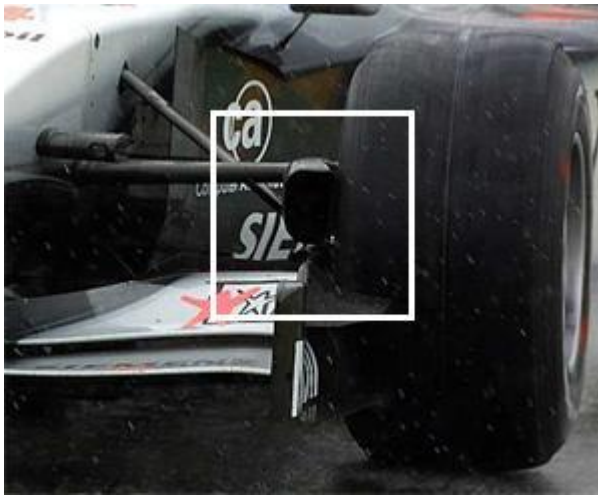


Brakes - what do they do?

Brakes are designed to slow down your vehicle but probably not by the means that you think. The common misconception is that brakes squeeze against a drum or disc, and the pressure of the squeezing action is what slows you down. This in fact is only part of the reason you slow down. Brakes are essentially a mechanism to change energy types. When you're travelling at speed, your vehicle has *kinetic* energy. When you apply the brakes, the pads or shoes that press against the brake drum or rotor convert that energy into *thermal* energy. The cooling of the brakes dissipates the heat and the vehicle slows down. This is all to do with The First Law of Thermodynamics, sometimes known as the law of conservation of energy. This states that energy cannot be created nor destroyed, it can only be converted from one form to another. In the case of brakes, it is converted from kinetic energy to thermal energy.

Thermodynamics, brake fade and drilled rotors.



If you ride a motorbike or drive a race car, you're probably familiar with the term brake fade which is used to describe what happens to brakes when they get too hot. A good example is coming down a mountain pass using your brakes rather than your engine to slow you down. By the First Law of Thermodynamics, as you start to come down the pass, the brakes on your vehicle heat up, slowing you down. But if you keep using the brakes, the drums or discs and brake pads will stay hot and get no chance to cool off. The next time you try to brake, because the brake components are already so hot, they cannot absorb much more heat. Once they get to this stage, you have to look at the brake pads themselves. In every brake pad there is the friction material which is held together with some sort of resin. Once this lot starts to get too hot, the resin holding the pad material together starts to vapourise, forming a gas. That gas has to have somewhere to go, because it can't stay between the pad and the rotor, so it forms a thin layer between the two trying to escape. The result is very similar to hydroplaning while going too fast in the rain; the pads lose contact with the rotor, thus reducing the amount of friction. Voila. Brake fade.

The typical symptom of this would be to get the vehicle to a stop and wait for a few minutes. As the brake components cool down, their ability to absorb heat returns, the pads cool off which means they have more chance to heat up again before the resin vapourises, hence the next time you use the brakes, they seem to work just fine.

So how do the engineers design brakes to reduce or eliminate brake fade? You give that vapourised gas somewhere to go. Cross-drilled or grooved brake rotors. While grooving the surface may reduce the specific heat of the rotor, its effect is negligible in the grand scheme of things. The rotors will heat up to cool down no faster or slower. However, under heavy braking once everything is hot and the resin is vapourising, the grooves give the gas somewhere to go, so the pad can continue to contact the rotor, allowing you to stop.

The whole understanding of the conversion of energy is critical in understanding how and why brakes do what they do, and why they are designed like they are. If you've ever watched Formula-1 racing, you'll see the front wheels have huge scoops inside the wheel pointing to the front (see the picture on the right). This is to duct air to the brake rotors to help them cool off because in Formula-1 racing, the brakes are used viciously every few seconds and spend a lot of their time trying to stay hot. Without some form of cooling assistance, the brakes would be fine for the first few corners but then would fade and become near useless by half way around the track.

Rotor technology.

If a brake rotor was a single cast chunk of steel, it would have terrible heat dissipation properties and leave nowhere for the vapourised gas to go. Because of this, brake rotors are typically modified with all manner of extra design features to help them cool down as quickly as possible as well as dissipate any gas from between the pads and rotors. The following diagram shows some examples of rotor types with the various modification that can be done to them to help them create more friction, disperse more heat more quickly, and ventilate gas. From left to right.

1. Basic brake rotor. 2. Grooved rotor. The grooves give more bite and thus more friction as they pass between the brake pads. They also allow gas to vent from between the pads and the rotor. 3. Grooved, drilled rotor. The drilled holes again give more bite, but also allow eddy currents to blow through the brake disc to assist cooling and ventilating gas. 4. Dual ventilated rotors. Same as before but now with two rotors instead of one, and with vanes in between them to generate a vortex which will cool the rotors even further whilst trying to actually 'suck' any gas away from the pads.

An important note about drilled rotors: Drilled rotors are typically only found (and to be used on) race cars. The drilling weakens the rotors and typically results in microfractures to the rotor. On race cars this isn't a problem - the brakes are changed after each race or weekend. But on a road car, this can

eventually lead to brake rotor failure - not what you want. I only mention this because of a lot of performance suppliers *will* supply you with drilled rotors for street cars without mentioning this little fact.



Big rotors.

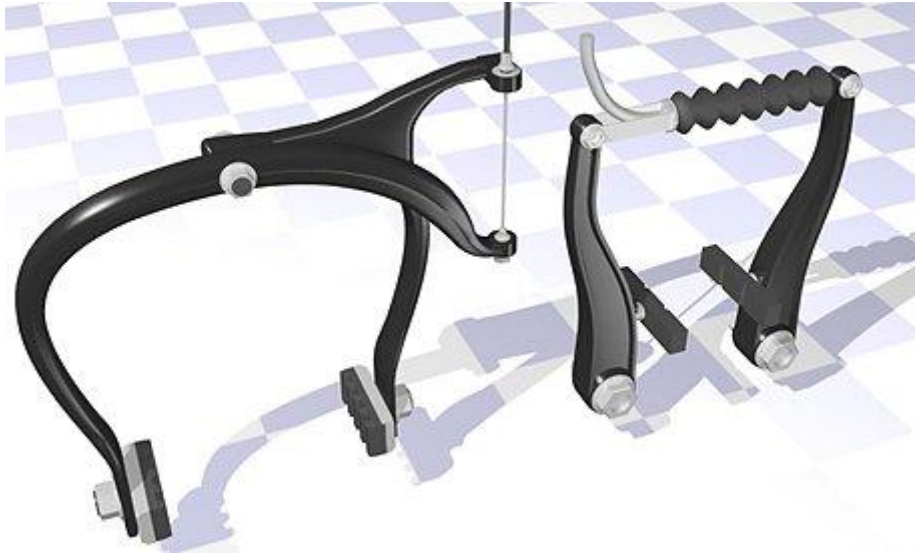
You know I've been drumming into you the whole mechanism that causes you to stop? Here's another reason. Sports cars and race bikes typically have much bigger discs or rotors than your average family saloon car. The reason? Heat and friction. A bigger rotor has more material in it so it can absorb more heat. More material also means a larger surface area, which as well as meaning more area for the pads to generate friction with, also translates to better heat dissipation. ie. bigger rotors = better stopping power. Taking it one step further, composite brake rotors, as found on high-end Ferraris, the McLaren F1, and most Formula-1 race cars, are even better again at heat transfer.

The different types of brake.

All brakes work by friction. Friction causes heat which is part of the kinetic energy conversion process. How they create friction is down to the various designs.

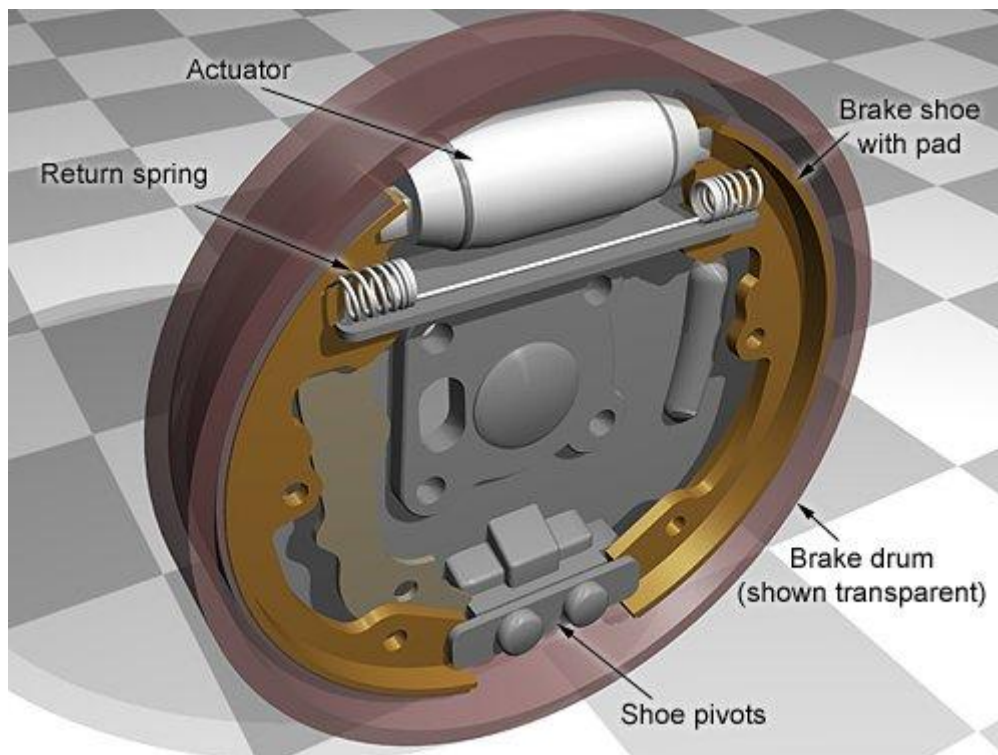
Bicycle wheel brakes

I thought I'd cover these because they're about the most basic type of functioning brake that you can see, watch working, and understand. The construction is very simple and out-in-the- pivot points. If you can look at a bicycle brake and not understand what's going on, the rest of this page is going to cause you a bit of a headache. open. A pair of rubber blocks are attached to a pair of calipers which are pivoted on the frame. When you pull the brake cable, the pads are pressed against the side or inner edge of the bicycle wheel rim. The rubber creates friction, which creates heat, which is the transfer of kinetic energy that slows you down. There's only really two types of bicycle brake - those on which each brake shoe shares the same pivot point, and those with two

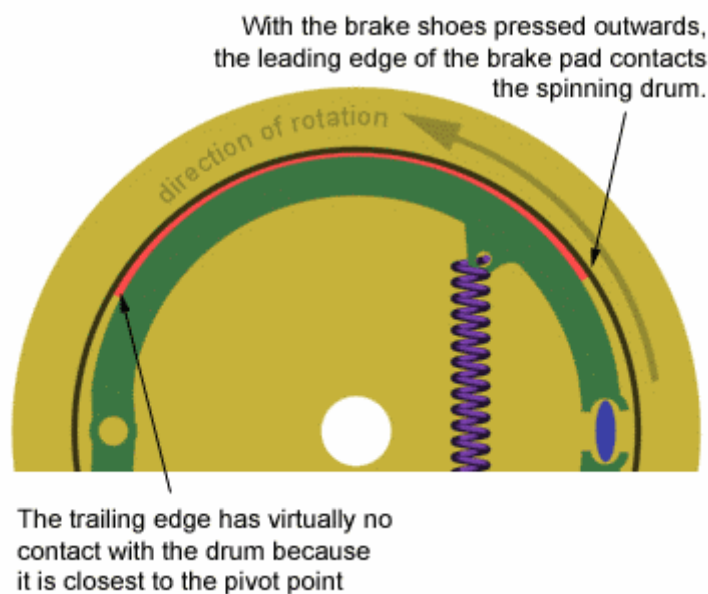
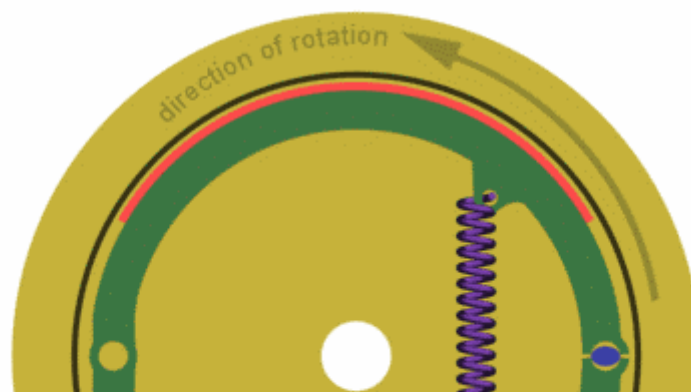


Drum brakes - single leading edge

The next, more complicated type of brake is a drum brake. The concept here is simple. Two semicircular brake shoes sit inside a spinning drum which is attached to the wheel. When you apply the brakes, the shoes are expanded outwards to press against the inside of the drum. This creates friction, which creates heat, which transfers kinetic energy, which slows you down. The example below shows a simple model. The actuator in this case is the blue elliptical object. As that is twisted, it forces against the brake shoes and in turn forces them to expand outwards. The return spring is what pulls the shoes back away from the surface of the brake drum when the brakes are released. See the later section for more information on actuator types.



