CHAPTER 4

The Jabberwock

The lecturer entered from the back of the theatre, placed a gyroscope on a sloping wire from the back row of seats down to the lecture bench and it slid down ahead of him into the waiting hands of Mr Owen.

'Twas brillig, and the slithy toves
Did gyre and gimble in the wabe:
All mimsy were the borogoves,
And the mome raths outgrabe.

'Beware the Jabberwock, my son!
The jaws that bite, the claws that catch!
Beware the Jubjub bird and shun
The frumious Bandersnatch!'

The Introduction was read by a latter-day 'Alice' (actually Louise, see Plate 4.1).

Plate 4.1 A latter-day 'Alice' (Louise) reads 'The Jabberwock' poem.

The Jabberwock was a monster with many heads. As such it resembles, in some way, the manner in which we divide our science into Physics, Chemistry, Biology, etc., and then Physics into Heat, Light, Sound, Magnetism and Electricity. Often one can spot the various heads as being Laws of Physics, and some of them look into mirrors, see their reflections and think that the total number of their kind is bigger than it really is. Thus they attempt to co-exist with their own shadows and reflections. One of the best examples I can give you is the collection of Laws of Electromagnetic Induction. When I was at school, I was taught Fleming's left- and right-hand rules, and taught to remember what the fingers and thumbs represented by emphasising the initial letters of the electrical quantities thus:

thuMb – Motion
ForeFinger – Field
seCond finger – Current (see Fig. 4.1)

Then we had to remember which hand to use for motor and which for generator. After that

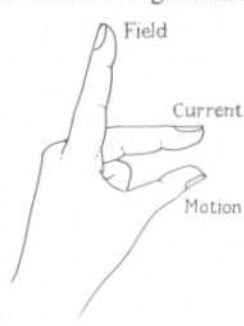


Fig. 4.1 Fleming's left-hand rule.

we were taught Lenz's law, the Gripping rule, Corkscrew rule and Ampère's swimming rule. What a business! They were all, apparently, separate, independent heads. But those were the bad old days – I hope. Electromagnetism is a good deal easier than that. From what we have considered already about left and right hands, and about motors on one side of the Looking Glass being generators on the other, I think you can see that the mirror really *is* Lenz's law itself, for it changes hands for you as you go through the mirror and changes the motor to a generator at the same time.

The idea of science as a monster is certainly not a new one, but a neat way of expressing the same sentiment is due to Martin Gardner who wrote: 'Laboratory bangs can range all the way from an exploding test tube to the explosion of a hydrogen bomb. But the really Big Bangs are the bangs that occur inside the heads of theoretical physicists when they try to put together the pieces handed to them by the experimental physicists.'

One of the things you may not have been taught is that there is apparently no *simple* connection between gravitational mass and inertial mass. Yet if we compare two masses, either by weighing them on the same spring balance, or by subjecting each to a known force and measuring their relative accelerations, we always get the same answer. Of those two heads, one *must* be in some way, a 'reflection' of the other. When you think about it, there are many interpretations of the word 'reflect'. In novels, for example: 'He reflected on what might happen . . .' 'The same attitude is reflected in . . .' etc. 'When I use a word,' says Humpty Dumpty, 'it means just what I choose it to mean, neither more nor less.' Lewis Carroll created lovely 'combination words' in the nonsense rhyme. 'Slithy' is a mixture of 'lithe' and 'slimy' and is beautifully onomatopoeic. 'Mimsy' is likewise a mixture of 'flimsy' and 'miserable'. There is an old Lancashire word 'witchit', which is not merely a dialect word for 'very wet'. It implies something even more emphatic than 'soaked to the skin'. It probably originated as a mixture of 'wet and wretched'.

Within a generation, technology has put a precise meaning on a combination word. 'Stiction' is a deliberate mixture of 'sticky' and 'friction'. Whilst not attempting to quantify it, it signifies that the frictional force necessary to start one surface sliding over another is greater than that required to keep it going, once started. In the 1966 Christmas lectures I did an experiment with five brass blocks on an inclined plane, which I should now like to repeat.[1] The blocks measure $2'' \times 2'' \times \frac{1}{2}''$, $1'' \times 1'' \times \frac{1}{4}''$, $\frac{1}{2}'' \times \frac{1}{2}'' \times \frac{1}{8}''$, $\frac{1}{4}'' \times \frac{1}{4}'' \times \frac{1}{16}''$ and $\frac{1}{8}'' \times \frac{1}{8}'' \times \frac{1}{32}''$ and were all placed with a large surface on the plane. The assumption of a constant value of frictional coefficient μ, or of 'angle of friction' λ, tells us that as the plane is tilted to greater and greater angles, all the blocks will begin to slide at the same time. In practice, they go off in order, biggest first. But to emphasise the beautiful descriptiveness of the word 'stiction', let us have 'jam today' and smear each block with strawberry jam, and try again! The two smallest blocks remain stationary when the plane reaches an angle of 90°, where $\mu = \infty$. But after a minute or two the blocks *will* be seen to begin to move. The viscosity of strawberry jam is *not* infinite. We are in trouble with the $\mu = \infty$ only because we created the infinity ourselves by *defining* μ as equal to tan λ.

Circularity is a powerful concept, the idea of a closed loop even more so. In circular motion there is magic, just as there is in electro-magnetism. But it only manifests itself when it is, like (shall we say for the moment, rather than a 'reflection' of) its 'neighbouring head', truly three-dimensional.

Here is a circular coil of wire carrying alternating current. Here is a similar coil connected to an a.c. voltmeter. We can induce current into the one from the other by a means totally unintelligible to us, but to which we give the name 'electromagnetic induction'. But if I place one coil with its axis at right-angles to that of the other, there is *no* induced voltage. It is as if the two circuits lived in different worlds and each never knew of the existence of the other. The artist M.C. Escher made a splendid drawing to illustrate this by using a staircase that could be

[1] *The Engineer in Wonderland* (English Universities Press, 1967).

imagined to lead either up or down. Of the men using the staircase, he said:

Here we have three forces of gravity working perpendicular to one another. Three earth-planes cut across each other at right angles, and human beings are living on each of them. It is impossible for the inhabitants of different worlds to walk or sit or stand on the same floor, because they have differing concepts of what is horizontal and what is vertical. Yet they may well share the use of the same staircase. On the top staircase illustrated here, two people are moving side by side and in the same direction, and yet one of them is going downstairs and the other upstairs. Contact between them is out of the question, because they live in different worlds and therefore can have no knowledge of each other's existence.[1]

Although the artist has only used a trick of perspective to influence the mind of the observer it is a *lively* influence indeed. What is the meaning of perspective in a four-dimensional space?

Gyroscopes are essentially circular things. A scientific gyro is a wheel mounted in gimbal rings as shown in Plate 4.2. The two rings in this example consist of a complete *inner* ring whose pivot axis is always horizontal, and a half circular *outer* ring mounted on a vertical axis. In this situation the rotor axis is perpendicular to each of the others and all three axes pass through the centre of mass of the wheel. With this apparatus you shall see two different worlds, separated for you *visually* as they never are in electromagnetism, because with a gyroscope you can *touch* and *feel* rather than merely *observe* the result, as you do with electricity. There one gets the feeling that a voltmeter in an electromagnetic arrangement is just another mysterious instrument that we do not understand. Apparently we are using it to translate the 'magnetic language' into the 'electric language' by the same shady means as those by which we first made the current in a coil produce an entirely fictitious 'magnetic field'. To see is to believe, they say, but to believe is not necessarily to see.

