
The Science of Flight

by Amanda Kear & Leia Fee, with some physics advice from James Norton

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INTRODUCTION

This is a run-through of some of the physical principles behind flight by living organisms. While there is physics at the heart of this, it isn't intended just as a physics lesson (no test at the end!), but instead to give you some insight into what dragons or firelizards are up to in the air, and hopefully provide some information that will prove useful to you when writing stories.

Right, let's get over the first hurdle: **Pernese dragons can't fly!** They are just too damn big and too damn heavy to ever get airborne. There are various scientific explanations that I can think of to get around this – such as Pern being a lower gravity than Earth, or having a thicker atmosphere than Earth does, or both (like Venus). But Anne McCaffrey has made it clear in her writings that this isn't the case – Pern is as close a twin to Earth as all those planets they keep visiting on science fiction TV shows like *Star Trek* and *Stargate*. Solution two is to hand-wave and say that Pernese animals have a muscle system that is more efficient than that of Earth animals – it can throw out more power for a given size of muscle, so the flight muscles of a pigeon could keep a goose aloft. That helps a bit, but still doesn't explain how something the size of Ramoth or Mnemeth can ever get into the air without a jet engine or a helium-filled dirigible to help them.

So there are two solutions to this conundrum:

1. They just can. Don't worry about it.
2. They use telekinesis to assist in staying airborne.

Whichever of these you favour doesn't really matter when you are reading the Pern books. However, in terms of Kadanzer's take on Pern, option 1 is the favoured one. This is because Kadanzer canon does not include the books in which increasingly powerful dragon telekinesis was introduced.

So – they just can! Dragons therefore soar like an albatross, hover like a kestrel, or turn on a wingtip like a bat. In Kadanzer, however, watchwhers just [U]can't[U]. At best watchwhers can only manage short, ungainly flights like a domestic chicken does. In short, all the laws of physics apply to watchwhers, but dragons get to break a couple now and then!

This article covers:

- The Principles Of Flight
- Putting It All Together
- Getting Lift for Free
- Getting Thrust for Free
- Fast or Slow Flight?
- Wing Types
- Safety Factors and Spare Capacity – Wing Loading
- On Dragon Wings
- Flying, Soaring And Gliding
- Tails And Their Uses In Flight
- Is It Easier To Fly At Night?
- A Note on Aeroplanes and Oxygen

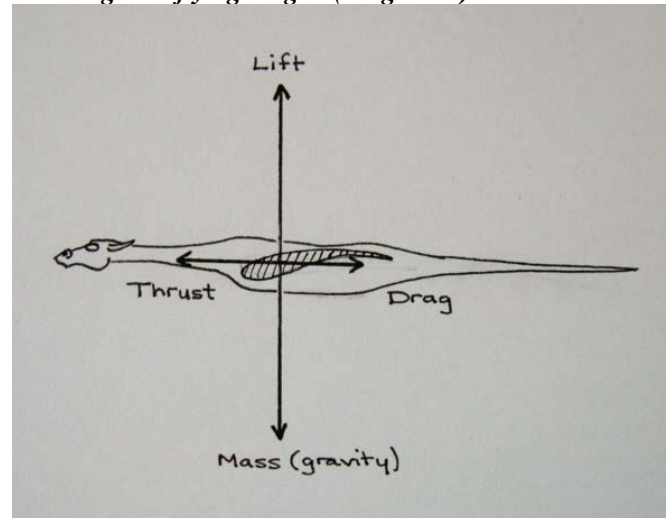


THE PRINCIPLES OF FLIGHT

This section will give you a brief run through the main principles of flight, i.e. aerodynamics. That is, what an animal has to overcome to get airborne and stay there. As an aside, all this also applies to swimming animals – it doesn't matter if the fluid you are moving through is air or water. The basic forces acting on an animal moving through a fluid are:

- Buoyancy - can be negative (so you sink), neutral (stable) or positive (you rise)
- Gravity - downward motion (sinking or falling)
- Lift - upward motion
- Thrust - forward motion
- Drag - resistance caused by the motion itself

Forces acting on a flying dragon (Diagram 1):



BUOYANCY is a measure of whether you rise, float or sink. It is how dense you are relative to what substance you are currently trying to fly through, swim through or float in. Hot air is less dense than cold air, so hot air balloons are positively buoyant and rise upwards. Being buoyant is very important in aquatic creatures – they often possess floatation mechanisms such as an air-filled swim bladder, or a liver

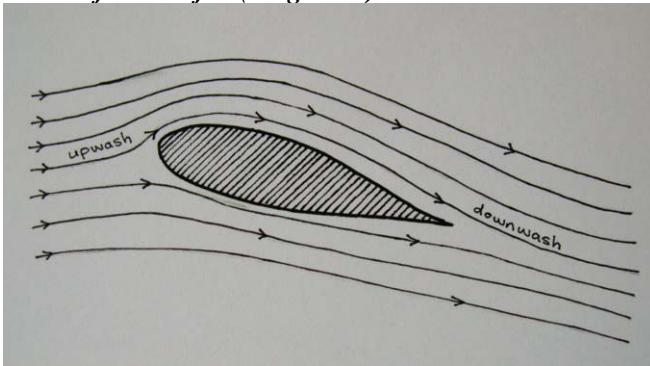
filled with low-density oils to make them neutrally buoyant (i.e. to have the same density as the water around them). But no land animals on Pern or Earth are neutrally buoyant (same density as air) or positively buoyant (lighter than air). They are all heavier than air, so we can pretty much ignore buoyancy when talking about flight in dragons and their relatives.