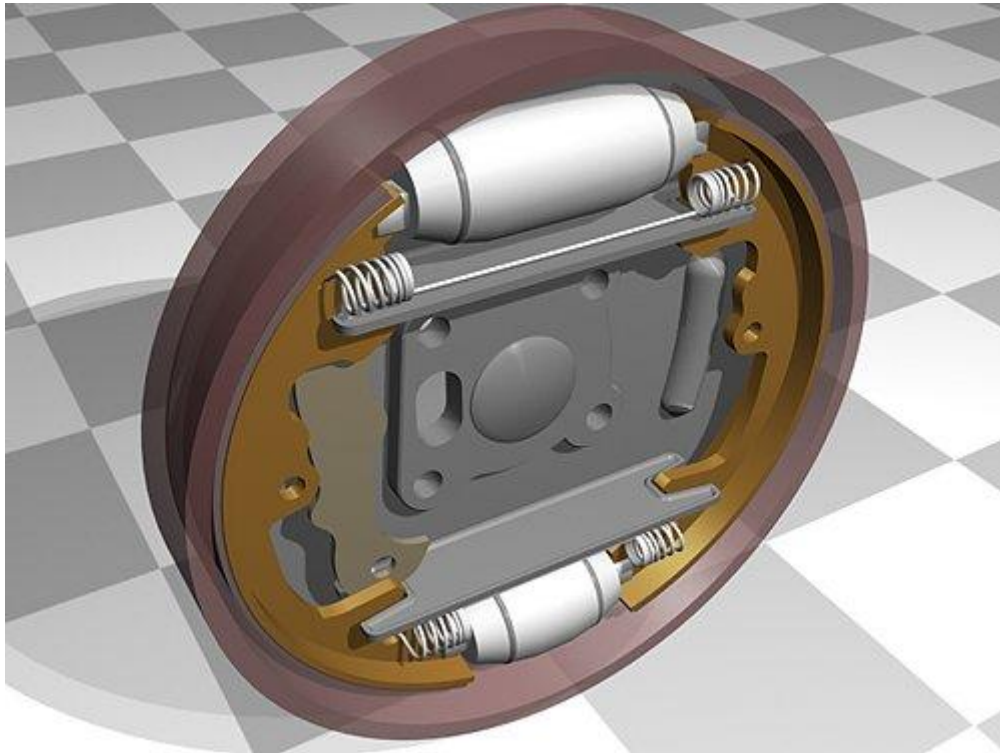
The "single leading edge" refers to the number of parts of the brake shoe which actually contact the spinning drum. Because the brake shoe pivots at one end, simple geometry means that the entire brake pad cannot contact the brake drum. The leading edge is the term given to the part of the brake pad which *does* contact the drum, and in the case of a single leading edge system, it's the part of the pad closest to the actuator. The diagram below shows what happens as the brakes are applied. The shoes are pressed outwards and the part of the brake pad which first contacts the drum is the leading edge. The action of the drum spinning actually helps to draw the brake pad outwards because of friction, which causes the brakes to "bite". The trailing edge of the brake shoe makes virtually no contact with the drum at all. This simple geometry explains why it's really difficult to stop a vehicle rolling backwards if it's equipped only with single leading edge drum brakes. As the drum spins backwards, the leading edge of the shoe becomes the trailing edge and thus doesn't bite.



Drum brakes - double leading edge

The drawbacks of the single leading edge style of drum brake can be eliminated by adding a second return spring and turning the pivot point into a second actuator. Now when the brakes are applied, the shoes are pressed

outwards at two points. So each brake pad now has one leading and one trailing edge. Because there are two brake shoes, there are two brake pads, which means there are two leading edges. Hence the name double leading edge.



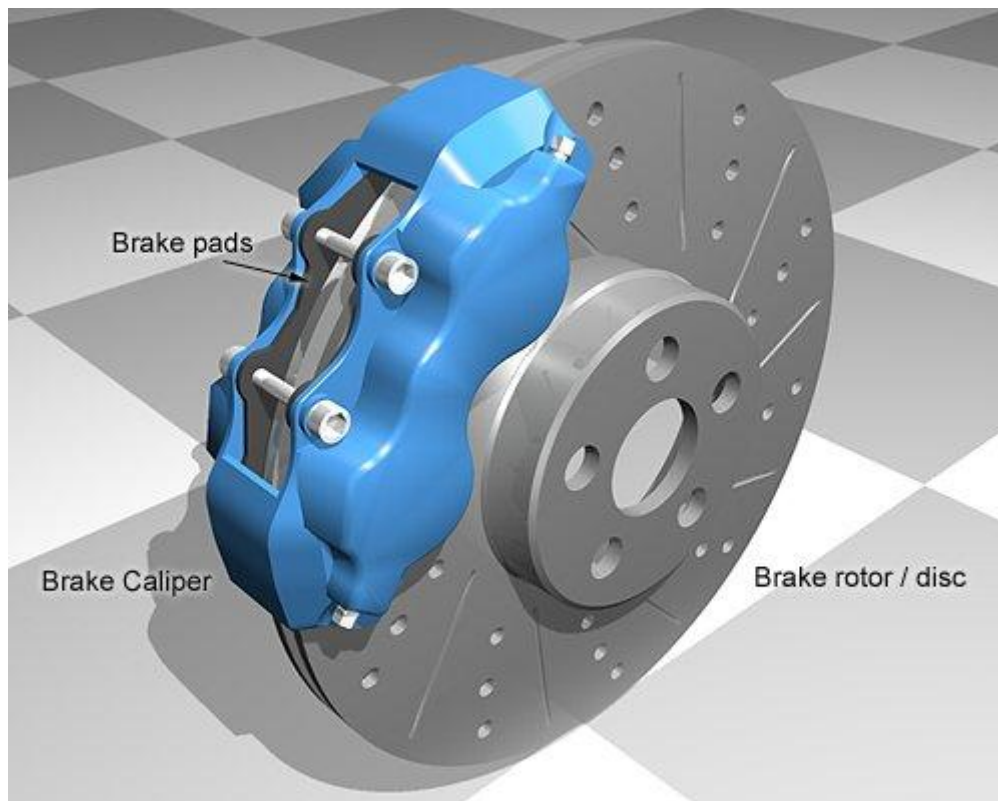
Disc brakes

Some background. Disc brakes were invented in 1902 and patented by Birmingham car maker Frederick William Lanchester. His original design had two discs which pressed against each other to generate friction and slow his car down. It wasn't until 1949 that disc brakes appeared on a production car though. The obscure American car builder Crosley made a vehicle called the Hotshot which used the more familiar brake rotor and calipers that we all know and love today. His original design was a bit crap though - the brakes lasted less than a year each. Finally in 1954 Citroën launched the way-ahead-of-its-time DS which had the first modern incarnation of disc brakes along with other nifty stuff like self-levelling suspension, semi-automatic gearbox, active headlights and composite body panels. (all things which were re-introduced as "new" by car makers in the 90's).

Disc brakes are an order of magnitude better at stopping vehicles than drum brakes, which is why you'll find disc brakes on the front of almost every car and motorbike built today. Sportier vehicles with higher speeds need better brakes to slow them down, so you'll likely see disc brakes on the rear of those too.

Disc brakes are again a two-part system. Instead of the drum, you have a disc or rotor, and instead of the brake shoes, you now have brake caliper assemblies. The caliper assemblies contain one or more hydraulic pistons which push against the back of the brake pads, clamping them together around the spinning rotor. The harder they clamp together, the more friction

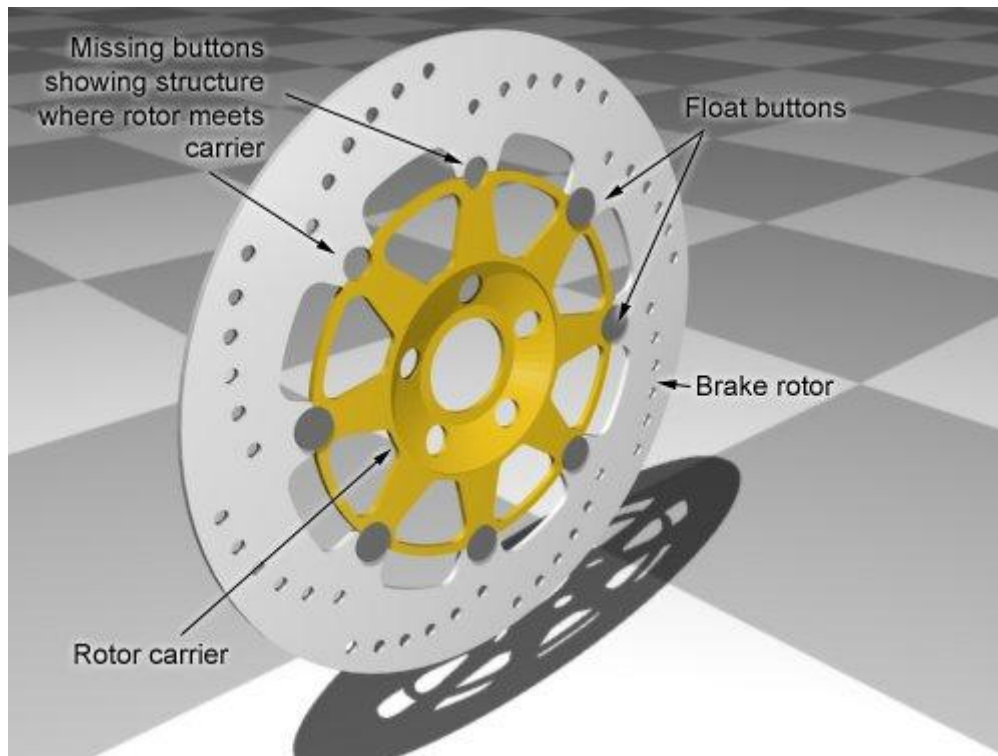
is generated, which means more heat, which means more kinetic energy transfer, which slows you down. You get the idea by now.



