The British Gliding Association Manual

Gliding

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Contents

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Introduction

What do you need to know?

Originally aimed at giving gliding instructors a general feel for how gliders work, this book is not a Technical Manual in the usual sense, and veers off into areas not directly relevant to the basic theory. Some readers may find this irritating, but there is no statutory requirement for the entire book to be read. The index at the back of the book refers readers to the chapter summaries, where concise definitions can be found, and the summaries point to the relevant page in the chapter where there are fuller explanations. A few summary items may not refer to anything explicit in the chapter text, and are there to tie up a few loose ends.

It is debatable which parts of the theory a glider pilot needs to know, and in how much detail. Ideally everyone would be interested in the theory, but it is often seen as:

(a) difficult. It would be a lie to say that it was always easy, but it is often very straightforward if you keep your head. Paradoxically, and rather annoyingly if one is clearly failing to get the point, the extreme simplicity of some of the theory can make it difficult to grasp

(b) intellectual. In the most insulting sense, intellectual is tabloid-speak for useless. Arguing that this is untrue would be regarded by such publications as intellectual

(c) requiring a brain the size of a planet. Not really. A couple of attentive neurons is usually sufficient, plus a bit of imagination

(d) causing eruptions of spots and pimples.

If you are interested in how useful Theory can be, the subject is discussed in chapter two as part of the Requirements for Flight.

Rather than provide a vast list of items which can be skipped and those which can't, the contents page of each chapter has been coded. Items which glider pilots, instructors in particular, ought to know about are marked with a ★. Less important items about which you need to know something, but where detailed knowledge isn't required, are marked with a ☆. Anything unmarked will be largely for interest. The Meteorology chapter has not been coded because if you want to know about the weather you need to know all of it, and quite a lot more.

It has been suggested by friends in engineering and science that I state that I am neither an engineer nor a scientist. Probably as a result of being a graphics illustrator, there will be errors in this book, and they will be my fault, either through misunderstanding something I've been told, or simply not believing it. Whatever else this book might have set out to do, it certainly doesn't claim to be the last word on any theory.

Readers can rest assured that whatever the current theory happens to be, reality will continue to work as well or as badly as before.

chapter 1

Definitions

Chapter contents

★ -should know ☆ -useful

1 Definitions

Skip this chapter if you are familiar with basic Physics

Scary science

Whatever your views about what scientists do, what they think they're doing, and how and why they go about doing it, there is no question that science is the most powerful tool ever to come into the hands of the human race. No other way of looking at the physical world has anything even remotely approaching science's practical horsepower, and in terms of our understanding it has been both hugely successful and, it has to be said, occasionally woundingly destructive. Either way, it has changed forever how we look at and see the world and ourselves, and, like it or not, will continue to do so in ways we cannot even guess.

Scientists are not always science's best ambassadors, and non-scientists don't always take kindly to being told they don't really know anything. Worse, when mathematics is wheeled out to provide elegant and logical proof of something – it hardly matters what – many of us experience an overwhelming desire to become completely unconscious. In fact, a general understanding of how gliders work doesn't need anything more elaborate than the 'three apples plus two pears' variety of arithmetic. We do, however, need to understand basic physics, as without it we have little chance of realising how a glider manages its tricks.

This first chapter looks at some of the basics, with many of the examples being taken from gliding. In fact, you can check out most of the physics for yourself by doing nothing more strenuous, mentally or physically, than going to an airfield and either taking a flight, or just pushing something around at the launch point.

Physics in the field

The list below contains a selection of airfield activities and some of the relevant physical laws, for the moment stated without any explanation:

- helpers somehow manage to run a glider over your foot. The pain you feel is a result of the glider's *weight* (weight equals *mass* times *gravity*)
- you are momentarily distracted by something else on the airfield. Helpers run the glider into your back. The pain you feel is related to the glider's *momentum* (momentum equals *mass* times *velocity*)
- you land on a runway. Helpers come to push the glider. Even though the surface is smooth and flat, the effort you have to make to get the glider moving,

particularly if this needs to be done in a hurry, is far more than what's needed to keep it moving once it's rolling. The difference is due to *inertia* (Newton's First Law of Motion)

- the effort you expend pushing the glider also demonstrates *energy conversion* (breakfast cereal into bodily movement) and illustrates something about *vectors* (force(s) applied in a specific direction)
- to manhandle a K13 with two people already on board up the launch queue, you first have to push down on the tail to lift the nose-skid off the ground. If you move closer to the wing you have to push down much harder to get the same result (*moments* and *levers*)
- you have a cable break on the launch. As you push over you experience a reduction in your weight (*acceleration*, Newton's First and Second Laws of Motion).

We spend every minute of every day demonstrating these and other laws to ourselves, even if we aren't aware of doing so. What is important about all the examples given above is that the physical laws they illustrate describe things which, apart from the specific injuries mentioned, happen with a high degree of regularity and predictability; all of which suggests that the world has a natural and inherent order, as indeed appears to be the case.

Dimensions

We'll take it as read that the physical world exists. If we think about why it works in the way it does rather than in any other way, then most of what we take completely for granted turns out to be a bit strange, to say the least. Take the space around us. Each of us lives at the centre of a sphere of perception dotted with objects that are separated from each other by ... well, by what exactly? Empty space? Nothing? Whatever it is, without it none of us would be anywhere.

It is useful to think of this space as either containing or consisting of three related physical *dimensions* (figure 1), at right angles to each other.

Despite the world's hills and valleys, we spend most of our life pinned by gravity to the surface of the two-dimensional plane represented by figure 1, example ②. As with so much of the natural toolbox bequeathed to us by Nature and evolution, we are not aware that our existence is governed by the need for us to continually measure and calculate where we are within the surrounding space. True, we don't leap about saying '$x^2+y^2=z^2$', or '$d=r \times \alpha$', but if we weren't doing something similar we would not last very long. The information required by the brain for the necessary calculations and comparisons comes from two main sources:

(1) force information provided by the semi-circular canals in each ear, and sensations from other parts of the body, particularly the feet and legs (tension in the muscles and so on)

(2) visual information from the eyes (directions, angles, distances).