GRAVITY, as the saying goes, gets you down. It's the force that pulls any object towards the ground. That force pulling you down is the same at all heights a dragon can fly at and is in proportion to the mass of the thing falling. Consequently everything and everyone falls the same: accelerating at around 10 metres per second squared, rather than falling at a constant speed. The longer you fall, the faster you are travelling (at least until you reach terminal velocity – that's the speed at which drag cancels out any further acceleration. See below for more about drag). In fact, gravity's proper name is "acceleration due to gravity". This increase in speed as you fall has implications for the ability of an animal's wing to generate lift – sometimes falling can be to your advantage (see *Getting Lift For Free* below).

LIFT is upward movement. In order to fly, an animal (or aircraft) has to generate lift – otherwise it can't counteract the effects of gravity and stays firmly on the ground. Once in the air, lift must continue to be provided for the animal to avoid sinking back to the ground. Extra lift must be generated for the animal to gain altitude.

Normally, lift has to be generated actively by the animal in order to fly. Wings do this by moving through the air, causing it to flow over and under the wing. The *shape* of the wing (an aerofoil) causes the air to flow faster over the upper surface than the lower surface (see *diagram 2*). The result of this is higher air pressure under the wing and an upward motion.

Action of an aerofoil (Diagram 2):



- lower pressure above the aerofoil. The air travels a long path at a high velocity as it is accelerated over the rounded leading edge & curved upper surface of the wing. It 'falls off' the back of the wing in a downwash, and pulls the air above the wing with it. This creates a low pressure area above the wing. The more and the faster the downwash, the greater the lift it imparts to the wing.

- higher pressure below the aerofoil. The air travels a short path & has a low velocity, with a much smaller

downwash. The pressure thus remains high below the wing, so the air below it will 'push' up, attempting to equalise the areas of high and low pressure.

The amount of lift needed to get an animal, or other object, into the air is determined by its mass. For instance, it only takes a light wind to send a twig tumbling along the ground and spinning into the air. A tree trunk, however, would require a hurricane force wind to respond in the same way. If they want to get airborne, big, heavy animals like dragons will have to generate more lift than small, light ones like firelizards.

The surface area of the object also influences its ability to generate lift as air flows over it. A large sheet of paper and a small coin may both weigh 1 gram, but the paper has a larger surface area, so more lift is generated as the wind blows across it – and thus the paper is lifted by the wind more easily than the coin. Flying animals therefore have wings with a large surface area to provide them with lots of potential to create lift. It follows that a big wing can give more lift than a small wing. (For more information on different wing shapes see *Wing Types* below.)

At any given angle of attack of the wing, lift increases with increased air speed – the faster the air flows over the wing, the larger the amount of lift created. This is why aircraft have to accelerate down a runway before they take off: they are big and heavy and hence need the air to be racing across their wings before enough lift is generated for take-off. For an animal that can flap its wings – say a firelizard – more vigorous flapping will pass the air over its wings faster and thus make more lift. The firelizard can also run forward at the same time (increase its ground speed), increasing the relative speed of the air further. If the 'lizard is running forwards at 5 kilometres per hour, then air will be moving over its wings at that speed. Or the air itself may be moving (wind speed), so the firelizard could face into the wind, adding the wind speed to the total velocity of the air passing over its wings. If the 'lizard runs north at 5 kph and the wind is blowing south at 5 kph, then the air moves over the wings is 10 kph – plus whatever extra speed some vigorous flapping will add!

In summary, the bigger and heavier the animal, the more lift it needs to generate in order to take off. However, sometimes the animal can 'cheat' – see *Getting Lift For Free*.

THRUST is forward motion. Like lift, it has to be generated actively. In aquatic animals the thrust system is often separate from the lifting system: a tail at the back to generate thrust and then fins near the front to generate lift. However, on land wagging your tail can't create enough motion to push you forward. Firstly, because air is much less dense than water. Secondly, because land animals – as mentioned above – are not neutrally buoyant, so they also have to overcome friction with the ground. Tails are no use for this, but you can use your legs to run or jump as long as you are still in contact with the ground.

Once airborne, flying animals lose this help from their legs and must use their wings to both generate lift (to

function as an aerofoil) and to generate thrust (to function as a propeller).

In Earth's birds, the different types of feathers on the wing are specialised for these different functions: the primaries provide the thrust and the secondaries provide most of the lift. Dragons, watchwhers and firelizards are more like Earth's bats or pterosaurs, with naked wings made of membrane. Different areas of this naked wing are still responsible for lift and thrust, but the divisions are less easy to point to unless you are a trained dragonhealer. This can be useful if you are writing about your dragon's particular abilities or an injury sustained in Threadfall. Perhaps his wing shape gives him greater speed – that is to say more thrust – than his wingmates. Or perhaps her Threadfall injury means that she can get airborne easily enough, but finds it a struggle to make any headway – the lift areas are undamaged, but the thrust areas have still to heal.

On Pern the wherries – with their feather-fur – are intermediate between bats and birds, and will have features of both types of wing.

