How real electric motors work

John Storey

Note: These pages are intended to be read in conjunction with Joe's "Electric motors and generators" pages of the HSC Physics resources (/%7Ejw/HSCmotors.html). Read those pages first. Once you've got the basic idea and understand the physical principles and the maths, you're ready to explore how real-life engineers have put physics into action to make our lives easier.

When it comes down to it, all these motor are using the same basic principle. In some cases, it's easiest to think in terms of the force on a current-carrying wire in a static magnetic field. In other cases it's easiest to think about two magnets (at least one of which is an electromagnet) attempting to align their poles north-to-south and south-to-north. However, both these explanations amount to the same thing, as James Clerk Maxwell so elegantly described with his four equations that form the basis of electromagnetism.

If you're tempted to pull a motor apart yourself, please think carefully about the risks involved before reaching for the tool kit. Some of the more important risks (URL) are listed at the end of this article.

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You can download this entire document as a 5.4 MB PDF file here (URL), or read individual sections by following the links.

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Web pages designed by George Hatsidimitris

Last update: 9 September 2005

1. Induction motors

No modern home should be without one – or maybe a dozen. You'll find an induction motor in the fan, fridge, vacuum cleaner, washing machine, dishwasher, clothes drier, and the little pump that circulates water in the fish tank to stop the water turning green and the fish going belly-up. Chances are there's also one in the air conditioner – unless it's a particularly high-tech one.

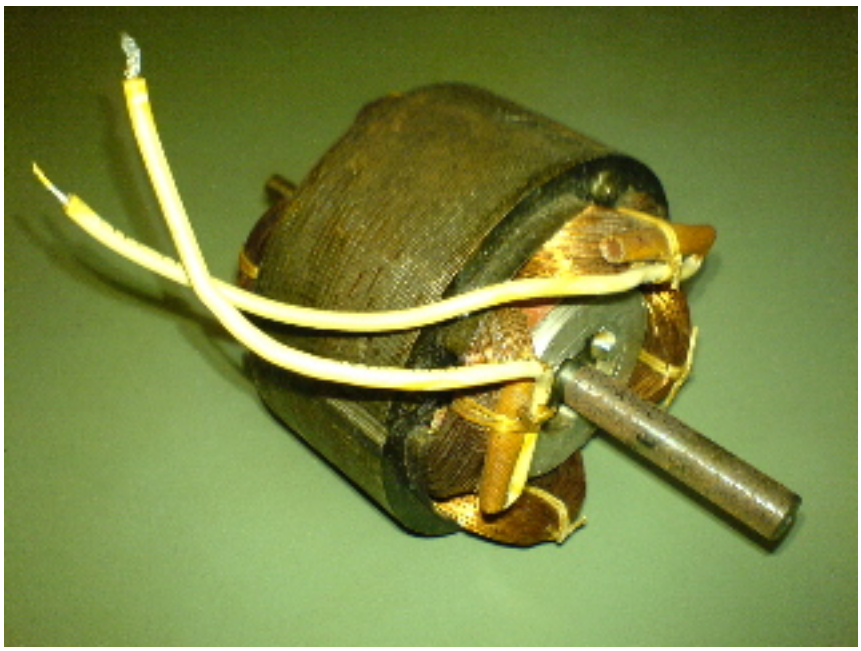
Advantages:

- Cheap
- Quiet
- Long lasting
- Creates no interference

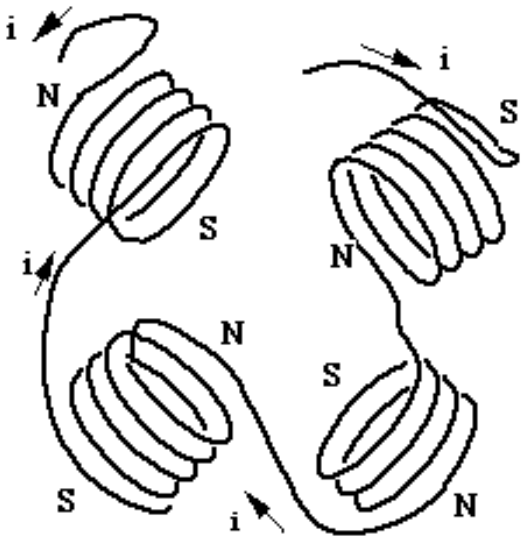
Disadvantages:

- Wants to turn at constant speed (50Hz divided by half the number of poles)
- Cannot turn faster than 1500rpm (4-pole motor)
- Draws a massive starting current, or is inefficient, or both
- Kind of big and bulky for the power it develops

This one came out of a fan.



Actually, the bearings and end-caps of the motor have already been removed. (In retrospect, I should have used something more delicate than an axe to disassemble the fan.) We can pull the rotor out and this is what we're left with. There are four windings, and they are all simply in series.

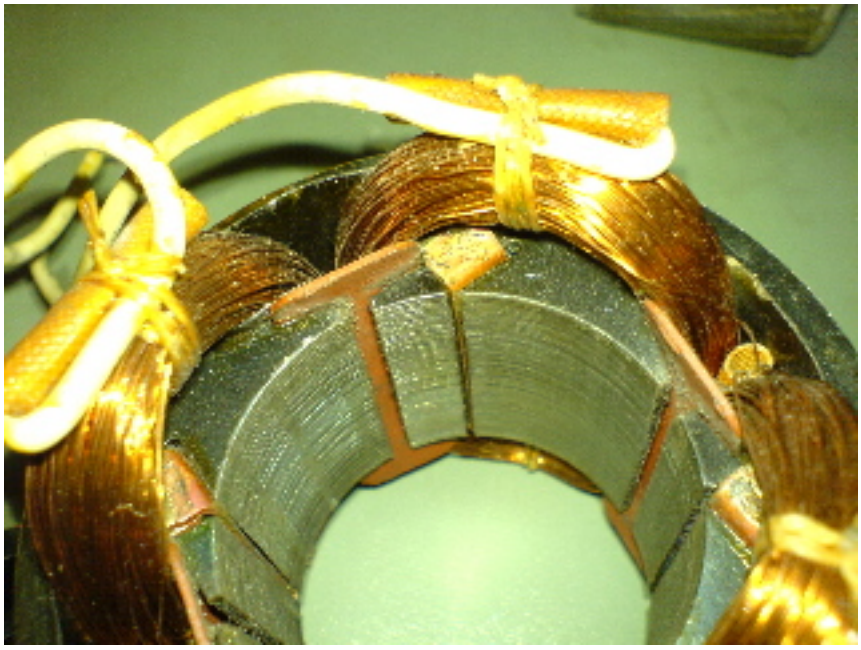




Well, not quite simply – the current comes in the white wire, then the first winding (top right) is clockwise, the next one (bottom right) is anticlockwise, bottom left is clockwise again, top left is anticlockwise, then out the other white wire. So, imagine a positive half-cycle of the mains, with the current actually coming in that first wire. The first winding produces a north pole facing in; the second a south pole facing in; etc, like this: N-S-N-S.

