

SCIENCE COURSE

How Flight Works

The science and story of getting airborne.

12 Chapters

Philip Osztromok

Generated with Claude

HOW FLIGHT WORKS

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How Flight Works 🏆

Chapter 1 · Why Anything Flies

An airliner weighing around seventy tonnes leaves the ground, climbs to eleven kilometres and crosses an ocean, and nothing about it looks as though it should work. Yet the explanation is not mysterious. It comes down to four forces, one fluid (the air), and one trick: a wing pushes air downwards, and the air pushes back. This course combines the physics, the history and what you feel from a passenger seat. This first chapter builds the foundation the other eleven stand on.

> **WHAT WAS RUN, AND WHAT TO TRUST**
>
> Every Python snippet in this chapter and in the three exercise solutions was executed, and the output in the comments is what Python printed. The aircraft figures (mass, wing area, lift coefficients, glide ratios) are *illustrative assumptions*, labelled where they appear, not the figures of any real aeroplane. The physical ideas are standard textbook physics. This chapter was written from established knowledge and I did **not** run a fresh web check for it, so treat the numbers as teaching values.

The Four Forces

A plane in steady, level flight is pulled and pushed by four forces. Two act up and down, two along the direction of travel.

FORCE	DIRECTION	WHERE IT COMES FROM	EVERYDAY ANALOGY
Weight	down, towards the Earth	gravity acting on the aircraft's mass	the load on a shelf
Lift	up, at right angles to the airflow	the wing deflecting air downwards	a hand held out of a moving car window and tilted
Thrust	forward	propeller or jet engine pushing air backwards	a rower's push on the water
Drag	backward, against the motion	air resistance and the cost of making lift	wading through a swimming pool

The rule is Newton's: when the forces balance, there is no change of motion. Lift equal to weight means the plane neither climbs nor sinks. Thrust equal to drag means its speed holds steady.

Change the balance and the plane accelerates in the direction of the stronger force. Climbing, descending, speeding up and slowing down are all just a deliberate shift in these four.

Air Is a Fluid

Air feels like nothing, but it is a gas made of countless molecules with mass, and at sea level a cubic metre of it weighs about 1.2 kg. Gases and liquids both flow and are both called **fluids**, and the same laws govern water around a boat and air around a wing. A wing in the air is much like a hand in water: move it and the fluid has to get out of the way. That is why engineers can test aircraft shapes in water channels and wind tunnels, a trick Chapter 2 meets when the Wright brothers build their own tunnel.

The fluid is thinner the higher you go. Density falls to roughly 0.74 kg/m^3 at 5,000 m and 0.36 kg/m^3 at 11,000 m. That matters, because the lift a wing makes depends directly on how much air it meets.

Common Misconception: Equal Transit Time

> **COMMON MISCONCEPTION**
>
> The popular story says: the top of a wing is curved and longer, so air going over the top must travel further and therefore faster to meet the air from underneath at the back; faster air means lower pressure; so the wing is sucked up. **This is wrong.** There is no law that two neighbouring bits of air must arrive at the same moment, and in real measurements the air over the top arrives *well ahead* of the air beneath. The story also cannot explain how a flat plate, or an aircraft flying upside down, can fly, since both have a "longer" lower surface.

The faster air over the top is real, and so is the lower pressure. But they are effects, not the explanation. The explanation starts with the wing changing the direction of the air.

What a Wing Really Does

A wing is tilted slightly upwards into the airflow. The angle between the wing and the oncoming air is the **angle of attack**. The air meeting the wing is bent and sent downwards behind it, a

push called **downwash**. By Newton's third law, if the wing pushes air down, the air pushes the wing up. Lift is that upward reaction.

The same event can be described through pressure: the air above the wing is pulled into a faster, lower-pressure flow, the air below is slightly compressed, and the pressure difference over the wing's area adds up to the lift force. The force-on-the-air view and the pressure view are two descriptions of one thing. One does not cause the other, and neither needs the equal-transit-time story. A curved shape (camber) helps the wing turn the air efficiently, which Chapter 3 explores in detail.

A practical way to feel it: hold a flat hand out of a moving car's window and tilt the front edge up. The hand lifts. Tilt it too far and the smooth flow breaks up, the lift falls and the drag jumps. That breakdown is the **stall**, and it is a loss of smooth airflow, not a loss of engine power.

The Lift Equation, Once

This course keeps the mathematics light, so the lift equation appears exactly once. Lift depends on the air's density (ρ), the speed (v), the wing area (S) and a number called the **lift coefficient** (C_L) that sums up the wing's shape and angle of attack:

$L = \frac{1}{2} \times \rho \times v^2 \times S \times C_L$

The key is v^2: lift grows with the *square* of the speed, so doubling the speed makes four times the lift. For a plane to leave the ground, lift must reach the weight. Weight is mass times 9.81 m/s^2.

```
import math

G = 9.81

def lift(rho, v, area, cl):
    """Lift in newtons: 0.5 * density * speed^2 * wing area * lift coefficient."""
    return 0.5 * rho * v ** 2 * area * cl

def speed_for_lift(weight_n, rho, area, cl):
    """Speed at which lift just equals the given weight."""
    return math.sqrt(2 * weight_n / (rho * area * cl))

# assumed, illustrative airliner: 70 t, 125 m2 of wing, CL 1.5 with flaps out
```

```
weight = 70_000 * G
for v in (50, 70, 90):
    print(v, "m/s", round(lift(1.225, v, 125, 1.5) / 1000), "kN")
v = speed_for_lift(weight, 1.225, 125, 1.5)
print(round(v, 1), "m/s", round(v * 3.6), "km/h")
# 50 m/s 287 kN
# 70 m/s 563 kN
# 90 m/s 930 kN
# 77.3 m/s 278 km/h
```

The weight is about 687 kN, so at 50 m/s the wing falls short (287 kN) and at 70 m/s it is still short (563 kN). It gets there at about 77 m/s, roughly 278 km/h: the speed at which an airliner of this assumed size lifts off. That is why takeoff needs a long run, and why the faster you go the easier it is. Speed alone does not keep a plane up, though. Lift needs speed *and* wing area *and* a good angle of attack *and* enough air.

Drag, Thrust and the Cost of Lift

Making lift is not free. Pushing air downwards also costs energy, and the engines supply that energy as thrust against drag. A wing that is efficient makes a lot of lift for a little drag. The ratio of the two, lift over drag, is the single best measure of how good the aeroplane is as a glider. A ratio of 15 means that for every metre of height lost the plane travels forward 15 metres. Sailplanes can exceed 40, airliners are around 15 to 20 in cruise, and a paper plane is far lower.

CRAFT (ASSUMED TYPICAL VALUES)	LIFT / DRAG	DISTANCE FROM 1,000 M OF HEIGHT
Paper plane	about 6	6 km
Hang glider	about 15	15 km
Sailplane	about 40	40 km

COMMON MISCONCEPTION

"Planes stay up because of speed alone." Speed is only one ingredient. A sailplane has no engine at all and still flies for hours, because it is a very efficient wing that trades height for forward speed. What an engine adds is the thrust to overcome drag, which keeps the speed (and therefore the lift) up. If every engine on an airliner failed, it would not drop like a stone: it would glide, as a heavy but efficient wing.

From the Passenger Seat

On takeoff you are pressed into the seat as the engines add thrust and the plane accelerates down the runway. You hear the tyre rumble stop at the moment of lift-off: lift has just overtaken weight. A few minutes later come a soft thump and a change in engine sound as flaps are drawn in and power is set for the climb. In cruise the wing is carrying the full weight of the plane, and all the while it is quietly pushing a column of air downwards. Later chapters explain each of these sensations in turn.

Challenges

EXERCISE 1

Using the lift equation and an assumed airliner (wing area 125 m^2, C_L 1.5, sea-level air), find the lift-off speed for masses of 50, 70 and 80 tonnes. Then show what doubling the speed does to the lift.

View solution

EXERCISE 2

Same 70-tonne airliner, but a cruise C_L of 0.5. Using air densities of 1.225, 0.7364 and 0.3639 kg/m^3, find the speed needed to stay level at 0, 5,000 and 11,000 m. What does it say about thin air?

View solution

EXERCISE 3

A thought experiment in gliding: with assumed lift/drag ratios of 6 (paper plane), 15 (hang glider) and 40 (sailplane), find how far each travels from 1,000 m of height, and how long it stays up at the assumed sink speeds. Why does weight not change the distance?