If you have the right type of flapping wing, they can also generate thrust in a downward direction to assist in take off – you point your nose skywards and angle your body and wings so that 'forward' is also 'up'. As a dragon's legs power her body upwards, that first downstroke of her wings will be providing not lift, but instead downward thrust to add impetus to her leap. Once that leap is underway, the dragon must quickly switch the direction of thrust and rely on lift to stay in the air. The explosive take off of a startled pigeon or pheasant is a good illustration of this type of downward thrust (see *Wing Types*).

Finally, a word about the wind and thrust. Imagine a firelizard flying at 5 kph into a headwind of 5 kph. The poor animal will be making no headway! She has plenty of lift (flapping + wind), but her forward motion is counteracted by the air propelling her backwards. However, sometimes the wind will be behind the hapless firelizard and her luck will change – see *Getting Thrust for Free*.

DRAG is resistance to motion through a fluid – basically, how much effort you have to put in to push your way through it. Air is obviously is a lot easier to move through than water, which is why an Olympic gold medal winning sprinter can do the 100 metres in a tenth of the time that an Olympic gold medal winning swimmer can do the same distance. There are three elements to drag: form, friction and turbulence. Form is how the air interacts with the animal's whole body shape – is it streamlined or as aerodynamic as a brick? Friction is the interaction of the air with the creature's skin surface. The microscopic texture of the skin can reduce air friction, and we have to imagine that the smooth hide of dragons and firelizards has this property – firelizards evolved it, and Kitti Ping made sure that dragons kept the feature. Dragon skin may feel completely smooth to human touch, but we can imagine that if we looked at it under a microscope there would be extremely tiny hairs, scales or feather-fur – just like bat wings.

Just as lift causes pressure differences over the wing, drag creates more pressure differences in an animal or aircraft's wake, as the air is displaced and thrown hither and thither. This wake of irregular vortices and eddies is known as *turbulence*. Turbulence is not a desirable thing. Energy is required to set this air in motion, so any creature that is creating a lot of turbulence is not being energy efficient.

The way to minimize turbulence, form and friction drag is to be *streamlined*. A streamlined shape keeps the air flowing smoothly over the body and – as much as possible – in its wake, rather than becoming turbulent. Obviously the posture that a dragon adopts in the air can modify its form... and thus its streamlining... and thus the amount of turbulence it creates. A dragon flying with its legs tucked up against its body will be more streamlined than one flying with its legs hanging down. A dragon with a rider and packs and bundles strapped all over its body will be less streamlined than one flying riderless and unburdened. So some activities will be more tiring than others for your dragon.

This video shows streamlining and drag in a variety of birds:

<http://www.bbc.co.uk/nature/adaptations/Flight#p00cn99m>



PUTTING IT ALL TOGETHER

Now that we've had a run through all the main factors involved in flight, we can have a look to see how they interact, and what they might mean for writing stories about dragons or firelizards! So to get started, **STABLE FLIGHT** is a system in equilibrium. It occurs when:

- LIFT is equal to MASS (i.e. it counteracts the effects of gravity)
- THRUST is equal to TOTAL DRAG on the wings and body

In this situation, the dragon is flapping happily away... but getting nowhere! She isn't sinking, but she isn't gaining height either. She isn't making headway, but she isn't losing ground. If she wants to gain more altitude or move forward, she'll have to put more effort in – in other words to increase her lift and/or her thrust.

STALLING SPEED is the lowest speed at which flight can be maintained for a given wing shape. Below this speed the wing will be generating less lift than is required to keep the animal in the air - and the animal or aircraft will stall. In colloquial terms that means the animal or aircraft will stop flying and start falling!

As noted in *Lift* (above), big animals need to generate more lift to stay aloft than small animals do, simply because they are heavier. Big animals – such as dragons – therefore must fly faster than small animals or they will stall. At very slow speeds, air is simply not passing quickly enough over their wings to generate the lift they need.

However, stalling isn't all bad. An animal may do a controlled stall in order to land – for instance a small wherry may hover, then deliberately stall and drop a few inches to

perch on a branch. That's no more dangerous than you or I jumping down from a step or small wall. But remember, an uncontrolled stall is always undesirable as it transforms flying into plummeting!

It is also worth noting that if you are landing significantly faster than stalling speed you're setting yourself up for an accident. Too fast is just as bad as too slow. Leia Fee is a pilot and says on the topic, "I'm a happy, smug little pilot when my stall warner goes 'peep' just a second or so before the wheels touch down!"



GETTING LIFT FOR FREE

A dragon can always flap furiously to generate lift, but there are other ways of getting a 'free lunch' – namely the wind and gravity. We touched on wind speed above, in our example of a firelizard running into the wind to take off. If the wind is strong enough, the firelizard could be lifted into the air simply by spreading its wings. It wouldn't have to flap at all.

Aircraft usually face into the wind when landing, unless there are extremely strong reasons not to. This is so that the wind will generate lift by passing over the wing as the aircraft (or dragon) slows down in preparation for landing. The lift created by the wind keeps the plane aloft, by making the relative speed of air over the wings (wind speed + plane speed) greater than the plane's stalling speed. If the wind suddenly drops as your dragon is coming into land, he may stall and there will be either some frantic flapping or a sudden thump!