Half a mains cycle later (10 ms) the current has reversed and so must the magnetic sense of the poles, which are now: S-N-S-N. The rotor is an electrical conductor, and therefore tries to follow this field. To do so it has to rotate through 90 degrees. The rotor thus takes two full cycles of the mains (40 ms) to make a complete rotation, and so revolves at 1500 rpm. At least, it would if it could keep up with the rotating field. But it can't, quite, and in fact it's only because it's slipping behind that any torque is developed at all. So, it rotates a bit slower than 1500 rpm (typically 1440 rpm) depending on how much torque it is being called upon to produce.

Note that the motor, as described so far, could rotate happily clockwise or anticlockwise. This kind of motor therefore needs some kind of internal cleverness to ensure it only turns in the right direction. This is achieved, in this motor, by the use of *shaded poles*.



Notice the winding at the top of the picture. See how there is a small additional pole (or set of iron laminations) off to the left of the main pole. It's excited by the same winding as the main pole, but is "shaded" from it by a thick copper and that wraps around the laminations and acts like a shorted electrical turn. The current induced in this band by the magnetic field generates a phase shift so that the shaded pole can generate a small component of magnetic field at right angles to the main field, and with the correct phase to ensure the fan turns the right way (otherwise the fan would suck instead of blowing).

So in fact our induction motor is using induction already, and we haven't even got to the rotor yet!

Now we look at the rotor. This is a real disappointment – it looks nothing like the "squirrel cage" in the text book! Where's the squirrel supposed to go, for starters?



What's happened here is that the rotor is actually made up of a stack of disc-shaped laminations of soft iron. That's right – it's solid. This concentrates the magnetic field (generated by the windings) into the region where it will do the most good (the conducting bars of the rotor).

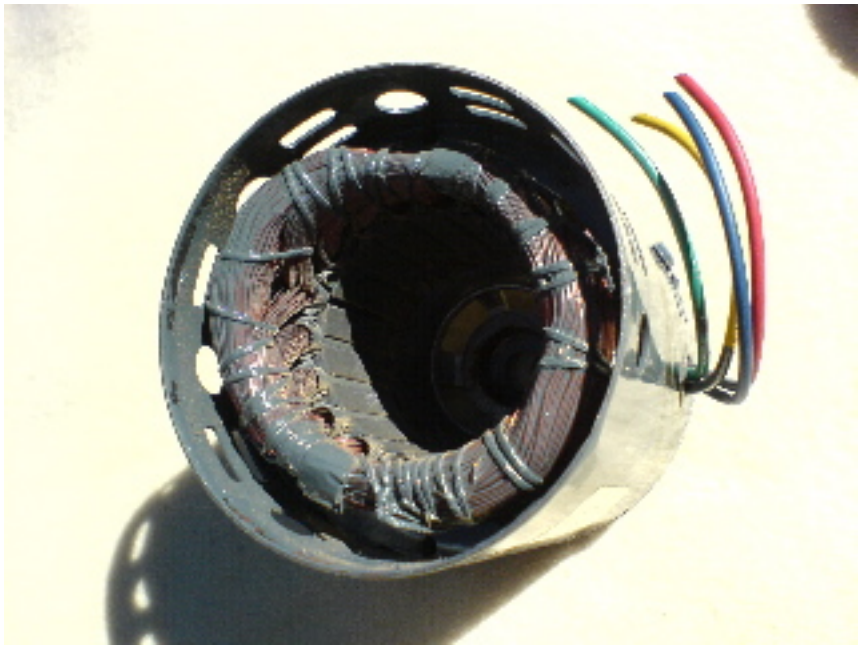
You can actually see the edges of the bars that run along the axis of the rotor, but they're at an angle of maybe 30 degrees to the shaft. What's going on here? Bad day at the factory? Chances are it's been designed that way to reduce *cogging torque*. If the bars ran parallel to the axis, the torque would rise and fall as each bar passed under the windings. By slanting the bars, the torque is kept more uniform as the rotor turns.

Now let's look at a different type of induction motor.



This induction motor came out of an astronomical telescope. It was part of the photographic film transport, and needed to be able to turn both forwards and backwards. It therefore has two separate windings, and four wires coming out. One winding is fed directly from the mains (or *"line"* as our US colleagues call it); the other is fed through a capacitor that provides the necessary 90 degree phase shift. Swap the windings over, or reverse the connections to one of the windings, and the motor goes the other way.

No surprises when we take it apart, although note a very different winding pattern to the previous motor. It has more poles, and therefore turns slower.



Once again, the rotor is solid, and we can't see what's inside. The aluminium plate at the end of the rotor has been stamped and turned up into a series of small fins to make a crude cooling fan. (This wasn’t necessary with our first motor – it kept itself cool by the simple expedient of placing itself in the middle of, well, a fan.)



Since astronomical telescopes no longer use film, we may as well cut the rotor in half and see if there's a squirrel in there.



No squirrel, but a magnificent set of aluminium conducting bars, just like in the text books. If you think of the rotor bars as forming (via the end rings) a single-turn secondary winding of a transformer, the primary of which (the windings on each pole) has some 50 ~ 100 turns, it is clear that the current through the rotor bars can be very high – as much as 100 amps for a 240 watt motor. This explains the need for really chunky bars!

One disadvantage of the shaded pole motor is that the *starting torque* is rather low. This doesn't matter for something like a fan, where the load when stationary is almost zero. For other applications, like a washing machine, it would be a disaster. Such motors therefore use a capacitor to generate the required phase shift for the quadrature windings, as in this example.

Induction motors also come in other variations, but the two described above are the most common in domestic use.

For serious grunt, however, you need a *three-phase* induction motor. This takes advantage of the fact that commercial 3-phase power is delivered by three conductors, each of which carries a 50 Hz sine wave with 120 degrees of phase shift relative to the other two [See <a href="http://www.phys.unsw.edu.au/~jw/power.html"3 phase power]. A 3-phase motor simply places three windings at 120 degree intervals around the casing, and a rotating magnetic field is automatically produced. Three-phase induction motors are the "workhorse" of industry, with large units having ratings well in excess of a megawatt.

Sydney's new Millenium trains use 3-phase induction motors, each rated at 226 kW, breaking away from the traditional DC motors used on Tangara trains and earlier models. However, since the overhead power to the train is 1500 volts DC, each Millenium train must use an *inverter* to create the three AC phases to feed to its motors.