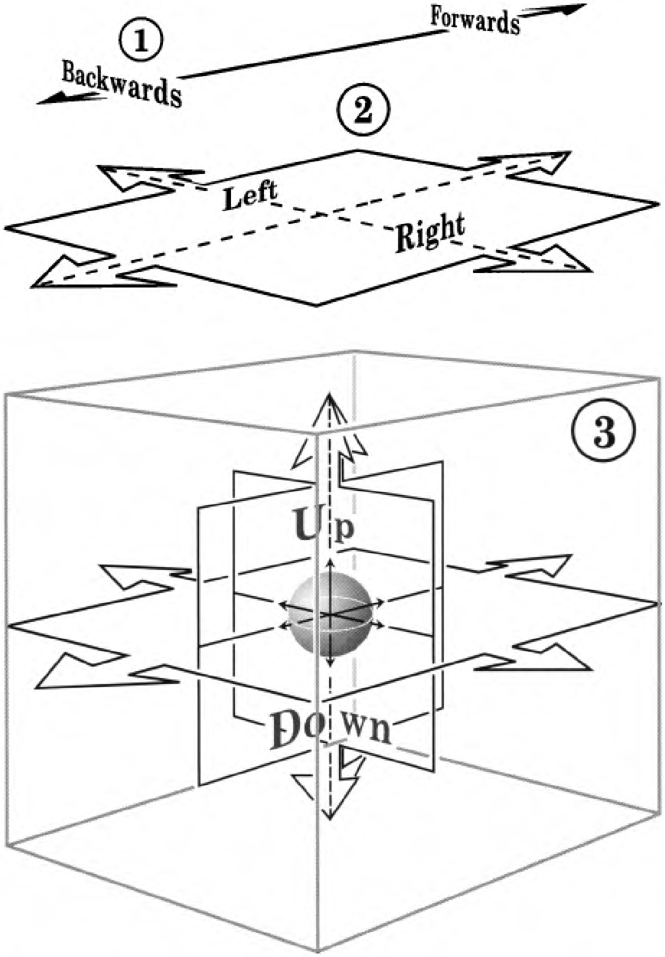


Figure 1 The three dimensions and associated planes

An apparently coherent and fluid reality is conjured out of this information, but it takes time to create it, however short, so our perceived world trails a fraction of a second behind the real one. The brain also has an editorial function, and is masterly at ignoring things which 'don't fit'. Faced with a contradiction, or a gap that 'should not be there', it will make something up. Just how much of our experience is sneakily extemporised in this way is obviously difficult to say.

Exactly how the brain decides whether a sensory input is worth including in its world view or not is another matter. Pilots are well aware when flying in conditions of good visibility, that when they bank, *they* are tilting and not the world. When circling in cloud or very poor visibility, visual input falls below some critical threshold, and 'up' becomes almost entirely dependent on the sensed, or apparent direction of gravity. In a balanced turn this is straight down our spines, i.e. in the 'upright' direction. In each ear we have three semi-circular canals which lie at right angles to each other. They contain tiny lime crystals whose contact with sensory hairs projecting into the canals supply the brain with information about orientation and acceleration. During a constant and balanced turn the crystals settle onto sensory hairs associated with 'upright'. Without instruments or any other input to confirm or contradict this message, the brain takes it to mean, quite literally, upright as in 'not banking'. Still turning, we suddenly pop out of cloud, and the world appears to have fallen over. We feel distinctly sick while the brain readjusts itself.

The reason for mentioning any of these things is that (a) there can be serious discrepancies between how we see the world and what's really happening (this begs a few questions), and (b) our personal sense of where we are is, in the most general sense of the term, self-centred, and it's difficult to see how it could be anything else. Some of the results of this can be confusing! You point at the sky and say, 'that's up'. On the opposite side of the world someone else does the same thing. A remote observer would see two people pointing in completely opposite directions. What we take to be 'up' is a universal standard only in so far as everybody relates it to themselves. 'Up' is determined largely by our body's orientation, and the direction of any forces acting upon it. Since the major force to which we are subjected appears to be weight, and, by association, gravity, 'up' normally means 'head at the top and feet at the bottom'.

Giving directions – starting from where?

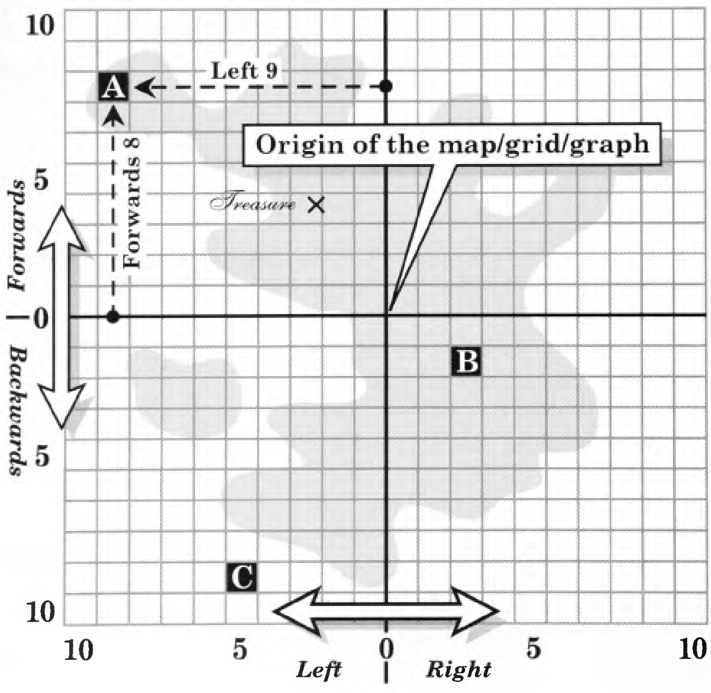
If there was only one person on the planet, the self-centred view would be neither here nor there. One could believe exactly what one liked. Suddenly, someone else appears and they are asking for directions to some place. Once over the shock, what does one actually say? Not much if we don't know where we are in relation to this other place. If we do know, then we have, in effect, to create a map, which implies measurement.

Way back, the standard might have been the length of the ruler's foot. Systems based on one person's physical quirks, however regal, are hardly ideal. The ruler will die and the foot go with him, causing economic and social distress. Maybe the foot could be cut off and pickled, but far better to persuade him to sanction an accurate reproduction to be copied by the thousand. That way everyone has access to the foot, wherever the original, and it becomes an independent, neutral, and public standard of measurement.

In whatever way a measuring system/standard is set up, it must have:

- a consistent and agreed set of units (e.g. walk 35 paces)
- an imaginary and usually regular grid centred on a fixed *origin* (e.g. start from here)
- a location defined on the grid by at least two, possibly three unique pieces of information (e.g. go east until you meet the river, then walk one mile north).

Figure 2 Maps – two dimensional coordinates



Coordinates (you are here)

To pinpoint the position of anything on a map, or a graph – both two-dimensional grids – a minimum of two *coordinates* are needed, one for each dimension. There's a left/right coordinate, and a forwards/backwards coordinate, each defined in relation to the grid's origin. For example, if you stand at position A in figure 2, your coordinates are *forwards eight, left nine.* At position B your coordinates would be *backwards two, right three.*

Whilst two coordinates are enough to define a position on the surface of a map, a minimum of three are needed to describe any position above it (figure 3). There's no point adding extra dimensions if all they do is duplicate information you already have, so on that count alone the third dimension must be at right angles to the other two.

Positions can also be defined using a *bearing* and distance from a known point, e.g. *five miles south west of Aston Down.* Our height will need describing in terms of another angle, an *elevation*, or as a vertical distance above the end of the line from the origin.

Algebra and being lost

Describing a position in terms of coordinates is straightforward if you happen to know where you are. 'I am three miles due west of the Long Mynd at 3,500ft,' you might say. But what if you're lost?

Most of us associate numbers with specific things: there are three apples in the fruit bowl and minus two hundred pounds in the current account. Easy stuff, yet confront us with numbers which aren't stuck like flags to objects, or flash us arithmetic with alphabetical bits – the cursed algebra – and the IQ gauge falls to zero. This is a very odd reaction because a lot of what we say (and do) is suspiciously algebraic. For example, we might recall that there was fruit in the bowl, but not how much or even what sort. We wouldn't think twice about saying, 'I know there's some fruit in the bowl,' but though essentially the same thing, we would not say 'there are X fruit(s) in the bowl, where X is a number.' A mathematician might describe the situation thus, but go further and lop off anything even a whisker beside the point, leaving us with a fruit-bowl-contents-probability-function such as X_{FRUIT}, or something equally cryptic.