Let me try to twist the gyroscope about its vertical axis. It refuses to go in the direction in which it is pushed. Instead it rotates about its

Plate 4.2 A scientific gyroscope consists of a wheel mounted in gimbal rings.

horizontal, inner ring axis. This motion is called 'precession'. So I was unable to give it energy, for it refused to be moved. The ring that moved had no load torque to combat (except bearing friction, and there is very little of that) so its energy output was zero for a different reason – lots of precessional velocity, this time, but no torque or twisting force. It is at this point that we may return momentarily to the electromagnetic world and contemplate for a moment the possibility of a coil of wire that had no resistance (the equivalent of no bearing friction in our gyro). We should find that when a *changing* current flowed through it, we could measure a voltage across it, yet it would not get hot. It has current, voltage, but *no power*.

This should be a more staggering result, for those of us who have been taught Ohm's law, than if we were to find that a gyroscope clearly displayed mass, velocity and no momentum. But

[1] *The Graphic Works of M.C. Escher* (Macdonald and Co., London, 2nd edn, 1967).

we were enlightened about the electromagnetic 'impossibility' by the idea of *inductance*, and in alternating current calculations, where the current is forever changing, we know that the result of such changes is to produce a voltage that can conveniently be regarded as quite separate from the Ohm's law (IR) drop, for it does not rise and fall in phase with the IR drop. Mathematically it is then again *convenient* to put the letter j in front of such voltages, where $j=\sqrt{(-1)}$,[1] and this in turn leads to the idea that you could transfer the j to the quantity L we have called 'inductance', and hence obtain a still further useful idea of 'impedance' (Z):

$$Z=(R+jL\omega)$$

where ω is the angular frequency of the cyclical rate of change of currents and voltages. A new form of Ohm's law now emerges as

$$E=IZ$$

and life becomes simple again.

I use this well-known example to show that there is no suggestion either that Ohm's law as originally written is 'wrong', nor that it is 'true' that real quantities should be naturally expressed as *imaginary* numbers. The only questions that ever need be asked are:

1 Does the new notation and set of rules give answers that are supported by experiment?

2 Is the method convenient? (In this case, the alternative would have been the solution of the differential equation $L(\mathrm{d}i/\mathrm{d}t)+Ri=E\sin\omega t$. The skilled physicist knows that the solution $E=I(R+jL\omega)$ neglects the initial transients that occur when a circuit is switched on or off, but the engineer knows from 100 years' experience just when these transients matter and when, therefore, he must solve the differential equation and when they can be ignored. The latter situation largely predominates in practice.)

[1] Mathematicians often use 'i' for $\sqrt{(-1)}$, but electrical engineers reserve i for the instantaneous value of a current. 'I' they retain for direct current or the R.M.S. value of alternating current.

There are several phenomena that we can observe with a gyroscope that suggest that it might *conveniently* be treated as analogous to an electromagnetic device. First, in which direction will it precess if I hang a mass on one side of the inner ring (Plate 4.3)? Viewed from above,

Plate 4.3 The gyro 'precesses' about a vertical axis when a weight is hung from the inner ring.

will it rotate clockwise or anti-clockwise? A simple rule is illustrated in Fig. 4.2. Imagine the force, in this case the weight, transferred so that it pushes directly on the rotor itself, as at F.

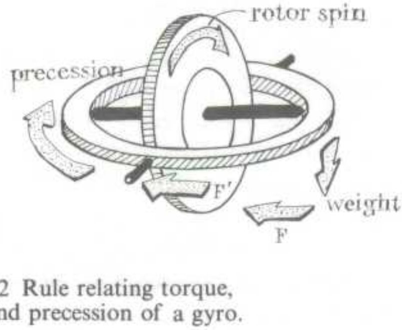


Fig. 4.2 Rule relating torque, spin and precession of a gyro.

Allow this force to be transferred to position F′, having been, as it were, 'dragged around' 90° in the direction of the rotor movement. If now the rotor be regarded as stationary, F′ will produce rotation in the 'common sense' direction, in this case, clockwise from above.

This method brings out the 90° shift that one observes with the phase of the current in an inductance as compared with the current in a resistance. Alternatively we could agree to regard a spinning wheel as having an angular momentum vector M (as shown in Fig. 4.3a) pointing in such a direction as would make the rotation appear right handed (as in Maxwell's corkscrew rule). If we then regard twisting force (torque, T) in a similar manner, likewise angular velocity

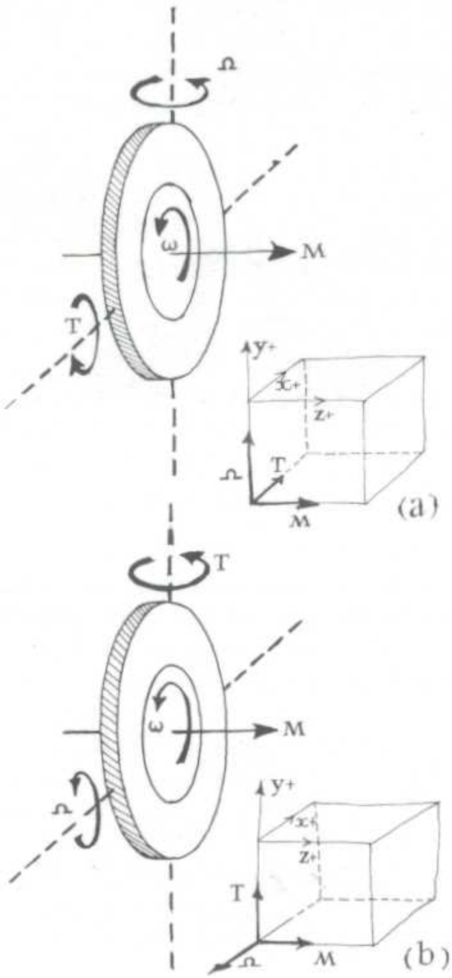


Fig. 4.3 The left-hand rule for electric motors used on a gyro.

of precession, Ω, we may hold up the fingers and thumb of the left hand, as for an electric motor, and declare the quantities to correspond as follows:

thuMb	– Motion, as before, but in this case it is precessional motion, Ω
ForeFinger	– Force, in this case *twisting* force, T
*Middlefinger	– Momentum (angular)

In such a concept, might we not be tempted to look for 'wattless current', now universally referred to as 'reactive volt-amps' (the result of inductance) in a gyroscope? Let us do some more experiments. If I treble the mass that I hang from the inner ring I treble the precession rate. If I treble the rotor speed, I divide the precession rate by 3, for the same weight hung. It appears that the rule connecting M, T and Ω is simply $T = M\Omega$. If the moment of inertia of the gyro rotor on its own axis of spin is I, and its rotation speed is ω then $M = I\omega$ and $T = (I\omega)\Omega$. Notice however that if the torque, T, is on axis x, (say), and we denote it T_x, then Ω is rotation in axis y. Let us call it Ω_y therefore, so that

$$T_x = (I\omega)\Omega_y \quad \ldots \quad (1)$$

Earlier we saw that a torque on the vertical (y) axis produced precession about the x-axis, so

$$T_y = (I\omega)\Omega_x$$

But examination of Fig. 4.3b shows that we must take account of backward vectors (anti-clockwise) as negative and therefore strictly

$$T_y = -(I\omega)\Omega_x \quad \ldots \quad (2)$$

Equations (1) and (2) are the two worlds of Escher, co-existing and co-related but from certain viewpoints 'unaware' of each other.