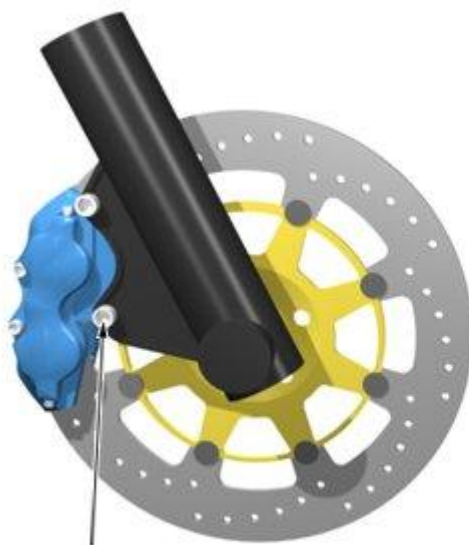
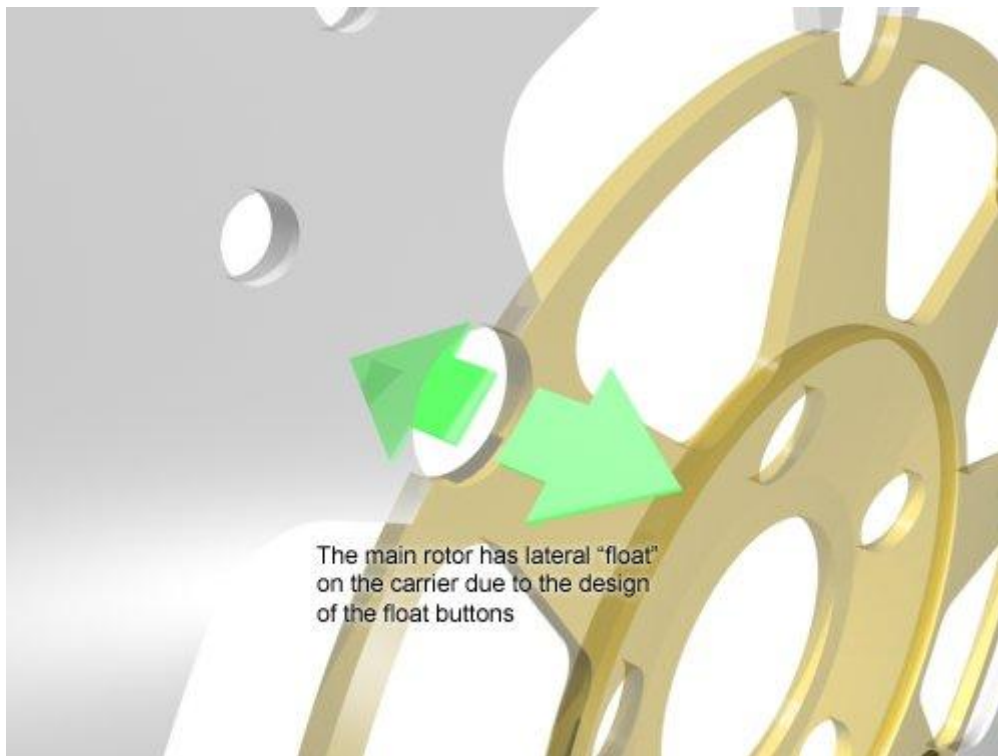
Standard disc brakes have one or two cylinders in them - also known as one or two-pot calipers. Where more force is required, three, or more cylinders can be used. Sports bikes have 4- or 6-pot calipers arranged in pairs. The disadvantage of disc brakes is that they are extremely intolerant of faulty workmanship or bad machining. If you have a regular car disc rotor which is off by so much as 0.07mm (3/1000 inch) it will be Hell when you step on the brakes. That ever-so-slight warp or misalignment is going to spin through the clamped calipers at some ungodly speed and the resulting vibration will make you wonder if you're driving down stairs. To combat this problem, which is particularly critical on motorbikes, floating rotors were invented.

The floating rotor.

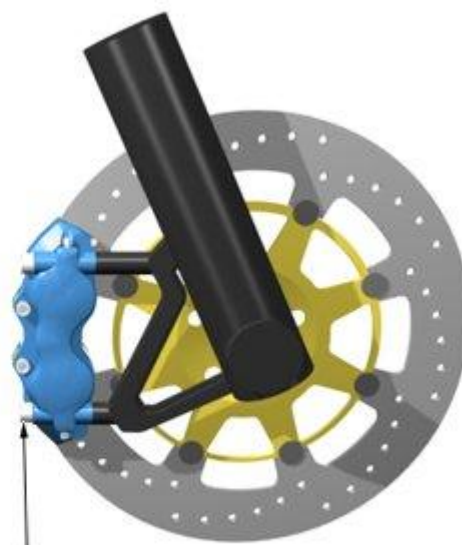
Standard brake rotors are cast in a single piece which bolts directly to the wheel or drive plate. If the mounting surface of your wheel or drive plate isn't perfectly flat, you'll get vibration at speed. Floating rotors are typically cast in two pieces - the rotor and the carrier. The carrier is bolted to the wheel and the rotor is attached to the carrier using float buttons. The other method of floating a brake rotor is to have the rotor bolted directly to the wheel itself without a carrier, but the bolts have float buttons built into them.



These buttons allow the brake rotor some freedom to move laterally, but restrict the angular and rotational movement as if they were bolted directly to the wheel. This slight lateral motion which can be less than 0.03mm, is just enough to prevent vibration in the brake system. Because the calipers are mounted solidly, and warping or misalignment in the wheel or brake rotor mounting face can be compensated for because the rotor will "float" laterally on the float buttons. This side-to-side vibration is separated from the carrier by the float buttons themselves, so none of the resulting motion is transferred into the suspension or steering. Clever eh? The rendering below shows an extreme close-up of the brake disc shown above. I've rendered the components slightly transparent so you can see what's going on.



Regular caliper mounting
Attachment bolts are at 90 degrees to the face of the brake rotor



Radial caliper mounting
Attachment bolts are parallel to the face of the brake rotor

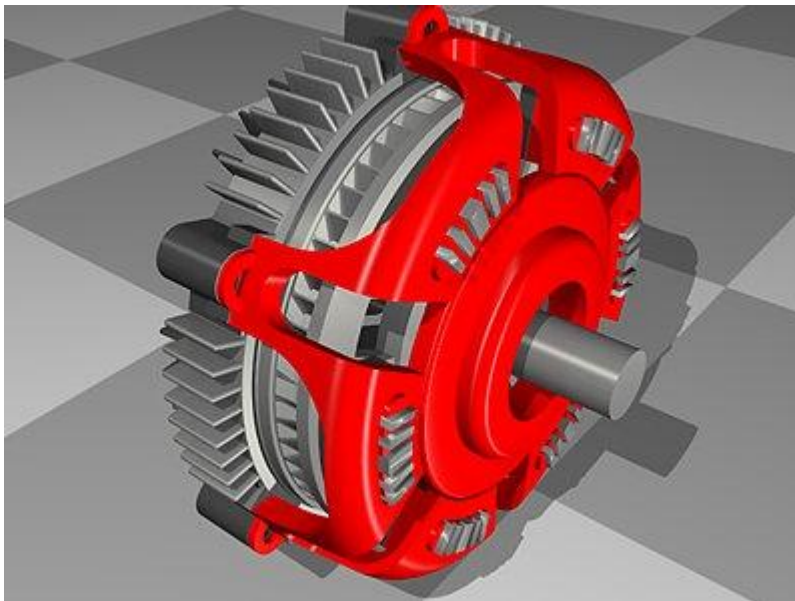
Radial calipers / radial brakes.

Around the year 2003, motorbikes started to hit the showrooms with a new feature - radial brakes. The magazines and testers will all tell you that radial brakes make the bike stop quicker. Not true - they have nothing to do with stopping power and everything to do with the design of the front forks of the bike. More and more bikes are coming out with upside-down forks. ie. instead of the fat canister part of the fork being at the bottom of the assembly, it's at the top. This means that the fork pistons are now the part of the suspension with the wheel attached to them. It also means that it's impossible to put a

stiffening fork brace down there now because the brace would need to move with the wheel, and the length of the fork pistons precludes that.

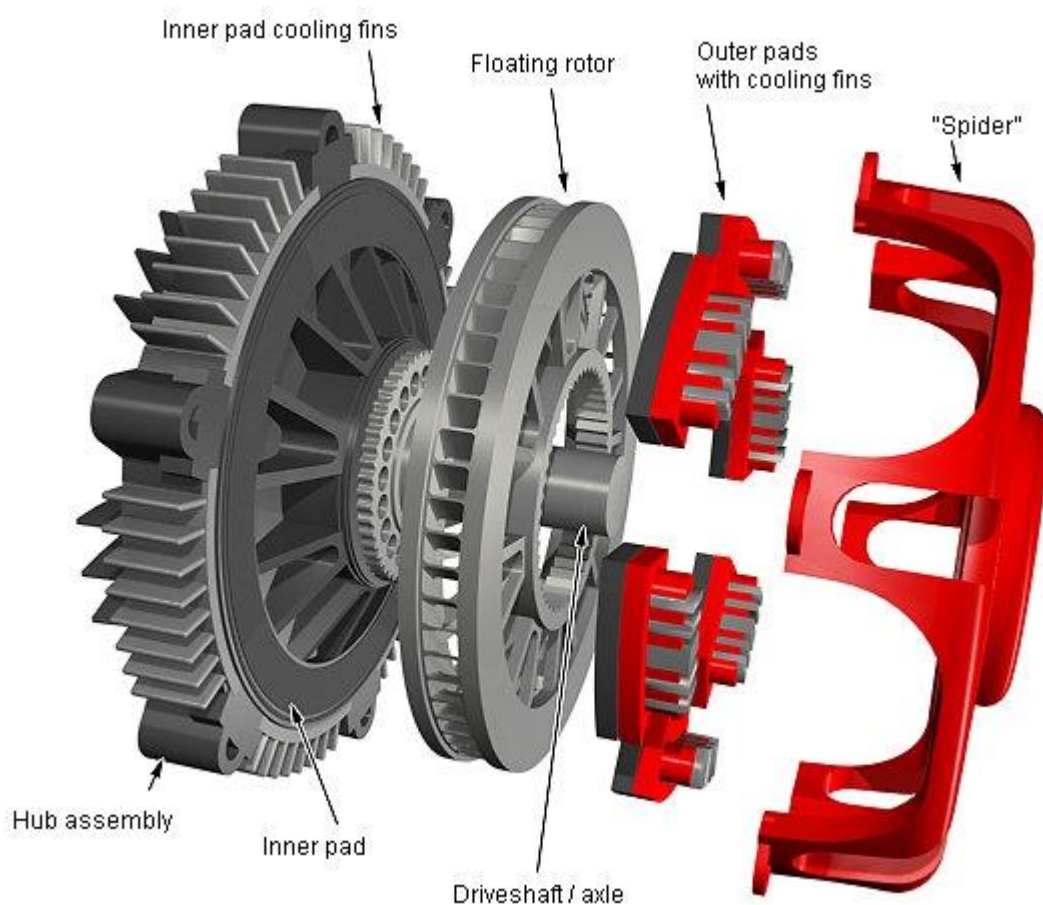
The stiffness of the front end is now entirely dependent on the size of the front axle. Bigger axle = stiffer front end. A side-effect of this design was that traditionally-mounted brake calipers could cause a lot of vibration in the steering because of flex between the wheel (with the brake disc bolted to it), and the fork leg (with the caliper). The slight tolerance allowed by floating brake rotors couldn't compensate for the amount of flexing in the forks. To reduce the brake-induced fork vibration, the brake calipers were moved around the rotors slightly so that they fell into the front-rear alignment of the wheel axle. This is because there is less lateral flex at that point, which means less or no vibration. The caliper mounts were changed too. Traditional calipers bolt on to the forks with bolts going through them at 90 degrees to the face of the brake rotor. With radial calipers, the bolts are aligned parallel to the brake rotor - effectively also in the front-rear alignment of the wheel. The image on the right here shows the difference between traditional and radially mounted brake calipers.

Full-contact Disc brakes.