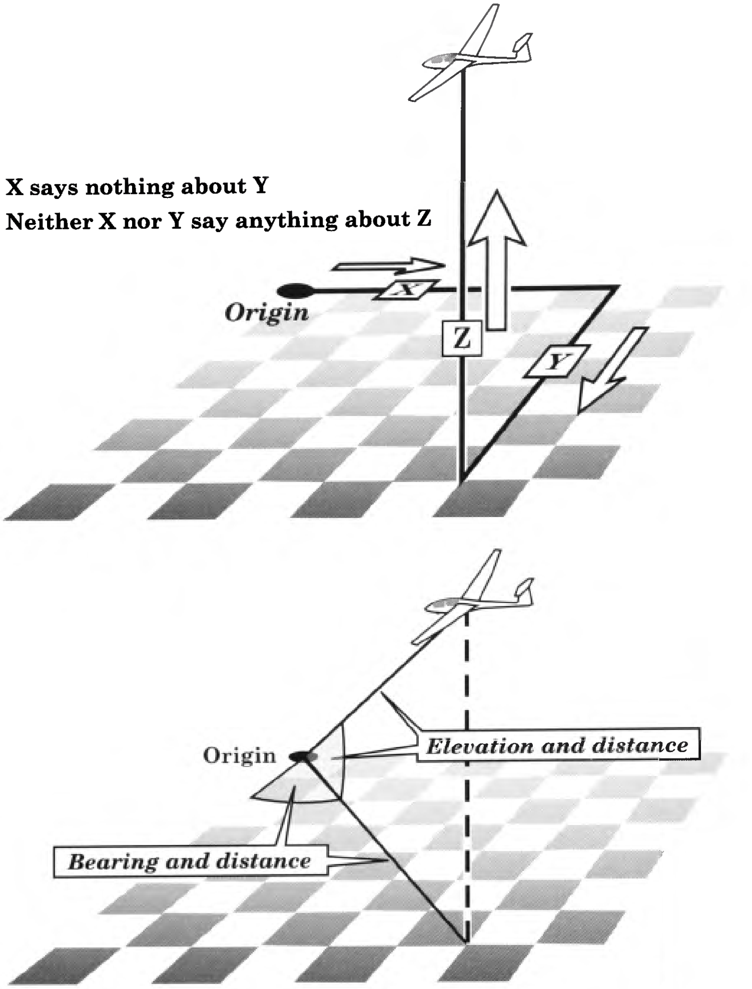


Figure 3 Three-dimensional coordinates

Whether lost in flight or not, our position requires three coordinates to describe it, either exactly (we know the numbers), approximately (we know some of the numbers), or abstractly (we haven't the faintest idea what the numbers are, but we know they're needed). If asked, we could describe our uncertain location as 'at coordinates XYZ,' where X is along, Y is up, and Z is at right angles to X and Y (figure 3). Without the numbers, this is about as helpful as saying 'Hello, I'm somewhere.'

Time's arrow

Time is also a dimension and a coordinate. A four-dimensional position report would be something like: 'I knew where I was at four o'clock.' Even though we are aware of time, it's probably true to say that no-one really knows quite what it is that clocks are actually measuring.

Forces, vectors, loads

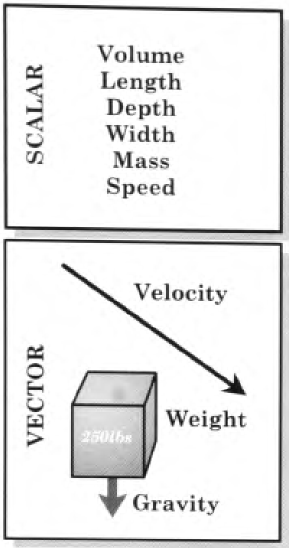


Figure 4 Quantities

Whereas objects are visible, *force* and *energy* are only so indirectly. Like many biological and biodegradable entities, we are in the unusual position of being aware of the expenditure of energy (what an effort), and can sense force (I was hit), without being able to see either of them. In order to apply forces ourselves (move this), we have to burn some of the energy stored in our bodies, and then eat to replenish the store. On that basis we might conclude that only biological organisms have energy and can apply force, but inanimate objects can have plenty of both. You can prove this by dropping a brick on your foot!

Volume, length, depth, width, mass and speed are *scalar* quantities. A *vector*, on the other hand, is a quantity which has both magnitude and direction. *Velocity*, which is speed in a specific direction, is a vector, as are gravity and weight (figure 4).

Loads are the internal response of a material to an applied force, and have no independent existence. For example, if you hold a rod just touching a wall (figure 5), no pressure or force is applied until you push the rod against it. The 'push' then becomes a load which is transferred through the rod's material to the wall. Loads are vectors.

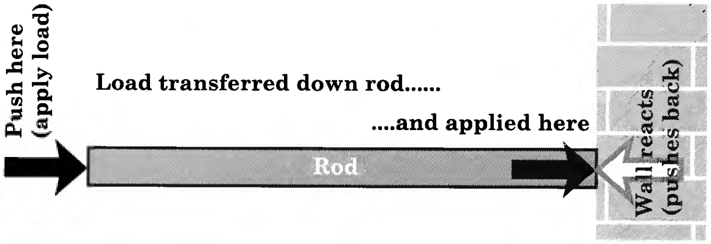


Figure 5 Loads and the transference of force

Equilibrium

Equilibrium is a condition in which all the forces involved balance out, but that doesn't necessarily lead to things being steady in the conventional sense of the term. An object can be in equilibrium when it is motionless, and when it is ripping along at several hundred miles an hour and tumbling crazily end over end. Equilibrium can be very deceptive and hide extreme forces, as seen in the following example. Out of reach in the flames of the garden bonfire is an empty aerosol can. The contents are expanding in the heat and the internal pressure is rising, yet nothing appears to be happening. Suddenly the can explodes. Shrapnel and fragments of bonfire fly all over the place. So much for equilibrium!

Weight, gravity and mass (W, G and m)

It is doubtful whether, in our everyday lives, any of us make distinction between mass and weight, and there's no reason why we should. Had the distinction been crucial to our survival, then natural selection would have shaken out sense organs capable of distinguishing between the two, but it didn't. Nor did it equip us specifically for flight, which is an area where the distinction between mass and weight is more obvious and, in some respects, far more critical. Pilots are familiar with how manoeuvring in flight can alter their weight to zero, or to so heavy that they cannot move. That these changes occur at all is significant enough, but even if we momentarily weigh nothing we don't as a result wink out of existence. Pinch yourself at the appropriate weightless moment during a vigorous push-over after a cable break and, yes, you are still there. This implies that even if weight is an inconsistent and, indeed, an unreliable quantity, there is something else which is not.

On the face of it, the pain suffered in the first two examples of airfield activities on pages 3–4 – the helpers running the glider over your foot, then into your back – have an identical cause. Yet even though weight was responsible when the glider ran over your foot, it had nothing to do with your pain when the glider ran into your back.