That sudden thump is obviously due to gravity as it pulls your dragon towards the ground. But if your wings are angled in the right direction, accelerating towards the ground will send air rushing over them – and produce lift. Many birds use this phenomenon as a 'lazy' (i.e. efficient) way of getting some lift. Seabirds that nest on cliffs simply jump off! As they hurtle down, getting faster and faster, the lift created goes up and up, until they have enough to swoop upwards. In the old Kadanzer Weyr where there were ledges around a bowl, a dragon that didn't fancy vigorous flapping for take off – or whose rider enjoyed aerobatics – could instead just drop off the ledge like a sea bird. Unfortunately the ground-based wallows of the new Kadanzer Weyr mean that energy saving method is no longer an option...

It is also worth noting that the gravity assist is not a completely free lunch. You can't swoop higher than the perch you jumped off (flying in thermals excepted – see *Flying*, *Soaring* and *Gliding*), so you'll still have to flap hard to get to a decent altitude.

This video shows the landing techniques of large birds – some are noticeably better than others:

<http://www.bbc.co.uk/nature/adaptations/Flight#p00m8rz1>



GETTING THRUST FOR FREE

If you face into the wind, you get lift for free. But what if the wind is behind you? No extra lift, but that wind will be carrying you along with it. In other words, you get 'thrust' for free. On Earth some small animals, such as locusts, rely on a tailwind to migrate. If they used their own powers of flight alone, they would not travel nearly as far.

For dragons and firelizards, with their ability to go *between* a tailwind is not as important as it will be for other creatures who need to travel long distances, such as migrating wherries. But it will be something that will affect a sweeprider's patrol and Threadfighting.



FAST OR SLOW FLIGHT?

The overall area of a wing influences its performance. Both lift and drag are proportional to the wing area multiplied by the square of the speed. This puts constraints on the design of the 'optimum' wing, and results in different sizes and shapes of wing being better for different purposes. For instance:

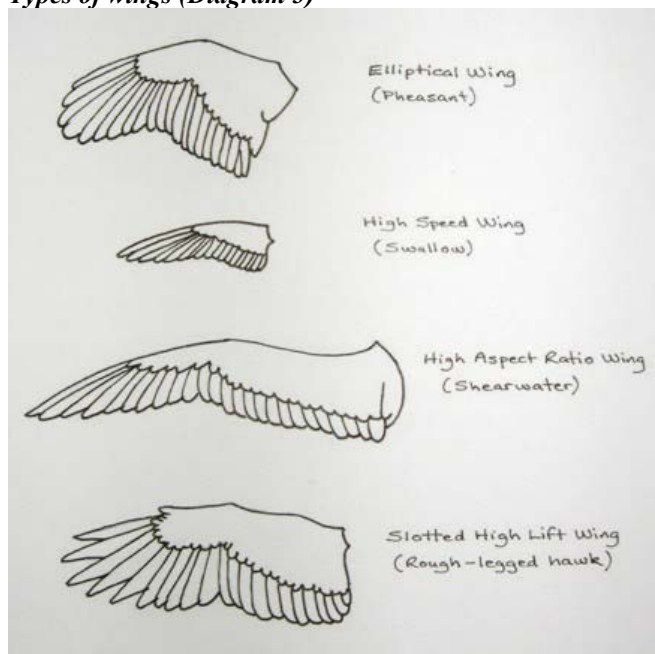
- If you want to be a fast flier, a small wing is best, because a small area means less drag. That means more of your thrust will be dedicated to moving you forwards and less to overcoming drag.
- Small wings are also lighter and easier to move, so you can flap them more swiftly than a large wing, which again makes for faster flight.
- If you are big and heavy, you need to generate a lot of lift to get into the air, so you'll need large wings to do this. A dragon with wings the size of a watchwher's can flap all it likes, but those small wings will never generate enough lift to get it off the ground.
- However, large wings will create a lot of drag, so large creatures with their correspondingly large wings will be most energy efficient if they fly slowly. It is not *impossible* for them to fly fast, but it will definitely be more tiring to do so.



WING TYPES

Wing types in flying vertebrates fall into four structural & functional types:

Types of wings (Diagram 3)



- **ELLIPTICAL WINGS** - found in those wherries and birds that are adapted to enclosed habitat, e.g. woodlands. They are associated with SLOW FLIGHT but HIGH MANOEUVRABILITY. These wings are typical of gamebirds that have fast take off speeds, but a slow, sustained flight. They want to get into the air quickly when a tunnelsnake or lizardhawk appears! An Earth example would be a pheasant.

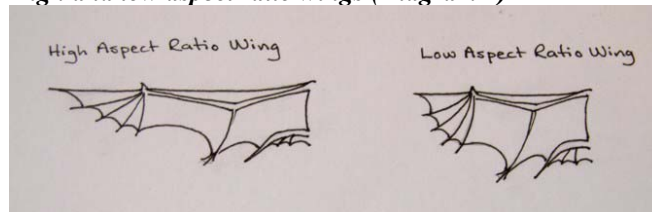
- **HIGH SPEED WINGS** – possessed by those wherries and birds that dive, stoop, or go on long migrations. They are associated with FAST FLYING birds and wherries, which flap their wings rapidly. On Earth these include falcons, swallows, waterfowl and pigeons. The Pernese equivalent of these creatures, such as the lizardhawk, will have similar wings. These wings also have high wing loading – see later section.

- **HIGH ASPECT RATIO WINGS** - are for the specialized type of flight known as ‘dynamic soaring’ which takes place over the sea (see Flying, Soaring & Gliding below). On Earth these wings are possessed by birds such as shearwaters and albatrosses. Aspect Ratio refers to the ratio between the wing’s area and its span. These wings give LOW MANOEUVRABILITY and rely on FAST GLIDING to avoid stalling. They have low wing loading – see later section.