View solution

QUICK REFERENCE

- **Four forces:** lift against weight, thrust against drag; balanced forces mean steady flight
- **Air is a fluid:** it has mass and flows round a wing like water round a hand; it thins with height
- **Lift:** a wing at an angle of attack sends air downwards and is pushed up in return; pressure differences describe the same event
- **Equal transit time:** a myth; air over the top arrives early, and flat or inverted wings fly
- **Lift equation:** $L = \frac{1}{2} \rho v^2 S C_L$; double the speed, four times the lift
- **Glide ratio:** lift over drag; distance forward per unit of height lost

COMING NEXT

How Flight Works 2 is about dreamers and gliders: kites, Cayley, Lilienthal, the Wright brothers' wind tunnel and their control insight, and Kitty Hawk in 1903.

How Flight Works

Chapter 2 · Dreamers and Gliders

How Flight Works 1 showed that a wing makes lift by sending air downwards, and that lift grows with the square of the speed. People worked this out slowly, over centuries, and mostly by trying things. This chapter follows that trail from kites to gliders to the first powered flight, and shows why the order was glider first, engine second, and control the real prize.

> **WHAT WAS RUN, AND WHAT TO TRUST**
>
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Kites: The First Wings

The oldest flying machine is the kite. Kites were being flown in China more than two thousand years ago, and over time they were used to measure distances, carry signals and, in some accounts, lift a person. A kite is a wing held by a string: the wind provides the speed, the string provides the "engine", and the lift and drag balance exactly as in How Flight Works 1. Kites proved early that a flat, tilted surface in moving air could lift weight. They also taught a lesson that mattered later: a kite that is not stable simply tumbles.

Cayley: The Aeroplane on Paper

For centuries the dream was a machine that flapped like a bird, and nearly all of them failed. The turning point came with the English baronet **Sir George Cayley**. In 1799 he sketched a design that separated the jobs: a fixed wing to make lift, a separate means of propulsion for thrust, and a tail for stability. That layout, with wings, a tail and an engine, is still the layout of an airliner. Cayley also studied lift and drag with a whirling-arm test rig, and flew model gliders. In 1853 he is said to have flown a full-size glider carrying a person across a valley in Yorkshire, an event now remembered as the first adult-carrying glide, though accounts differ on the details.

IDEA	FLAPPING WINGS (ORNITHOPTER)	CAYLEY'S LAYOUT (FIXED WING)
Lift and thrust	one moving wing does both	wing makes lift, engine makes thrust
Engineering difficulty	very high; strong and light moving parts	manageable; a wing is a fixed structure
Outcome in the 1800s	repeated failure	the basis of every aeroplane since

Why Gliding Came Before Engines

A glider has no engine, yet it can still fly because it trades height for forward speed (the glide ratio from How Flight Works 1). That makes gliding the perfect place to learn. Nobody could build an engine light enough and powerful enough in the 1800s, but a pilot on a hill could practise controlling a wing, and a failure was a bump rather than a fire. The pattern is a familiar one for anyone in software: test the part you can control in a small environment before adding the complex part.

Lilienthal: Learning to Fly by Flying

The German engineer **Otto Lilienthal** turned the study into practice. During the 1890s he made around two thousand glides from a man-made hill near Berlin, using cambered wings (curved, like a bird's) and steering by shifting his body weight. He published tables of lift measurements, which other pioneers used, and photographs of his flights spread the idea round the world that flight was possible. His method of repeated trials is what made progress. He died in 1896 after a gust stalled his glider and he fell, a reminder that control and safety are the hard part of flight, not the lift.

> **COMMON MISCONCEPTION**
>
> "The Wright brothers invented the aeroplane out of nothing." In fact they stood on a long chain of work: Cayley's layout, Lilienthal's gliders and data, and many others. Their own contribution was something narrower and deeper: a method for *controlling* an aircraft, and the habit of testing their data rather than trusting it.

The Wrights: Control Is the Problem

Wilbur and Orville Wright, bicycle makers from Ohio, studied the earlier work and reached a key insight: the unsolved problem was not lift or power but control. A bicycle is unstable, yet a rider steers it by constantly adjusting, and they believed a pilot should do the same with a wing. Their approach had three parts.

- **Roll control by wing warping.** The pilot twisted the wing tips, so one side made more lift than the other and the plane banked, linked to a rudder for turns. (How Flight Works 4 explains roll, pitch and yaw and why modern planes use ailerons instead.)
- **A wind tunnel.** When their glider performed worse than the published lift tables predicted, they built a small wind tunnel in 1901 and tested many wing shapes, collecting their own data. This is the same fluid idea from How Flight Works 1: moving air past a fixed model is equivalent to moving a wing through still air.
- **A purpose-built propeller.** They treated the propeller as a rotating wing and designed it with their own data, rather than copying ship propellers.

From 1900 to 1902 they flew gliders at Kitty Hawk on the North Carolina coast, chosen for steady winds and soft sand. By 1902 they had a glider that could be controlled in all three directions. Only then did they add an engine.

Kitty Hawk, 17 December 1903

On the morning of 17 December 1903 the powered Flyer made four flights. The first, by Orville, lasted about 12 seconds and covered about 120 feet (37 m). The fourth, by Wilbur, lasted about 59 seconds and covered about 852 feet (260 m). The aircraft flew into a strong headwind, which is why its speed over the ground looks so low. A wing only cares about airspeed, the speed of the air past it, and a headwind adds directly to it.

```
import math

G = 9.81

def liftoff_airspeed(mass_kg, rho, area, cl):
    """Airspeed at which lift equals weight (the lift equation, rearranged)."""
    return math.sqrt(2 * mass_kg * G / (rho * area * cl))

# assumed, illustrative values: 340 kg loaded, 47.4 m2 of wing, CL 0.6
v = liftoff_airspeed(340, 1.225, 47.4, 0.6)
```

```
print(round(v, 1), "m/s", round(v * 3.6), "km/h")
for wind in (0, 5, 10):
    print("headwind", wind, "-> ground speed", round(v - wind, 1), "m/s")
# 13.8 m/s 50 km/h
# headwind 0 -> ground speed 13.8 m/s
# headwind 5 -> ground speed 8.8 m/s
# headwind 10 -> ground speed 3.8 m/s
```

With these assumed values the aircraft needs about 14 m/s (50 km/h) of airspeed to lift off. Into a 10 m/s headwind it needs only about 4 m/s over the ground, which is why early flights look so slow on the clock and why aircraft still take off and land facing the wind.

The flights were short, and the Wrights did not yet have a practical machine. But the problems that had stopped everyone before were solved: lift, thrust and control all worked together, under the pilot's command. Within a decade, aircraft were being built in several countries, a story picked up when How Flight Works 6 looks at what war did to flight.

From the Passenger Seat

Next time you taxi out, notice that the plane lines up into the wind, and that a gentle rocking in a crosswind during landing is the pilot making the same kind of constant small corrections the Wrights taught themselves on the sand. Control by continuous adjustment, a bicycle rider's skill, is still how every aircraft is flown.

Challenges

EXERCISE 1

Using the commonly cited figures for the four flights (12 s and 120 ft, 13 s and 175 ft, 15 s and 200 ft, 59 s and 852 ft), work out each flight's speed over the ground and the total time and distance. Why are these speeds not the speed through the air?

View solution

EXERCISE 2

Assume an aircraft needs 11 m/s of airspeed to lift off and accelerates at 1.0 m/s^2. Find the ground speed and the takeoff run for headwinds of 0, 5 and 10 m/s. What does this say about taking off into the wind?

View solution

EXERCISE 3

A thought experiment in hill gliding: for a launch hill of 15 m and of 30 m, and assumed glide ratios of 3, 4 and 5, find the distance and the time in the air at 10 m/s. Why did gliders alone never lead to sustained flight?

View solution

QUICK REFERENCE

- **Kites:** wings held by a string; early proof that tilted surfaces lift
- **Cayley (1799):** fixed wing for lift, separate thrust, a tail for stability: the aeroplane layout
- **Lilienthal:** thousands of glides in the 1890s; learning by repeated trials
- **Wrights:** control was the key problem; wing warping, a wind tunnel (1901) and their own data
- **Kitty Hawk, 17 December 1903:** four flights, the longest about 59 s and 260 m
- **Headwind:** airspeed = ground speed + headwind, so it shortens takeoff

COMING NEXT

How Flight Works 3 is about the anatomy of a wing: aerofoil shape, camber, angle of attack and stall, and the flaps and slats that change a wing in flight.

How Flight Works

Chapter 3 · Anatomy of a Wing

How Flight Works 1 showed that a wing makes lift by turning air downwards, and How Flight Works 2 showed that the Wrights built their own wing data because the published tables were wrong. This chapter opens the wing up: its cross-section (the aerofoil), the angle at which it meets the air, what happens when that angle goes too far, and the moving surfaces that let one wing do several jobs.