That 'something else' is mass, and could be defined as 'the stuff left over when you've taken weight away'. Mass creates the force we know as gravity, and gravity creates weight. Anything with mass will attract anything else which has mass, so weight depends to a certain extent on who is having the greatest effect. We attract the Earth towards us, but with little result given the scale of its effect on us. It is convenient, therefore, if not strictly accurate, to think of the Earth as being the only source of gravitation at its surface.

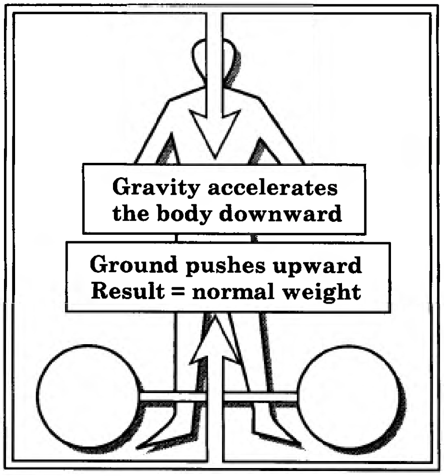
Since the Earth's mass is effectively acting upon itself, the planet's natural shape is a sphere. A falling object will accelerate towards the Earth's centre at a constant rate of 32 feet per second, every second (32ft/sec^2 or 9.8m^2), but if already on solid ground, it can't get to where it is being drawn, so one can look upon weight as the frustrated acceleration of mass. That's not to suggest that weight is an illusion – try lifting a grand piano on your own – just that it isn't quite what it seems.

Two further points need to be made about gravity and mass:

(1) two objects of dissimilar mass but similar volume, dropped together, will fall in tandem. The effects of air resistance are considerable, so this is hard to demonstrate! Assuming no air resistance, a large ball of expanded polystyrene dropped from a high tower will accelerate downwards at the same rate as a lead ball of identical volume, and they will reach the ground simultaneously, i.e. at the same velocity. Here's a practical tip: air resistance or not, if you are going to be hit by either, make sure it isn't the lead ball (see *inertia* and *momentum*, below)

(2) when we stand on any solid surface it pushes passively upwards against us with a force exactly equal and opposite to our weight (figure 6). If the ground's reaction were anything else we would either sink out of sight or be hurled into the air. The normal passive reaction has consequences for flight in that, if aircraft are to fly at all, an upward force must act upon them which is at least equal to that provided by the ground when they are sat in the hangar.

Figure 6 Ground, gravity and weight



Since the strength of Earth's gravity is broadly constant at the Earth's surface and within the wafer thin layer of the atmosphere where we conduct most of our activities, it is treated as a *constant* and, for convenience, 32ft/sec^2 is regarded as 1G. Comforting to know, because, everything else being equal, the glider which injured us earlier will always weigh the same amount no matter how often it is run over our foot.

Inertia

The same cannot always be said of *inertia*, which is the irritating thing that makes any object, particularly a large one like a glider, difficult to get moving and then equally hard to stop. Even though mass and weight are related (see box), an object's inertia is dependent solely upon its mass; the greater the mass of an object, the greater the effort required to start it moving or bring it to a halt.

Weight = Mass × g, or W = mg. If g = 1 then W = m

Measuring inertia is not straightforward. Experimenters are constantly faced by Nature's prodigal habits, and detail which they would like to study is surrounded by equally insistent detail jostling for attention, and simply getting in the way. The cleverest part of experiments aimed at measuring something specific often lie in avoiding measuring anything else! For example, try to measure inertia by moving a glider on soft ground and the wheel will dig a deep hole and want to stay in it. Most of our effort goes into trying to shove the glider up an effectively endless hill, and has nothing to do with inertia.

There are easier ways of observing inertia at work than pushing a glider all over the place. Take a spring balance and hang a large object from the hook (figure 7). The result is a minimalist model of a glider at rest on the ground. Normally we wouldn't attempt to lift a glider straight up into the air, but that's what a wing has to do, so the following experiments will tell us something about the mechanics of flight.

By lifting and lowering the balance and the suspended object several times in the ways indicated, we can come to the following conclusions:

- when lifted very slowly and steadily the scale reading remains constant
- when the balance is lifted abruptly the scale indicates briefly that the suspended object became heavier – the more so the quicker we try to raise it
- if we lower the balance very suddenly and quickly the scale reading reduces and may briefly register zero
- the same momentary loss of weight occurs if we suddenly stop moving the balance upwards.

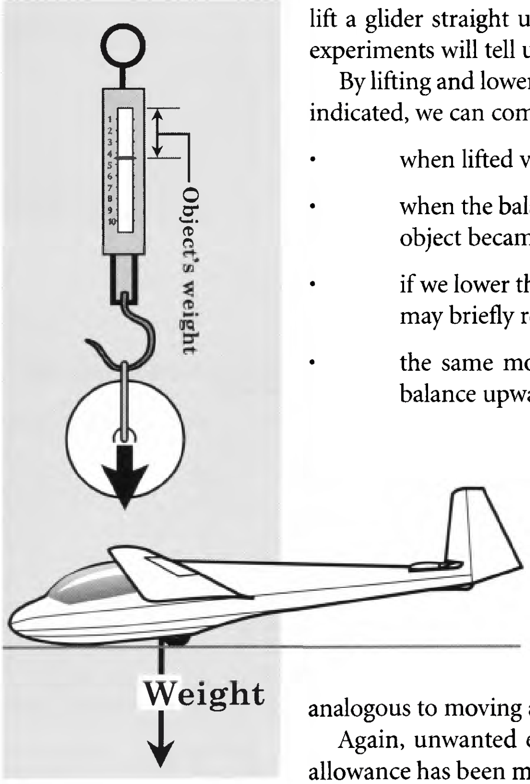


Figure 7 Spring balance, and glider at rest

The majority of these examples demonstrate inertia, and how weight is affected by acceleration. It could be argued that weight was responsible for some of the effects, but to prove otherwise we'd have to get rid of it. Impossible as that might sound, it can be done. If weight is a direct result of gravity acting on mass, and gravity acts vertically downwards, then that is the direction in which weight acts. All we have to do is support the weight in, say, a small cart. The set-up is now as illustrated in figure 8, and analogous to moving a glider around on the ground.

Again, unwanted effects like friction can make nonsense of the results, but when allowance has been made for them, we note that a sudden horizontal pull on the spring balance produces a marked positive reading on the scale. The swifter and harder we pull, the larger the initial reading. Scales normally measure weight, but because the cart and the ground have taken care of that, what we are measuring is the object's mass and inertia. Interestingly, the scale would indicate the object's weight if we accelerated the trolley sideways at 32ft/sec^2!

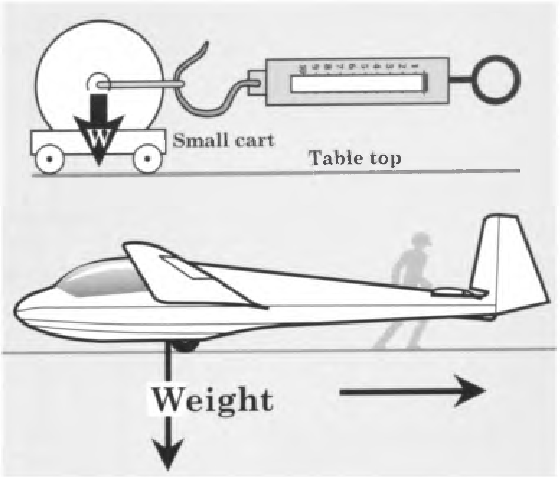


Figure 8 Measuring inertia

Momentum

Momentum is the energy possessed by a moving object. The speed and direction (*velocity*) of an object add energy to the object's mass.