- **SLOTTED HIGH LIFT WINGS** - are adapted for slow soaring flight, particularly ‘static soaring’ – i.e. soaring on thermals. They are possessed by large birds like storks, vultures and eagles. These wings give a SLOW flight speed and GOOD MANOEUVRABILITY, such as a small turning radius. The presence of slots (i.e. gaps between the feathers on the edge of the wing) reduces the stalling speed of the bird by permitting air to pass through the wing and thus reducing turbulence. Dragons and their relations don’t have feathers, so slots will have to be created in a different way,

such as a wing with a fluted edge or with holes in its membrane at biomechanically appropriate intervals. (Note: Steve Weston, who has illustrated the covers of many of the UK Pern books, habitually portrays his dragons with fluted edges to the wing and a few holes in the membrane. However, given his love of non-streamlined spurs and tendrils on some of his dragons, I think it was for artistic rather than aerodynamic reasons! Michael Whelan’s dragons have wings based on fruit bat wings.)

High and low aspect ratio wings (Diagram 4)



Please note that for Earthly creatures these wing types are associated with particular species, not with individuals. Dragons too would be expected to tend towards one type of wing rather than another, especially if you compare them to another Pernese species. All dragons will have slotted, high-lift wings in comparison to watchwhers’ elliptical wings or lizardhawks’ high speed wings.

However, between the different colours of dragons there will be more subtle differences within that generic species wing type. Greens perhaps have a lower aspect ratio than golds and bronzes, contributing to the generally accepted and common reference in Pern fandom to "more manoeuvrability but less stamina".



SAFETY FACTORS AND SPARE CAPACITY – WING LOADING

A dragon, bird or aircraft has limits on what its wings can manage to get into the air, without coming a cropper. Evolution – and sensible aircraft designers – have incorporated safety factors into wings. The easiest one to incorporate into stories is wing loading.

Wing loading is the weight of the creature and everything it is carrying, divided by the area of the wing. Basically wing loading tells you the maximum weight that can be supported in the air by that wing. If that weight is exceeded, then at best, the wings won’t be able to generate enough lift for take off. At worst the muscles and tendons of the wing may be injured trying. Hence the Weyrlingstaff insist that young dragons have attained a certain size and strength before they attempt to carry a rider. And a queen trying to catch a falling dragon is a very dangerous strain on her wings – she’s trying to carry the body weight of two dragons with one set of wings.

Another complication is that drag is proportional to wing loading. This means that creatures with a high wing loading are putting a lot of effort into overcoming that drag

just to move their own body around the sky – as a result those safety factors come with a cost. Creatures with a light wing loading expend less energy in flight. Soaring birds such as eagles or vultures have lighter wing loadings than powered fliers like falcons and thus require less power to sustain flight. Compare the golden eagle (0.71 g per cm² of wing) to the peregrine falcon (0.91 g per cm²). For a larger comparison, Leia's aircraft (750kg, 32' wingspan, fairly high aspect ratio as little aeroplanes go) has a wingloading of 6.4 g per cm². That's not properly aerobatic, but occasionally successful in the fun balloon popping contests her flying club goes in for.

High wing loading also decreases your manoeuvrability, so creatures with high values may have a ponderous flight. Think about that when your greenrider offers to take all her friends to the Gather, or a weyrling decides to carry an extra couple of firestone sacks 'to save time' – the poor dragon may be reduced to a cumbersome and very tiring flight.

In nature, most birds have a considerable safety factor built into their wing loading – the figure for their wing loading vastly exceeds their weight. This enables birds of prey to carry food almost as heavy as themselves, and also for a pregnant bird – or dragon – to fly before she has laid her clutch. The weight the golden eagle can carry is 1 kg in still air, or 3.5 to 4.5 kg in a favourable wind. Sometimes the eagle catches a mountain hare, but leaves half of the kill on the hillside, presumably because it is too heavy to carry away.

The dragonhealers will have a good working knowledge of what the safety factors in dragon wings are. Their advice to riders of injured dragons will reflect this: *No flying for a sevenday, then no carrying passengers for a sevenday after that.*



ON DRAGON WINGS

In flight, the wing membrane of dragons, firelizards – like that of Earth's bats – must be kept taut. There are elastic fibres and some small muscles within the wing to aid with this. The muscles of the individual digits of a dragon's or firelizard's wing 'fingers' allow fine control of the three dimensional shape of wing. This gives the dragon or 'lizard great manoeuvrability compared to many birds with wings of similar dimensions.

As they fly, creatures alter the shape and area of their wings, and the position of the wing relative to the body. A wing can be tilted, levelled, extended, retracted, angled back, angled forward, raised or lowered. This manipulation of the wing in these ways is what allows a dragon or other flying creature to do more than fly in a straight line! It is these motions, from major to subtle, that enable the flier to manoeuvre, change direction, land, take off and so on.

Air provides no support to a flying animal, therefore even stable level flight is very energy demanding. If there were two similar sized animals and one walked 10 kilometres and the other flew the same distance, the flier

would use up more energy. It would burn more calories and have to eat more food than its ground-bound counterpart to replace what was used in the journey. Long distance fliers, such as migratory birds on Earth, have to build up their fat reserves before they can attempt the journey. They also utilise various methods of flying that help them save energy, such as thermal soaring (see Flying, Soaring & Gliding below). On Pern such tactics will be likely be used by sweepriders, so as not to tire out their dragons.