The analogy with the electric motor is strengthened by this concept (see Fig. 4.4). A magnetic field B_y induces current I only in the loop (1), whose axis is horizontal, and the current is therefore to be designated I_x. A field B_x as shown only induces current I_y in loop (2) and, taking magnitudes into account, if A be the area of each coil and R its resistance,

$$I_y = \frac{2}{\pi}\left(\frac{A}{R}\omega\right)B_x$$

and

$$I_x = -\frac{2}{\pi}\left(\frac{A}{R}\omega\right)B_y$$

which compare nicely with equations (1) and (2).

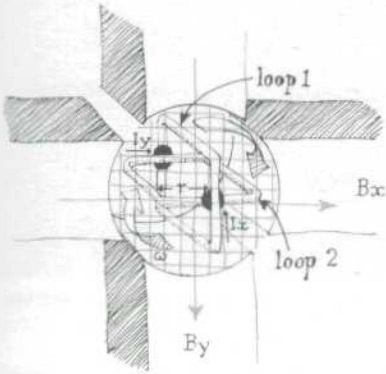


Fig. 4.4 Gyro analogy with a.c. machine.

The whole of modern electrical machine theory ('Generalised machine theory') is based on this idea of the two independent axes, co-existing, co-related but nevertheless identifiably separate. We deal with complicated matters when we deal with rates of change of current, matters that require not only the Special Theory of Relativity, but the General Theory (the world of relative accelerations) to justify them to a theoretical physicist. Might there not exist a similar complexity also in the gyroscope, if rates of change of acceleration are involved? The usual interpretations of Newton's Laws of motion are very sound when applied to situations in which the acceleration does not change. Work on rates of change of acceleration (American scientists have called it 'surge') is very sparse.

Let us subject our gyro/electric motor analogy to sterner tests. Let us exert torques on two axes simultaneously and see if the precessions appear to occur in appropriate senses. Attaching the weight to the inner ring again as in Plate 4.3, I push on the outer ring so as to try to increase the precession rate. The velocity appears unaffected by the push, but the weight rises! The two worlds *can* co-exist.

Now to do the experiment designed to look for momentumless motion. I hang a large mass (1 kg) on the inner ring, giving the gyro a precession rate of over 5 radians/second. As the 1 kg weight goes by I lift it as fast as I can, and the gyro ring system appears to come to rest in zero time! If we were to photograph it with a high-speed camera we would be able to examine just what happened, in slow motion. We should undoubtedly be impressed by the small amount of movement that occurs, the net result of which would be a slight upward movement of the point of suspension of the weight. This small movement occurred in the reverse direction when the weight was first added and here lies the secret of the momentumless motion.

The gyro rotor has a very large angular momentum about its own axis. Suppose that axis is precisely horizontal as the weight is dropped on to the inner ring. A deflection of only 2° may suffice to give the gyro wheel a *component* of vertical angular momentum of $(I\omega)\sin 2^\circ \approx 0{\cdot}03(I\omega)$, just the amount to counteract the precession angular momentum about the vertical. But this last is a *strange* momentum indeed. It is in one sense 'unavailable' momentum inasmuch as the removal of the cause reduces it to zero in the same order of time as switching off an inductive circuit takes to reduce the current to zero. We can, if we like, declare the precession angular momentum to be only 'apparent' momentum and write it mathematically as $j(I'\Omega)$ where I' is the momentum of all the parts about the vertical axis.

Perhaps the most amazing thing about this last experiment is that the moment of inertia of the gimbal rings about the vertical axis is almost exactly equal to that of the rotor itself about the same axis, so the gimbal rings must have had a *real* momentum immediately before the weight was lifted. In such circumstances (where the 'dead' mass has a moment of inertia comparable with that of the 'live' rotor) we can only conclude that the rotor exhibited some *negative*, *real* momentum in the sense that we are building this analogy – and why not? Negative resistance is commonly accepted in modern electronics but it is usually a term applied to a system that 'appears' to exhibit negative R. We must never let ourselves become obsessed with 'realities' in engineering – we must concentrate on *concepts*.

That a perfect gyro released from a horizontal axis never displays angular momentum is not in doubt. Authorities on the subject will confirm this. What I am pointing out to you now is that it is a strange situation to say the least, for since all points on the wheel move in a plane at right-angles to its axis, and all precessional movement takes place in planes at right-angles to this, the velocity of any point on the gyro wheel relative to the table on which the apparatus stands can never be zero, at any time. Yet the whole displays no momentum.

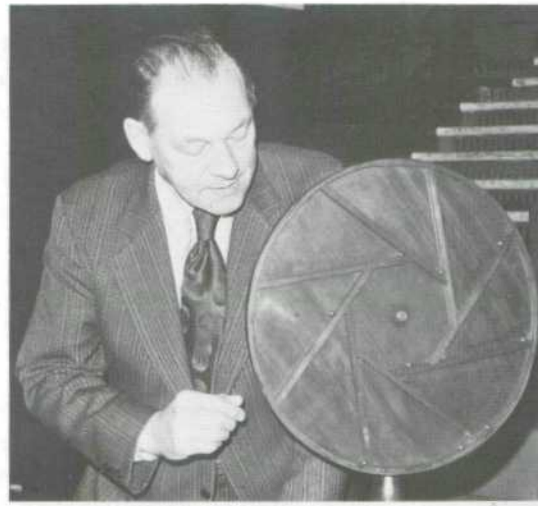


Plate 4.4 An early 'perpetual motion' machine illustrated by Leonardo da Vinci.

Plate 4.5 An alternative 'perpetual motion' machine that doesn't work either!

What is often not stated is that if a weight be added when the gyro axis is not horizontal, but displaced at an angle θ from it, a similar tiny deflection in θ results from adding, or subtracting a weight as before. In this case the gyro starts with a real momentum and the *extra* momentum (plus or minus) due to adding or subtracting the weight on the inner ring is partly 'apparent', partly 'negative real' as before, returnable to 'source' on detaching the weight, just as the magnetic energy stored in an inductance attempts to return to source if d.c. is switched off, or does so periodically and continuously in the case of a.c.

Let me also say very firmly here that I know no property of a gyroscope that conflicts in any way with the conservation of energy. I *must* say this and underline it before some journalist says that I claim to produce energy out of nothing and therefore perpetual motion. Perpetual motion is in the same state today as it was in the fifteenth century when Leonardo da Vinci denounced it so properly. He knew of the machines shown in Plates 4.4 and 4.5 and others like them, equally incapable of generating energy out of nothing. If you *really* want to see perpetual motion, look into the sky on a cloudless night and marvel at the size and movement within the Universe. We have no reason to believe that if we fire a missile from an orbiting space station into space there is anything to stop it except a chance interference with another body, which is probably as unlikely an occurrence as the molecules in a glass jar simultaneously organising their movements such that the jar jumps off the shelf! *There* is perpetual motion of a kind and let that be an end of it. In space – who knows? But so long as we remain earth-bound, we shall have friction and this, as Osborne Reynolds declared 100 years ago, is just as well, or this would be no fit place to live, for the air would be filled with flying objects! And talking of perpetual motion...