A rifle bullet may only weigh a few ounces, but fired at point blank range into a plank it will pass straight through at upwards of 600mph. If the gun subsequently misfires and the bullet falls out of the barrel and bounces off the plank onto the ground, it will be clear that (a) something has gone seriously wrong, and (b) no damage has been done. The only relevant difference between the shots was the speed of the bullet which, in one case, added lethal amounts of extra energy to the bullet's small mass, and turned the other into feeble slapstick.

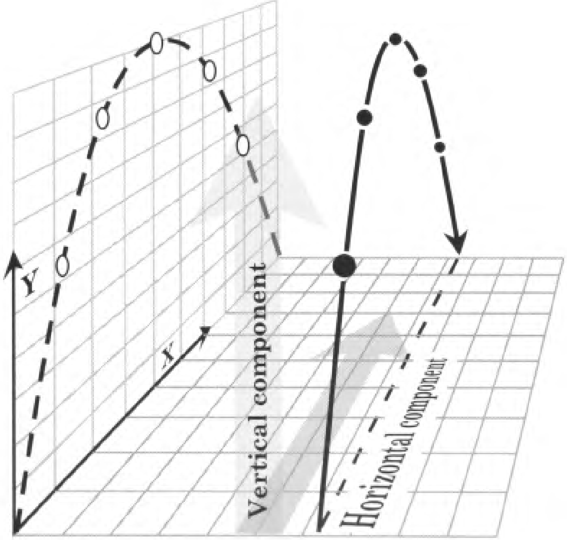
In terms of the clumsy helpers mentioned earlier, the very practical result of the above is that if they run the glider into your back very slowly, it won't hurt nearly as much as it will if they do it quickly.

Chucking one's weight about

Map coordinates help us locate where things are, but the basic principles extend to objects moving through 3D space. The flight of a ball can be treated as two-dimensional because only two coordinates are needed to describe it: a horizontal and a vertical component of velocity at right angles to each other (figure 9).

Any *ballistic object* is clearly influenced by gravity because if you throw a ball straight up it eventually comes straight down again. What is not so obvious is that this up and down motion, the vertical component, is unaffected by any horizontal component you give the ball when you throw it. The ball's vertical velocity in free flight is gravity driven and will change at a constant rate. Ignoring the considerable effects of air resistance, the horizontal velocity is dependent on how hard and at what angle the ball is thrown. Once in free flight nothing accelerates or decelerates this component – it remains constant. The result is that regardless of whether the ground is flat or not, the flight time of any ballistic object is dependent solely on the vertical component of velocity, i.e. on gravity.

Figure 9 Flight path components of a ball



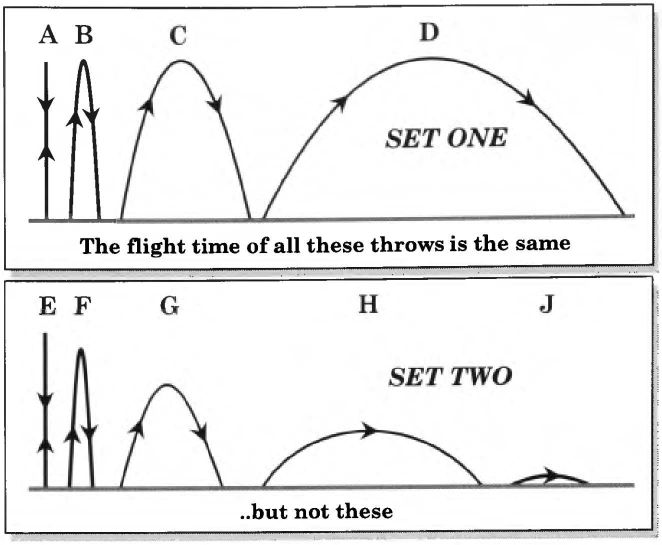


Figure 10 **Parabolic, free fall curves**

Ballistic objects trace out *parabolic curves*, and figure 10 shows two sets of these. The vertical lines, A and E represent a ball thrown vertically upwards and coming straight down again. There are differences between the two sets, but they have nothing to do with the angle of any of the throws, only with the initial force. In set one, for example, regardless of the angle, the ball is always thrown hard enough to reach the same height, and the more angled the throw the more effort has to be made (figure 11). In set two, each throw has the same initial impetus put into it. As the angle of the throw becomes shallower, more of the impetus goes into the horizontal component and less into the vertical one, so each time the ball goes less high and hits the ground sooner.

Ballistic objects in flight trace out a *free fall* parabola, and because the vertical velocity component is influenced solely by gravity (forgetting air resistance again), they are weightless. This probably doesn't sound quite right, so let's take a really surreal example. We've just fallen out of a glider at altitude and happen to have with us a pair of bathroom scales. As we accelerate downwards at 1G we are weightless, or at least, that's the theory we will now check out. We try to sit on the scales. What do they read? A lot, a little, or nothing? Contrary to everything we might expect, the reading will depend entirely on

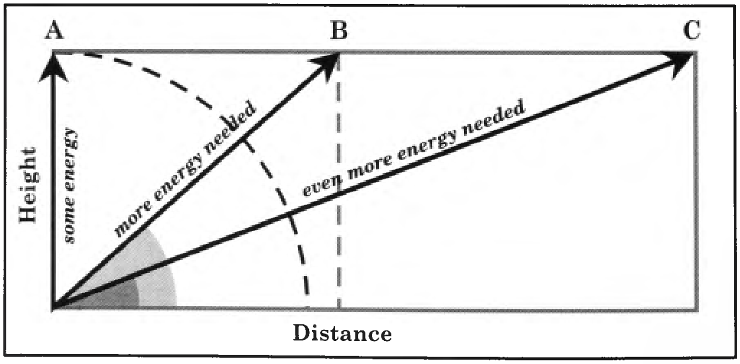


Figure 11 **Angled throws and velocity/energy input**

what we do with the scales. For example, if we just slide them underneath us, they will read zero. If we pull them up against our backsides and make a very determined effort to be 'sat down', all they will measure is how hard we are trying!

Accelerations not due to gravity

On those rare occasions when we think about acceleration, we tend to associate it with pressing down on a car accelerator and being pushed back into our seats (figure 12). Similar sensations occur at the start of a winch launch. Despite what we feel, we are not being thrust back by some unseen force from ahead, but being pushed from behind and proving rather reluctant to go forwards (inertia).