2. "Universal" motors

No home should be without a dozen or so of these as well. They'll be where you want something compact that spins fast (food processor, coffee grinder, electric nose-hair trimmer) or needs variable speed (sewing machine, hand-held electric drill).

Advantages:

- Will turn at any speed you want it to, including really fast
- A lot of power in a small package

Disadvantages

- Horrible
- Arcing brushes create radio interference, ozone, noise.

A universal motor has both a wound field (on the stator) and a wound armature (on the rotor). It cannot use a permanent magnet to create the stator field because it needs to reverse its magnetic polarity every half cycle of the mains. The voltage being fed to the commutator brushes is also changing polarity every half cycle, and in fact is simply in parallel with the field winding.

This one ran for 30 years in a sewing machine.



Note the brushes at the right hand end of the shaft. To look at, it's almost indistinguishable* from a DC motor. In fact, it will run quite happily on DC. However, unlike a permanent magnet motor, a universal motor will always turn in the same direction, regardless of which way round it's connected to the DC source. Knowing this simple fact can sometimes enable you to win bets involving small amounts of money.

This motor only has two poles, and so does not have a lot of starting torque. That's why you sometimes need to turn the big wheel on the end of the sewing machine to get it started.

*Somewhat astute readers will notice that, unlike a conventional DC motor, it has a laminated stator. Totally astute readers will also understand why.

3. Advanced AC motors

The compressor motor in an airconditioner is the thing that draws most of the current. Obviously it should be as efficient as possible, and it would be desirable to be able to run it at varying speeds depending on the required load. With its miserable efficiency and lack of enthusiasm for running at anything but one particular speed, a single-phase induction motor is a poor – if inexpensive – choice.

Many modern airconditioners therefore instead use "Inverter" technology. What this means is that they rectify the mains to create DC, then use an inverter, or *DC to AC converter*, to go back to AC again. However, the AC that is produced is no longer at 50Hz, but is at a variable frequency. Even if we just used a conventional induction motor now we'd be ahead, because we'll be driving it at the optimum frequency, and hence rotational speed, for the required load. However, we can go one better than this and use a *switched reluctance motor* (which has a rotor made from soft iron) or a *brushless DC motor* (which has a permanent-magnet rotor), and achieve even higher efficiencies. It is one of the strange perversities of life that we will now call this a DC motor, even though it's quite decidedly running off AC!

Advantages:

- Can be optimised for task
- Can be much more efficient
- Can run at variable speed
- Can last forever

Disadvantages:

- Expensive (relative to a simple induction motor)
- Requires complex drive electronics
- Takes longer to explain than simple motors



Look closely and you'll see the word *"inverter"* on the box.

(I don't yet have any good pictures of the insides of a switched reluctance motor, but I'm working on it…)

4. "Conventional" DC motors

There are plenty of these in the average household, lurking inside battery powered toys, the cassette player, cordless drill and electric toothbrush. Inside a car, everything from the cooling fan to the windscreen wipers will have a DC motor. In fact, a luxury car with electric headlight washers, electric seat adjustment and remote rear-vision mirrors has more electric motors than you can poke a stick at – an interesting competition is to simply to count them and see who can find the most!

Advantages:

- Reasonably inexpensive
- Easy to control
- Adaptable

Disadvantages:

- Brushes eventually wear out
- Brushes create electrical interference
- Brushes are bad

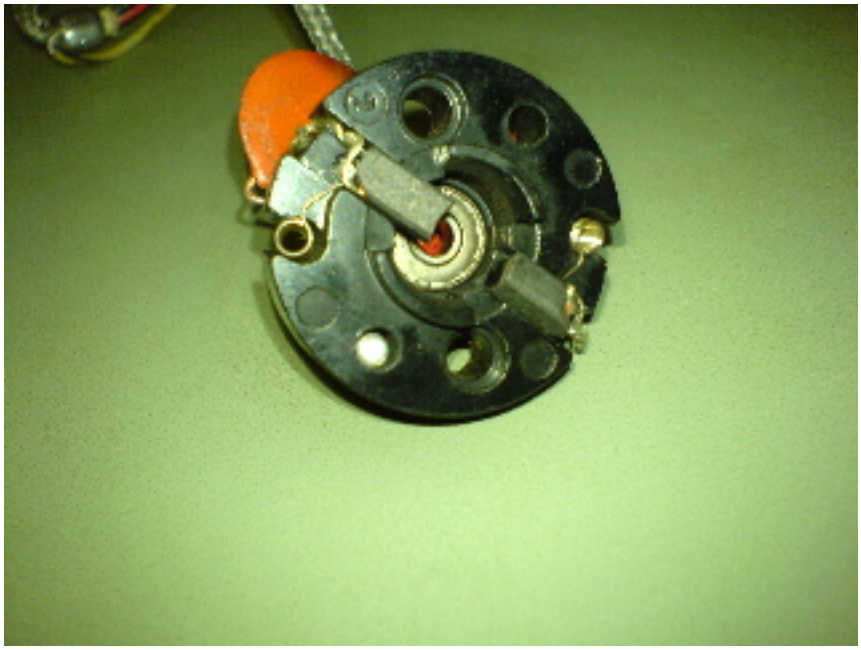
Most DC motors look something like this. This particular one is beautifully made and probably cost at lost of money.



However, that won't stop us taking it apart.



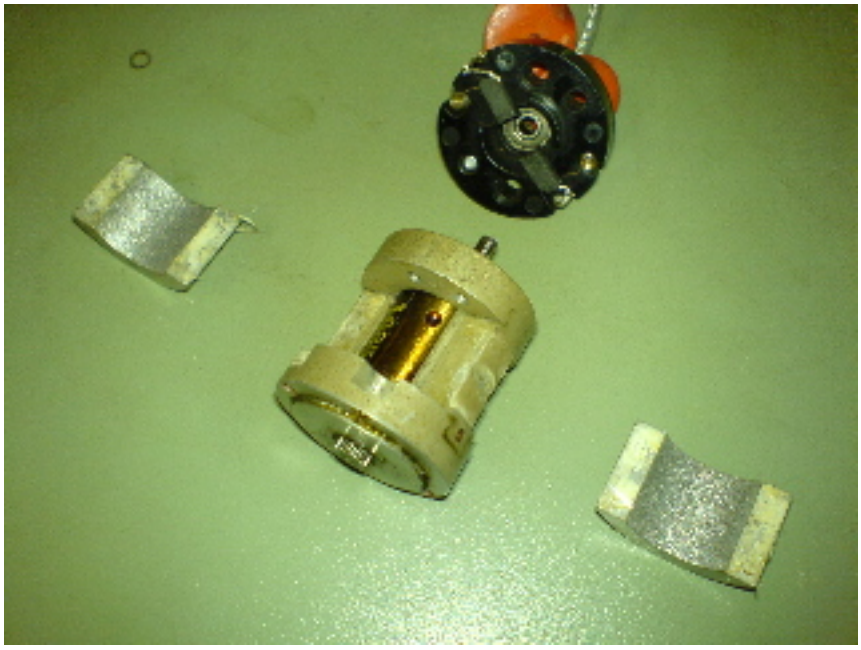
Starting at the left we have the end cap and the two carbon brushes that contact the commutator, then the rotor, the stator casing and its two C-shaped permanent magnets, the gearbox housing, a little gear-wheel that fell out of somewhere, and the gear-head and output shaft.



