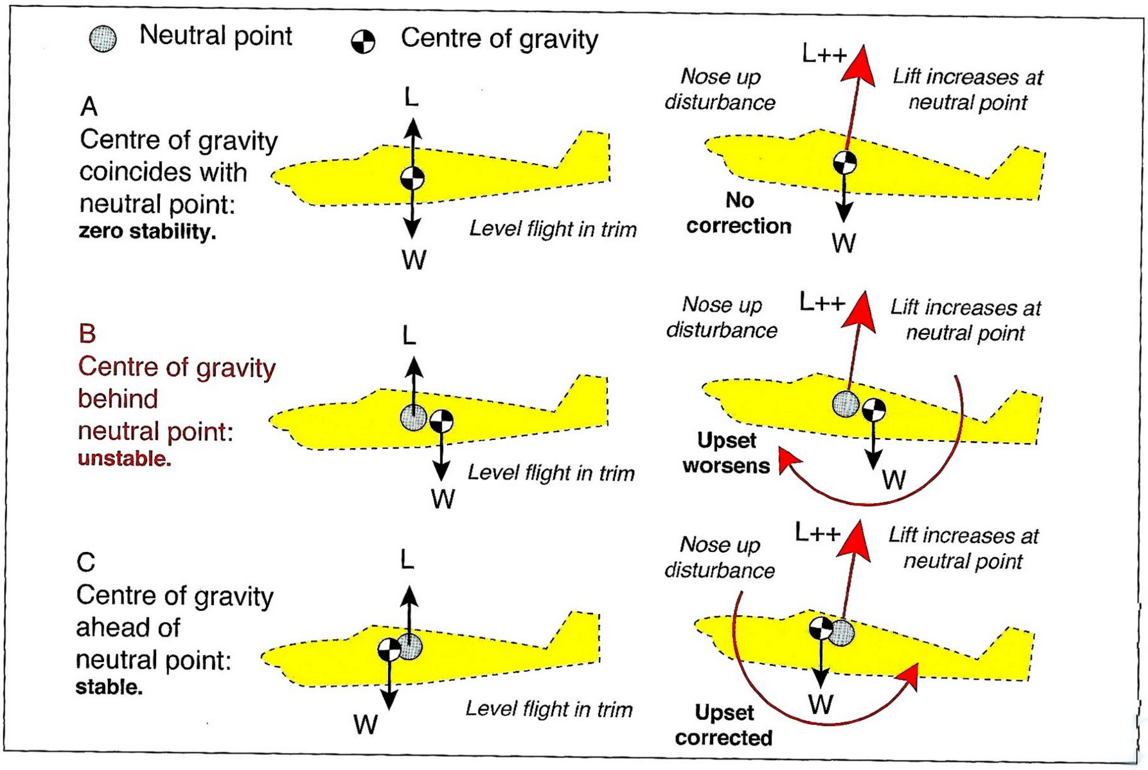
From accrodaviation.be
Picture 16

Servo torque
Torque is measured in Nm but the strength of a servo (torque) is usually given in kg cm. This because people know what a kg feels like and a cm is more manageable for small things than a metre. How much force a servo produces depends on the length of the servo arm. A 20 kg cm servo will make a force of 10 kg at the end of a 2 cm arm but only 4 kg on a 5 cm one.

Centre of gravity, pitching moments and neutral point
There are two vertical forces on a model aircraft. Weight acts downward and lift acts upward. In level flight they are equal and opposite in magnitude. The weight acts through the centre of gravity (CG) and the lift through the centre of lift (CL) also called Neutral Point. What if the CG and CL are separated horizontally? This will create a turning effect – a torque – that will cause pitching. If the CG is in front of the CL the model will tend to pitch nose down. This makes it stable but unresponsive. If the CG is behind the CL the nose will pitch up and the model will tend to a stall. In this state, provided the pilot can maintain stabilty, the model will fly slower and for gliders this usually means a longer flight. Note the term neutral point is often used in place of CL. This will include lift from the tailplane and fuselage so will be slightly different from CL.