There is a quiet but major revolution happening in the world of brakes, and its being brought about by a Canadian company called NewTech. Rather than the piecemeal improvements we've seen over the last few years, with slight design changes, and materials improvements, the new system is a radical redesign from the ground up. NewTech have designed a disc brake system called "full contact disc brakes". They looked at traditional pad and rotor design and figured that the pads only contact about 15% of the rotor surface at any one time. With a change of design, NewTech have been able to add 5 more pads to the system so that 75% of the brake rotor is in contact with the pads at any one time. With traditional pads and rotors, the brake rotor is clamped between the pad. With the NewTech design, the brake rotor itself becomes a floating rotor, similar to those found on motorbikes. It is covered with a 'spider' (the red

structure in my renderings below) and the spider has 6 brake pads on the inside of it. The hydraulic system acts on fully circular elastomer composite diaphragm behind the brake disc, mounted in the black structure in the renderings. This had 6 pads on it which push the entire disc out against the 6 pads inside the spider. This provides an even force across the entire disc to push it out, and the disc gets an even contact with all 12 pads. To ensure the brakes remain cool, the system is covered in cooling fins connected to the outer pads to dissipate heat. The inner pads are fitted with a moulded thermal barrier made of a composite material. Special inserts made of a variety of frictional materials are distributed evenly on the entire surface of the pad. The range of materials is used to ensure performance under diverse conditions.



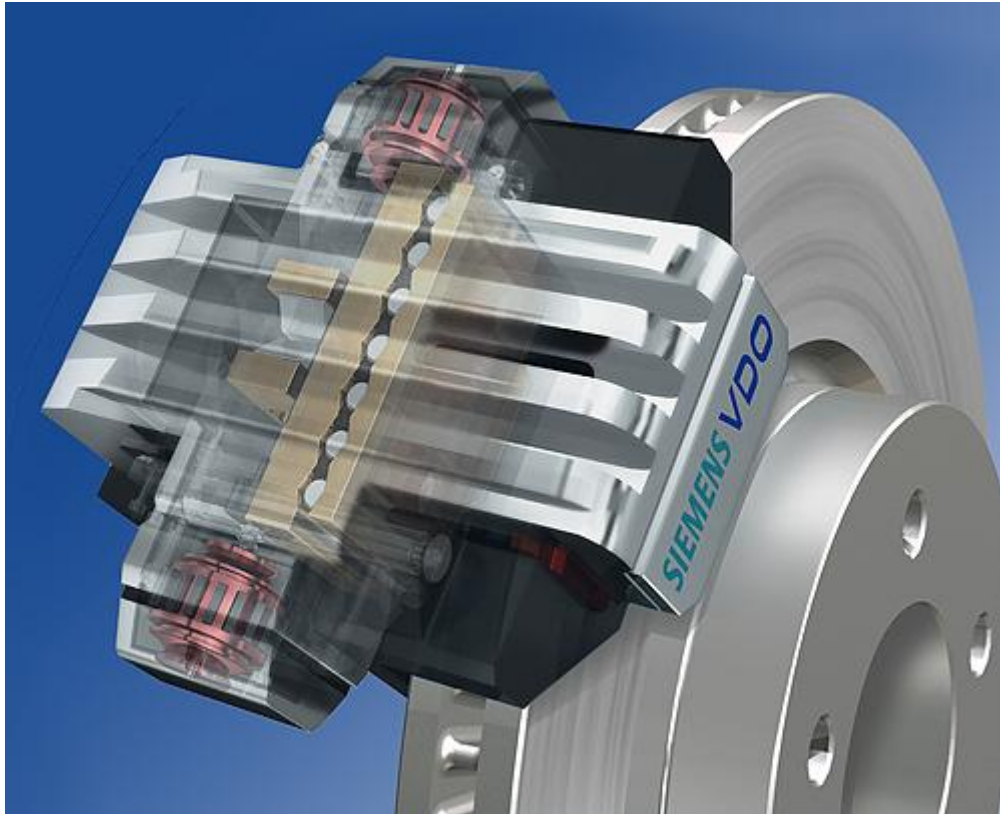
The Siemens VDO Electric Wedge Brake.

[Siemens VDO](#) in Germany are trying to bring a prototype electric wedge brake (EWB) to the market. As much as it sounds like a high school prank involving underwear, it's actually the latest attempt to remove hydraulics from the braking circuit in a car. The EWB is an innovative idea based on technology developed by a company called eStop. Siemens acquired eStop early in 2005 and have been continuing their work on the wedge system ever since. The principle is both simple and clever. The brake pad is pressed against the brake rotor by means of a wedge-shaped thrust plate. The more the brake rotor turns, the harder the slope of the wedge forces the pads against it.

Because of the shape of the wedge bearings and thrust plate and the rotation of the brake rotor, the pad is actually forced against the rotor harder the faster the rotor is spinning. In effect, a lot of braking force for very little input.

The system runs off a normal 12v vehicle electrical system which means no more hydraulics. It also allows the system to eliminate all the plumbing associated with ABS as the EWB is entirely electronically controlled. The final advantage, if you could call it that, is that it allows the first true all-electronic brake-by-wire system. Current brake-by-wire systems use electronics behind the brake pedal to send signals to actuators in the hydraulic system. With the EWB there is no hydraulic system so the only link from the brake pedal to the brake caliper is a 12v electrical feed and signal actuation wire. The operation of the wedge system is based on several roller bearings and a wedge-shaped thrust plate connected to a pair of 12v electric motors. As the brake pedal is depressed, the signal is sent to the motors to start moving the thrust plate. Because of its shape and the design of the roller bearings, as the thrust plate moves, it forces the brake pad to press against the brake rotor. The reaction time of the electric motors can be measured in milliseconds - far quicker than any hydraulic system could react, so in theory, when connected to a full computer-monitored brake-by-wire system, the EWB ought to be able to shave milliseconds off brake reaction time. Doesn't sound like much but if it means a few less metres in stopping distance, that can only be a good thing. The brake caliper unit itself has an intelligent wheel-braking module built into it. As well as the motors, bearings and wedges, the module also has a sensor system for monitoring movement and force - basically this is what replaces the traditional ABS items so each brake caliper becomes a self-governing ABS unit. Because there's no physical link back to the brake pedal any more, the ABS doesn't force the brake pedal to judder when it activates which will make it far more acceptable for a lot more drivers. Finally, because the system is totally electronic, the traditional cable-pulled handbrake can also be eliminated and replaced with a parking switch that simply activates all four EWB modules.

Of course there are pros and cons to any new system like this. Obviously reducing the weight and complexity of the braking system is a good thing, and because of the design of the EWB, there's a lot less space taken up in the engine bay, freeing up more room for the car designers to work with. But by removing the hydraulic lines, ABS actuators and sensors, and master and slave brake cylinders, the EWB concept becomes entirely reliant on the 12v electrical system and the vagaries of a computer. Knowing how often a single dodgy earth connections in a car can totally screw up the electrics, I've got to wonder what would happen if a grounding strap came loose and the electronic brake system started playing up. Will these brakes have a fail-safe or backup system like the double hydraulic circuits we use now, or will you sail off into some solid object because you've got no brakes left? Siemens aren't clear on this matter. Until I get the chance to render up some illustrations of my own to better show how the system works, the one you see here is from the Siemens press pack.



Brake pad compounds.

Just a quick word on brake pad compounds. Most pads used to use asbestos but we all know what that stuff is like. Today they use all manner of combinations of materials. The pads themselves are made up of a friction material bonded to the backing plate. The brake caliper piston pushes against the backing plate and the friction material is pushed against the brake rotor. The material combinations typically fall into the following broad categories now.

Organic

These pads are well-suited for street driving because they wear well, are easy on the ears, don't chew up the rotors and don't spew dust everywhere. They're favoured for your average family saloon because they work well when they're cold. Of course the drawback is that they don't work so well when they get hot.

Semi-metallic / sintered

This is a good compromise between street and track. These seem to be the pad of choice for sportier vehicles such as the Subaru Impreza WRX. They won't work as well as organic pads when they are cold, so you need to be a bit wary of the first couple of stops. Conversely they do work well when hot. Occasionally the weak link in semi-metallic pads is the bonding material that holds the friction pad to the backing plate. There have been occasions where the friction material has come away completely. That's infrequent though.

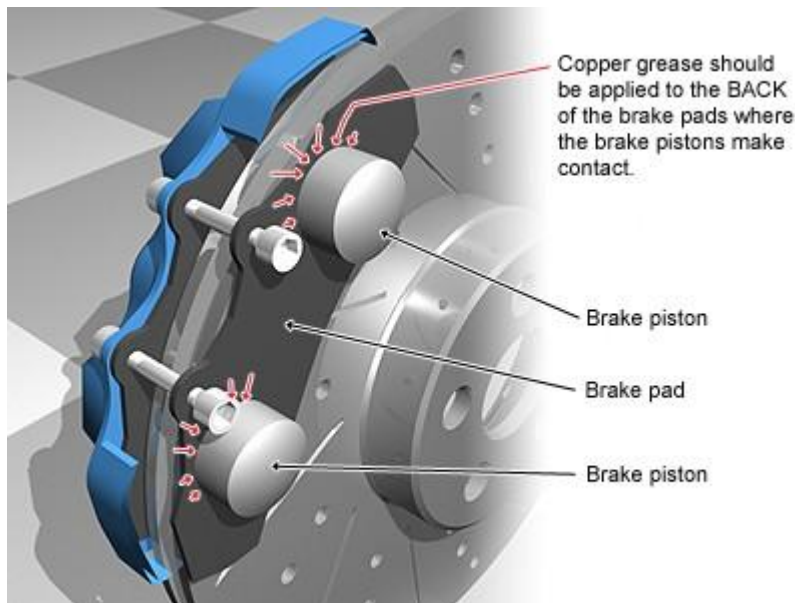
Metallic

These pads are typically reserved for racing or the extremely rich. They squeal and dust like crazy, are hard on rotors and don't work well when cold.

Ceramic

Ceramic pads still have metal fibers (about 15% vs. about 40% for semi-metallic) but they are copper instead of steel and therefore cause less wear and transfer heat better. They don't fade as easily as other pads, cool faster, last longer, and are effectively silent, as the sound they generate is outside of the human range of hearing. Dogs will go crazy though. The dust created by ceramic pads is also very light in color so your wheels look cleaner.

Brake squeal.



Squealing brakes are a sign of one of two things : the friction material is all gone and you're jamming the backing plate against the brake rotor, or the fit of the brake pad against the caliper piston isn't as snug as it could be. Either way, the squealing is the result of an extremely high-frequency vibration between the pad, the caliper piston and the brake rotor. Some vehicles have problems with squealy brakes right from the factory. In those cases, simply changing brake pad manufacturer can often cure the problem as the different pads will have a slightly different harmonic frequency, which is harder to attain. A classic example was one of the BMW R1100 touring bikes. From the factory, they'd squeal like crazy, and BMW redesigned the brake calipers and rotors a couple of times until they finally just switched to a different brand of pads and the problem vanished.

Solving brake squeal.

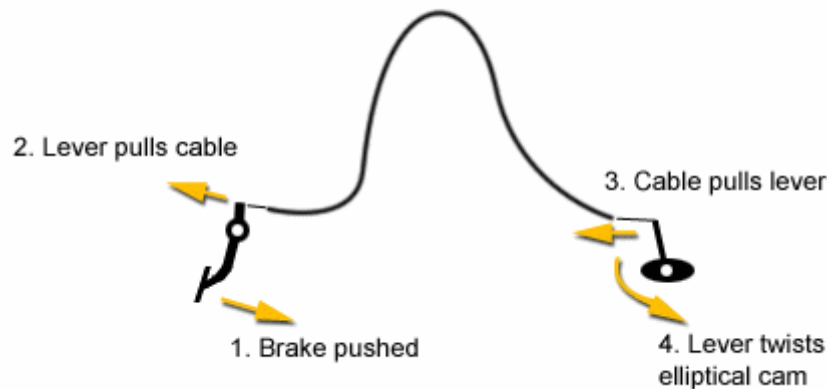
A good way to solve brake squeal is to put some copper-based grease on the back of your brake pads. That's very important so I'll say it again in CAPS : **THE BACK**. Copper grease is extremely resistant to pressure and heat and if you get any on the front of your pads, you'll need new pads and rotors or discs. The picture here shows a cutaway of a disc brake assembly. The blue caliper housing on the right is missing to show the two silver brake pistons. The idea is that it creates a small pocket of sticky lubrication between the front side of the brake pistons and the back side of the brake pads. This is usually enough to prevent the high-frequency squeal. If you're not happy doing this yourself (working on a safety-critical part of your car like the brakes isn't something just everybody should be doing) then ask your friendly greasemonkey to do it for you.