At this point, the lecturer spun a small top on a plastic dish (see Plate 4.6). The top con-

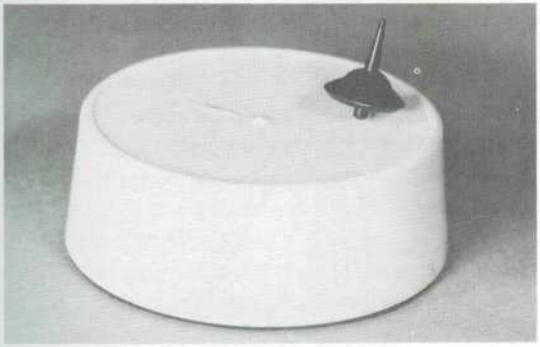


Plate 4.6 A tiny spinning top that will run for $5\frac{1}{2}$ days.

tinued to spin for the remainder of the lecture! Its mechanism is quite complex. Under the dish is a tiny mica chip containing transistors in a printed circuit fed from a battery. Under the very centre of the dish is an electromagnet whose current is controlled from the printed circuit. The coil acts both as detector of the presence of iron near the centre of the dish, and as force-producer, when fed with current. The bottom part of the spinning top is a steel disc. A part of the

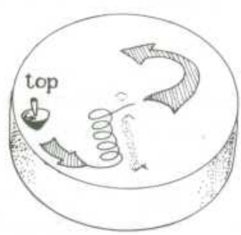


Fig. 4.5 The 'perpetual motion' spinning top.

disc top is raised – the shape of an exclamation mark (see Fig. 4.5). When the top is pulled against and along it, the shape of the spindle is such that friction between spindle and raised portion imparts more spin to replace the energy lost in friction, much as one does in a toy 'whip and top' exercise (see enlarged view, Fig. 4.6). With a new battery that top will spin continuously for $5\frac{1}{2}$ days.

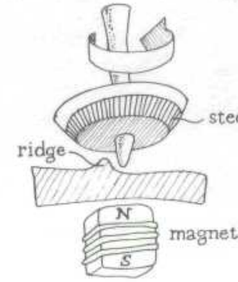


Fig. 4.6 The secret of the top shown in Fig. 4.5 (enlarged).

Toy gyroscopes are fun – but they have much more to offer us than fun! The toy manufacturer cannot afford to put his wheel in gimbal rings. He has to sell it for 50p and make a profit. But he discovered by experiment long ago that a simple ring to hold the pivots would allow the user to perform many almost unbelievable experiments, such as balancing the whole on a tightrope (Plate 4.7) or on the edge of a wine glass, or on a model Eiffel Tower (Plate 4.8).

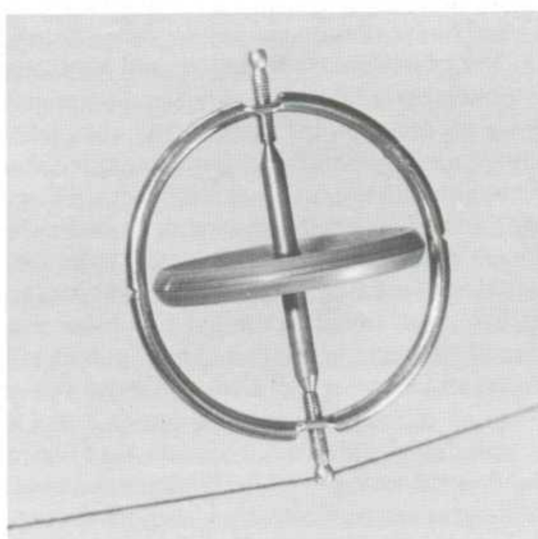


Plate 4.7 A toy gyroscope on a tightrope.

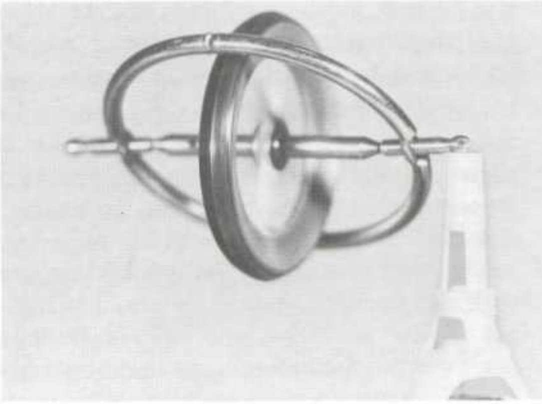


Plate 4.8 A toy gyro on a model of the Eiffel Tower.

(The resemblance to the real Eiffel Tower has decreased in these days of affluence!) The precession rate is still as predicted, in this case the torque being provided by gravity on the wheel mass and a vertical reaction from the tower.

Look carefully as the wheel precesses and see if you get the same unusual physical experience as I do. Things just don't behave like that. The gyro weighs over 40 times the tower weight, yet the wheel precesses around the tower, not the light tower around the wheel, as elementary mechanics would suggest or require that it should. Let us assume that friction between tower and bench is responsible for this effect and repeat the experiment with a tower base set in ice and free to slide on melting ice, when the coefficient of friction is about 0·02, and let us use an old-fashioned wheel made of lead (over 400 times the mass of the tower). Still the tower hardly moves, yet still we might be deceived, for if true it should be possible to start the gyro from one end of a diameter and catch it at the other, thus displacing mass through space. Once displaced it would be a relatively simple matter to push it back again by ordinary mechanised means and thus progress the experimenter in any chosen direction – which seems unlikely!

Let us repeat the experiment with a much larger wheel (18-lb mass on a 6-lb shaft) on a stand, as shown in Plate 4.9. If I release the wheel from a position where its axis is horizontal it performs curious dipping motions called 'nutations', as illustrated in Fig. 4.7. These are the

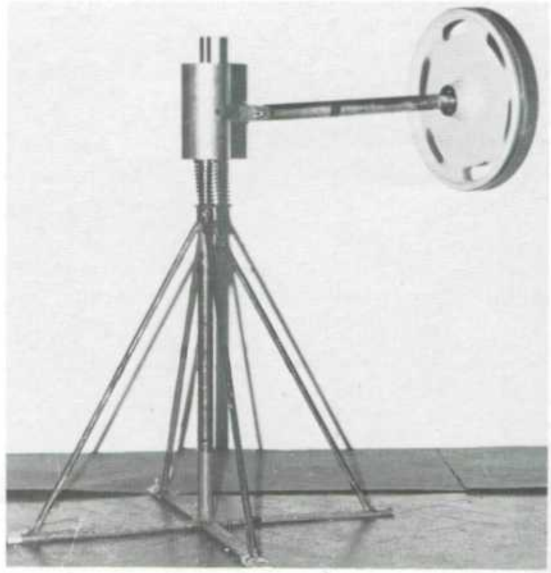


Plate 4.9 An enlarged version of the gyro on tower. The wheel weighs 24 lb.

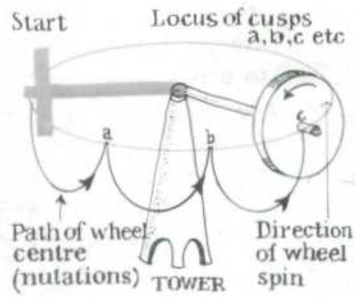


Fig. 4.7 'Nutation' of a gyro-on-tower.

equivalent of transients in an electric circuit that occur on switch-on. The nutations soon die out. Now it costs but little effort to stop the precessing wheel, large though it is, for its momentum is only apparent, and to lift the shaft through a fraction of an inch stops it dead.