> **WHAT WAS RUN, AND WHAT TO TRUST**
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The Aerofoil: A Wing Sliced Open

Cut a wing across, front to back, and the shape you see is the **aerofoil** (airfoil in American English). The front edge is the **leading edge**, the back edge the **trailing edge**, and the straight line joining them is the **chord**. The top surface is usually more curved than the bottom. That curve is called **camber**, and a cambered wing (like Lilienthal's) makes useful lift even when it points straight along the airflow.

PART	WHAT IT IS	AN EVERYDAY COMPARISON
Chord	straight line from leading to trailing edge	the width of a page, edge to edge
Camber	curvature of the wing's mean line	a gently bowed ruler
Thickness	depth of the section, often 10 to 15 per cent of the chord on an airliner	a thick book against a thin one
Span	tip to tip distance	an arm's reach, fingertip to fingertip

COMMON MISCONCEPTION

"The curved top makes air travel further, so it must go faster to catch up, and that is the lift." How Flight Works 1 explained why this "equal transit time" idea is wrong: the two streams do not have to meet at the trailing edge. The shape matters because it guides the air smoothly downwards, not because of a race.

Angle of Attack: The Wing's Main Dial

The **angle of attack** is the angle between the chord line and the air that is arriving. It is not the angle of the aircraft against the horizon (that is called pitch), and the two can differ a lot, for example in a steep climb. Raising the angle of attack turns more air downwards, so lift goes up. It is the main control a pilot has over lift at a given speed, and it is why lift can be changed without changing speed at all.

To keep level flight, lift must equal weight. If speed falls, the angle of attack must rise to make up for it, which is why an aircraft descending to land holds its nose higher at low speed than in cruise.

Stall: When the Smooth Flow Gives Up

The lift does not keep rising forever. At a certain angle (often around 15 degrees for a typical wing) the air can no longer follow the top surface and breaks away into a turbulent wake. Lift drops sharply and drag climbs. That is a **stall**.

COMMON MISCONCEPTION

"A stall means the engine has stopped." A stall is a wing condition, not an engine one. It depends on angle of attack, not on power, and it can happen at any speed and any attitude if the angle is too large. Aircraft are designed so that the wing gives a clear warning and can be recovered by lowering the angle of attack. Pilots practise this as a routine skill.

The model below is a deliberately simple wing: lift coefficient rising in a straight line to a stall angle, then falling. It is a teaching sketch with assumed numbers, not a real wing, but it shows the shape that matters, a rise to a peak and then a collapse.

```python
import math

G = 9.81
RHO = 1.225

def lift_coefficient(alpha_deg):
    """Simple wing model: CL rises with angle, then collapses at the stall."""
    if alpha_deg <= 14:
        return 0.2 + 0.09 * alpha_deg
    return max(0.6, 1.46 - 0.12 * (alpha_deg - 14))

def lift_newtons(speed, alpha_deg, area=125):
    return 0.5 * RHO * speed ** 2 * area * lift_coefficient(alpha_deg)

weight = 60000 * G   # assumed 60 000 kg airliner
for alpha in (0, 4, 8, 12, 14, 16, 20):
    ratio = lift_newtons(80, alpha) / weight
    print(alpha, "deg -> CL", round(lift_coefficient(alpha), 2), "lift/weight", round(ra
# 0 deg -> CL 0.2 lift/weight 0.17
# 4 deg -> CL 0.56 lift/weight 0.47
# 8 deg -> CL 0.92 lift/weight 0.77
# 12 deg -> CL 1.28 lift/weight 1.07
# 14 deg -> CL 1.46 lift/weight 1.22
# 16 deg -> CL 1.22 lift/weight 1.02
# 20 deg -> CL 0.74 lift/weight 0.62
```

At 80 m/s this wing makes more lift than weight from about 12 degrees, peaks at 14, and by 20 degrees has lost about half of its peak lift, so at that angle the aircraft can no longer be held up at this speed. Note the shape: it is an edge, not a gentle slope, which is why the stall matters and why stall warning systems exist.

Flaps, Slats and Spoilers: One Wing, Many Jobs

A wing built for fast cruise is thin and nearly flat, which is poor at low speed. Rather than compromise, airliners fit moving surfaces that change the wing's shape on demand.

DEVICE	WHERE	WHAT IT DOES	USED FOR
Flaps	trailing edge, inboard	increase camber and often wing area	takeoff and landing, more lift at low speed
Slats	leading edge	open a gap that keeps air attached at high angles	delaying stall at low speed
Spoilers	top of the wing	break up the flow, dumping lift and adding drag	descent, and landing roll to put weight on the wheels
Ailerons	trailing edge, outboard	raise one wing, lower the other	rolling (explained in How Flight Works 4)

On a flight you can see this from a window seat over the wing. The panels slide back and down as you approach to land, the leading-edge slats move out, and after touchdown the spoilers pop up. The sounds and sensations are walked through in How Flight Works 12.

```
import math

def stall_speed(mass_kg, area, cl_max, rho=1.225):
    return math.sqrt(2 * mass_kg * 9.81 / (rho * area * cl_max))

# assumed 60 000 kg airliner, 125 m2 of wing
for label, cl_max in (("clean", 1.4), ("flaps and slats", 2.6)):
    v = stall_speed(60000, 125, cl_max)
    print(label, round(v, 1), "m/s", round(v * 3.6), "km/h")
# clean 74.1 m/s 267 km/h
# flaps and slats 54.4 m/s 196 km/h
```

Raising the maximum lift coefficient with flaps and slats lowers the stall speed by about 70 km/h in this example, which means a slower approach, a shorter runway and a gentler touchdown.

Why Wings Differ

A wing is a compromise, and what you want from it decides its shape.

AIRCRAFT	WING SHAPE	WHY
Glider	very long and narrow, thin, lightly loaded	a long span reduces drag from the wingtips, giving a high glide ratio and slow flight
Airliner	moderate span, swept back slightly, thin section, big flaps and slats	efficient at high cruise speed yet able to land slowly with its devices out
Fighter	short, thin, often highly swept or delta	low drag at very high speed and strength for hard manoeuvres, at the cost of high landing speeds

The sweep of an airliner wing is not decoration. It delays the problems that appear near the speed of sound, a topic for How Flight Works 7. Wingtip devices at the ends of an airliner wing, called winglets, cut the drag that the tips would otherwise create by letting high-pressure air spill round them.

From the Passenger Seat

Look at the wing from the window on a flight. On takeoff you will see the flaps set partly down and the wing visibly flexing in turbulence (it is built to). The best view of the moving surfaces is the approach, when everything extends at once. Compare it with the same wing in cruise, flat and clean.

Challenges

EXERCISE 1

For an assumed 60 000 kg aircraft with 125 m^2 of wing, compute the stall speed with a clean wing (CL max 1.4) and with flaps and slats out (CL max 2.6). By how much do the devices lower it?

View solution

EXERCISE 2

Compare the wing loading (mass per square metre of wing) and the clean stall speed of an assumed glider, airliner and fighter. What does a lightly loaded wing buy you?

View solution

EXERCISE 3

Using the chapter's simple wing model, find the angle of attack needed to hold level flight at 60, 70, 80, 90 and 120 m/s, and say which speeds are impossible with a clean wing.

View solution

QUICK REFERENCE

- **Aerofoil:** the wing's cross-section; chord, camber and thickness describe it
- **Angle of attack:** the angle between the chord and the arriving air; the main dial for lift
- **Stall:** the airflow separates above a critical angle, so lift collapses; nothing to do with the engine
- **Flaps and slats:** raise maximum lift, lowering stall speed for takeoff and landing
- **Spoilers:** dump lift and add drag
- **Glider, airliner, fighter:** long and thin, swept and flapped, short and thin

COMING NEXT

How Flight Works 4 is about staying in control: pitch, roll and yaw, the elevator, ailerons and rudder, and why a plane is both steered like a boat and balanced like a bicycle.

How Flight Works

Chapter 4 · Staying in Control

How Flight Works 3 showed how a wing is shaped and how its angle to the air sets the lift. This chapter is about the other half of flying: pointing the aircraft where you want it and keeping it there. A ship only turns on a flat surface, but an aircraft can turn about three different lines at once, and it needs a control for each.

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Three Axes, Three Motions

Picture three straight lines through the centre of the aircraft. Turning about each one has its own name and its own control surface.