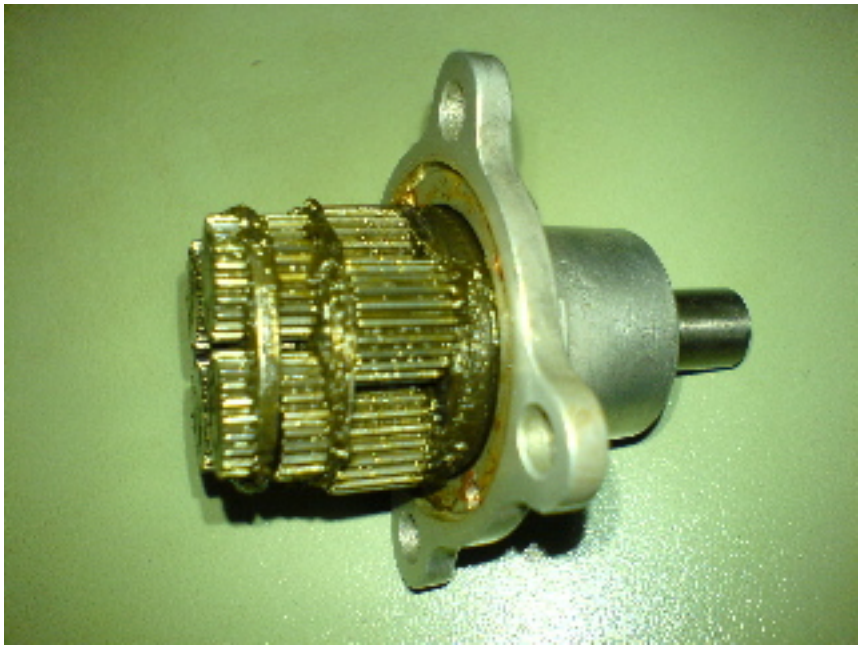
The two brushes are solid blocks of graphite, and are pressed against the commutator by the two small coil springs (situated slightly anticlockwise of the brushes). The orange disc is a capacitor that is directly across the power supply to the motor and helps to reduce radio interference caused by sparking where the brushes contact the commutator.



The rotor is very simple…



…and goes in an equally simple housing with two “C” shaped magnets. The housing is made of soft iron and creates the *magnetic poles* of the stator.



The best thing about this motor is the multi-stage planetary gearbox on the end!

5. Printed circuit motors

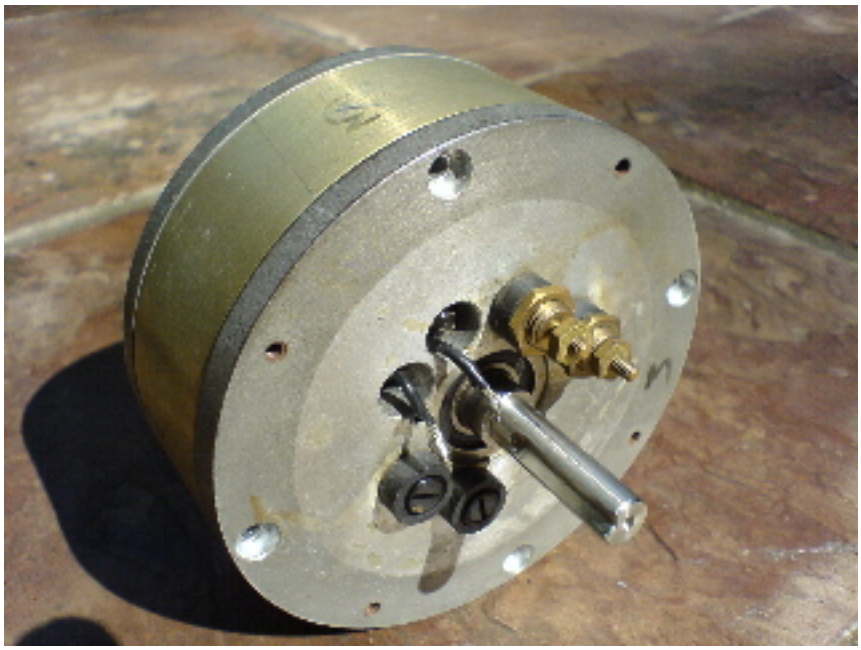
Sometimes called "pancake motors", these are a particular cunning motor configuration whose operation is in some ways is easier to visualise than that of a conventional motor. They fit into confined spaces (say inside a car door, to make the windows go up and down) and, because the rotor is light and has little rotational inertia, can accelerate to full speed and stop again very rapidly. This feature isn't so important for car windows (unless you're into drive-by shootings), but is essential for industrial robots and other servo mechanisms.

Advantages:

- Efficient – no hysteresis or "iron" loss
- Very low rotational inertia
- Light weight
- Flat, so fits into confined space.

Disadvantages:

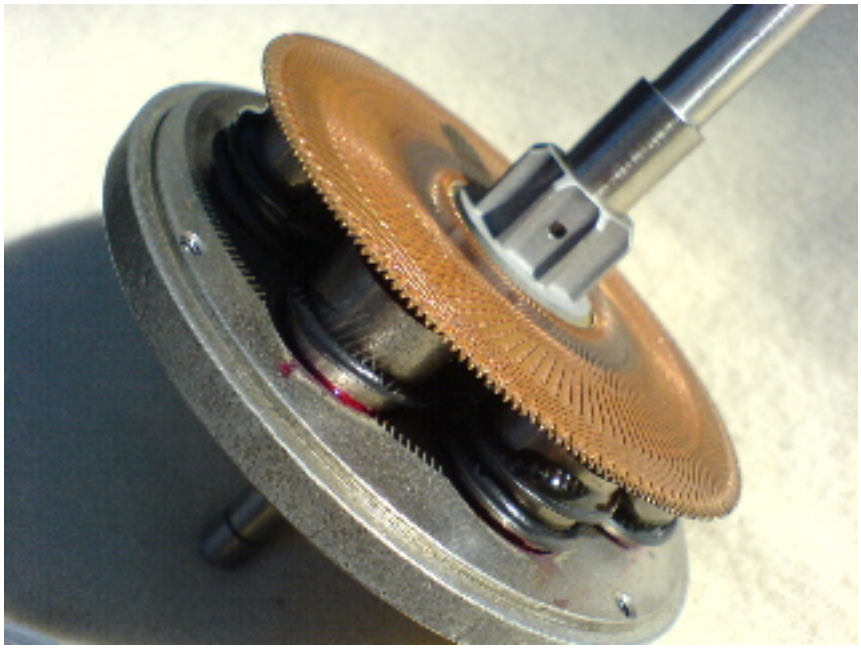
- Expensive to make
- Armature has little mass, and therefore can overheat quickly



This is what a typical printed circuit motor looks like. Don't worry about the two black wires for the moment.