“Neutral point is a **point** around which the pitching moment does not change with angle of attack (a.k.a aerodynamic centre; **neutral point** is usually that of the whole **aircraft**, aerodynamic centre of individual airfoils).” From aviation.stackexchange.com

This excellent picture (Picture 17) from Martin Simons’ superb book Model Aircraft Aerodynamics explains it better than I can. You can read more in my article on Martin’s three books.



Picture 17 Martin Simons
Included with permission

Thrust lines and neutral point
Motors are nearly always set at a slight angle right and down. Only a few degrees. The idea is that the thrust (force) vector should go through the neutral point. If it does the thrust produces no moment of force so a change in throttle won't cause yaw or pitching. Of course in the case of propellors it is more complicated. There is a torque opposite to propellor rotation and other effects that cannot be cancelled by thrust line adjustments for all throttle settings.

Tailplane upforce and stability
A tailplane stabilises a model automatically. That is why it is sometimes called a horizontal stabiliser. I dislike the latter as it exhibits verbal diarrhoea with eight syllables where the word tailplane is short with two and tells you exactly what it is. We all know that a model with a small tailplane on a short fuselage is less inherently stable so needing a more forward centre of gravity. The small tailplane generates a smaller force and the shorter tail boom gives a shorter distance for it to act, so the restoring torque or moment is less. Similarly a long boom will strengthen the moment of the elevator. A glider can tolerate a tiny tailplane if the boom is long as is the case with my ASW.

Inertia.
Mass opposes change in velocity. It is one the fundamental laws of the universe that 'the universe fights back'. Starting in 1884 Le Chatelier devised a law, initially for chemical reactions but later applying it to all changing systems, that whenever something external to a physical system causes a change the system will oppose the change. In the case of objects being speeded by a force the mass of the object opposes the force. We call this inertia. Newton described the two forces as action and reaction. In the case of an accelerating thrust he wrote the equation for his second law $F = m\,a$.

When we speed up a model the inertia of the mass of the model will try to stop us. When we increase the current in our motor wires the resulting changing magnetic field induces a 'back EMF' in the wire that opposes the applied voltage. Both are reactions.

We use the same word, 'reaction', in the field of human behaviour. People who habitually oppose change in their communities are called reactionary. That is not always negative. I like the ironic phrase, 'The Power of Negative Thinking', meaning that people who are critical are of great value in testing new ideas. I learn a lot from justifying new technologies to the reactionary old guard on the flying field.

Henry Louis Le Chatelier

Henry Louis Le Chatelier was born on 8 October 1850 in Paris and was the son of an influential French materials engineer Louis Le Chatelier and Louise Durand. His mother raised the children strictly. As he said, "I was accustomed to a very strict discipline: it was necessary to wake up on time, to prepare for your duties and lessons, to eat everything on your plate, etc. All my life I maintained respect for order and law. Order is one of the most perfect forms of civilization."

As a child, Le Chatelier attended school in Paris. At the age of 19, after only one year of instruction in specialized engineering, he followed in his father's footsteps by enrolling in the École Polytechnique in1869. Like all pupils of the Polytechnique, in September 1870 Le Chatelier was named second lieutenant and later took part in the Siege of Paris. After brilliant successes in his technical schooling, he entered the School of Mining in Paris in 1871.

Despite his interests in industrial problems, Le Chatelier chose to teach chemistry rather than pursue a career in industry. He taught at the Sorbonne university in Paris.

He is best known for his work on his principle of chemical equilibrium. He also also carried out extensive research on metallurgy and was a consulting engineer for a cement company, today known as Lafarge Cement. His work on the combustion of a mixture of oxygen and acetylene in equal parts rendered a flame of more than 3000 degrees celsius and led to the birth of the oxyacetylene industry.