MOTION	ABOUT WHICH LINE	CONTROL SURFACE	WHAT YOU SEE
Pitch	wingtip to wingtip	elevator (on the tail)	the nose rises or falls
Roll	nose to tail	ailerons (outer trailing edge of each wing)	one wing drops, the other rises
Yaw	top to bottom	rudder (on the fin)	the nose swings left or right

Each surface works as a small wing. Deflecting it changes the lift it makes, and that force, acting at a distance from the centre of the aircraft, turns the whole machine. The ailerons move in opposite directions so one wing gains lift and the other loses it, which rolls the aircraft. The elevator on the tail pushes it down or up, which pitches the nose the other way.

Steered Like a Boat and a Bicycle

The rudder swings the nose, just as a boat's rudder does, but swinging the nose alone is a sloppy way to turn in the air. To turn properly an aircraft **banks**, as a bicycle leans, so the lift of the wing points partly sideways and pulls the aircraft round. The rudder then only keeps the nose lined up with the path (a "coordinated" turn). The boat part handles the pointing; the bicycle part does the turning.

> **COMMON MISCONCEPTION**
>
> "The rudder is the steering wheel." On an aircraft the main turning control is the ailerons, which bank the wing. Using the rudder alone makes the nose skid sideways and turns the aircraft slowly and untidily. Passengers feel a coordinated turn as being pressed into the seat, not slid sideways.

Banking has a price. In a steady level turn the wing must make more lift than the weight, in proportion to one over the cosine of the bank angle, because only part of the lift now holds the aircraft up. The turn radius also depends on speed and bank, as the model below shows. The figures are for an assumed 80 m/s.

```
import math

G = 9.81

def turn(speed, bank_deg):
    bank = math.radians(bank_deg)
    load = 1 / math.cos(bank)                # lift must exceed weight
    radius = speed ** 2 / (G * math.tan(bank))
    rate = math.degrees(speed / radius)      # degrees per second
    return load, radius, rate

for bank in (15, 30, 45, 60):
    n, r, w = turn(80, bank)
    print(bank, "deg bank -> load", round(n, 2), "g, radius", round(r), "m, turn rate",
# 15 deg bank -> load 1.04 g, radius 2435 m, turn rate 1.9 deg/s
# 30 deg bank -> load 1.15 g, radius 1130 m, turn rate 4.1 deg/s
# 45 deg bank -> load 1.41 g, radius 652 m, turn rate 7.0 deg/s
# 60 deg bank -> load 2.0 g, radius 377 m, turn rate 12.2 deg/s
```

A steeper bank turns tighter but loads the wing harder. Airliners usually fly gentle turns (around 25 to 30 degrees is typical), so the passengers barely notice them.

Stability by Design

An aircraft is built so that, if a gust disturbs it, it tends to return by itself. That is **stability**. Three design features do most of the work. The **tailplane** at the back acts like the feathers of an arrow, pushing the nose back into line. The wings are often mounted with a slight upward V (**dihedral**) so that a rolled aircraft slips sideways and rights itself. The tall **fin** keeps the nose pointing into the wind like a weathercock.

Stability is a trade. A very stable aircraft is calm and restful, but slow to respond. A fighter is built close to the edge, so it turns eagerly, and a modern one uses computers to make up the difference (see How Flight Works 8). The model below pushes the nose up by 5 degrees and watches what happens with three settings: a stable aircraft that damps the motion well, a stable one with little damping, and an unstable one.

```
def pitch_response(stiffness, damping, steps=400, dt=0.05):
    angle, rate = 5.0, 0.0        # nose pushed 5 degrees up by a gust
    history = []
    for _ in range(steps):
        accel = -stiffness * angle - damping * rate
        rate += accel * dt
        angle += rate * dt
        history.append(angle)
    return history

for label, k, c in (("stable, well damped", 2.0, 3.0), ("stable, lightly damped", 2.0, 0
    h = pitch_response(k, c)
    crossings = sum(1 for a, b in zip(h, h[1:]) if a * b < 0)
    print(label, "-> crossings of level:", crossings, "| size after 20 s:", round(abs(h[
# stable, well damped -> crossings of level: 0 | size after 20 s: 0.0 deg
# stable, lightly damped -> crossings of level: 9 | size after 20 s: 1.83 deg
# unstable -> crossings of level: 0 | size after 20 s: 6269.84 deg
```

The well-damped aircraft slides back to level without swinging. The lightly damped one bobs through level nine times and is still moving after 20 seconds. The unstable one runs away: the disturbance grows without limit (a real pilot, or a flight computer, would have to catch it). That runaway is a feature of the model, not a prediction for any real aircraft.

Trim: Letting the Aircraft Hold Itself

At different speeds and loads the tail needs a different push to hold the nose steady. Rather than make the pilot hold the control all the time, the aircraft has a **trim**: a small adjustment (a small tab on the elevator, or on many airliners a movable tailplane) that shifts the neutral point so the aircraft flies hands-off at the chosen speed. Think of it as a "set and forget" setting, like the zero-offset on a sensor. On an airliner you may hear the trim motor as a soft whirr during climb or descent.

> **WHY CONTROL GETS HEAVIER WITH SPEED**
>
> The air force on a control surface grows with the *square* of airspeed, so the same deflection at twice the speed pushes four times as hard. Light aircraft have direct cables. Fast ones use powered actuators, and the pilot's feel is deliberately scaled to something comfortable. Exercise 3 puts numbers on it.

From the Passenger Seat

From a window seat over the wing you can see an aileron move just before the aircraft banks into a turn. Look at the tail on a flight if you can, where the elevators and the rudder move in small, quick steps, especially in rough air. During a gentle turn the horizon in the window tilts but your drink stays put, because the aircraft keeps the net force pressing you down into the seat. That steady feeling is the coordinated turn doing its job.

Challenges

EXERCISE 1

Using the clean stall speed from How Flight Works 3 (74.1 m/s), find the load factor and the new stall speed at bank angles of 0, 30, 45, 60 and 70 degrees. Why do airliners avoid steep banks near the ground?

View solution

EXERCISE 2

Reuse the chapter's pitch model with stiffness 2.0 and scan damping values of 0.1, 0.5, 1.0, 2.0 and 3.0. Count how many times the nose crosses level for each. What does damping do?

View solution

EXERCISE 3

Control force is proportional to speed squared times deflection. Compute the force for a 5 degree deflection at 60, 120 and 240 m/s, and express each as a multiple of the 60 m/s value. Why do fast aircraft use powered controls?

View solution

QUICK REFERENCE

- **Pitch, roll, yaw:** nose up and down, wing up and down, nose left and right
- **Elevator, ailerons, rudder:** the surfaces that control each of them
- **Turning:** bank like a bicycle, then use the rudder to keep the nose lined up like a boat
- **Banked turn:** load factor is 1 / cos(bank), and stall speed rises with it
- **Stability:** tailplane, dihedral and fin make a disturbed aircraft return; damping stops the bobbing
- **Trim:** removes the steady control force at the chosen speed

COMING NEXT

How Flight Works 5 turns to power: propellers and piston engines, Whittle and von Ohain, and why modern airliners carry such enormous fans.

How Flight Works

Chapter 5 · Engines and Thrust

How Flight Works 4 showed how an aircraft is steered. None of that works without thrust, the forward push that balances drag (How Flight Works 1). This chapter follows the engine from the first petrol piston motors to the great fans on a modern airliner, and keeps returning to one idea: every engine makes thrust by throwing air backwards.

> **WHAT WAS RUN, AND WHAT TO TRUST**
>
> Every Python snippet in this chapter and in the three exercise solutions was executed, and the output in the comments is what Python printed. The numbers (speeds, flows, efficiencies) are *illustrative assumptions* and are not data for any real engine. I did **not** run a fresh web check for this chapter, so treat the history and descriptions as standard textbook material and check a manufacturer or aviation-authority source before quoting any figure.

Thrust Is Thrown Air

Newton's third law does the work. An engine pushes air backwards, and the air pushes the aircraft forwards. The thrust is the mass of air moved each second multiplied by how much faster it leaves than it arrived. A propeller is a rotating wing that does this to a big slice of air. A jet does it by burning fuel in the air flowing through the engine and letting the hot gas rush out of the back.

That gives a choice: move a little air very fast, or a lot of air gently. For the same thrust, the gentle option wastes far less energy as fast-moving exhaust, and that single fact explains most of the history below.

Propellers and Piston Engines

The Wright brothers (How Flight Works 2) built a light petrol engine and two propellers, shaped like twisted wings. For almost forty years, the piston engine turning a propeller was the only choice. Engines grew from a few horsepower to thousands, gaining multiple rows of cylinders, superchargers to cope with thin high-altitude air, and propellers whose blade angle could change in flight, like gears on a bicycle.