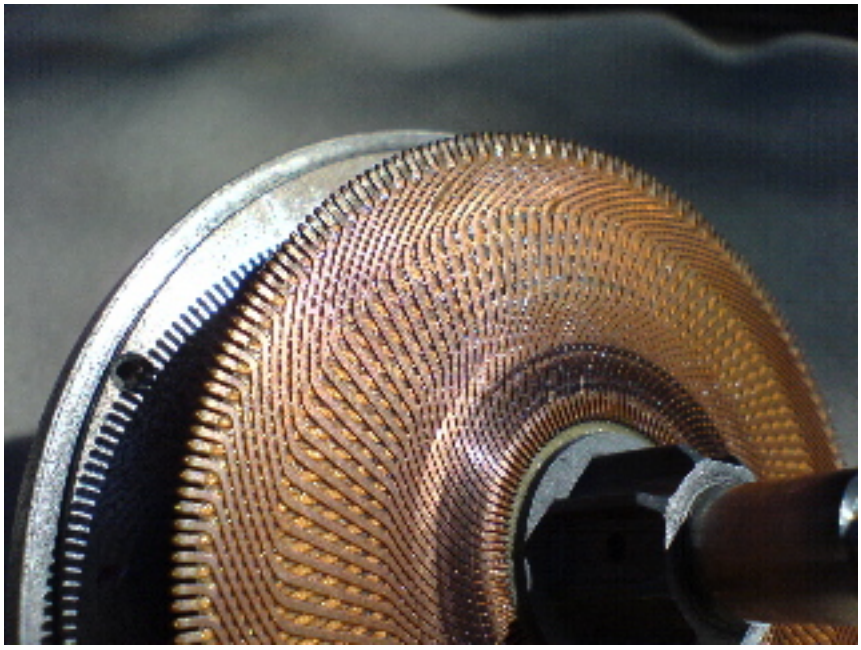


This is what's inside. Glued to each "face" of the motor are (in this case) eight magnets. Their poles alternate N-S-N-S etc as you go around.



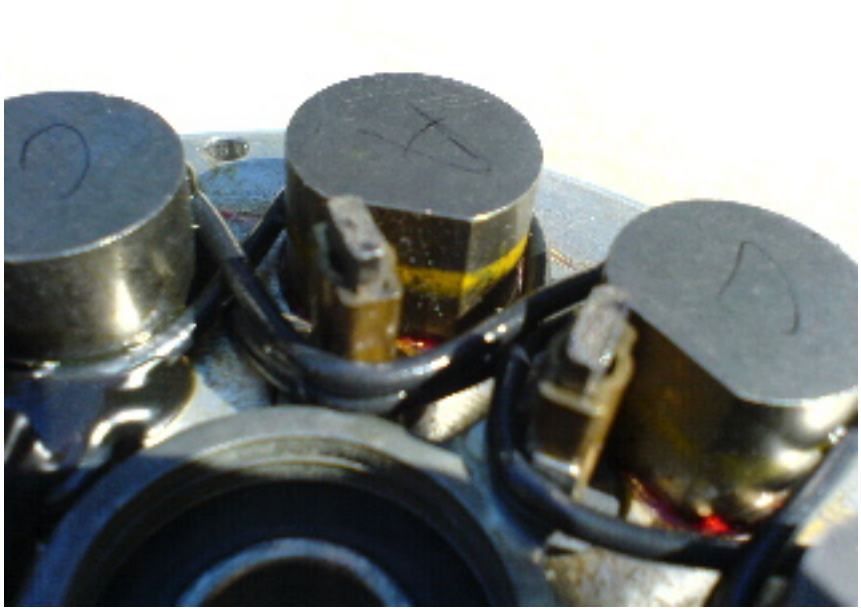
Here's the other face, with its eight magnets. These line up exactly (north to south) with the magnets on the other face, creating a strong magnetic field across the gap where the rotor sits. (Try not to think about that black wire for the moment.) So, now we've set up a strong magnetic field running *axially* (ie, parallel to the motor shaft). That field threads back and forth eight times through the small gap that will be occupied by the rotor when we put it all back together. (Note that the end faces are made of iron and complete the magnetic circuit.)

Now, if the magnetic field is parallel to the shaft, and we want a tangential force on the rotor, which way does the current have to be flowing? Well, it has to be at right angles to both, and therefore *radial.*



Now it should all make sense. The brushes contact the rotor on that blackened area near the shaft. The current goes out along the copper wire, and is travelling almost radially as it goes through the region of highest magnetic field. (*Almost* radial but not quite, to reduce cogging torque.) So, a force is exerted on the wire that is at right angles to the wire and at right angles to the magnetic field, causing the rotor to turn. Now, if the wire just turned around and came back in towards the shaft again, the force on the bit coming back would be equal and opposite to what it was going out, cancelling out any useful torque and the whole thing would just sit there with smoke pouring out of it. So, once the wire has gone out past the magnet, let's take it over diagonally to the right and bring it back in to the shaft past the *next* magnet which, you'll recall, has its magnetic field in the opposite orientation. Now the force on the returning piece of wire will *add* to the torque, and away we go.

Once back on the blackened piece of rotor the current can pass out through the second brush and back to the battery or whatever it is that's powering the robot.



Try not to think about the black wire for a moment. In this picture you can see the two brushes. They simply rub on the rotor which, as you saw, consists simply of a flat piece of insulator with copper lines etched or stamped on it, like a printed-circuit board. The other side of the brushes ends up as brass terminals on the outside of the motor, as in the first photo.

So there we have it. The only problem now is that the magnets themselves cannot retain their strongest permanent field unless they are always in a completed magnetic circuit. So, you can't magnetise them and *then* assemble the motor. But, once you've assembled the motor, you can't get at them to magnetise them. So, we can't actually build this kind of motor. Pity, really, it was looking rather promising.

But wait a moment! Suppose we thread a black* wire back and forth between the magnets, as in the picture above. Let's bring the wire outside the motor, and once everything is assembled we zap a gazillion amps through the wire. Think about what direction the magnetic field created by the current through that wire will be in. Perfect! Admittedly it's not a very thick wire to be coping with such a large current (typically several thousand amps), but it's only for a few milliseconds and the wire doesn't have time to complain. Also, it only has to happen once...