If I now set it precessing again and apply torque to the shaft to try to increase the precession rate, you will see the spring beneath its central pivot block (see Plate 4.9) expand momentarily. This is a dangerous experiment not recommended for anyone but an 'old hand at the game', for during the transient the stand of the gyro suffers toppling torques, and they are not always in the direction that you might expect, i.e. centrifugal forces trying to *pull* the tower along the wheel shaft.

The way that Ohm's Law is generally taught is that in an electrical conductor, an e.m.f. *causes* a current. This is not the way Ohm himself expressed it, rather he defined a constant (R) as being the ratio E/I. The fact that we elected to supply all houses and factories at a constant *voltage* ensured that most of us would always tend to think of e.m.f. as cause and current as effect, for all houses are wired in parallel. The alternative of a series-connected national network *was* open to us, but we wisely rejected it purely on the grounds of cost. But *locally* one may build a constant-current system, as shown in Fig. 4.8, by having a very high voltage feeding a load r through a very high resistor R. If r is always less than 1 per cent of R, but variable, we can say

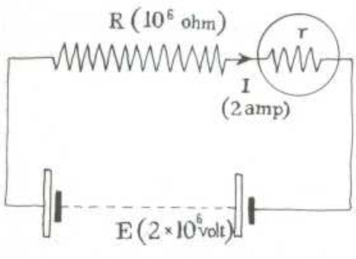


Fig. 4.8 Electric current can be the *cause* of a voltage.

to a close approximation that the current is constant (in this case at 2 amps) and that the voltage across the load is simply $2r$, whatever value r has below 10,000 ohms. We thus tend to regard I as cause and E as effect.

So it is with gyros. A torque may be treated as cause, if cause it is. However, one may always rotate a gyro at a demanded precession speed, irrespective of what then happens: the resulting torque on the perpendicular axis can be seen as *effect*, rather than cause.

Let us leave the big wheel for a few minutes in favour of a less dangerous, but still quite large offset gyro. Plate 4.10 shows the apparatus hav-

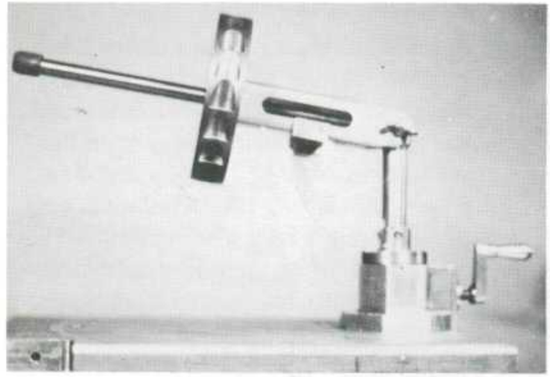


Plate 4.10 A 5″ diameter brass wheel that can be force-precessed.

ing a 5″ diameter wheel, 1″ thick and mounted on a base. I can 'communicate' with the gyro by pushing in a handle in the base to cause bevel gears to engage. As before, if I try to increase precession speed, the wheel rises; if I try to retard it, it falls. Now let us stop the wheel and push the gyro stand until it overhangs the bench – as shown in Fig. 4.9 – and is on the point of toppling. Now spin up the wheel with compressed air and release it. It does not fall at all, for the precession produces a torque that transfers the weight of the wheel to the top of the tower, as shown in Fig. 4.10.

Let us rebalance the system when the wheel is not spinning, and its axis is parallel to the edge of the bench, as shown in plan view in Fig. 4.11. Now if the wheel transfers its weight to the tower when spinning and precessing freely, we should still be exactly balanced. Any centrifugal force should therefore topple it, in theory. The precession rate for this experiment is of the order of 0·5 revolution per second. The wheel weighs about 6 lb f. Centrifugal force for a radius of 8″ (the shaft length, tower centre to centre of wheel) should be of the order of 1·0 lbf. We can counterweight this 1·0 lbf. at 5″ (the height of the tower) by a counterweight of 0·5 lbf at 10″ from the edge. It now appears possible to move the counterweight nearer to the edge of the table without the system toppling, which suggests that perhaps a *part* of the centrifugal force appears to be missing. From one point of view this might be expected from a rotating device with no angular

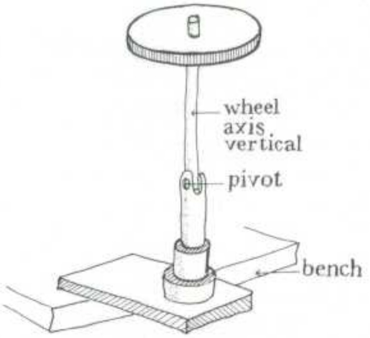


Fig. 4.9 Balancing the offset gyro.

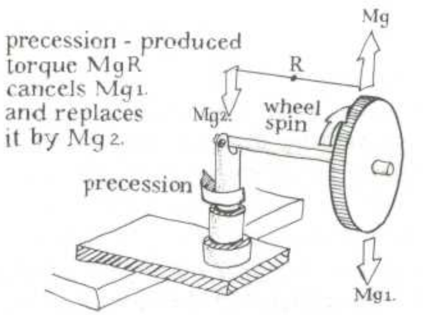


Fig. 4.10 The precessing gyro does not overbalance.

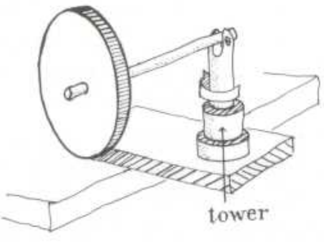


Fig. 4.11 Plan view of stationary wheel in balance position.

momentum, for do we not calculate centrifugal (or centripetal, depending on where you are standing when you observe it, not on how you were taught!) force by the *change* in angular momentum? Yet is this not also an *exciting* thought, for it is not every day that one discovers the *absence* of something where it ought to have been!

Edward de Bono encourages us to do 'lateral thinking' and his books contain delightful examples. Well, here is a beauty he might like to add to the collection. Gyroscopes do not exhibit a new *force*. They show a *lack* of a force *where we would have expected one!* That is why it was so hard to see. 'I see nobody on the road,' said Alice. 'I only wish *I* had such eyes,' the King remarked in a fretful tone. 'To be able to see Nobody! and at that distance too!' Lewis Carroll must be laughing at us all. If there is a *lack* of force, the rest is just engineering.

What surprises me is that the gyro did not avail itself of the opportunity to tilt as shown in Fig. 4.12, thus lowering the centre of gravity of the whole system without changing its axis of spin in this outermost position. For it has two effective pivots A and B in the same plane, and A will prevent any torque from being transferred to B. Perhaps it is because the gyro would have to move *away* from the bench to do so. (This thought occurred to me only three hours before the lecture began.) So let us turn the experiment upside down, as shown in Fig. 4.13, for now a tilt involves the wheel in moving *nearer* the table. But the result is the same, stability *all* the time.

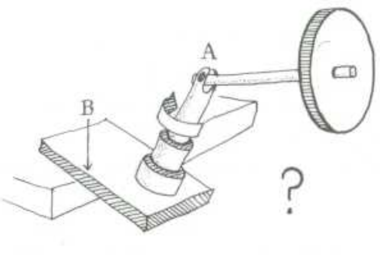


Fig. 4.12 Why does the gyro not do this?