Brake actuators.

Brakes are all well and good, but you need some method of applying them in order for them to work. The method by which the force from your hand or foot reaches the brake itself is all to do with the brake actuator system.

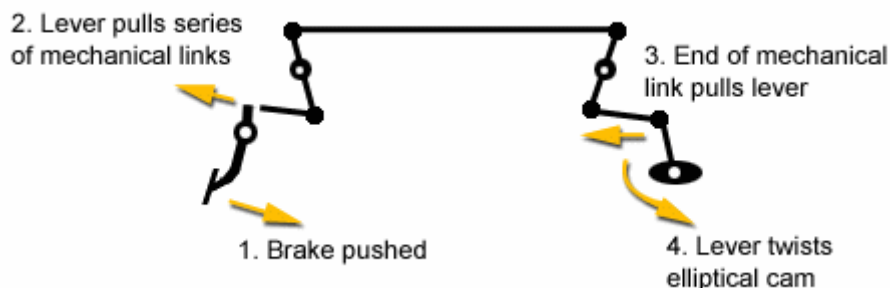
Cable-operated

This is about as basic as you get. A cable is connected to a lever at each end. You press on one lever with your foot or squeeze it with your hand, and it pulls the lever at the other end. On the back of the brake-end lever there's an elliptical cam which rotates inside a circular cup in the brake shoe. As the long axis of the ellipse rotates, it forces the brake shoes to move apart. In the case of a bicycle brake, the brake-end of the cable just pulls the two calipers together.



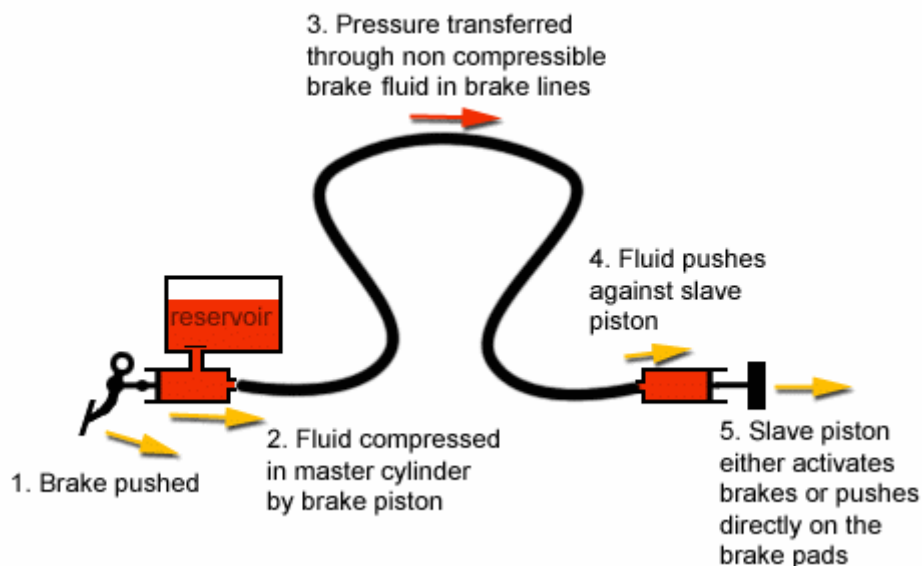
Solid bar connection

One step up, and found on the rear brake of older motorbikes, the solid bar connection. This allows the use of mechanical advantage (see below) to amplify your force on the pedal or lever before it gets to the brakes themselves. Typically these systems are used on drum brakes with the elliptical actuator described above. The disadvantage of this system is that it needs hinge and pivot points that match the position of the suspension components. If they're not present, going over a bump could put the brakes on as the suspension moves relative to the lever.



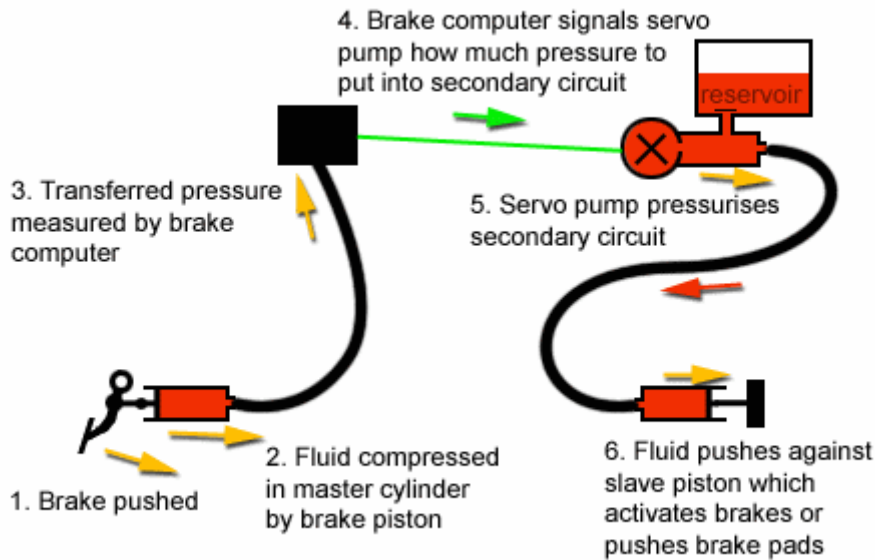
Single-circuit hydraulic

Another step up and we get to the type of brake system used on most cars and motorbikes today. Gone are the cables and bars, replaced instead with a system of plungers, reservoirs and hydraulic fluid. Single-circuit hydraulic systems have three basic components - the master cylinder, the slave cylinder and the reservoir. They're joined together with hydraulic hose and filled with a non-compressible hydraulic fluid (see brake fluid below). When you press your foot on the brake, or squeeze the brake lever, you compress a small piston assembly in the master cylinder. Because the brake fluid does not compress, that pressure is instantaneously transferred through the hydraulic brake line to the slave cylinder where it acts on another piston assembly, pushing it out. That slave assembly is either connected to a lever to activate the brakes, or more commonly, is the brake caliper itself, with the slave cylinder being the piston that acts directly on the brake pads. Because of the arrangement of the slave cylinder, heat from the brakes can be transferred back into the brake fluid.



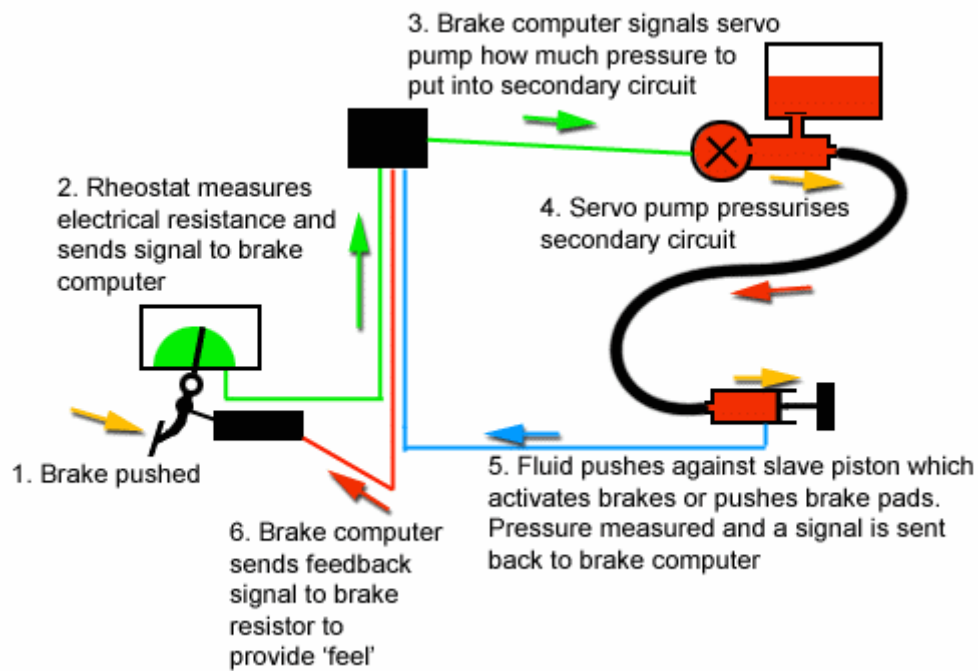
Dual-circuit hydraulic

Dual-circuit hydraulic systems are available on high-end luxury vehicles and newer motorbikes, in particular BMW bikes. These have two separate circuits. One is the command circuit - that's the one you act on with your hand or foot. The second is a separate circuit controlled by an onboard computer, and that's the one which is actually connected to the brakes. As you apply the brakes, you're sending a pressure signal via the command circuit to the brake computer. It measures the amount of force you're applying, and using a servo / pump system, applies the same force to the secondary circuit to activate the brakes. If you do something stupid like trying to slam on the brakes at 100mph, the computer will realise that this would result in a skid or spin, and will not send the full pressure down the secondary circuit, instead deciding to use it's speed and ABS sensors to determine the optimal brake pressure to maintain control of the vehicle. The advantage of a dual-circuit system is that the command circuit never gets heat transferred into it because it is totally separated from the brakes themselves. The disadvantage of course is that you now have two hydraulic circuits to maintain.



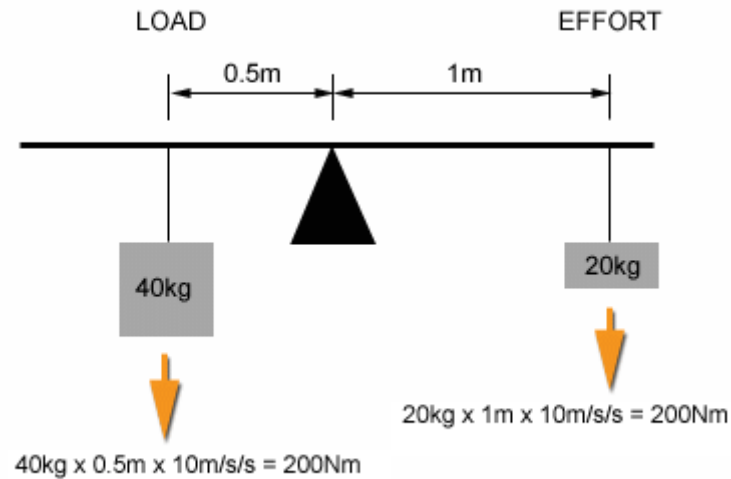
Brake-by-wire

The most advanced system of brakes to date are brake-by-wire. These are a direct copy of Formula-1 racing brakes and are very similar to the dual-circuit hydraulic system described above, but instead of the command circuit being hydraulic, it's replaced with electronics. The brake pedal or lever is connected to a hypersensitive rheostat (measures electrical resistance). The more you push it, the greater the electrical signal sent to the brake computer. From there on, it performs just like the secondary circuit described above. The advantage to this system is that the brake pedal or lever can be placed just about anywhere you like as it no longer is encumbered by the plumbing that goes with a hydraulic circuit. To combat driver complaints of "lack of feel" in the brakes, most brake-by-wire systems have a reverse feedback loop built in. This measures the pressure being applied to the brakes on the secondary circuit, and actuates an electrical resistor in the pedal or lever assembly to provide resistance. This is needed *because* there is no physical connection to any part of the brake system at all.