*Actually, any colour would do.

6. Brushless DC motors

Instead of having the magnets on the stationary casing and the windings on the rotor, we could put the magnets on the rotor and the windings on the stator. That way, we won't need brushes at all because the winding is stationary. However, now we need to find a way to switch the current through the windings at the right moment to ensure the torque on the rotor is always in the same direction. In a conventional motor, this happens automatically as the commutator acts as mechanical switch. With a brushless motor, we need some way to sense the position of the rotor, and then electronically switch the current so it's going the right way through the right winding.

Brushless motors are found in computer hard drives, CD and DVD players, and in anything else where efficiency and reliability are more important than price. As the cost of electronics continues to come down, perhaps one day all DC motors will be built this way.

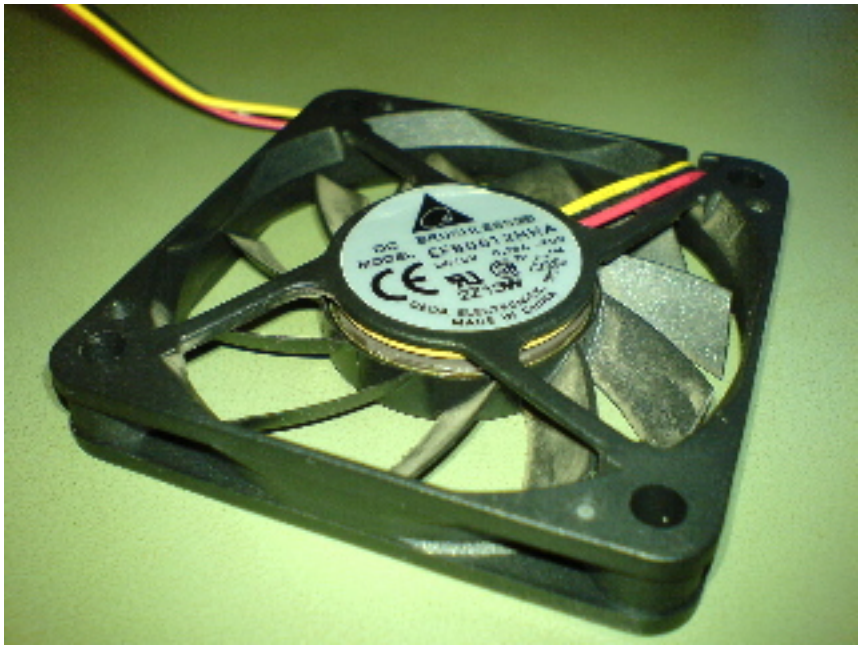
Advantages:

- No brushes
- Simple
- Efficient
- Windings are attached to the casing, and easier to cool.

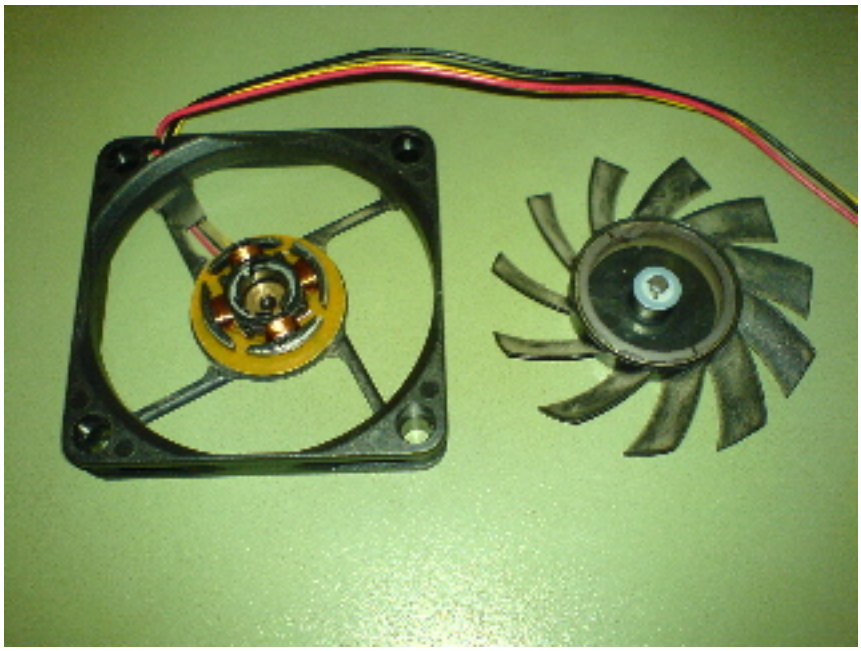
Disadvantages:

- Requires complex drive electronics

In fact, brushes are bad news. True, they're a clever way to ensure that, as the rotor turns, the current is automatically switched around the windings to ensure the motor keeps turning. However, everything else about them is bad: they are noisy, create friction, generate electrical interference (because of the sparking) and reduce efficiency (because there will always be a voltage drop across the brushes). Not only that, but they eventually wear out. With modern electronics, we can instead sense the position of the rotor (for example, with a Hall-effect device), then switch the current with, for example, a MOSFET transistor.



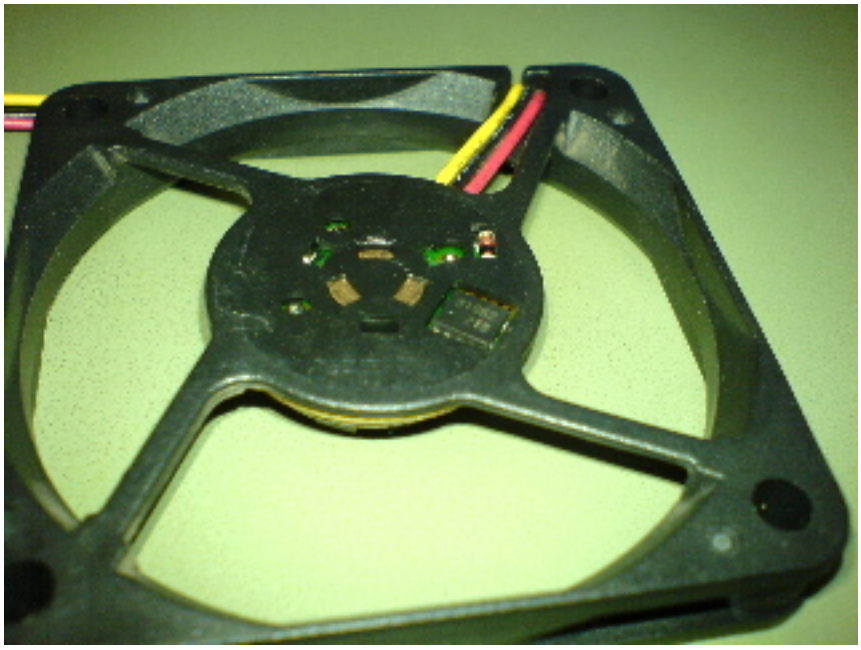
This is a fan that spent most of its life inside a computer keeping the microprocessor cool. It runs off 12 volts DC and has a brushless motor, as it thoughtfully explains with large friendly letters on the label.