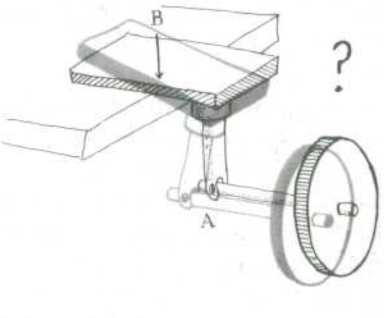


Fig. 4.13 An upside-down gyro does not answer the question posed by Fig. 4.12.

The idea of this second joint at the bench edge intrigued me to the extent that I told Mr Coates that we needed a second joint proper in the radius arm. Whereupon with no hesitation at all, he took a hacksaw to a very precious gyro and sawed its shaft in half, inserting a pivot at the cut. We only had time to try it out *once* before this lecture, but what an experiment it turned out to be!

First the system is balanced by means of the adjustable weight about the tower pivot, as shown in Fig. 4.14, with the stationary gyro and bearing ring hanging freely from the second pivot. The wheel is then spun and raised until the whole gyro axle is horizontal and from this position it is released. If the spinning wheel succeeds in transferring its weight to the second pivot by precession, the bearing ring and piece of spindle up to the second joint are 'dead-weight', and must surely cause the gyro to precess about the vertical tower pivot whilst adopting an attitude as shown in Fig. 4.15.

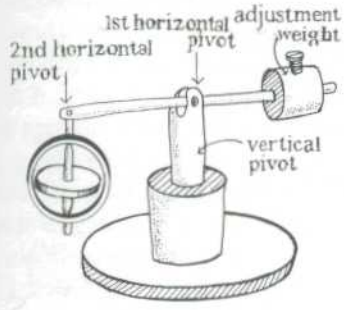


Fig. 4.14 The start of the double-joint experiment.

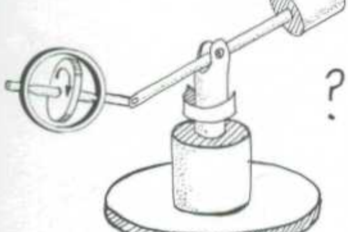


Fig. 4.15 The expected result of the double-joint experiment.

What *did* happen was that the gyro end raised itself to the position shown in Plate 4.11, whilst precessing about the vertical tower axis in the expected direction. There appeared to be no ordinary explanation for this but it reaffirmed my belief, which I first expressed in a Friday evening Discourse at the Royal Institution on 8 November 1974, that a gyro exhibited phenomena that were not to be found in any other mechanical object, and could well be worthy of a study at a level not hitherto attempted. (That my audience at this lecture was able to share in this thrilling experiment, only performed for the first time three hours earlier, and now only for the second time, has continued to bring me great joy whenever I recall the demonstration.)

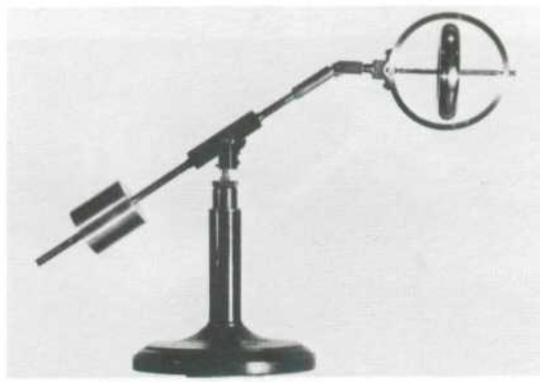


Plate 4.11 The double-joint experiment.

Gyro experiments are inclined perhaps to make some of us think about atomic physics where orbiting electrons are said to *spin* also. Difficulties always begin when we cannot *see* what goes on. Let me show you what I mean by replacing the second pivot on the gyro we have just used by a solid connector, and removing the counterbalance weight, to leave the gyro in the condition shown in Fig. 4.16.

Now the gyro can be spun and the whole cross arm assembly will rotate about the vertical axis. But suppose we choose its orbit so that its total angular momentum about the vertical is much smaller than would be calculable from its dimensions and the formula, momentum $= I\omega$, and suppose we now enclose the gyro in a light box, as shown in Fig. 4.17. We can measure the speed about the vertical axis, measure the angular momentum (by, for example, allowing the

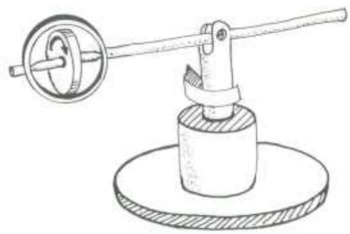


Fig. 4.16 The offset gyro as seen.

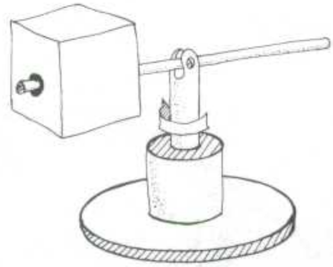


Fig. 4.17 The gyro wheel is enclosed in a box.

revolving shaft to run up a small inclined plane mounted on wheels, as shown in Fig. 4.18 and measuring the velocity of the trolley when the arm has come to rest relative to it) and deduce that there is very little mass inside the box.

We can then detach the box still containing the spinning wheel, weigh it on a spring balance and find the mass to be far greater than the first experiment had indicated.

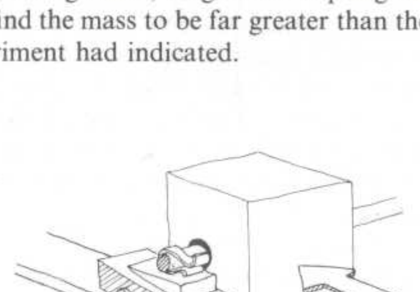


Fig. 4.18 Demonstration of a precessing gyro that has no momentum about the axis of precession.

It is a disturbing thought that an angular momentum may not always be that which we predict on the basis of weighing a mass and observing its subsequent rotation, unless we can be sure that nothing *inside* the mass, that we cannot see, is rotating also.

One of the things that has long worried me is that rotary things appear to belong to a different 'world' from things that move in a straight line. Yet there are analogous rules in which angular velocity, Ω, corresponds to linear velocity, V, and moment of inertia, I, corresponds to mass, M. So we can calculate momentum m as

$m = I\Omega$ (rotary)

or

$m = MV$ (linear)

Twisting force (torque) $= I\left(\dfrac{d\Omega}{dt}\right)$

or

Linear Force $= M\left(\dfrac{dV}{dt}\right)$

Energy $= \frac{1}{2}I\Omega^2$

or

Energy $= \frac{1}{2}MV^2$

This seems very 'tidy', but for one thing. We know that there is a very big difference between *force* and *energy* (or work done), likewise between *torque* and *energy*. In either case the former can exist without *motion* and therefore without energy. Only when force *and* motion co-exist is there energy.

Yet when we examine the relationship between rotary and linear motion we find that the *dimensions* of linear energy – for example, kinetic energy ($\frac{1}{2}MV^2$) – and of rotary *force* (torque) are the same, and each is equal to [force × distance] or $[ML^2T^{-2}]$ in the mass, length and time notation.

If we examine the rotary and linear interpretations of Newton's laws of motion dimensionally we find that on the one hand

$F = M\dfrac{dV}{dt}$ has dimensions $[MLT^{-2}]$

whereas torque

$= I\dfrac{d\Omega}{dt}$ has dimensions $[ML^2T^{-2}]$

The second equation appears to have been multiplied throughout by length to get the first and there would appear to be no reason why, in mechanical systems, that 'length' need be constant with the passage of time. There is a 'magic' in spin that I have seen elsewhere only *once* in my professional capacity – and I learned that it was called 'electromagnetism'!