A propeller is very efficient at moderate speed, but its thrust falls as the aircraft speeds up, and its blade tips run into trouble near the speed of sound (How Flight Works 7). Pistons are also heavy for the power they give. Both limits pointed toward a different kind of engine.

Whittle and von Ohain

In England, Frank Whittle patented the idea of a gas-turbine jet engine in 1930. In Germany, Hans von Ohain, working independently with the Heinkel company, built a working jet engine, and the Heinkel He 178 made the first jet-powered flight in August 1939. Whittle's engine flew in the Gloster E.28/39 in May 1941. Neither engineer knew of the other's work at first. How Flight Works 6 returns to how war pushed the jet into service.

> **COMMON MISCONCEPTION**
>
> "A jet engine pushes against the air behind it." It does not need anything to push against: the thrust comes from the reaction to the gas leaving the engine, which is why rockets also work in space. Any engine that throws mass backwards gets a forward push.

How a Jet Engine Works

A jet engine is a continuous loop of four steps, in a row from front to back.

STAGE	WHAT HAPPENS	AN EVERYDAY PICTURE
Intake and compressor	air is squeezed to many times its pressure	a bicycle pump
Combustor	fuel is sprayed in and burns steadily	a gas ring on a cooker
Turbine	the hot gas spins a wheel that drives the compressor	a windmill on the exhaust
Nozzle	the remaining hot gas leaves fast, making thrust	a hose with the thumb over the end

The turbine takes only the power needed to keep the compressor turning, and the rest of the energy goes out as the fast jet. A pure **turbojet** sends all its air through that core. It is simple

and fast, but loud and thirsty at everyday speeds, because its exhaust is so much faster than the aircraft.

Why Airliners Have Huge Fans

A **turbofan** puts a large fan at the front, driven by the core's turbine. Most of the air goes round the outside of the core (the *bypass*) and leaves gently, and only a small part passes through the core itself. The model below uses the efficiency formula for a propulsive jet, 2 divided by (1 plus exhaust speed over flight speed), at an assumed flight speed of 250 m/s.

```
V0 = 250.0

for label, ve in (("turbojet", 700.0), ("early turbofan", 450.0), ("modern turbofan", 32
    eff = 2 / (1 + ve / V0)
    wasted = 1 - eff
    print(label, "-> exhaust", round(ve), "m/s, propulsive efficiency", round(eff, 2), "
# turbojet -> exhaust 700 m/s, propulsive efficiency 0.53 , wasted 0.47
# early turbofan -> exhaust 450 m/s, propulsive efficiency 0.71 , wasted 0.29
# modern turbofan -> exhaust 320 m/s, propulsive efficiency 0.88 , wasted 0.12
```

The bigger the bypass, the slower the average exhaust and the less energy is wasted. The next model adds a fan to a core that makes 100 kg of air per second, with an assumed core exhaust of 600 m/s and fan exhaust of 300 m/s, and shows how thrust grows with bypass ratio (fan air divided by core air).

```
def bypass(core_flow, ratio, core_ve, fan_ve, v0=250.0):
    fan_flow = core_flow * ratio
    thrust = core_flow * (core_ve - v0) + fan_flow * (fan_ve - v0)
    return fan_flow, thrust

for ratio in (0, 2, 5, 9, 12):
    ff, t = bypass(100, ratio, 600, 300)
    print("bypass", ratio, "-> fan air", round(ff), "kg/s, thrust", round(t), "N, thrust
# bypass 0 -> fan air 0 kg/s, thrust 35000 N, thrust per kg of core air 350
# bypass 2 -> fan air 200 kg/s, thrust 45000 N, thrust per kg of core air 450
# bypass 5 -> fan air 500 kg/s, thrust 60000 N, thrust per kg of core air 600
```

```
  # bypass 9 -> fan air 900 kg/s, thrust 80000 N, thrust per kg of core air 800
  # bypass 12 -> fan air 1200 kg/s, thrust 95000 N, thrust per kg of core air 950
```

The same core gives far more thrust when it drives a bigger fan, which is why airliner engines have grown wider over the decades. The limit is practical: a fan this large is heavy and needs ground clearance under the wing. A **turboprop** takes the same idea further, using the core's turbine to turn a propeller (a very high-bypass engine in effect), which suits slower regional flights.

ENGINE	MOVES	GOOD AT	TYPICAL USE
Piston and propeller	a lot of air, slowly	low speed, low cost	light aircraft
Turbofan	air at medium speed	fast and efficient cruise	airliners
Turbojet	a little air, very fast	very high speed	early jets, some military aircraft

Thrust Against Fuel

Engineers care how much fuel it takes to push an aircraft a given distance. The work done is thrust times distance, and the fuel needed is that work divided by the engine's overall efficiency and by the energy in each kilogram of fuel. Exercise 2 puts numbers on it. The lesson is that every percent of efficiency gained is a percent of fuel saved, on every flight, which is why engine design is so heavily tuned.

From the Passenger Seat

On the ground you hear the whoosh of the fan and, at takeoff, a deep roar that quietens as the engines are throttled back for the climb. In a turboprop the cabin hums at the propeller's blade rate. Look at the engine from a window seat: the large inlet at the front is the fan, and the smaller circle in the middle of the exhaust is the core. On landing you may see panels slide open on the engine casing, and hear the engine note rise as the thrust reversers redirect the air forwards to help brake.

Challenges

EXERCISE 1

For a target thrust of 60,000 N at 250 m/s, find the air mass flow and propulsive efficiency for exhaust speeds of 700, 450 and 320 m/s. What does the pattern say about fan size?

View solution

EXERCISE 2

Using 43 MJ per kilogram of fuel, find the fuel for 1,000 km at 50,000 N of thrust for overall efficiencies of 0.20, 0.30 and 0.38. What does each step of efficiency save?

View solution

EXERCISE 3

A propeller gives thrust of 0.8 times power divided by speed, and a simple jet gives a constant 6,000 N. For 1 MW of propeller power, scan speeds from 50 to 300 m/s and find where the jet wins. Why do regional aircraft use propellers?

View solution

QUICK REFERENCE

- **Thrust:** mass of air moved per second times the gain in its speed
- **Propeller:** efficient at moderate speed, thrust falls as speed rises
- **Jet engine:** compressor, combustor, turbine, nozzle
- **Turbofan:** a large bypass fan moves more air more slowly, wasting less energy
- **Turboprop:** a gas turbine turning a propeller, for regional routes
- **Fuel:** proportional to thrust times distance, divided by overall efficiency

COMING NEXT

How Flight Works 6 looks at how two world wars drove the aircraft and the jet engine forward, and how commercial air travel was born.

How Flight Works

Chapter 6 · War and Wings

How Flight Works 5 ended with the jet engine just invented. This chapter asks why it, and the whole aircraft, advanced so fast in a few decades. A large part of the answer is war: two world wars gave engineers money, urgency and thousands of test pilots, and left behind the technology that made the airliner possible.

> **WHAT WAS RUN, AND WHAT TO TRUST**
>
> Every Python snippet in this chapter and in the three exercise solutions was executed, and the output in the comments is what Python printed. The figures (speeds, seat counts, heights) are *round illustrative numbers*, not data for any particular aircraft. I did **not** run a fresh web check for this chapter, so treat the dates and history as standard textbook material and check a museum or archive source before quoting any of them.

Before the First War

When the first war began in 1914, the aircraft was barely a decade old (How Flight Works 2). Armies saw it as a way of scouting: a cheap, fast eye over the other side of the hill. Aircraft were slow, fragile, and powered by piston engines of modest output (How Flight Works 5).

The First War: Scouts Become Fighters

Scouting led at once to fighting, because each side wanted to stop the other seeing. Within a year, aircraft carried guns, and engineers solved the problem of firing through a spinning propeller. Bombers, reconnaissance aircraft and fighters each began to specialise. Structures changed from wood-and-fabric frames toward stronger designs, engines gained power, and the pace of change was unlike anything in peacetime. The code below uses round top speeds for a fast aircraft of each date.

```
rows = ((1914, 130), (1918, 220), (1939, 570), (1945, 870))
base = rows[0][1]
for y, s in rows:
```

```
    print(y, "-> top speed", s, "km/h, times the 1914 figure", round(s / base, 1))
# 1914 -> top speed 130 km/h, times the 1914 figure 1.0
# 1918 -> top speed 220 km/h, times the 1914 figure 1.7
# 1939 -> top speed 570 km/h, times the 1914 figure 4.4
# 1945 -> top speed 870 km/h, times the 1914 figure 6.7
```

In four years the fast end of the scale gained more than half again, and by the end of the second war the figure was nearly seven times the starting one. Exercise 1 turns these into growth per year.