Going *between* is the dragons' and firelizards' unique method of avoiding a long, tiring flight. Though, of course, teleportation will have its own energy demands. For instance, after the cold of *between* you'll have to warm up those tiny muscles in the wing membrane for them to work at maximum efficiency again.



FLYING, SOARING AND GLIDING

In colloquial use, soaring and gliding are just synonyms for flying. But when you are talking about the principles of flight, then soaring and gliding have specific meanings. Definitions and explanations are given here so that you can make use of the bits of information that interest you in your stories. But don't worry, the Kadanzer SAT will not be pouncing on you and insisting you should have written '*Nioranth soared over the Weyrhall*' rather than '*Nioranth glided over the Weyrhall*'!

GLIDING is always a downwards motion: a stable glide (where air speed remains constant in still air) is like stable level flight, but the flight path is inclined downwards at an angle. Why does a gliding dragon always lose height? Well basically a glide can only maintain its speed by a loss of altitude. The dragon or bird is holding its wings still and using the speed imbued by gravity rather than by flapping to create lift.

SOARING is a special form of gliding. An aircraft, dragon or bird can remain airborne by gliding in air masses that are rising faster than it is sinking – this is known as static soaring or thermal soaring. Thus the aircraft named 'gliders' and 'hang-gliders' would more accurately be called 'soarers' and 'hang-soarers'!

Soaring is an energetically cheap way of flight, particularly for large birds. For example, a stork uses 20 times more energy when it flies by flapping its wings, than when it flies by soaring. As dragons are very conspicuously large creatures, then soaring will be a less tiring way for them getting around than flapping flight.

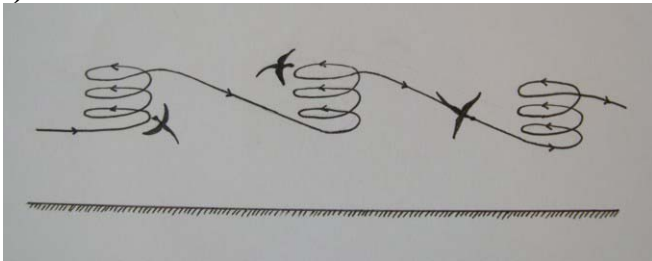
Rising air masses occur in a number of situations. One is the thermal – a column of warm air that rises because it is less dense than surrounding colder air. Thermals occur on land because some terrain heats up faster or slower than others, and heats the air above it. Spotting thermals is often easy since fluffy cumulus clouds form at the top of them. A dragon and her rider can find thermals by looking at the clouds.

Kadanzer Weyr is in the tropics, so locally there will be sea thermals, formed by the cool air of the trade winds being warmed by the heat of the ocean. Over temperate seas, and in places where there are no trade winds, those oceanic thermals will be lacking.

Thermals are quite small volumes of rising air, perhaps only a few tens of metres across. To take advantage of them, you must have a small enough turning circle to stay within the column. This isn't a problem for a vulture or a stork, but is beyond the capabilities of some aircraft. Dragons can be assumed to have a small turning circle, despite their large size, and to take advantage of thermals the way that gliders and hang-gliders do.

Remember: there are no big thermals to soar on in winter in those climates that have a winter season. That will make a difference to sweepriders flying their route at different times of year. In addition, thermals are much more limited in occurrence and extent over the sea than on land. Over the seas around Cibola or Ierne Island, a dragon will hunt for thermals in vain. In those cold climates it might be less tiring for a dragon to stick to the coast and glide from land thermal to land thermal and soar within them, rather than take a shortcut across a wide bay. But the thermal route will be much more time consuming!

Using thermals by soaring up and gliding down (Diagram 5)



The rising air of a thermal has other interesting effects that can be of use in stories. Hang-glider pilots have observed that smell and sound are both brought up to them on a thermal. One spoke of seeing a train far below them on the ground, but the sound they heard made it feel much, much closer than it was. Others mentioned the scent of crops or heather moorland on the ground as smelling much stronger than you might expect given the distance you are above it.

Another situation where your dragon may encounter rising air is where the terrain forces winds upwards – for instance when the wind hits a range of hills or a seaside cliff. Depending on local prevailing weather conditions, these may be reliable or fickle, and only relevant at very low altitude or something that a sweep rider could use at great heights. Weyrlings would be expected to learn the regular wind patterns at set locations, and how to interpret possible wind patterns in unfamiliar terrain.



TAILS AND THEIR USES IN FLIGHT

It is noticeable in the evolution of Earth's flying vertebrates – birds, bats and pterosaurs – that the primitive ones all had long bony tails, but their descendants have considerably shortened tails. Basically you seem to need a long tail to work out how to start doing this flying business, but once you've got the hang of it, you can do without. Why is this and what bearing does it have on dragons?