I am now going to repeat the 'gyro on Eiffel Tower experiment' on the grand scale. I am going to ask a human guinea-pig called Dennis, who is aged nine, to submit himself to some rough treatment. I am going to have him stand on a circular rotatable platform and be securely fastened to a vertical pole that will revolve with it (Plate 4.12). The platform shaft is linked by sprockets and chain to another shaft carrying a handle. If I turn this handle I can make Dennis rotate in either direction. But I can do the same by giving him a spinning, offset gyro to hold, and I propose to give him the *big* one! But first I would like a much older volunteer to try to hold the 24-lb wheel and axle at arm's length, allowing the shaft to hang vertically – he cannot do this, nor to be honest, can I. But when it is spun up, using a drill (Plate 4.13), not only you and I, but young Dennis also, can hold it out horizontally, provided it is allowed to precess (see Plate 4.14).

When he is revolving, I will turn the handle so as to try to speed him up and you see an apparently Herculean act, no less, as Dennis raises (without knowing how he does so) the 24-lb mass into the air (Plate 4.15). Notice the angle of his shoulder and elbow joint and the relaxed expression on his face. This is not the face of a 9-year-old boy holding a 24-lb weight in *that* position. This act was involuntary on Dennis' part. He just found the gyro rising in his hands (Plate 4.16). Stopping him by catching the gyro, as we know, requires little effort, and freeing him again brings relief, for I know that he was much concerned lest he drop the gyro. I

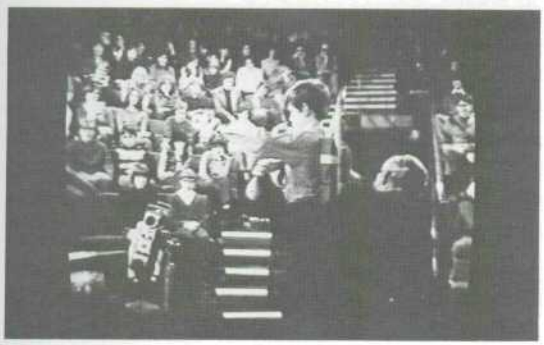


Plate 4.12 Dennis is securely tied to a pole on the turntable.

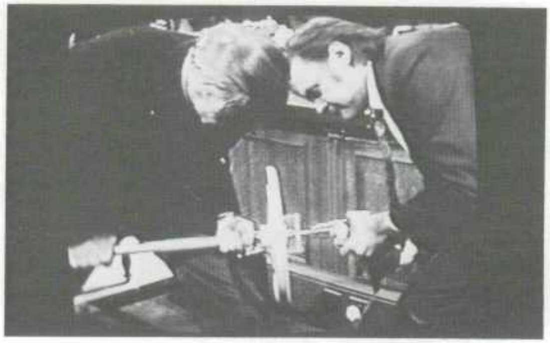


Plate 4.13 Bill and Barry spin the big wheel up to 2400 r.p.m.

Plate 4.14 Dennis rotates as he holds the big wheel.

Plate 4.15 As torque is applied the wheel lifts without pressing down on Dennis.
Is this the face of a 9-year-old boy under stress?

Plate 4.16 Eyes full of wonder, Dennis knows that the wheel rises without conscious action by himself.

want to shake this brave young man by the hand. *This is no experiment to try yourselves.* It is more dangerous than holding a sizeable sky rocket while it is burning. The big wheel is more dangerous than connecting apparatus to the household electricity supply. If the wheel were to be dropped and to run amok, I can tell you now that its energy is sufficient to throw it 200 feet into the air – and this theatre is less than sixty feet high!

You see, rotating mass is a very compact form of storing energy, more compact than most of us realise. In the league table of energy/weight ratio it comes a good third to those much sought and used creatures, nuclear fuel and chemical fuel. Electromagnetism, hydraulics, pneumatics, fuel cells, solar batteries and so on, are much lower down the table, with electrostatics bottom of the league, and car batteries not leading them by very much (which is why we have not got our electric cars yet). But we *did* have flywheel-driven buses – in Switzerland, where the route is all up hills and down. The one thing a petrol engine will not do is to pour petrol back into the tank as you go downhill. But a flywheel will accept the energy back, so there is enough energy in a flywheel to drive a bus for half a day. A nice figure to remember is that a high tensile steel flywheel spun up to its bursting speed (oh, I forgot to tell you, sometimes they burst, too!) is equivalent in energy to the same volume of water as the volume of the flywheel raised to 100,000 feet. When my colleague Professor Eastham and I accidentally burst a flywheel only 1 foot in diameter at Imperial College some two years ago, pieces of it split the 3-foot-square cast-iron lid of a circuit breaker 7 feet up the wall and hurled a half of it some 15 feet across the room. Only Providence herself dictated that we were out of the room at the time.

As one final danger signal here is a modest gyro (Plate 4.17). It is a ball race 3″ in diameter. I propose to spin it up with an airjet and let it go free on a rubber mat where the frictional force is considerable. (The result was that the gyro leapt some 10 feet in the air and was caught by Bill Coates in a butterfly net.) In rehearsal when there was no fear of hurting members of the audience, we ran the wheel faster and it leapt some 40 feet, just short of the ceiling of this lecture theatre. So stick to *small* gyros for any experiments you might like to make. By all means hang a toy gyro on a string and study its motion. There are many good projects that begin this way.

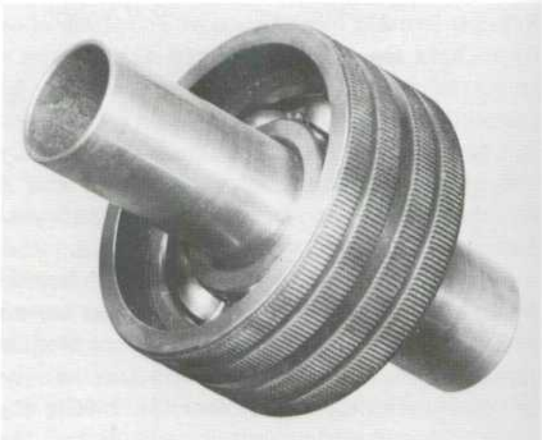
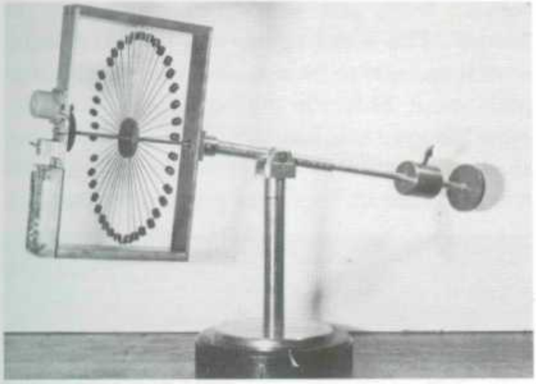
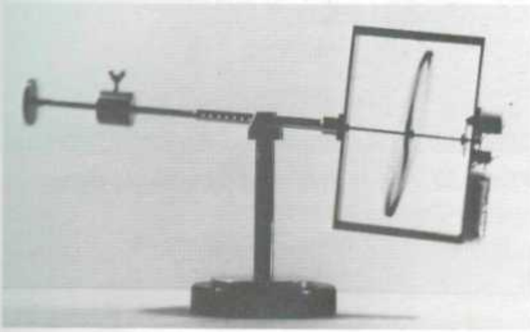


Plate 4.17 A 3″-diameter ball race to be used as a gyro.