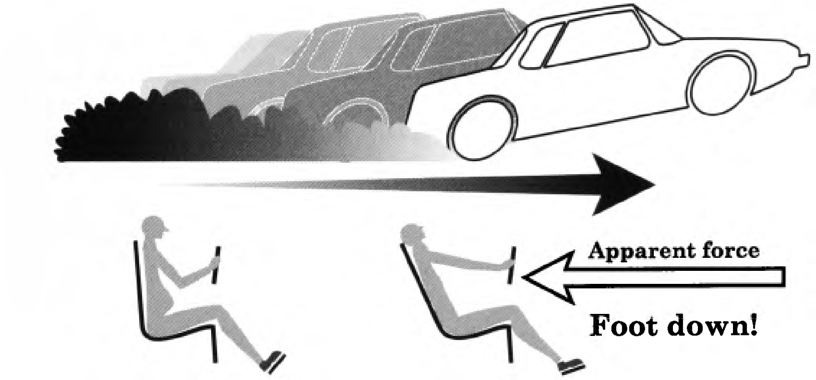


Figure 12 Normal view of acceleration

Cars and winch launches provide examples of 'fore and aft' acceleration, reinforcing the notion that acceleration is just a process of 'speeding up'. In fact, acceleration can occur in any direction and is fundamental, not only to changes of speed brought about by putting your foot down, but to changes of direction where, confusingly, we can accelerate without altering our speed in the slightest.

For instance, we are driving home at 50mph from the airfield, and reach a corner we have rounded uneventfully many times before. When we turn the wheel now, though, the car ploughs straight on through the hedge and into a field. The thought least likely to have passed through our heads is that on every corner, anywhere, the car has *always* wanted to go straight on. There is nothing odd about this. Ploughing straight on is the option involving the least effort, and 'least possible effort' is a majestically lethargic principle that dominates the material world. We may sweep round the corner at a constant 50mph, but our direction keeps changing, so a force (an acceleration) must act towards the centre of the circle whose circumference we are attempting to follow (figure 13).

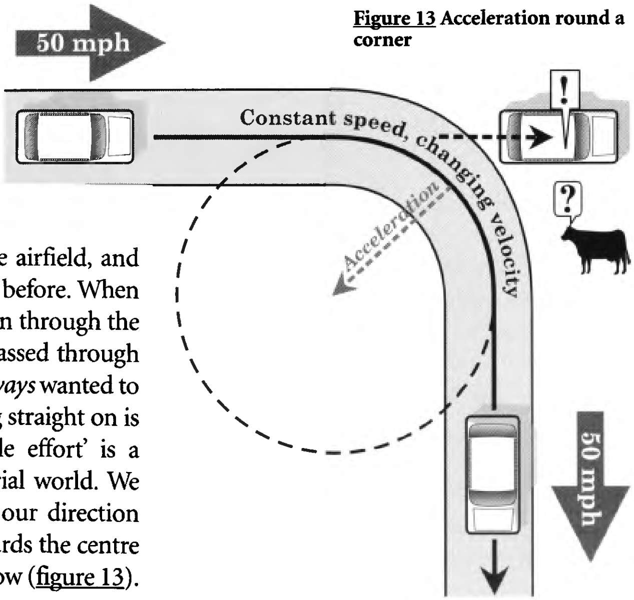
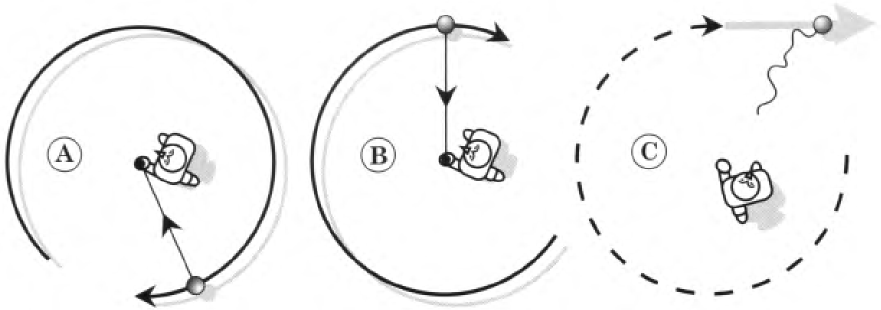


Figure 13 Acceleration round a corner

Figure 14 Stone on a string



Normally, when the steering wheel is turned, *friction* between the road surface and the tyres provides the into-turn force, but this time there was ice on the road, so turning the wheel had no effect. Unable to alter our velocity in any way whatsoever, we bowed to the principle of least effort and quit the road.

There's no need to wreck a car to understand what happened. Whirl a stone around on the end of a string (figure 14). As you whirl the stone faster the force in the string increases. If the stone normally weighed a quarter of a pound and the force in the string was three pounds, then that would be the stone's current effective weigh. Three pounds is a twelve-fold increase, so the stone was being subjected to an acceleration of 12G (3/0.25). The equivalent of 'ice on the road' here is to remove the inward accelerating force by letting go of the string. Viewed from above, the stone instantly flies off in a straight line Ⓒ.

Figure 15 Direction of gravity (G)

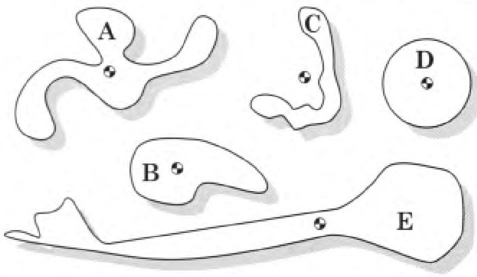


Figure 16 CG of two-dimensional shapes

Centre of gravity (CG), centre of mass

The centre of gravity of a body is its centre of mass. Because the Earth is more or less a sphere, its CG is in the centre. It can be located by noting in which direction gravity appears to be acting at various points on the surface, and then extending these *lines of action* downwards to their meeting point. Gravity acts at right angles to the surface , and so we are able to stand anywhere upon it and be in no danger of either falling or sliding off into space (figure 15).

Finding the CG of a two dimensional shape cut from card, like those in figure 16, can be done by trial and error. Pin shape A to a vertical surface, making sure it can rotate freely. With the pin placed in an arm, or along an edge, the shape will always try to hang as shown in figure 17. This is because in the starting position, there is always more of its weight/area to one side of the vertical line through the pivot than to the other. (The dumbbells represent the approximate distribution of weight to each side of the pivot line. The arrows show the direction in which the shape will swing when released.)

After some experimentation you'll find a pivot point where the shape doesn't swing whatever the position in which it begins – or, if you spin it, however fast, each and every position in which it stops will be a balanced one. This indicates that the pin is at the shape's CG, as in figure 18.

In point of fact, what has just been described is a monumentally long-winded way of locating the shape's CG. The easiest method is to pin it up by an arm, as shown in figure 19, and with a pencil draw a vertical line down from the pivot pin. Using a different pivot point, preferably as far away from the first line as possible, draw another line in the same way. These two lines will cross at the CG. How you would pin up a shape with an external CG (figure 16, example C), is anybody's guess.)

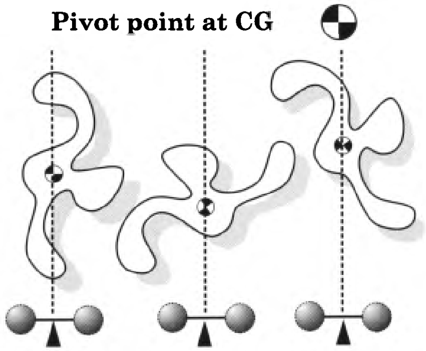


Figure 18 Pivot at CG

The CG of a two dimensional shape is the geometric centre of its surface area, but the same principle used to find its CG can be applied to certain types of 3D object. Gliders aren't spherical, they contain lots of empty space, have no appreciable gravitational effect on anything, and their mass tends to be concentrated in particular places. Even so, working out a CG position is fairly straightforward because, like most aircraft, gliders have a vertical *plane of symmetry*, i.e. left mirrors right (figure 20). Providing the glider is weighed wings level, it can be treated as if it were a two-dimensional object, and this is what CG calculations assume (see Appendix B).