One thing passed him by. In 1901 he combined nitrogen and hydrogen at a pressure of 200 atmospheres and 600 °C in the presence of metallic iron – a catalyst. An explosion occurred which nearly killed an assistant. Thus it was left for Fritz Haber to develop and, less than five years later, Haber was successful in producing ammonia on a commercial scale, used both for explosives and fertilisers. Remember the huge explosion in Beirut harbour in 2020? He wrote, "I let the discovery of the ammonia synthesis slip through my hands. It was the greatest blunder of my scientific career". One rather worrying fact I have learned recently is that fertiliser production results in huge quantities of carbon dioxide being produced, roughly 1% of the world's greenhouse gas each year. I only learned that because fizzy drinks (soda) were in short supply in 2021/22 as fertiliser production dropped due the war in Ukraine.

Incidentally Haber's work on chemical warfare and explosives deserves a grim read. The First World War would have ended far sooner without Haber. His wife shot and killed herself probably due to Fritz's war work.

Mostly from wikipedia

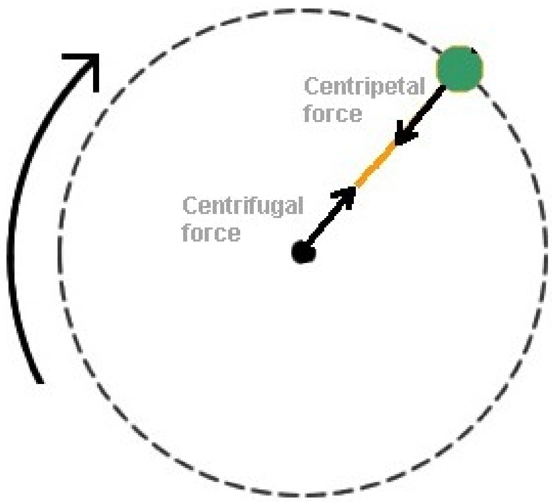
Negative and positive feedback

In negative feedback the reaction opposes the change. When you try to push something the friction forces oppose you. The opposite, positive feedback, can be very dangerous in our field. This is where the reaction adds to the change. Imagine if friction was reversed. As soon as you start pushing, the object would accelerate away without stopping.

Suppose you had reversed the movement on your ailerons. Yes I have done that!. You? You can take off straight but, as soon as you try to bank, the ailerons bank you the wrong way. So you automatically apply more stick which would normally oppose the bank but in this case makes the problem worse. Crunch! A gambler who is losing, instead of stopping can convince himself that another bigger bet will get his money back. Bang goes the house. Many believe that the speed at which automated trading systems work increases the instability of the market. People are selling, so the system does more selling in microseconds. Positive feedback. Prices plummet. That happened in London just after the 'Big Bang' of 1987.

Dynamic forces

Dynamic forces either cause a change in motion or result from it. One example is centrifugal and centripetal forces, shown in Picture 18, which are oft misunderstood. When you twirl a ball on a string your hand feels the ball pulling on you through the string. This is the centrifugal (inertial) force. What the ball feels from you through the string is centripetal force, which is what makes it circle. Let the string go and the ball initially flies in a straight line tangential to the circle as the centripetal force drops to zero.



Picture 18 Peter Scott

Newton's Third Law can also be worded,' Nature fights back.' If you impose a force on something it pushes back on you with an equal and opposite force.The string experiences both as a stretching tension force.

Experiment one: Inertia
This could be a thought experiment or, with care, done practically. Find a weight onto which you can tie a string. Ideally it should be a few hundred grams but softish so it does not damage you or anything else when it falls. Some lead shot or baking pellets in a bag would work.

Find a piece of fairly weak string but strong enough just to hold the weight. Cut off about a metre. Tie it to something solid, then tie the weight in the middle. You will pull at the bottom of the string. For the first time gradually increase the pull until the string breaks. Where will it break? Yes of course, it will be above the weight because your pull adds to the weight so is greatest above the weight. Now retie the string. This time snatch hard at the bottom. What happens? The string breaks below the weight. It didn't? Do it again and snatch harder. This time the inertia of the mass of the weight gives a large inertial force that does not reach the upper part of the string.