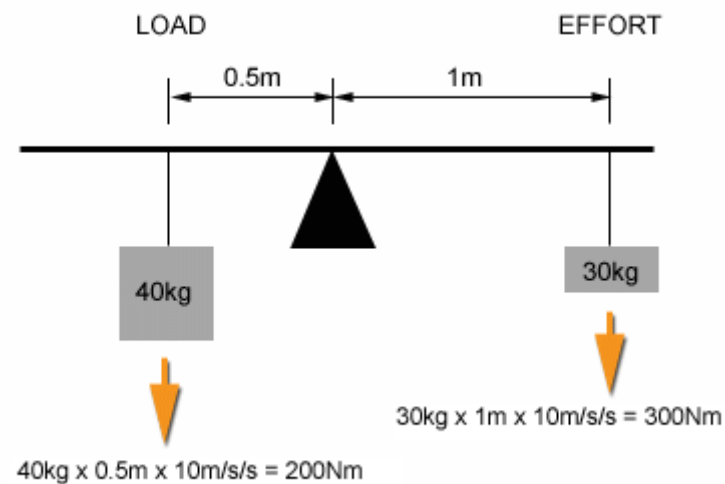


Mechanical advantage - why you can stop a 2-ton car with one foot.

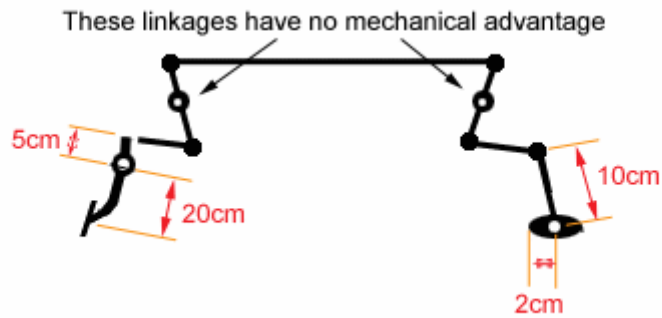
If you did any sort of physics classes when you were back in school, you might remember something called mechanical advantage. In its most basic form, mechanical advantage is the ratio of force-in to force-out in a mechanical system. $\text{Mechanical Advantage} = \frac{\text{Effort Torque}}{\text{Load Torque}}$. For example a 20kg weight 1 metre from a pivot can lift a 40kg weight 0.5m from the pivot on the other side. The effort torque and load torque calculations are to do with force in Newtons and distance from pivot point. Hence torque is measured in Newton-metres, or Nm. A Newton is the amount of force required to accelerate a mass of one kilogram by one metre per second². On Earth, where acceleration due to gravity is 9.8m/s², the force exerted upon a mass of 1kg is 9.8N (usually rounded up to 10N). Another popular notation is lbf.ft - pound-force-feet, commonly referred to as foot-pounds. 1 Newton-metre is equivalent to 0.737 foot-pounds. The diagram below shows a simple lever system on a pivot. The load torque is 200Nm, and the effort torque is also 200Nm. $\text{Mechanical advantage} = \frac{\text{effort}}{\text{load}}$, which in this case is $200 / 200$, which is 1. ie. the system is balanced.



Now imagine increasing the weight on the effort side to 30kg instead of 20kg, but leaving everything else the same. The load torque is still 200Nm, but the effort torque is now 300Nm. Mechanical advantage = effort / load, which is $300 / 200$, which is 1.5. Any mechanical advantage value larger than 1.0 means that the effort has the advantage. In this case, a 30kg weight which is lighter than the 40kg load, is able to lift it off the ground.



If you now take your new-found / remembered knowledge about physics and look at the simple lever brake system, you'll realise how it's possible to generate enough force using your foot to stop a car or motorbike. Look at this diagram of the lever-operated cam brake.



This system has 4 levers in it. The middle two have no mechanical advantage as the levers are connected the same distance from the pivot in each case. However, look at the pedal. The values I've put in are arbitrary but they serve the purpose. On the pedal we have some amount of force 20cm from the pivot, but the other end of the lever is only 5cm from the pivot. This gives us a mechanical advantage of 4 on the brake lever (20cm / 5cm). At the other end, the lever attached to the cam is still a lever system - it's just bent. The input lever is 10cm long but the cam is only 4cm across - or 2cm to the tip from the pivot. So at the brake cam we have a mechanical advantage of 5. (10cm / 2cm). So across this entire system, we have a total mechanical advantage of 20 - 4 from the brake pedal and 5 from the lever and cam. Apply force to this little system and be amazed. The units of force used are irrelevant - they're multiplied just the same. To use easier-to-comprehend values, let's imagine that when you're braking, your foot is pushing on the brake pedal with about 60pounds of force - 27Kg. Through the brake pedal, that is amplified 4 times to 240pounds, and through the lever and cam its amplified a further 5 times from 240pounds to 1200pounds. You pushed the pedal with 60pounds of force, but the cam inside the drum brake is being forced out against the brake drum with 1200pounds of force - about 544Kg. Sweet.

Mechanical advantage as applied to hydraulics.

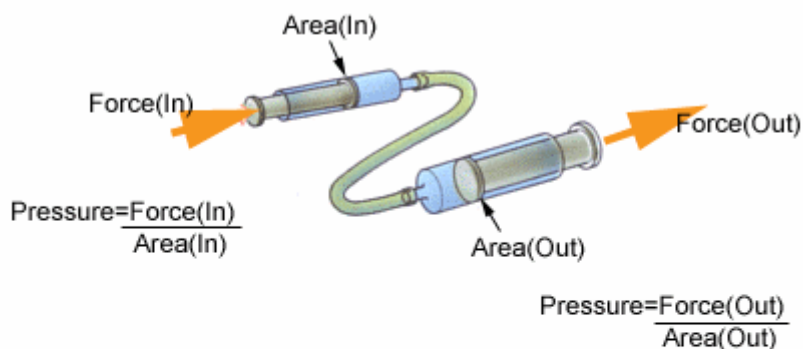
Most braking systems now use hydraulics. This is a slight change in the equation but the concept of mechanical advantage still exists, this time by the use of pressure equations. Pressure = force / area. If you apply 20 Newtons of pressure to 1m², it's the same as applying 200 Newtons to 10m². Why? Because 20 Newtons of force divided by 1m² of area generates 20 Pascals of pressure. Similarly, 200N / 10m² is also 20Pa.



If you now think of that in terms of a hydraulic braking system, it becomes clear how mechanical advantage works for you. Brake fluid is incompressible - it has to be. This is good because it makes calculation for hydraulic brake systems quite easy - you can eliminate the internal pressure from the equation.

Split the system into two parts - input and output - the brake pedal and the brake caliper piston.

For each part, Pressure = Force / Area. The Pressure is the same at all points in the system, so some basic algebra gives a simple formula:



Pressure is the same throughout the system,

$$\text{So } \frac{\text{Force(In)}}{\text{Area(In)}} = \frac{\text{Force(Out)}}{\text{Area(Out)}}$$

$$\text{So } \text{Force(Out)} = \text{Force(In)} \times \frac{\text{Area(Out)}}{\text{Area(In)}}$$

Using our previous example, we apply 60pounds (27Kg) of input force to the brake pedal. This is attached to a master piston which (for example) is 1.25cm across - ie. it has a surface area of 0.000491m^2 (remember your maths? $\text{area} = \text{PI} \times r^2$). At the other end of the system is the caliper piston, which for example is 2cm across - ie. it has a surface area of 0.001257m^2 . Using our sparkly new formula, the output force from the caliper piston is $60 \times (0.001257\text{m}^2 / 0.000491\text{m}^2)$ Get your calculator out and that comes out to 154pounds (69.8Kg) - more than double the force at the brake pedal. The ratio of output area to input area is sometimes referred to as the area differential.

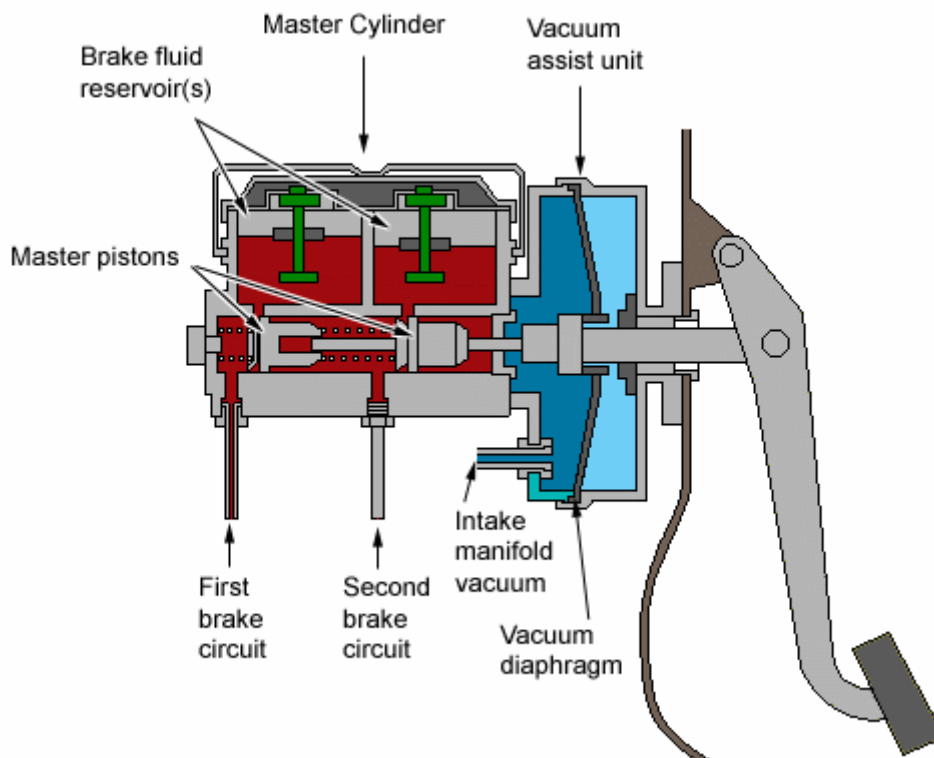
So that, my friend, is why you can stop a speeding vehicle with a single foot.

Power Brakes and master cylinders.

Power brakes (also known as power assisted brakes) are designed to use the power of the engine and/or battery to enhance your braking power. Whilst you can generate a fair amount of force using your foot, using systems from elsewhere in the car to help you apply even more force means that you get more powerful brakes as a result.

The four most common types of power brakes are: vacuum suspended; air suspended; hydraulic booster, and electrohydraulic booster. Most cars use vacuum suspended units (vacuum boosters). In this type of system, when you press the brake pedal, the push rod to the master cylinder opens a vacuum control valve. This allows vacuum pressure (normally from the intake manifold) to "suck" on a diaphragm inside the vacuum assist unit. This extra vacuum suction helps you to produce more force at the pedal end of the brake system.

You'll notice in the image below (which I scurrilously had to modify from someone else's site - if that's you, I apologise), that the master cylinder has two brake circuits and two master pistons. These circuits are separate and are typically connected to the front-left and rear-right wheel on the first circuit, and the front-right and rear-left wheels on the secondary circuit. This means that if one circuit fails, the second one will still work and it will still apply braking force to the front and rear of the car.



Hydraulic booster systems usually utilise pressure from the power steering system to augment pressure on the master brake cylinder.

Electrohydraulic booster systems use an electric motor to pressurize the hydraulic system downwind of the brake pedal which has the effect of amplifying the internal pressure in the whole system. The advantage to this system is that as long as you have battery power, you have power brakes even if the engine fails. With vacuum-assist brakes, no engine means no assistance.

If you're curious about how power brakes work, go out to your car and with the engine off, step on the brakes. They'll have a slightly solid, almost wooden feel to them. Turn the engine on and do it again and you'll notice a lot less back-pressure on the pedal. This is the power assist which is making it easier for you to depress the pedal.

One last thing about brake master cylinders : they cost an absolute bomb to replace. If you find yours is leaking, patching it up is not an option. Brand new master cylinders can go for around \$1500 without labour costs. Remanufactured ones come in slightly cheaper at around \$900. Bear that in mind when your 20 year old beater develops a leak - it's probably cheaper to buy another used car than to replace the master cylinder.

A word about handbrakes.