Between the Wars: The Airliner Appears

After 1918 there were thousands of surplus aircraft, and trained pilots with no job. Some flew mail, some carried the first paying passengers in cramped, noisy cabins, and some set records that kept public interest high. Through the 1920s and 1930s, designs changed in ways every later airliner kept: metal skins instead of fabric, enclosed cabins, retractable wheels, and variable-pitch propellers (How Flight Works 5). Long flights over the ocean were first made by flying boats, which could land on calm water and needed no airfield.

> **COMMON MISCONCEPTION**
>
> "The jet airliner arrived because someone invented a better wing." The wing mattered (How Flight Works 3), but the airliner came from several things landing together: strong light metal structures, reliable engines, pressurised cabins to fly above the weather, and the navigation and radio systems below. Remove any one and the others are not enough.

The Second War: A Workshop for the Whole World

The second war multiplied everything. Aircraft were built in huge numbers, which taught industry how to mass-produce complex machines. Engines grew far more powerful and were fitted with superchargers, so aircraft could fight where the air is thin. Pressurised cabins appeared on high-flying bombers. Long-range aircraft pushed the limits of fuel and navigation, and the crews who flew them showed what could be done by routine procedure rather than heroics, an idea that matters again in How Flight Works 8.

The Jet Goes to War

Whittle and von Ohain (How Flight Works 5) had built their engines before the war, and the war paid for their development. Germany flew a jet fighter in combat in 1944, and Britain flew one in the same year. Jets were faster than anything with a propeller, but early engines were short-lived and thirsty, and they arrived too late to change the outcome. Their real effect came afterwards, as every air force and airliner builder moved to jets, and engineers learned to build them to last.

Radar and Navigation

Radar sends out a pulse of radio waves and listens for the echo. The delay gives the distance, and the direction of the antenna gives the bearing. Britain built a chain of stations on its coast before the second war, and the system that joined radar to a control room, with plotters and radio links to the fighters, was as important as the radar itself. That idea of sensors, a picture and a controller reappears in How Flight Works 9. Radio waves travel in straight lines, so they cannot see over the horizon. The model below uses an assumed antenna height of 30 m and a simple horizon formula.

```
from math import sqrt

ANTENNA = 30.0
for target in (100, 1000, 10000):
    d = 4.12 * (sqrt(ANTENNA) + sqrt(target))
    print("target at", target, "m -> radar horizon about", round(d), "km")
# target at 100 m -> radar horizon about 64 km
# target at 1000 m -> radar horizon about 153 km
# target at 10000 m -> radar horizon about 435 km
```

A high-flying aircraft is seen much further away than a low one, which is why height was valuable to both sides. Navigation was changing too. Aircraft once found their way by landmarks, compass and a clock. Radio beacons, and then hyperbolic systems that measured the delay between signals from two ground stations, let crews fix their position over open sea and in cloud. These fed directly into the airways and routes of How Flight Works 9.

Commercial Travel Is Born

After 1945 the world had large airfields, thousands of trained crews, a ready supply of long-range aircraft, and a public that had learned to think of flying as ordinary. Piston airliners with pressurised cabins carried passengers across oceans in a day, and the first jet airliners of the 1950s halved the time again. Each step made the ticket cheaper and the market bigger. The model below multiplies seats by speed to compare how much passenger capacity one aircraft provides per hour.

```
for label, seats, speed in (("early airliner", 21, 300), ("piston airliner", 60, 500), (
    cap = seats * speed
    print(label, "->", seats, "seats at", speed, "km/h, seat-km per hour:", cap, ", time
# early airliner -> 21 seats at 300 km/h, seat-km per hour: 6300 , times the first: 1.0
# piston airliner -> 60 seats at 500 km/h, seat-km per hour: 30000 , times the first: 4.
# first jet airliner -> 140 seats at 900 km/h, seat-km per hour: 126000 , times the firs
# wide-body jet -> 350 seats at 900 km/h, seat-km per hour: 315000 , times the first: 50
```

ERA	WHAT CHANGED	EFFECT ON TRAVEL
1914-1918	scouting becomes fighting; engines and structures improve	aircraft proven to be useful
1919-1938	metal airframes, enclosed cabins, flying boats	first passenger services
1939-1945	mass production, radar, pressurisation, jets	skills, airfields and crews in place
1950s on	jet airliners, then wide-bodies	ocean crossing in hours, mass market

From the Passenger Seat

Almost everything a passenger sees comes from this period. The pressurised cabin is why your ears pop gently during climb and descent rather than painfully. The airline's long straight routes follow the beacons and airways that wartime navigation turned into a system. At night, the

blinking lights on the wing tips and tail go back to the same era, when aircraft had to be seen in a crowded sky.

Challenges

EXERCISE 1

Using the speed figures in this chapter, find the percentage growth per year for each of 1914-1918, 1918-1939 and 1939-1945. Which period grew fastest, and what does it say about war as an accelerator?

View solution

EXERCISE 2

For a 30 m antenna, find the radar horizon for targets at 100 m, 1,000 m, 5,000 m and 10,000 m. Why would an attacker choose to fly low?

View solution

EXERCISE 3

An ocean crossing of 5,500 km is made at 40, 300, 500 and 900 km/h. Find the journey time for each. What does the pattern say about why air travel became a mass market?

View solution

QUICK REFERENCE

- **War:** money, urgency and mass production sped up aircraft and engine design
- **Between the wars:** metal airframes, enclosed cabins, flying boats, first passenger services
- **Jet age:** jets entered service late in the second war and then took over airliners
- **Radar:** a pulse and its echo give distance and bearing, limited by the horizon
- **Airliner:** several advances arriving together made commercial travel possible

COMING NEXT

How Flight Works 7 asks what happens as aircraft approach the speed of sound, why shock waves appear, and why supersonic airliners came and went.

How Flight Works

Chapter 7 · Sound and Beyond

How Flight Works 6 ended with jets taking over. As aircraft got faster, they ran into a new kind of problem: the air stopped behaving like a gentle, easily moved fluid (How Flight Works 1). This chapter explains why, how engineers got through it, and why the one airliner that went beyond it did not last.

> **WHAT WAS RUN, AND WHAT TO TRUST**
>
> Every Python snippet in this chapter and in the three exercise solutions was executed, and the output in the comments is what Python printed. The figures (speeds, seat counts, sweep angles) are *round illustrative numbers*, not data for any particular aircraft. I did **not** run a fresh web check for this chapter, so treat the dates and history as standard textbook material and check a museum or archive source before quoting any of them.

Air That Can Be Squeezed

At everyday speeds air behaves as if it cannot be compressed: it simply flows around the wing. Near the speed of sound that stops being true. Sound is a pressure disturbance, and it travels through air at a fixed speed. An aircraft is a moving source of disturbance, and once it approaches that speed, the disturbances it makes can no longer run ahead and warn the air to move aside. The air is squeezed instead, and its density changes. That is what engineers call compressibility.

The speed of sound is not a single number. It depends on the temperature of the air, and the air gets colder as you climb. The model below uses a simple rule: temperature falls 6.5 degrees per kilometre up to 11 km, and stays constant above that.

```
from math import sqrt

for h in (0, 5, 11, 16):
    t = 288.15 - 6.5 * min(h, 11)
    a = 20.05 * sqrt(t)
    print(h, "km -> air", round(t - 273.15), "C, speed of sound", round(a * 3.6), "km/h"
# 0 km -> air 15 C, speed of sound 1225 km/h
```

```
  # 5 km -> air -18 C, speed of sound 1154 km/h
  # 11 km -> air -56 C, speed of sound 1062 km/h
  # 16 km -> air -56 C, speed of sound 1062 km/h
```

Pilots therefore do not talk about speed alone. They use the **Mach number**, the aircraft's speed divided by the local speed of sound. Mach 1 is the speed of sound wherever you happen to be, and Mach 0.85 is 85 per cent of it.

Shock Waves and the "Barrier"

Air does not have to be moving at the speed of sound everywhere at once for trouble to begin. Air speeds up as it flows over the curved top of a wing (How Flight Works 3), so part of the airflow can reach Mach 1 while the aircraft as a whole is still below it. Where the air goes from faster than sound to slower than sound, it does so abruptly, in a thin region called a **shock wave**. Across it the pressure and density jump.

The effects are the reason for the old phrase "sound barrier". Drag rises steeply, lift can fall away, the shock can make the airflow separate and shake the aircraft, and the control surfaces (How Flight Works 4) can lose their effect. Early designers saw their aircraft pushed to these speeds in dives and lost control without understanding why, and the idea grew that there was a wall in the sky. There was no wall, but there was a rapid change in the physics, and it needed new designs rather than more power.