Degrees of freedom.
There are three linear degrees – forward, down and sideways – and three rotational ones on the same axes. Our models have all six. They are the pleasure and scourge of model flyers. When we get it right it is a delight. Wrong and we pick up the pieces. Cars or boats have fewer degrees of freedom. Model railways even fewer.

To sum up:
- a single resultant force causes movement change in one or more linear degrees
- a pair of identical but opposite forces with a gap between them causes change in one or more rotational degrees.
- a pair of different forces with a gap between them causes change in all degrees.

Pressure
How can a performer lie down on a bed of nails without harm? Why do stiletto heels make holes in floors? How can a small force on a bicycle tyre pump make the tyres really hard?

Why do elephants have such wide legs? Why do snow shoes work? The answer is pressure. When a force is spread out over a large area it is less destructive.

Pressure = Force / area

The SI unit is the pascal Pa. This is one newton per square metre (N m^{-2}), which is a small amount. The result is that practical pressures work out to hundreds of thousands of pascals. Your car tyres will be a bit more than 200 000 Pa (200 kPa). This is one of the few SI units that really is a nuisance, so we often use the bar, which is 100 000 Pa - the average pressure of the atmosphere near the ground. In old units this will be about 14 psi (pounds per square inch).

Blaise Pascal (1623 – 1662)
Pascal was a polymath, working in the fields of mathematics, physics, mechanical inventions, philosophy and catholic theology. He was a child genius, educated at home by his father, a tax collector in Rouen. He was a strong proponent of the scientific method. He worked with Fermat on probability, influencing economics and social science. He invented one of the first mechanical calculators, called the Pascaline, and a hydraulic press. We know him for his work on fluid dynamics, pressure and vacua, so the SI unit of pressure, the pascal (Pa), is named after him. He always suffered poor health, not helped by living a very austere, ascetic life style stimulated by his belief that humans should suffer. The cause of his early death is uncertain but tuberculosis or stomach cancer are thought likely. I also wonder if he was affected by the mercury that sloshed around when he was experimenting with barometers.

Why we only need a tiny pressure change for lift
This is from a previous article in RCSD. We are at the bottom of a roughly 20 km deep sea of air. At sea level the forces from the air particles are high, though our bodies are adapted to it so we don't notice it. A cubic metre of air has a mass of about 1 kg. So a one square metre column of air 20 km high has a mass of 10 000 kg assuming the density steadily drops to zero. So each square metre has a pressure of about 100 000 pascals on it due to this air piled up on top of it. Each pascal is a newton per square metre. A newton (N) is the weight of a 100 g medium apple (nice!). A kilogram weighs ten newtons. So each square metre has 100 000 apples on it or 10 000 kg as suggested above. You can see that you only need a small change in this to create a large force. To generate a lift force of 1kg (10N) on a surface area of one square metre you only need a pressure difference between the upper and lower surfaces of 10/100 000 or a hundredth of one percent. A 5 kg model with a wing area of 0.5 m^2 will only need a 0.1% difference.

Yes, that surprised me and I had to check the data for that percentage figure again when I calculated it. I also tried again in older units where atmospheric pressure is 14 lb/square inch. There are 1550 square inches in a square metre. So there are 1550 x 14 or about 22 000 lb force. There are 2.2 lb in a kg so the answer is again about 10 000 kg and 100 000 N. Phew!

Friction
Even the smoothest pair of surfaces is rough at the microscopic level. For a highly polished surface the roughness peak to trough will be around 2 um (micrometres). Both surfaces will have that roughness and will settle into each other when stationary, making it more difficult to get them sliding.

As you can't make anything really smooth the only way significantly to reduce friction between two solid things is to keep the two surfaces apart. In any case if you could create two really flat surfaces, perhaps a single layer of atoms such as graphene, the two would stick due to different types of force that are outside our article.