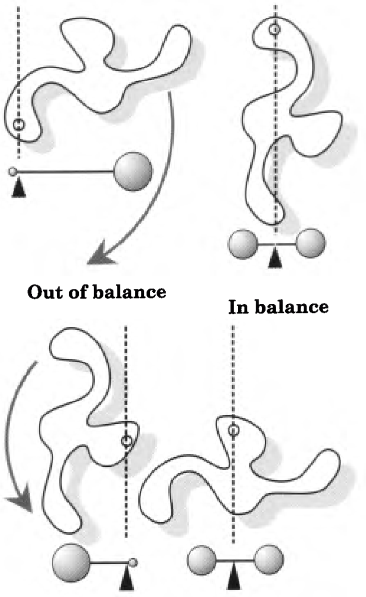


Figure 17 Pivot point locations

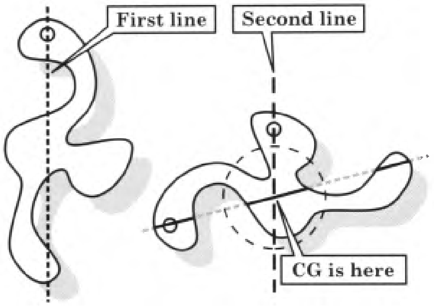


Figure 19 CG, the simple way

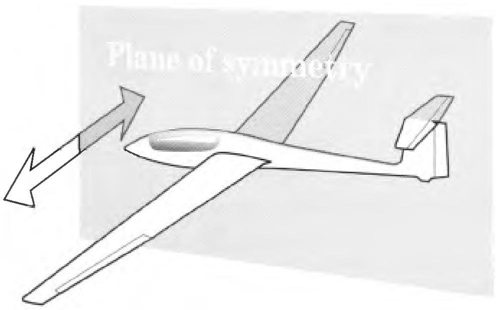


Figure 20 Plane of symmetry

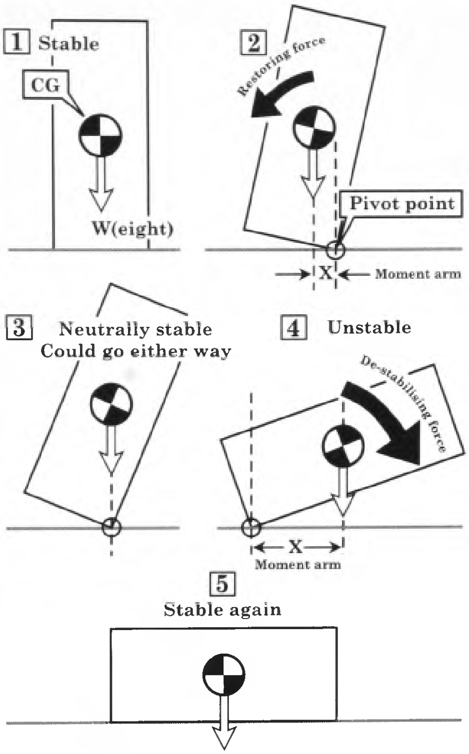


Figure 21 The toppling box

Falling over

Things topple when the *line of action* of their weight – vertically downwards from the CG – goes beyond some edge or place on the object which will act as a *pivot point* (figure 21). A ball on level ground doesn't and can't fall over because, being circular, the pivot point is always directly underneath the CG (figure 22).

As far as the box in figure 21 is concerned, it can be in one of four basic states:

(1) *Equilibrium.* The box's weight acts straight down through the middle of the base.

(2) *Positively stable.* The weight's line of action remains to the side of the initial equilibrium position, giving the box a tendency to tip back towards it.

(3) *Neutrally stable.* At some point the weight's line of action falls straight through a ground contact/pivot point, such as the box's edge. There is now the same weight/mass each side of the pivot. The box is in fine balance and can fall either way.

(4) *Unstable* or, depending on how you look at it, positively stable. The weight's line of action is well to the side of the pivot point and pulls the box over. If we think of the box as falling towards another equilibrium state [5], then [4] can be seen as positively stable.

Figure 22 Pivot point of ball

CG when there's no G

In zero gravity there would be no CG as such, so the in-balance and out-of-balance cases at which we've looked wouldn't seem to apply. However, the object still has a centre of mass, at the same place as the CG, and even if it cannot be located by any of the methods previously described, you only have to spin the object to realise the importance of where you put the pivot.

With the pivot in the wrong place the object jumps around, much as a washing machine does if it is put onto the spin cycle when the clothes inside aren't distributed evenly. Any rotating object will try to spin about its centre of mass, and any attempt to make it do otherwise produces an imbalance leading to the kind of behaviour just described.

Moments and levers

Moments and *levers* are fundamental to balance, and crucial in relation to glider stability (*see* chapter six). Moments and levers haven't been mentioned in previous sections, but they've been there, by implication.

We've all had a go on a see-saw. When someone of our weight sat on the opposite side (example Ⓐ, figure 23), everything balanced out and a joyful time was had by all. Put the inevitably heavier playground bully on the other end, and when he sat down we shot up in the air (example Ⓑ). After a bit of teasing, off he would leap and down we would crash (example Ⓒ). The practical solution to this problem is not a contract killing, but something which gives us at least an equal influence on the see-saw's behaviour.

The *moment of a force* is its distance from a pivot or *fulcrum*, multiplied by its *magnitude*. For the see-saw to balance, our two moments about the fulcrum must be equal. At the same distance from the fulcrum as ourselves, the bully had the greater moment (effect), so we took off when he sat down. If he inches nearer to the pivot and we stay put, he arrives eventually at a position where his moment about the fulcrum is the same as ours, and the see-saw balances. Alternatively, the fulcrum can be moved towards him (example Ⓓ), which puts more of the see-saw on our side and gives us some extra *leverage*. The effects are the same.

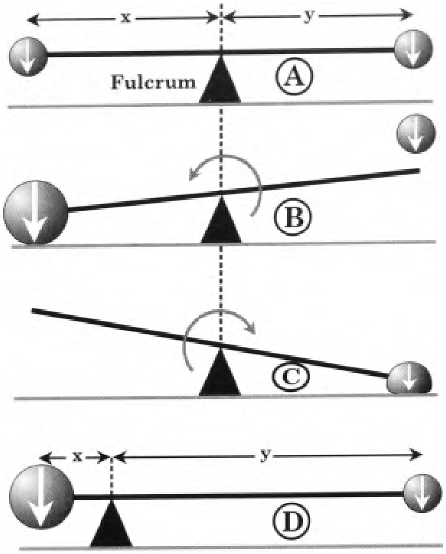


Figure 23 The see-saw

A similar see-saw act is needed to move a two seat glider around when the pilots are already strapped in. We first have to lift the nose-skid off the ground, otherwise we aren't going to go anywhere. The usual way to provide the appropriate moment is to push down on the lifting handles at the tail – line 4 in figure 24. If the pilots are very heavy, we may have to use most, if not all of our weight, but there is then so little friction between our feet and the ground that by ourselves we cannot provide any useful push.