Perhaps the only proper way to understand a gyroscope is to make its parts more flexible (as we did with the iron filings and mini magnets). Plate 4.18a shows a 'wheel' in which the heavy rim is broken up into small pieces and each piece mounted on its own spring steel, wire spoke. It is driven by a small electric motor and battery mounted on the inner ring. (The outer ring is the frame fixed to the bench.) When it has been run up to speed I give the inner ring a twist and you can see it precess. As the plane of the wheel



a



b

Plate 4.18 (a) A gyro in which the wheel is made up of masses on individual springy spokes. (b) The spoked gyro tilts due to enforced precession.

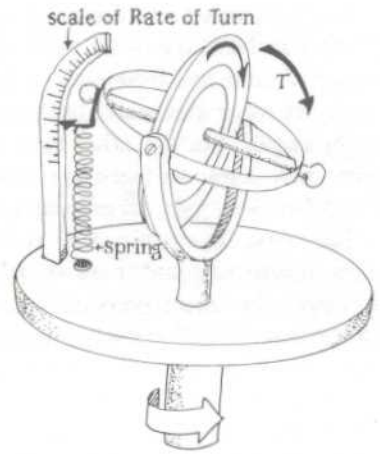


Fig. 4.19 A gyro to measure rate-of-turn.

comes into line with your eye, you can see that its plane is tilted due to attempted precession about a horizontal axis, as in Plate 4.18b. What is curious is that I do not need to keep applying torque about the vertical axis in order to keep the inner ring rotating. It appears to be capable of 'free-wheeling', as if nothing inside it was spinning at all.

It is a special case of a 'rate' gyro in which the bench and earth on which it stands are still to be seen as the 'outer' gimbal ring. The frame I spun was indeed the inner ring. It is easier to understand first the action of a more conventional rate gyro as shown in Fig. 4.19. If the turntable is rotated, that in itself constitutes precession of the outer ring. Such precession, as we have seen by analogy with a constant current electric circuit, is the cause of a torque that accelerates the inner ring until the restraining spring tension matches the demanded torque. The inner ring's deflection therefore acts as a *measure* of the rate of turn of the outer ring. This system is used as an aircraft instrument, and in space vehicles, to measure, simply, 'rate of turn'.

But beyond a few applications such as these, the gyro compass and the ship stabiliser, the subject of gyros, although older than that of induction motors, whose action they 'reflect' so well, is still relatively 'new'. In this subject the seas are remarkably uncharted and full of exciting exploratory journeys. So far I have only had time to make replicas of a few of the *real* machines I would like to try (Plate 4.19). They form a series of gyros that began with the gimballed gyro with

Plate 4.19 A series of curiously offset gyros.

all three axes coincident and mutually at right-angles (Plate 4.2). Next the offset gyro, the only type on which I have had time even to *begin* investigations. Its rotor axis meets both the other axes at right-angles, but the other two axes are orthogonal skew lines, so there are two intersections and one skew pair, all mutually perpendicular. The next has only the rotor and torque axes intersecting and there are two pairs of skew axes, the rotor/precession and the torque/precession, but all are still mutually perpendicular. Third in my line comes a monstrosity with all three pairs of skew axes, mutually perpendicular. Each of these will generate sub-families with non-orthogonal axes.

I said there was a lot to do, and I am now saying: as you do it, be sure to keep an open mind.

We have not yet covered the situation whereby energy could be injected or extracted from the rotor, other than via its bearings. If this is possible let us speculate on what this might be. Could it be a mechanical form of what we electrical engineers call 'radiation'?

One more demonstration to complete this lecture. The apparatus is a simple wheel in a bearing ring with the ring tethered near to one end of the wheel shaft and suspended from a point on the ceiling of this theatre some 50 feet above us. A retort clamp stem on the bench marks the point directly below the support point. The wheel is spun and held with its axis horizontal and with the supporting cord vertical. This cord contains a swivel to prevent it imparting torques to the gyro.

Upon release, the gyro traces out a path as shown in plan in Fig. 4.20, the end of the shaft

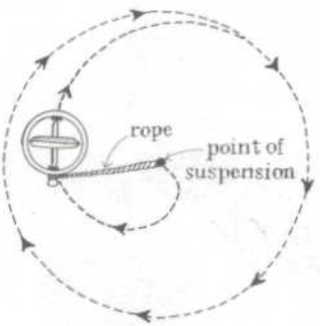


Fig. 4.20 A gyro tethered to the roof (over 50 feet high) orbiting (plan view).

remote from the supported end acting as 'leader'. The wheel spirals out from the centre until it appears to be in stable orbit in a circular path about 20 feet in diameter (see Plate 4.20). Now the gyro axis has 'drooped' to the position shown in Fig. 4.21. At first we thought that this was evidence of frictional power loss, but it is

Plate 4.20 A 16-lb gyro orbits the theatre when suspended on a 50-ft rope.

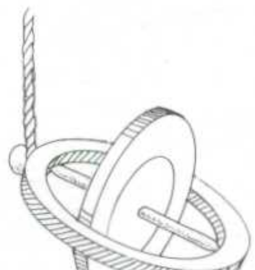


Fig. 4.21 Gyro angle when in maximum orbit.

not so. Fig. 4.22 shows that had it been otherwise it would have needed to extract energy from the rotor. Instead it chose not to raise its mass centre, as shown.

But what is happening now?–for no good reason we can find, it has begun to spiral *inwards*, still with 'nose leading' as shown in Fig. 4.23. As it does so, the axis of spin begins to rise again. Will it return to centre from where it started? No, it goes into steady orbit at about 6 feet diameter, completes about 6 revolutions–and then starts on an outward track again! Once again it reaches full amplitude, performs several orbits

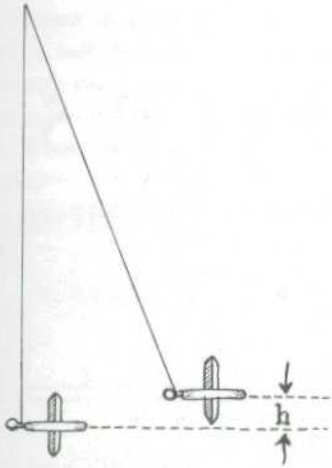


Fig. 4.22 If the gyro were to remain horizontal, how would it lift itself through height, *h*?

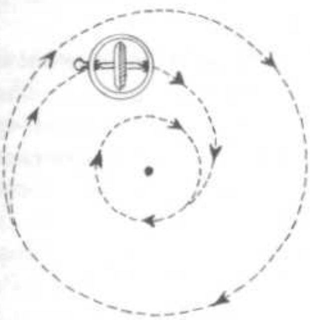


Fig. 4.23 Gyro illustrates the Bohr atom!

there and returns to the 6-foot orbit once again.

The most enthusiastic among us might be forgiven for exclaiming: 'The Bohr Atom!' It may be some twist in the string, some imperfection in the system, just some coincidence that means we cannot guarantee to repeat it. But we must keep trying and, above all, never forget.

Beware the Jabberwock, my son!
  The jaws that bite, the claws that catch!

There are many heads, many claws, but what an adventure!