The study of how you keep surfaces apart is called tribology – separating them with liquids, powders, air cushions or magnetic fields. Liquid lubricant molecules are often long and have ends that attach to surfaces. They line up like the bristles of a brush to hold the surfaces apart. The alternative is to make the surfaces from materials that are naturally slippery like Teflon (FTFE). I use a pair of tiny PTFE washers on my indoor model prop shafts for rubber motors. I make them from a thin PTFE sheet in which I drill holes 1 mm or smaller. I then punch them out using a 2.5 or 3 mm leather punch.

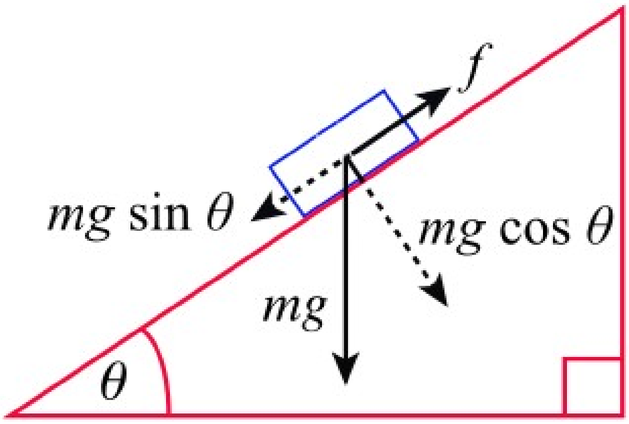
Experiment two: Friction
As you saw earlier the steeper the slope the greater is the component of weight pulling an object down the slope. The extremes are zero when horizontal and 100% when vertical. A very neat and fun experiment is to get a longish piece of wood, that does not have a high polish, to form a slope. You also need a block of wood or plastic, a protractor and some lubricants, for example water, cooking oil, car oil and talcum powder. You will no doubt think of others. Put the block on the slope and gradually raise one end until the block slides. You could gently tap the slope to unlock the two surfaces. Measure the angle.

Then try it for different lubricants. You could also pin other surfaces to the slope like a polythene bag, some PTFE sheet, a flat piece of glass and so on. The differences in slope should be striking. Even more so would be to use round rods or pencils as rollers. Using rollers or wheels means there is no sliding friction as the point of contact doesn't slip. That is how ball and roller bearings work. You can find the friction force as it is equal to mg sinθ. We compare frictions for two surfaces by finding coefficient of friction.

Coefficient of friction μ is the friction force (static or dynamic) divided by the force pushing the surfaces together.

μ = friction force / pressing force

Now we look at the more complicated slope diagram in Picture 19 at the point of sliding.
Friction force f (equals the component of weight down the slope) = mg sinθ
Force pushing the surfaces together (component of weight into the slope) = mg cosθ



Picture 19
From wikipedia

You can find the coefficient of friction μ ('mu') from:

$\mu = mg\sin\theta / mg\cos\theta = \tan\theta$ as $\tan\theta = \sin\theta / \cos\theta$

A slope angle of 45º give a tangent value and μ of 1. Most materials will slide at much lower angles. Typical values from wikipedia are:

Brass on steel	0.35 – 0.51	19º – 27º	e.g. bearings
Glass on glass	0.9 – 1	42º to 45º	surprising
Steel on 'ice'	0.03	1.7º	e.g. skating
PTFE on PTFE	0.04	2.3º	e.g. my indoor models
PTFE on steel	0.04 to 0.2	11.3º	e.g. PTFE bearings

Static and dynamic friction

If you do the experiment you will find that the angle and friction force is larger just before the block starts to slip as mentioned above. This is because the roughnesses of the two surfaces have settled into each other and need an initial lift. OK, that's not wonderful science but it gives you the idea. The initial friction is called static friction. When moving it is called dynamic friction. To measure that you need to give the block a slight shove, or the slope a tap, to get the block started.

Ice skating on water.

No-one skates on ice. The pressure produced by a narrow skate blade melts the ice so the skater rides on a layer of water, and the friction then drops as the skate and the ice are separated by the water. This is only true down to about -30ºC when a human body can't produce enough pressure to melt the ice. Does this mean that a light model with wide skis might feel greater friction? Anyone know? I don't fly from snow.

Last edit 10 April 2024