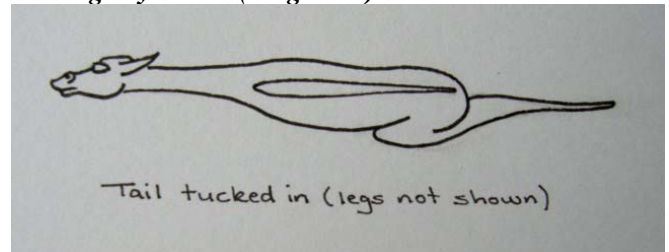
If you have a long tail, it gives great stability in flight – just what an early flyer like *Archaeopteryx* or *Rhamphorhynchus* needed. However, that stability comes at a cost, since a long tail also means low manoeuvrability. As birds, bats and pterosaurs evolved, the long tail was sacrificed to give them more flexibility in the air. To be able to dodge, weave and duck as they twisted and pounced on prey, zig-zagged between close packed branches, or evaded predators. The shortened tail could also take on other functions such as steering, since a short tail generates less drag than a long tail.

Birds like male pheasants or peacocks, which have long tails (feathers rather than bone and flesh), do it for the purposes of sexual display. It doesn't matter if you are a bit ponderous in the air, so long as you get the girls!

Dragons – both Pernese and western mythological ones – have long tails like those ancestral birds, bats and pterosaurs, and like their own ancestors, the firelizards. Which should make dragons and firelizards stable but not very manoeuvrable, though the fact that their tails are flexible rather than stiff will help a bit. 'A bit manoeuvrable', however, doesn't sound much like the Threadfighting dragons described in Anne McCaffrey's books.

One possibility is that dragons try to have the best of both worlds, by doing things with that flexible tail which are impossible for the feathered tail of a peacock or the rigid tail of a primitive pterosaur. The tail fully extended is handy for stable cruising, like a stork with its legs trailing out behind as it soars. But in other situations the dragon could pull the tail in, or tuck it in underneath itself – thus getting some of the advantages of being short-tailed, without having to wait for 2 million years of evolution to sort things out for it. A dragon would do with its tail, what a heron or pelican does with its long neck (Diagram 6). It's not a posture that is traditionally depicted in Pernese dragon art, but that doesn't mean it isn't aerodynamically useful.

Tucking in your tail (Diagram 6)



Which brings us neatly to long necks! A long neck will cause the same stability but low manoeuvrability as a long tail. Birds with long necks need them for feeding – and getting more food trumps having less manoeuvrability in the natural selection stakes every time. Some – like the heron mentioned above – tuck their necks in when in flight. Others, like swans, do not. Things would get very uncomfortable for the rider if his dragon decided it was a heron, so we can probably assume that they don't do this!

So... dragons can have long tails and long necks and still be amazingly manoeuvrable. Remember option 1: They just can. Don't worry about it.



IS IT EASIER TO FLY AT NIGHT?

The Pern books that Todd McCaffrey have written are full of information about how it is easier to fly at night because the air is cooler and therefore denser. This is his justification for the stumpy-winged watchwhers being able to perform aerial acrobatics and join in Thread fighting. But to quote Ben Goldacre, author of *Bad Science*: "I think you'll find it's more complicated than that." Cold air is indeed more dense than warm air, so in theory will support more weight. However, as mentioned in *Principles of Flight* above, dragons, birds and aircraft aren't neutrally buoyant. They are not hanging there, supported by the wonderfully dense, cool air – they get aloft by flapping like the clappers.

Denser air will require more energy to set into motion than less dense air. To put it simply, you are moving more mass, so you need to expend more effort. But cool air is also less viscous (sticky) than warm air. This means that it takes less effort to push through it (less drag). So you can see that cool night air has both pros and cons for a creature that wants to fly in it.

However, all these factors are *tiny*. If the shift from warm day to cool night is enough to let watchwhers get into the air, then they are flying on a knife edge. They have no reserve capacity or safety factors in their flying. A tiny shift in local conditions, such as a warm front moving through the area or the wher flying over the heat of the fire heights, will bring it crashing to the ground.

Factors like air temperature and density are important to animals in terms of daily energetics, not in terms of whether or not they can get off the ground. If a firelizard or bird is expending a teensy extra bit of effort to fly about, then it will have to eat a teensy extra bit of food to supply that energy. But other factors, such as the fact that it is cold in winter and food must be burned to keep warm, or it is growing a clutch of eggs within it, will dominate the creature's energy needs.

Todd McCaffrey also seems to forget that Pern – like Earth – is a planet. Planets are big. They have hot climates. They have cold climates. They have high, mountainous regions with thin air. They have flat bits at sea level with dense air. They have seasons with varying temperatures. They have weather – including high and low pressure areas

wandering about the place. As a result, the given density of the air in any given location is far more complicated than "Night = dense air, day = sparse air". Pay closer attention to your local weather forecasts and jot down some of the barometer readings – it won't be long before you come across a day with higher air pressure than one of the nights. Amanda's own city's forecast on the day she typed this predicts 1025mb at 15.00 Saturday, 1027mb at midnight Saturday and 1030mb at 9.00 Sunday morning! I rest my case, m'lud.

Anne McCaffrey never related dragons having any trouble taking off from their mountain Weyrs. And if a dragon can easily take off from a mountain Weyr on a summer day when a low pressure system is passing overhead (three situations that lead to less dense air), it is not going to have trouble in any other climate or temperature.

The important thing about the temperature is the day-to-day performance of a creature or aircraft that *can* fly, regardless. Leia observes that her aircraft undoubtedly performs better on cold days – in terms of runway length used and climb performance. At least part of that is that the engine is getting denser air to burn (see *A Note on Aeroplanes & Oxygen*), however the turn performance 'feels' sharper too. The wings sort of bite more - it feels like there's more sky holding you up, and like everything's more stable. Cold, still, high pressure winter days make Leia want to go hooning about in wingovers and lazy-eights purely for the feel of the way the aircraft handles. In contrast, a warm, humid sky makes the plane feel mushy by comparison.