As promised, the magnets are on the rotor (with fan blades attached) in a ring around the outside of the hub. By “feeling” them by using a small compass as a probe, we find that there are four poles, running N-S-N-S around the ring.



The “stator”, in the centre, has four small coils with shaped pole pieces to create a strong magnetic field next to the rotor. Depending on which director the current flows through each coil, it will attract or repel a north pole. So, all we have to do is to keep switching the direction of current flow through the coils in synchronisation with the rotation of the magnets, and we’ll keep exerting a torque that keeps the fan turning.



Now we've peeled the label off and can see the electronics that does the switching. It consists of a ingle integrated circuit and a few small capacitors, so it's actually not all that complex! If we google the part number of the chip (LB1962M), we find it is a *"Fan motor single phase full-wave driver"*, which I guess is reassuring.

But how does the motor know the exact moment that the magnet has passed one pole, and therefore that it's time to reverse the current flow? There are three techniques commonly used:

- Hall-effect sensors. This is a neat, non-contact way of knowing where the magnets are.
- Back EMF. This is even neater. We don't use sensors at all, but use the fact that the magnet moving past the coil will induce a voltage in it, and use this voltage to tell us where the magnet is.
- Don't bother. For the ultimate minimalist approach, just keep switching the coils in sequence and assume the rotor will keep up. For motors with a small load that is well defined (eg, a fan), this works pretty well.

7. Stepper motors

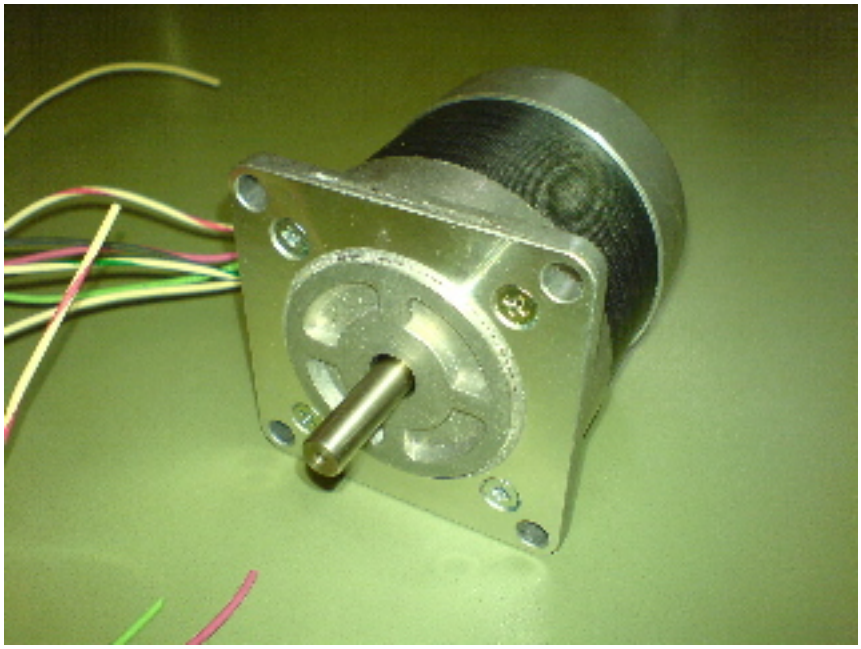
Stepper motors are useful for positioning things. Unlike a conventional DC motor that just goes round and round when you apply power to it, a stepper motor requires that the current through its two or more windings changes in a specific sequence. Each time this sequence is carried out, the stepper motor makes one step, clockwise or anticlockwise. With an appropriate piece of digital logic (or a computer) providing an appropriate number of repetitions of the sequence, the motor will move through the required angle. Stepper motors are used to move the paper in printers, to position the read heads on disc drives, and in simple servo systems.

Advantages:

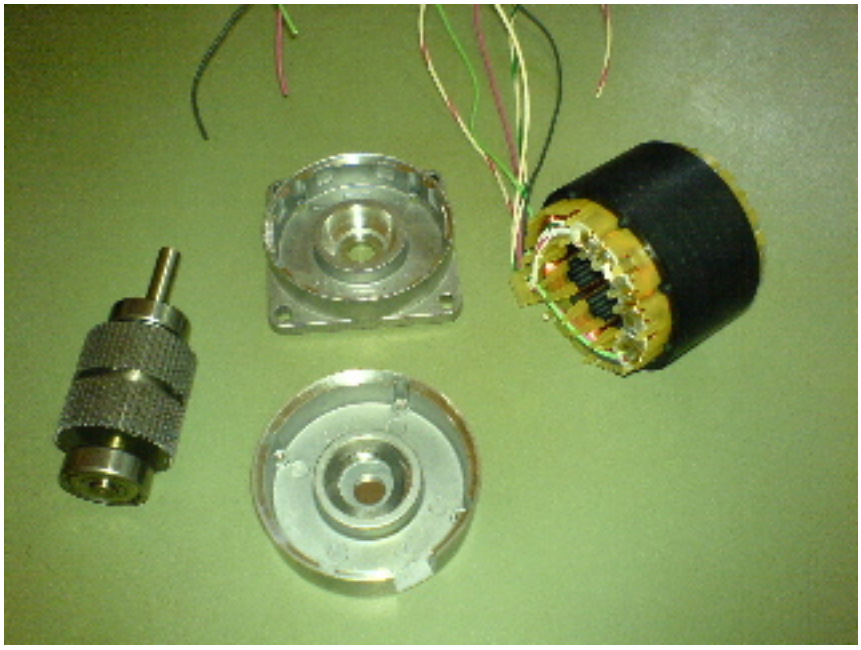
- Move in discrete, well defined steps
- Stay put when you remove the power

Disadvantages:

- Require complex drive electronics
- Not terribly efficient



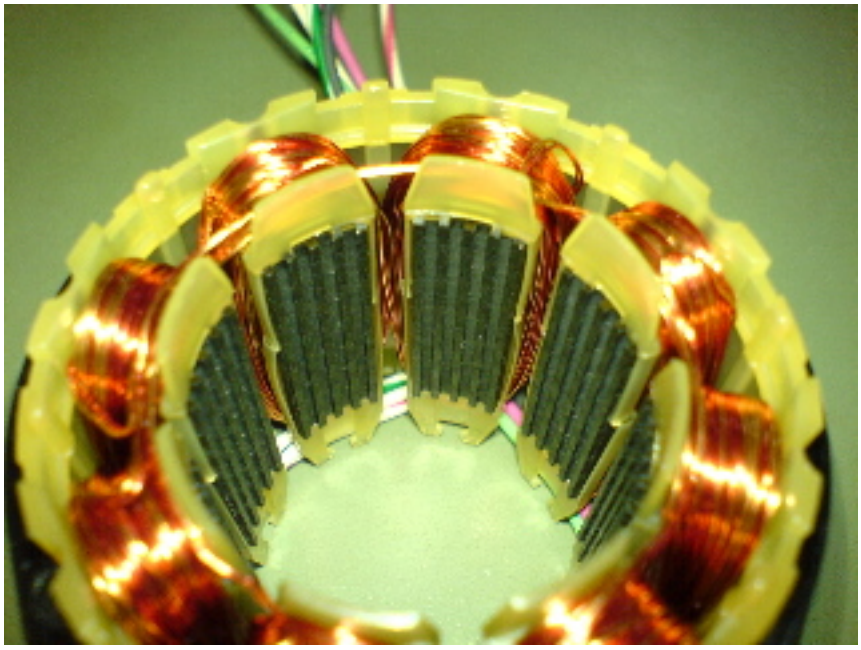
This particular motor steps 1.8 degrees at a time. It is an example of a *hybrid* stepper motor, one that has a magnetised rotor that also has iron teeth.



The stator has a set of coils (in this case eight) each of which energises a single pole. Those poles, in turn, each have four teeth. The windings on poles 1, 3, 5 & 7 are connected together: let's call this Phase A. Poles 2, 4, 6 & 8 are also connected together to form Phase B. There's then an external connection to each end of the two phases and to the centre-tap of the coils, making six wires in all.



The rotor also has a series of teeth that exactly correspond to teeth on the poles of the housing. However, not all the rotor teeth line up with all the stator teeth at any one time! In fact, the rotor teeth are in two sets, a front set and a back set. These two sets are rotated by half a tooth with respect to each other. Between the two sets is a permanent magnet, and so the front set corresponds to a north pole, and the rear set a south pole. (All this seems unnecessarily complicated, and it is. The only reasons it's done this way is so you can get nice small steps – in this case 1.8^{o} at a time.)



If we energise the Phase A coils, the rotor will turn so its teeth line up with the teeth of that phase. Now, if we energise Phase B as well, the rotor will turn slightly because the teeth of the Phase B are not aligned with those of Phase A. Now we de-energise Phase A, and the rotor will align fully with the teeth of Phase B. Next we energise Phase A with the reverse polarity to before, de-energise Phase B, energise Phase B with the reverse polarity, de-energise Phase A, re-energise Phase A with the original polarity, and we've made one full step! If we were writing this down as series of dance steps for a barn dance it would probably look something like: A+ A+B+ B+ A-B+ A- A-B- B- A+B- A+.

There are many other varieties of stepper motors. Some have no magnets on the rotor (so-called *switched reluctance* stepper motors), and some have magnets but no iron.

8. The infamous "ball bearing" motor

This motor is nothing more than a shaft supported by two ball bearings. Current is fed to the outside of one bearing, runs through the shaft, and out the other bearing. It sometimes needs a little kick to get it started, but once turning will run equally well in either direction.

Advantages:

- Perfect conversation-starter at parties
- Creates confusion amongst engineers

Disadvantages:

- Completely useless
- Requires staggeringly high currents to make it turn



This motor has no windings, brushes, magnets, and cannot possibly work. Except that it does. Click here (URL) for an explanation.

9. Taking motors apart.

This is not an exhaustive list. Always take extreme care when working around machinery. Wear protective glasses and think before you act. Below are a few safety tips that are important to observe when working with electric motors.

1. Before disassembling an electric motor, make sure you have owner's permission. This is really important – especially if you don't succeed in getting it back together again before they find out.

2. Disconnect the motor from the source of electricity. In necessary, cut wires off to ensure there can be no accidental reconnection. Never fool about with the mains.

3. In the case of permanent magnet motors, the magnets can be extremely powerful. Parts of the motor can unexpectedly slam together, trapping fingers and other sensitive body parts, or striking the eyes with metal splinters.

4. In many permanent magnet motors, simple disassembly and reassembly, even if you do it 100% right, will result in the magnetic field being weaker than before. Paradoxically, the motor will now spin *faster* than it did previously. This could lead to alarming results if, for example, the motor is part of your grandmother's electric wheel chair.

5. This one applies to any large inductor, including the windings of an electric motor. If you suddenly interrupt a current that is passing through an inductor (for example, if you are testing a winding with a battery and then disconnect the battery) a high voltage will appear briefly across the winding ($V = -LdI/dt$). This can kill you. Really. Ensure that you are not holding the bare wires when you are experimenting, even if the DC voltage is only 12 volts or so.

6. All rotating shafts are potentially dangerous - never be complacent where exposed shafts are concerned. Even a clean, smooth shaft can easily grab hair or clothing and cause serious injury. An induction motor inside a vacuum cleaner is pretty harmless (unless you're a mouse), but the same motor sitting on a bench is potentially lethal. For a start it's more powerful than you. Second, it has no common sense. Finally, remember that the torque the casing exerts on the rotor is exactly equal (and opposite) to the torque the rotor exerts on the casing. So, if the rotor is heavy (and it usually is), when you first switch the motor on the rotor tends to stay put while the casing rotates. Bolt it down first!

The ball-bearing motor

How can a DC motor with no windings, magnets, commutators, or tricky electronics work? Over the years, folk have tried to explain this motor by invoking strange new interpretations of Maxwell's equations, or by creating tortured descriptions of magnetic fields that are generated by a current-carrying conductor and then somehow end up doing what no other magnetic field ever does. Other folk have related the phenomenon to Energies Unknown To Science, and hypothesised that this might be a way of tapping into unlimited free energy. Some of these explanations have even been published in reputable journals, before being soundly demolished in even more reputable journals.

In fact the explanation appears to be very simple, if a bit bizarre. Think *hot balls.* The current through the ball bearings (100 amps or more, for the motor in the photograph) is enough to heat them up. The current is flowing *radially* through each ball, causing preferential heating along the axis of the ball perpendicular to the shaft. The ball therefore momentarily expands into an ellipsoidal shape. If the shaft is already rotating, this expansion can occur along an axis that is fractionally *after* the pure perpendicular, giving a little "push" to the shaft as it does so.

Following this up on the WWW is a good rainy-day project, but don't believe everything you read!