It's worth spending a moment here to talk about handbrakes. Or parking brakes, e-brakes or emergency brakes depending on where you come from. Whilst they're good for doing handbrake turns, they're not especially effective

at actually slowing you down. They will - don't get me wrong - but you won't be seeing any stellar performance out of them so the term 'emergency brake' is a bit of a misnomer. So why is this? Well, handbrakes are cable-actuated for a start so the amount of power they have is wholly dependent on the amount of tug you have in your arm. There's no hydraulic system to help you out. Apart from that, they only work on the rear wheels, so you're not getting four-wheel braking. On drum-brakes, the handbrake is connected to a small lever that pivots against the end of one of the brake actuating pistons. When you pull the handbrake, the lever gets pulled and the brake shoes are pressed out against the inside of the drum.

On disc brakes, the handbrake *normally* works a second set of brake pads in the rear caliper. They're little spots, about the size of a grown man's thumbprint and they're clamped mechanically against the brake rotor. These pads never need changing because they're normally only used at standstill so generally don't wear much. Their small size is the other reason you shouldn't expect stellar stopping performance if you yank on the handbrake. That being said, there are derivatives of disc-based handbrakes that use a mechanical arm to press the main brake pads against the rotor although these are less common as far as I know.

When to use handbrakes

Typically you ought to use your handbrake whenever you're stopped somewhere, be it parked, on a hill or waiting at traffic lights. The reason is simple : if you're parked or stopped, you generally don't want the car to run off without you. At traffic lights, it's an accident minimisation function as much as anything. If you're sitting there with your foot on the brake and someone drives into the back of you, the impact will cause you to take your foot off the brake and you'll go sailing into the car in front, causing more accidents. If you have the handbrake on in the same scenario, your car will largely stay put (apart from the initial shove across the ground as the energy from the impact is dissipated through your tyres). Of course there are personal habits and mechanical complications to contend with here. For example in a car with an automatic gearbox, it's force of habit to just use the footbrake. Even so, you should still use the handbrake when you're parked, especially on an incline. The 'park' setting on automatic gearboxes isn't sufficient to hold a car on a hill, and apart from that, it puts incredible strain on the transmission and clutch system if you let the whole weight of the car transfer into the transmission to try to keep it from moving. In some American cars, the handbrake isn't a handbrake at all, it's a second footbrake on the far left side of the footwell, which is basically totally useless because it's a pain to put on and even more of a pain to get off because it's a one-way ratchet system (you have to force the pedal all the way down to get it to release). Then there's the ignorance factor. When I went to my new owners orientation evening after buying a Subaru in America, one lady asked what the parking brake was for. (Apparently the name wasn't obvious enough). The dealer representative told her it was a relic of days gone by, not to be used, and he didn't understand why manufacturers even put them in cars any more!

When not to use handbrakes

The first and most obvious answer to this is : when you're going at any speed. If you yank on the handbrake at any speed much over 30km/h, the

back end of your car will start to slide. Great for stunts and tricks, not so great if you're trying to stop in 5 lanes of crowded motorway traffic. The other time you should not use your handbrake is in post-snow, freezing conditions. With the salt and grit that gets put down on the roads, you'll be driving through a salty, snowy slush and it will be spraying all over the underside of your car. If you park and put the handbrake on, you risk it binding on by freezing. Why? Well handbrake cables are almost always exposed to the elements at some point under your car. If you put the handbrake on and the cable is covered in slush, as it freezes again it will lock the handbrake on. There's no solution to this other than waiting for the weather to warm up. Well, not unless you fancy a crack at the Darwin Awards, because some people have tried using blowtorches to thaw the ice, not understanding that they were working right underneath the petrol tank. So here's a tip : don't.

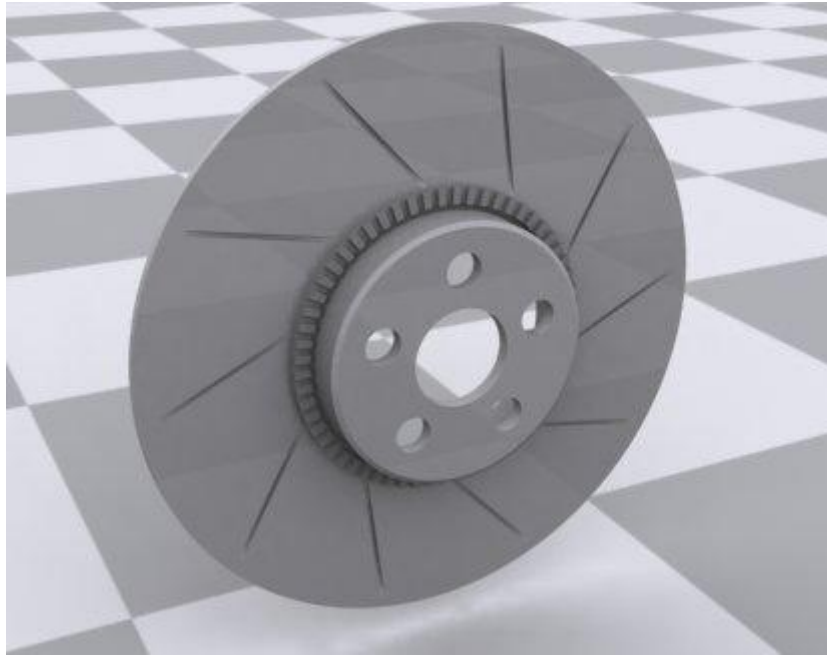
If you need to park in those types of conditions, try to find level ground and leave your automatic gearbox in "p" or your manual gearbox either in first or reverse gears.

Regional variations

One last thing to know about handbrakes : for some reason, from-the-factory settings on handbrakes vary largely with region. In Europe for example, the handbrake is easily capable of exerting enough friction to prevent the engine from being able to move the car from standstill. In America, it's not uncommon to see handbrakes adjusted to lightly that even when fully on, you can just drive off. The only way you'll notice is the handbrake light on the dash, the lack of performance, or the smell of burning as your rear brakes burn off.

Anti lock Braking Systems - ABS

Stop without skidding, and maintain control of the vehicle. That's the premise of ABS. It was first introduced in the 1980's and has been undergoing constant refinement ever since. The system is typically comprised of 4 ABS rings, 4 sensors, an ABS computer and a pressure-management system in the brake line. The ABS rings are attached either to the wheels, or more often, to the brake discs. They look like a notched ring - see the image below.



The sensors are magnetic field sensors which are held very close to the ABS rings and can detect the slight change in magnetic field as the teeth on the ring pass them. The pulsing field tells the ABS computer that the wheels are spinning, and how fast they're spinning. When you brake, the wheel rotation starts to slow down. The ABS computer "listens" to the input from the sensors and can detect if one wheel is slowing down much quicker than the others - the precursor to the wheel locking up. This all happens in milliseconds, by the way. When the computer detects this condition, the pressure regulator interrupts the pressure in the brake lines by momentarily reducing the pressure so that the brakes give the wheels a chance to keep spinning rather than locking up. The computer then instructs the regulator to re-apply full pressure and again measures the wheel rotation. This on/off/measure cycle happens around 15 to 30 times a second. If the ABS kicks in, you'll feel it through the brake pedal as a vibration because the pulsing in the brake circuit affects all the components.

Newer generation ABS systems

As technology marches on, so does the control / feedback system used in ABS. It used to be the case that any single wheel approaching lockup would cause the ABS system to pulse the brake pressure for all the wheels. With the latest vehicles, the ABS computer is connected to 4 pressure regulators instead of just the one. This means it can selectively apply pulsed braking only to the wheel(s) that need it. So if three of the tyres are gripping well, but the front-left is beginning to skid, the ABS can unlock the front-left brake and pulse it to try to regain grip. It's all very James Bond.

ABS and skid control

The biggest misconception about ABS is that it will make you stop faster. This is absolutely not true. ABS has nothing to do with stopping *power* and everything to do with stopping *distance* and maintaining control of your vehicle, be it a car, truck or motorbike. The problem with skidding whilst braking is that it removes you from ultimate control of where the vehicle is going. On a motorbike, skidding invariably causes highsides, flips and general

thoughts of "huh?" to the rider as he's flying through the air towards certain pain. In a car or truck, skidding stops the vehicle from going where you want it to, and instead makes it straight-line based on the camber of the road, the speed of the vehicle and how much damage it can do to your insurance policy. Skidding is caused because the wheels lock up. Once they stop rotating, the tyres can no longer grip the road surface and instead begin to skate across it. When that happens, it really makes no difference where the steering is pointing because without grip, steering is useless. As tyres skid, they become subject to dynamic attrition. In other words, if a tyre is rotating and gripping the road, the "stick" factor is much higher than if the wheel is locked and skating across the same surface. With ABS, the idea is that the wheels don't ever lock up, so you they keep turning, the tyres keep gripping. Whilst gripping, you have directional control over the car, so your steering still works, and you are slowing down quicker because the brakes are doing their job.

That's where ABS gets its name - Anti-Lock Brakes.

The bone of contention with ABS

So many people think ABS gives them a license to drive faster, because they mistakenly believe that ABS will get them out of any situation. It's yet another technical placebo that has been put into vehicles which is making the standard of driving worse. The more gadgets and "driver aids" that get put into a car, the worse the drivers become because they live in a pink-spectacled world where they believe that the car will get them out of any problem they cause. It bothers me so much I have a "rant" page dedicated to it [here](#) : [Nanny Cars](#).

Personally I don't like ABS. I don't like the idea of a computer interrupting the connection between my right foot and the brakes. It also doesn't work worth a damn on gravel or in the snow. With regular brakes, in the snow, you can jam them on and at least stand a chance of the tyres digging in and finding the road surface. Okay so I told you above that skidding tyres are worse than tyres that are gripping, but on snow, all the rules change. Skidding tyres digging down and finding the road surface are w-a-y better than rotating tyres on top of the snow; with ABS the system will do just that - take the brakes off and you'll carry on merrily along on the snow with no chance of slowing down.

The hidden gremlin of ABS - what they don't advertise.

If you look at the statistics for crashes, a large percentage of them are "fender benders" - low-speed impacts that only do a little damage and so slow that the vehicle occupants are in no danger. Less than 15mph normally. I'll give you one guess what the typical "minimum activation speed" is for ABS. That's right. Your average ABS system is useless much below 15mph. Seriously. Try it yourself. Find an empty road on a slight downhill grade - even better if its on a dewy morning. Run your ABS-equipped car up to about 15mph and jam on the brakes as hard as you can. The car will skid to a stop and the ABS system will remain totally silent.

Aftermarket ABS systems

To the best of my knowledge, there's no such thing. A few years back a couple of companies tried to market what they called ABS systems that could be retrofitted to any vehicle. The product was a cylinder with a pressure-relief

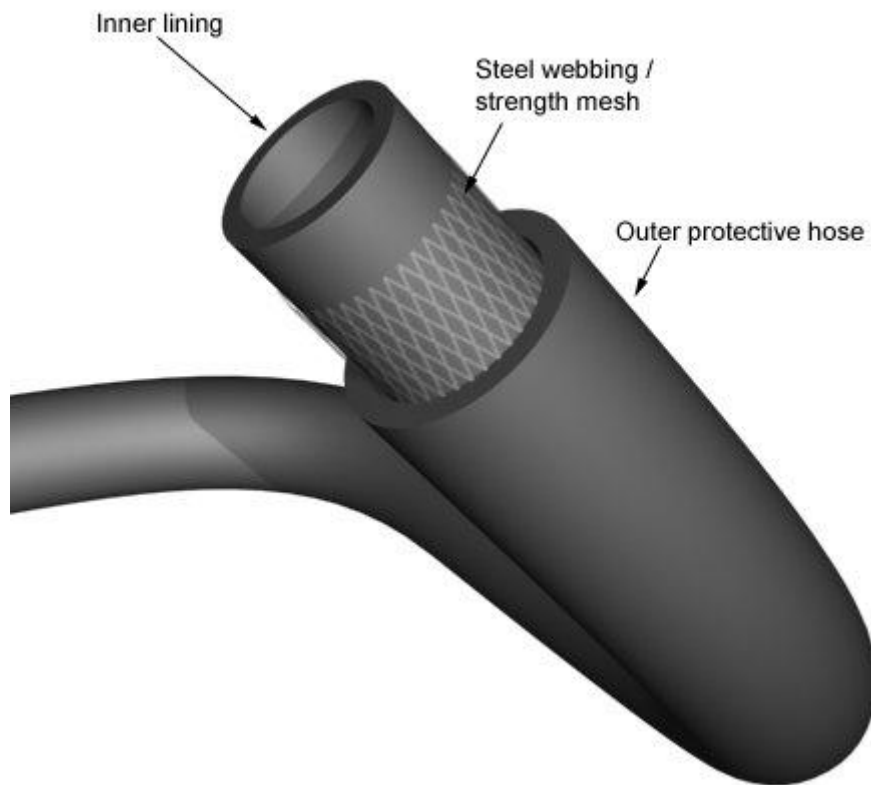
valve in it. The idea was that you inserted this system into the brake circuit somewhere. When you stomped on the brakes - symptomatic of locking up the wheels - the pressure relief valve opened and bled off some brake fluid into the cylinder, thus lowering the braking pressure being sent to the wheels. The idea was to take the "spike" off the initial push of the brake pedal so it wasn't ABS at all. The whole idea of putting something like this into a brake circuit makes me shudder - I wouldn't want to be the person trying to get their insurance and medical claims through after an accident when the investigators found one of these contraptions in their brake line!