> **COMMON MISCONCEPTION**
>
> "The sound barrier is a solid wall that an aircraft breaks through." It is a region of rapidly rising drag and changing airflow, not a physical object. The bang a person on the ground hears is the shock wave sweeping past, and it is not a single event at the moment of crossing. It trails behind a supersonic aircraft for as long as the aircraft is flying fast, a moving line on the ground.

Yeager and the X-1

The answer after the war (How Flight Works 6) was a purpose-built research aircraft, the Bell X-1, with a thin straight wing and a rocket engine. It was carried aloft under a bomber and released, so that it did not waste fuel climbing. On 14 October 1947 Chuck Yeager flew it faster than

sound. Its tail was adjusted as a whole rather than with a hinged elevator, because the ordinary elevator lost effect in the shock, a lesson that every fast aircraft has used since (How Flight Works 4). Altitude helped him too: at 13 km the speed of sound is lower, so a given speed is a higher Mach number. The model below converts speeds to Mach numbers for three flights, with illustrative figures.

```
from math import sqrt

def sound(h):
    return 20.05 * sqrt(288.15 - 6.5 * min(h, 11)) * 3.6

for label, h, v in (("airliner", 11, 900), ("X-1 flight", 13, 1130), ("Concorde", 16, 21
    print(label, "-> Mach", round(v / sound(h), 2))
# airliner -> Mach 0.85
# X-1 flight -> Mach 1.06
# Concorde -> Mach 2.02
```

Exercise 1 explores how the same speed becomes a higher Mach number as an aircraft climbs.

Sweep and the Delta

The wing of a modern airliner is not straight but angled back, or **swept**. The idea is that what matters to the wing is the airflow across it, at right angles to its leading edge, and that is smaller than the flight speed when the wing is swept. A swept wing therefore behaves as if the aircraft were flying a little slower, which delays the shock waves and the rise in drag. The model below uses the cosine rule to show how much a given sweep helps.

```
from math import cos, radians

for sweep in (0, 30, 45, 60):
    f = cos(radians(sweep))
    print(sweep, "degrees sweep -> airflow across the wing", round(f * 100), "% of fligh
# 0 degrees sweep -> airflow across the wing 100 % of flight speed, so Mach 0.85 feels l
# 30 degrees sweep -> airflow across the wing 87 % of flight speed, so Mach 0.85 feels l
# 45 degrees sweep -> airflow across the wing 71 % of flight speed, so Mach 0.85 feels l
```

```
# 60 degrees sweep -> airflow across the wing 50 % of flight speed, so Mach 0.85 feels l
```

Sweep has costs: a swept wing makes less lift at low speed, which is one reason airliners need the flaps and slats of How Flight Works 3 for takeoff and landing. Exercise 2 asks how much sweep is enough.

The **delta wing** takes the idea further. It is a triangle, deeply swept, with a long root that is structurally strong and deep enough to hold fuel. At supersonic speed its leading edge stays behind the shock, and at high angles of attack it creates a strong vortex over the top of the wing that keeps it flying at the steep nose-up angle needed for landing. That is why a supersonic airliner lands with its nose high.

WING	BEST AT	WEAKNESS
Straight	slow flight, gliding, light aircraft	high drag near Mach 1
Swept	fast subsonic cruise, airliners	poor lift at low speed
Delta	supersonic flight, strong structure	high drag at low speed, nose-high landing

Concorde

Concorde was the one supersonic airliner to give regular service, built jointly in Britain and France and flying passengers from 1976 to 2003. It cruised at about Mach 2 at 16 km, where the air is thin and cold, with a slender delta wing and a drooping nose that the pilots lowered for takeoff and landing so they could see the runway. At Mach 2, friction with the air heated the skin enough that the whole aircraft grew in length in flight. It crossed the Atlantic in under three and a half hours, against around seven for a subsonic jet. The model below compares a supersonic airliner with a wide-body jet for an ocean crossing, with illustrative figures.

```
DIST = 5500.0
for label, seats, speed in (("wide-body jet", 350, 900.0), ("supersonic airliner", 100,
    print(label, "->", round(DIST / speed, 1), "hours, seat-km per hour:", round(seats *
# wide-body jet -> 6.1 hours, seat-km per hour: 315000
```

```
  # supersonic airliner -> 2.6 hours, seat-km per hour: 215000
```

The supersonic aircraft saved hours, but carried far fewer people per hour of flying. That is the core of its economics, and Exercise 3 looks at how the saving varies with distance.

Why Supersonic Travel Faded

Concorde was a technical triumph and a commercial niche. Several things worked against it, and none was decisive alone:

- **Fuel:** drag is high at Mach 2, so fuel use per passenger was far higher than a subsonic jet, and so were the fares.
- **The sonic boom:** the shock wave reaches the ground as a loud double bang, so supersonic flight over land was banned in many countries. Concorde's routes were mainly over the ocean.
- **Noise at airports:** the engines were loud at takeoff, which limited where it could operate.
- **Small cabin and range:** few seats and limited range kept the market to a few routes, mostly business travellers.
- **Shocks to confidence:** a fatal accident in 2000, followed by a downturn in air travel, ended its commercial case, and it retired in 2003.

Research continues on quieter supersonic designs, where careful shaping turns the boom into a softer thump. Whether the economics can work is still an open question. Like many of the technologies in How Flight Works 11, it may be a matter of waiting for engines, materials and rules to catch up.

From the Passenger Seat

Airliners cruise at roughly Mach 0.8 to 0.85, chosen to stay below the rise in drag. The swept wings you see out of the window are the reason. On some flights the pilots announce the cruise speed as a Mach number, which is the figure that matters up there, not the speed over the ground.

Challenges

EXERCISE 1

An aircraft flies at a steady 1,000 km/h. Find its Mach number at 0, 5, 8 and 11 km using the temperature model in this chapter. Why does the Mach number rise even though the speed does not?

View solution

EXERCISE 2

An aircraft cruises at Mach 0.85. What sweep angle makes the wing feel like Mach 0.80, 0.75, 0.70 and 0.65? Why do designers not simply use the biggest sweep possible?

View solution

EXERCISE 3

Compare a 900 km/h jet with a 2,150 km/h supersonic airliner on routes of 1,000, 3,000 and 5,500 km. How much time does the faster aircraft save on each, and why does that matter for where it makes sense?

View solution

QUICK REFERENCE

- **Mach number:** speed divided by the local speed of sound, which falls as air gets colder
- **Shock wave:** a thin region where air slows abruptly from supersonic to subsonic, raising drag
- **Sound barrier:** a rapid change in the physics, not a wall
- **Sweep:** angling the wing back delays shock waves; the cost is poor low-speed lift
- **Concorde:** fast but small and costly, held back by fuel, boom and noise

COMING NEXT

How Flight Works 8 goes inside the cockpit: the instruments, the glass cockpit, autopilot and fly-by-wire, and why checklists matter.

How Flight Works

Chapter 8 · Inside the Cockpit

How Flight Works 7 ended at cruising speed, with the Mach number as the figure that matters. This chapter moves to the front of the aircraft and asks how the crew know what the aircraft is doing, how they tell it where to go, and why a flight deck runs on checklists. If you have worked on a support desk, parts of this will feel familiar.

> **WHAT WAS RUN, AND WHAT TO TRUST**
>
> Every Python snippet in this chapter and in the three exercise solutions was executed, and the output in the comments is what Python printed. The figures (speeds, miss chances, gains) are *round illustrative numbers*, not data for any particular aircraft or airline. I did **not** run a fresh web check for this chapter, so treat the history and descriptions as standard textbook material and check a manufacturer or regulator source before quoting any of it. This is passenger-level explanation, not operating guidance.

The Six Dials and the Screen

Early cockpits were walls of separate round dials. Pilots learned to scan a core set: the airspeed indicator, the altimeter, the attitude indicator (the artificial horizon showing nose and wing angle), the heading indicator, the vertical speed indicator and a turn indicator. They exist because, in cloud or darkness, the human body cannot tell which way is up, so the instruments have to do it (How Flight Works 4 covered the three axes they track).