So temperature and weather conditions can affect how much fun flying is, or how confident your dragon feels in the air, but it won't ground them. Nor will it allow cumbersome watchwhers to become aerobatic swallows.



A NOTE ON AEROPLANES AND OXYGEN

Powered aircraft rely on engines, not muscles, to get them aloft and keep them there. The engines consume fuel the way your car does – they burn it. They require oxygen for this combustion to happen - basically aeroplanes are air-breathers. If there is little oxygen they become less efficient. If there is no oxygen, the engine cuts out since there is nothing to combust the fuel with. (The space shuttle, the rockets used to launch satellites, and the Saturn V's that were used by the Apollo Moon Missions are non-air breathing engines, so can work in the vacuum of space.)

Leia's plane simply won't climb beyond 11,000 feet (3353 metres) – even at full throttle the aircraft just kind of wallows along with her nose way up in the air but not actually achieving any upwards motion. Which is probably just as well, because above 10,000 feet (3048 metres) is when UK flying rules say you're supposed to be on oxygen if you're hanging about longer than 30 minutes. It's also perishingly cold! The temperature typically drops off at

about 2 degrees centigrade for every 1000 feet (305 metres) of altitude.

Living creatures that breathe air – whether on land, in the sea, or in the air – do things a little differently from aircraft. Yes, they require oxygen, but their bodies have evolved to cope with the frequent times when their muscles are using it up faster than their lungs can re-supply it. The obvious example is a dolphin. Once it is underwater, there is no new oxygen available to it until it comes to the surface again!

Animals cope by storing oxygen in their body tissues, so that they can draw on it later. Earthly vertebrate animals store it in their red blood cells (using a substance called haemoglobin) and in their muscles (using myoglobin). People and animals that live at high altitudes, where the air is thin, have more red blood cells per unit volume of blood than their low altitude relatives. High altitude species that have millions of years to evolve biochemical changes to their blood possess haemoglobin that is better than normal at grabbing oxygen from the air in their lungs. Diving animals, such as seals, simply have a bigger blood supply than you would find in a land-bound animal of the same size – more blood means more oxygen can be stored in its haemoglobin.

You can tell how much myoglobin there is in the muscles of Earth's mammals and birds, by looking at the colour of their raw meat: the darker the red, the more myoglobin the muscle holds. Consequently, modern domestic chickens – which have been bred to have large breast muscles, but live in conditions where they never fly – have pale breast muscle. Pigeons, pheasants and other wild game birds that fly frequently and vigorously, have dark breast muscles. Whale and seal meat is so dark red it is almost black, because they have to hold their breath for long periods of time.

Accordingly, when these animals are not flying or diving, they are using all these mechanisms to store up oxygen in their blood and muscles for later use. In a situation where an aircraft engine might cut out, a bird would perhaps be feeling a tad short of breath, but it could keep flapping and keep aloft.

We can assume that Pernese dragons have similar adaptations. Their flight muscles will be packed with the Pernese equivalent of myoglobin. Their blood will have more 'red cells' (green cells?) with better 'haemoglobin' than creatures that never encounter the high altitudes of a sweep rider flying over the mountains. We can also assume that they have lungs more akin to birds' lungs than mammal lungs. Birds' lungs can strip about 99% of the oxygen out of the air, compared to the maximum 50% efficiency of a mammal's lungs. Therefore a dragon can fly for prolonged periods, engage in vigorous aerobatics such as fighting Thread in a stiff wind, or chasing a rising gold. All because it has a body designed to do so.

Yes, they will get tired. Yes, they will eventually have to land. And yes, that will happen quicker if the dragon is at high altitude than at sea level. But while an air-breathing plane engine at high altitude is struggling from lack of

oxygen from the instant the pilot decides to take off, a dragon is carrying a back-up supply of oxygen hidden in its muscles and blood. Its flight will be efficient and smooth until that oxygen starts to run out – signified by its muscles feeling tired, and eventually – when oxygen reaches critically low levels – cramping.

The crucial factor in a dragon's flight in low oxygen conditions or thin air is not its wings or its muscles or its lungs – it is its rider! People are mammals, and have those inefficient mammalian lungs mentioned above. The rider will be gasping for breath in conditions that don't affect the dragon at all. People need oxygen supplies to climb Everest with any vigour. If they do it without oxygen it is an incredible feat of endurance. And as they stand on the summit, gasping for breath, a flock of migrating geese will fly overhead, flapping heartily away...

One other thing to note is that when humans are suffering from lack of oxygen, their thinking becomes sluggish and they are prone to making silly mistakes (being unable to figure out why a square peg won't go into a round hole, for instance). More story fodder!



SOURCES AND FURTHER READING

- [Dynamics of Dinosaurs and Other Extinct Giants](#) by R. McNeill Alexander. Columbia University Press.
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- [Animal Flight](#) by Colin Pennycuik. Edward Arnold
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- Video of albatrosses soaring on updrafts <http://www.bbc.co.uk/nature/life/Waved...s#p00m8shb>
- Video of slow motion kestrel to show lift and hovering <http://www.bbc.co.uk/nature/adaptations/Flight#p00cnw5f>