Brake hoses - not just rubber.

Obviously with all the pressure in your brake system, the last thing you need is for the brake lines themselves to deform and flex. If they do, you lose brake pressure, and thus lose braking. Steel brake lines are no problem, but for the flexible areas of the brake lines, you need hoses. Brake hoses come in two basic flavours.

Rubber hoses.

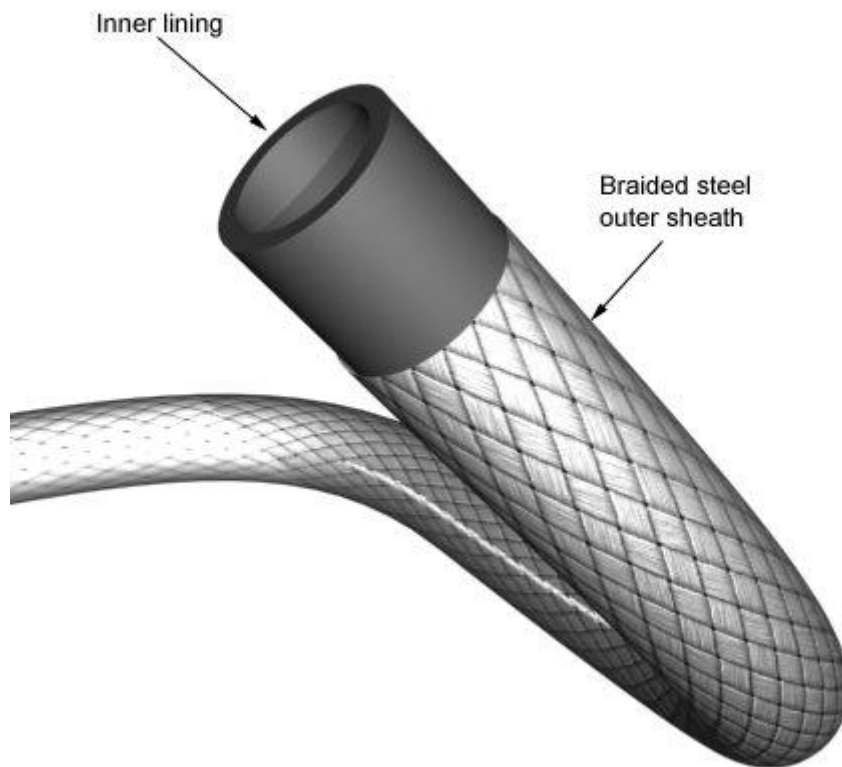
Ah the humble rubber hose. Only on your brake lines, not so humble. I don't recommend this but if you were to get under your car and cut one of your hoses in half, you'd notice a couple of things. First, it's amazing how quick all the brake fluid that spills out will stain your clothes and literally eat the paint off your car right in front of you. But second, and more importantly, the hose itself is actually made of three parts. The inner liner is a corrosion and brake-fluid resistant compound designed (normally PTFE / Teflon® based) purely to keep the brake fluid in. Around the outside of that, there's a steel webbed mesh. This is what gives the brake hose its strength and stops it from bulging and deforming. And around the outside of that there's a slightly thicker rubber coating, which is there to weatherproof the steel mesh. The three layers together give strength, flexibility and durability.



Steel-braided hoses.

Steel-braided hoses are a slightly different design. They only really have two components - the inner hose which carries the brake fluid and is lined with a PTFE compound, and the outer steel braid which contains and flexing or bulging. Steel-braided lines resist bulging a lot better which is why a lot of aftermarket tuners opt to put them on their vehicles. One downside is that the steel braiding itself is totally merciless and if it finds something to rub against in the vehicle, it will rub right through it, even if it's an alloy. For that reason, a lot of braided brake hose manufacturers put a third layer - a thin transparent rubber sheath around the outside simply to keep everything in check and prevent scuffing and rubbing.

I upgraded the lines on my Audi when I still owned it and put Goodridge steel braided hoses on. For a 15 year old car it did make a difference to the feel of the brake pedal. It didn't bring it up to modern standards, but it was better than the flexible, bendy rubber hoses that were on it from the factory.



Brake fluids.



As mentioned elsewhere on the page, brake fluid does not compress. It's a good job too - if you put your foot on the brake pedal and it went all the way to the floor, you'd be worried. But that's exactly what can happen if you disregard the "health" of your brake fluid. Brake fluid is hygroscopic - that means it attracts and soaks up water. This is why it comes in sealed containers when you buy it, and why when the crazy guy four doors down offers you some of the 15 gallons of brake fluid he's had in his garage since the war, you should turn him down. The problem with it being hygroscopic is that if it does start to take on water, Bad Things can happen. Pull up a chair and allow me to explain.

Your typical DOT 4 brake fluid (see later for DOT ratings) boils at about 446°F (230°C). Water boils at 212°F (100°C). Imagine your brakes are getting hot

because of a long downhill stretch. Whilst the brake fluid is quite OK, the temperature of the brake components might get up over the boiling point of water. If that happens, the water boils out of the brake fluid and forms steam - a compressible gas. Next time you put your foot on the brake, rather than braking, all the pressure in the brake system is taken up with compressing the steam. Your brakes go out, you don't stop. Getting a little more complex, the boiling point of a liquid goes up with its pressure (Physics 101). So when you step on the brake, the boiling point of the brake fluid might actually go up to 500°F (260°C) and the boiling point of the water content might raise up to 250°F (121°C). This is great, you might think, because now the boiling point is higher than the temperature of the brake fluid. At least it is until you take your foot off the brake again. Now the pressure in the system returns to normal, the boiling points revert to normal and instantly the water boils off into steam again. The symptoms are slightly different now. Under this scenario, the brakes work the first one or two times, but on the third or fourth press, they stop working because now the temperature and pressures have conspired to boil the water. The worst possible scenario is brake-fade (see right at the top) combined with air in the system. If this has happened to you, then you're likely reading this page from beyond the grave, because in most accidents where weak brakes become no brakes, there aren't any survivors.

D.O.T ratings

All brake fluids are DOT rated. Your owners handbook for your car or motorbike probably tells you to use DOT3 or DOT4 from a sealed container. The DOT ratings are a set of *minimum* standards the fluid must adhere to in order to get the rating, and thus work in your braking system. The following table shows the various properties of DOT ratings. Remember that the values here are the minimum values. Most manufacturers make sure their product far exceeds minimum ratings.

Boiling Point	DOT 3	DOT 4	DOT 5 (silicone-based)	DOT 5.1 (non-silicone based)
Dry	401°F	446°F	500°F	500°F
Wet	284°F	311°F	365°F	365°F

The "dry" and "wet" boiling points in the table above are for brake fluid which is fresh from the bottle (dry) and which has a 10% water content (wet). A DOT study in 2000 discovered that on average, the brake fluid in a vehicle absorbs about 2% water every 12 months.

The two types of brake fluids shown in the table are DOT3/DOT4/DOT5.1 which are glycol (Polyalkylene Glycol Ether) based, and DOT5 which is silicone based. DOT3 and DOT4 fluids are interchangeable* - the only real difference is their boiling point. Theoretically you could interchange DOT4 and DOT5.1 fluids too but I wouldn't recommend it. DOT3/4/5.1 and DOT5 fluids cannot be mixed or interchanged under any circumstances. They mix like oil and water (ie. they don't) and the silicon based fluids can destroy the seals in brake systems which rely on the moisturiser additives that are present in DOT3/4/5.1 fluids.

Other things you ought to know about silicone based fluids:
 - they are resistant to absorbing water, which is why their wet boiling points

are so high. Problem is that any water content eventually pools in the low spots of the brake system and causes rust.

- they don't strip paint.

- they are not compatible with most ABS system because they doesn't lubricate the ABS pump like a glycol based fluid.
- putting this fluid in systems which have had DOT3/4 fluid in will cause the seals in the caliper and master cylinders to malfunction. Which means they need replacing. Which is expensive.

Oh, and don't ask me why DOT5.1 is glycol and DOT5 is silicon based. It doesn't make and sense to me either.

* There has been some discussion as to the use of DOT4 fluid in Toyotas that recommend DOT3 fluid - apparently something in the Toyota braking system doesn't play well with DOT4 fluid, particularly the master brake cylinder seals. The discussion about this can be found in the archives at [the UK Pruis yahoo group](#).

Brake warning lights



Most cars nowadays have a brake warning light on the dash. Its purpose is to alert you that something is wrong in the braking system somewhere. If it comes on, check your owner's manual to find out its meaning. Unlike the single-purpose ABS warning light, the brake warning light doesn't have a standard meaning; it could be used for multiple purposes. For example, the same light may be used to show that the hand brake (parking brake for the Americans amongst you) is on. If that's the case and you're driving, you ought to have noticed the smell of burning brake dust by now. The light can also indicate that the fluid in the master cylinder is low. Each manufacturer has a different use and standard for this light. Which is nice. Because it would be such a drag if the same indicator meant the same thing in every vehicle.



If you've got an ABS-equipped car, you also have a second light - the ABS light. If it comes on, get it seen to as soon as possible. It means the ABS computer has diagnosed that something is amiss in the system. It could be something as simple as dirt in one of the sensors, or something as costly as an entire ABS unit replacement. Either way, if that light is on, then you, my friend, have got 1970's brakes. It's important to note that this light normally comes on when you start the car and then switches off a few seconds later. If it stays on, blinks, throbs, flashes or in any other way draws your attention to itself, take note. It's not doing it just to please itself.



If you see this light on your dashboard, then congratulations - you're flying the service module on an Apollo mission. The bad news is that you've got a current drain somewhere and your main batteries are critically low. Either way, drop me a line and let me know how you snagged a seat on a spaceflight - I'm dying to know.

And finally....LED replacement bulbs



You might have seen websites and automotive shops stocking LED replacement bulbs for cars and motorbikes. Basically its a cluster of 19 or 24 LEDS (light emitting diodes) in a housing with a regular push-fit or bayonet plug on the back. The idea is that if you want brighter lights, you can replace your tail or turn lights with these LED replacements. There is a gotcha though that the manufacturers often hide in the smallest of small print. A lot

of cars nowadays have onboard diagnostics which include a light check. Some of these use resistance to figure out if a bulb has blown. LED clusters have a radically different resistance to a filament bulb and its possible that when you replace your bulbs with LED versions, your car will continuously tell you that one or more bulbs is burned out. Getting one step more severe, if you use LED turn bulbs, your indicators could flash quicker or slower than you're used to. And the worst case scenario - some motorbikes have very tightly regulated voltages in their ABS systems and taking the filament bulb out of the brake light to replace it with an LED bulb can cause ABS errors and theoretically, an ABS shutdown. Granted thats worst-case scenario, but it is a possibility. So now you know.