If the combined weight of the people sitting in the cockpit is 308lb (22 stone), then their mutual fulcrum is the CG of their combined weights. This acts along line 1, three feet ahead of the glider's fulcrum, the wheel (line 2). The set-up is identical to almost all the weight being on the bully's side of the see-saw (figure 23 Ⓑ).

The formula which works out how hard you are going to have to push down on the tail ②, 11 feet behind the fulcrum, to exactly balance the people in front, is

$$W_P \times A = W_Y \times B$$

or
the left hand moment must equal the right hand moment.

What is the minimum downward force (W_Y) needed at the tail to lift the nose? Grit your teeth! $W_Y = W_P \times A/B$, which is 308 × 3 ÷ 11 = 84lb (6 stone). This only just balances the pilots' weight, so a bit more is needed to lift the glider's skid clear of the ground. If you push down just behind the wings, about four feet behind the fulcrum ③, the balancing force rises to 231lb (16½ stone). One foot closer and it is 308lb (22 stone). Six inches from the pivot it is 1,848lb, about three quarters of a ton.

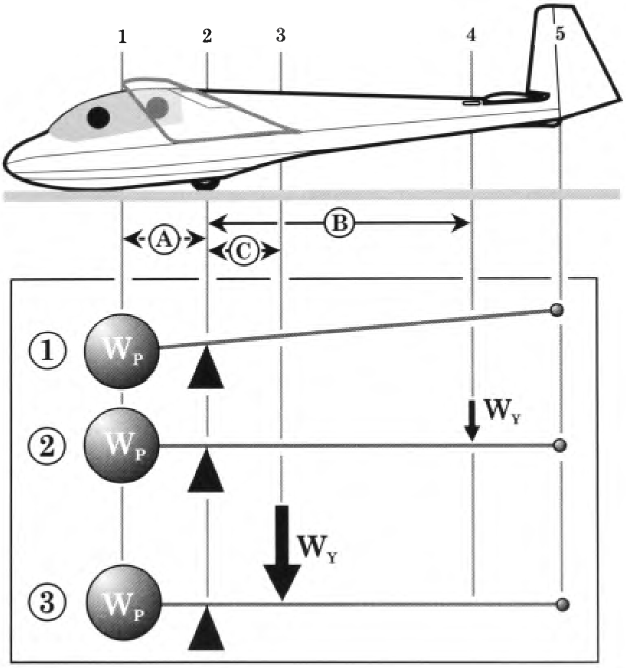


Figure 24 Raising the nose, easy or difficult?

Vectors and the resolution of forces

It is not unusual for groups of people to work against each other when they think they're cooperating, and moving gliders around is no exception. How often have you seen three people pushing on one wing and one on the other, with the wingtip holder trying desperately to keep such a lopsided set-up going in a straight line? Even two helpers can combine to successfully thwart each other's efforts, and yours.

In figure 25 Ⓐ, we have two such helpers. They are very reliable and will push consistently, or not at all. In example Ⓑ, helper H_1 always pushes eastward with a force of 100 units (lb, oz, kg, whatever), whilst helper H_2 is set on pushing blindly north with a force of 50 units. Both will act upon the glider through the same point – where the wheel contacts the ground – and the glider will respond to both their efforts.

Before these helpers even begin you can work out where the glider is likely to end up. This involves a process known as *resolution*, which can be done either mathematically or graphically. The graphical method involves drawing what is in effect a scale model of the forces involved, and uses something known as a *parallelogram of forces.*

Draw the forces out at scale lengths (1mm = 1lb, for example), ensuring that both lines start from the same point and have the correct angle between them. Complete the parallelogram, then measure the diagonal – the result, or *resultant.* Both the maths and the graphics say that when H_1 pushes the glider one foot to the East, H_2 pushes it six inches to the North. Their efforts result in a roughly norteasterly force on the glider of 111.8lb (example Ⓑ).

Example Ⓑ shows H_1 and H_2 acting at right angles to each other, but more likely they'll act at some other angle. Ⓒ shows them becoming hopelessly confused and pushing away from each other. As you might expect, the useful result(ant) is less than before (approximately 80lb), but still in a roughly north-easterly direction. In the extreme case (example Ⓓ), they are pushing in completely opposite directions. The resultant is 50lb in an easterly direction, with the helper on the left being dragged backwards. It is easy to see what a desperately inefficient way this is of returning a glider to the launch point.

Graphical resolution becomes more inaccurate the more vectors involved, and only works well for very basic situations where the forces are neither too different in magnitude, nor too alike in direction. As a way of sketching out a likely resultant, however, it will give a rough idea of what is likely to happen, and can serve as a useful cross check for any arithmetic.

When hundreds, even trillions, of small forces are acting on a surface, resolving them becomes complicated. At sea-level pressures each molecule of air is about a millionth of a millimetre from its nearest neighbour. How each behaves is critical to

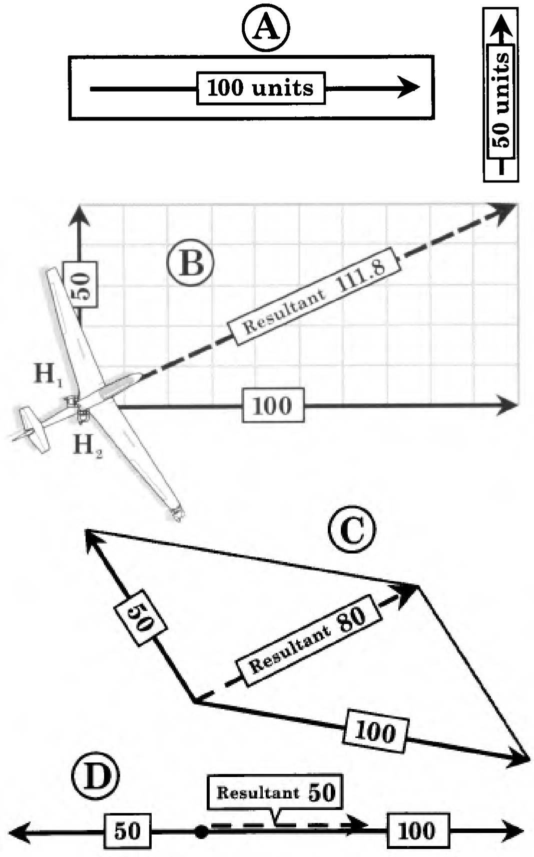


Figure 25 Vectors and their resolution

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Internet sources

These are too numerous to mention individually, but my experience is that a great deal of caution needs to be exercised when using the net as a research source, as the information isn't always reliable. Google is one of the better search engines for queries like 'Sir George Cayley', or 'Evaporation', to name but two, and will usually provide more references than anyone's ever likely to want to trawl through. Generally speaking, the first three or four pages of 'hits' are enough.

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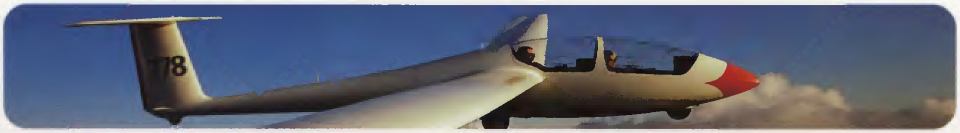

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