Two of these are simple pressure instruments. The airspeed indicator compares the pressure of air forced into a forward-facing tube with the surrounding pressure, which is a measure of how hard the air is pushing, the same quantity that drives lift (How Flight Works 1). The altimeter measures the surrounding pressure and converts it to height with a standard model of the atmosphere. The model below prints that standard pressure at a few heights.

```
def pressure(h_m):
    return 1013.25 * (1 - 2.25577e-5 * h_m) ** 5.25588

for h in (0, 1000, 5000, 11000):
    print(h, "m ->", round(pressure(h)), "hPa")
# 0 m -> 1013 hPa
```

```
  # 1000 m -> 899 hPa
  # 5000 m -> 540 hPa
  # 11000 m -> 226 hPa
```

The weakness is obvious: the altimeter really measures pressure, and the weather changes pressure from day to day, so pilots set the local pressure on the instrument. Exercise 2 shows how large the error is if the setting is wrong.

The Glass Cockpit

From the 1980s the separate dials were replaced on many aircraft by flat screens. The same information is drawn by software: attitude, speed, altitude and heading on a primary display, with a map, engine data and system status on others. A screen can show many more things than a dial, can show only what matters at that moment, and can colour or highlight a problem. Computers also took over the sensing: small units measure air pressure and motion and feed them to every display, so the crew sees one consistent picture.

COCKPIT	INFORMATION	COMPARED WITH
Round dials	one dial per quantity, read by scanning	an old server rack with a light for each fault
Glass cockpit	screens that combine and prioritise data	a modern monitoring dashboard

Autopilot

An autopilot is a control loop, much like a thermostat. It compares what the aircraft is doing with what was asked for, and moves the controls to shrink the difference. Pilots tell it a target altitude, heading or speed, and it does the steady work of holding it. It does not replace the crew; it frees them to monitor, plan and deal with the unexpected.

The key design number is how hard it reacts, called the gain. The model below holds a target height of 10,000 m starting 300 m below it, with a gain of 0.2.

```
  target, alt, climb = 10000.0, 9700.0, 0.0
  GAIN = 0.2
```

```
    for sec in range(0, 61, 10):
        print(sec, "s -> altitude", round(alt), "m")
        for _ in range(10):
            climb = GAIN * (target - alt) * 0.1 + climb * 0.5
            alt += climb
    # 0 s -> altitude 9700 m
    # 10 s -> altitude 9795 m
    # 20 s -> altitude 9866 m
    # 30 s -> altitude 9913 m
    # 40 s -> altitude 9943 m
    # 50 s -> altitude 9963 m
    # 60 s -> altitude 9976 m
```

The aircraft eases up to the target and slows as it arrives, which is what a passenger wants: no sudden climb or drop. Exercise 3 compares gains. Too low, and the aircraft is sluggish. Too high, and it overshoots and hunts around the target.

Fly-by-Wire

On older aircraft the pilot's controls moved the surfaces through cables, then through hydraulics. In a **fly-by-wire** aircraft the pilot's stick or yoke is a sensor: its movement is read by computers, which then command electric or hydraulic actuators on the surfaces (How Flight Works 4). The computers sit between the pilot and the aircraft.

That brings real advantages. The computers can smooth out rough air, keep the aircraft within safe limits of angle and load (so that a stall, as in How Flight Works 3, is much harder to reach), and allow designs that are unstable on purpose and so more manoeuvrable, as some fighters are (How Flight Works 6). They also cut weight, with wires replacing heavy linkages. The cost is that the software is now part of the safety case, so the systems are duplicated several times over, with computers checking each other and a vote taken when they disagree. This will sound familiar to anyone who has designed for redundancy and failover.

> **COMMON MISCONCEPTION**
>
> "Modern planes fly themselves, so the pilots do nothing." The automation holds the aircraft steady, but the crew decide what it should do, watch for faults and mismatches, handle weather and traffic, and take over when the automation reaches its limits. The skills have moved from hand-flying to monitoring and decision-making, which is demanding in its own way.

How a Pilot Finds the Way

Before satellites, navigation meant **dead reckoning**: from the speed, heading and time since the last known position, work out where you must be. The wind is the complication, because the air itself is moving over the ground. To follow a straight track in a crosswind, the aircraft has to point partly into the wind, which is why the nose and the track do not agree. The model below finds the angle for a 60 km/h crosswind and an aircraft airspeed of 800 km/h.

```
from math import sin, asin, radians, degrees

# Dead reckoning: heading needed to hold a track in a crosswind
TAS, WIND, ANGLE = 800.0, 60.0, 90   # km/h, km/h, wind direction relative to track
wca = degrees(asin(WIND * sin(radians(ANGLE)) / TAS))
print("correct into the wind by about", round(wca, 1), "degrees")
# correct into the wind by about 4.3 degrees
```

Modern aircraft add radio beacons, inertial systems that sense every acceleration, and satellite positioning, and a flight management computer combines them into one position, plans the route, and offers it to the autopilot to fly. The crew still keep the old skill of asking, "does this make sense?", and compare the screen with the clock, the map and the radio. Routes and the radio roads they follow are the subject of How Flight Works 9.

Checklists: Reliability Made Visible

The most important piece of technology in the cockpit is made of paper or a screen. In 1935 a new bomber crashed on a test flight with experienced crew, because it was complicated enough that one step was missed. The response was not more training alone but a short list of items to be done and checked in order. Checklists have been used ever since, and the habit spread into surgery, construction and software operations.

The reason is simple. People forget things, especially when busy, interrupted, or doing a task they have done a thousand times. A checklist does not make the pilot cleverer; it removes reliance on memory at the moments when memory is weakest. A challenge-and-response style, where one person reads the item and the other checks and replies, adds the second pair of eyes.

The model below compares one person against two for lists of 10 and 30 items, with a 2 per cent chance of missing any step.

```
P_MISS = 0.02          # chance one person misses one step
for steps in (10, 30):
    one = (1 - P_MISS) ** steps
    two = (1 - P_MISS * P_MISS) ** steps
    print(steps, "steps: one reader", round(one * 100, 1), "% all done, two checkers", r
# 10 steps: one reader 81.7 % all done, two checkers 99.6 %
# 30 steps: one reader 54.5 % all done, two checkers 98.81 %
```

A second checker turns an unreliable process into a very reliable one, which is the idea behind change reviews and runbooks on a support desk. Real people are not perfectly independent, so the true gain is smaller; Exercise 1 explores the effect of the numbers. Cockpits also use a related idea: crew members are trained to speak up, to say what they see, and to cross-check each other, because a good process lets the junior voice be heard.

From the Passenger Seat

The chimes and the soft "ding" you hear are usually the crew or the system signalling between cabin and cockpit. A pause after boarding often means a checklist and a cross-check, not a fault. If you see the crew reading from a card or screen before takeoff, that is the process doing its job.

Challenges

EXERCISE 1

For a 20-step checklist, compare one reader against two independent checkers when the chance of missing a step is 1, 2 and 5 per cent. What does it tell you about when a second check is most worth having?

View solution

EXERCISE 2

An altimeter setting is wrong by 1, 5, 10 and 20 hPa. How many metres and feet does the displayed height change, using the standard model in this chapter? Why does it matter more near the ground?

View solution

EXERCISE 3

Run the altitude-hold model for 60 seconds with gains of 0.05, 0.2 and 1.5. Which settles best, which is slow, and which overshoots? What would a passenger feel in each case?

View solution

QUICK REFERENCE

- **Core instruments:** airspeed, altitude, attitude, heading, vertical speed, turn
- **Glass cockpit:** software-drawn screens replace separate dials
- **Autopilot:** a control loop that shrinks the gap between target and actual; the gain sets how hard it reacts
- **Fly-by-wire:** computers sit between the pilot's controls and the surfaces, adding limits and smoothing
- **Checklists:** remove reliance on memory; a second checker raises reliability sharply

COMING NEXT

How Flight Works 9 looks at air traffic and the invisible roads: airways, flight levels, controllers, transponders and how airports sequence landings.

How Flight Works

Chapter 9 · Invisible Roads

How Flight Works 8 looked at how a crew know where their aircraft is and where it is going. This chapter looks outwards: thousands of aircraft share the same sky, and they stay apart because the sky is organised into roads you cannot see, managed by people on the ground who can. If you have ever worked on a network, think of it as routing, addressing and traffic shaping, with people in the loop.

> **WHAT WAS RUN, AND WHAT TO TRUST**
>
> Every Python snippet in this chapter and in the three exercise solutions was executed, and the output in the comments is what Python printed. The figures (spacing, speeds, demand) are *round illustrative numbers*, not the rules of any particular country, airport or airline. I did **not** run a fresh web check for this chapter, so treat the descriptions as standard textbook material and check a regulator or air navigation provider before quoting any of it. This is passenger-level explanation, not operating guidance.

Airways: Roads in the Sky

Open sky looks empty, but busy regions are mapped like a road network. **Airways** are corridors that join navigation points, which are named fixes (often five-letter names you can pronounce) or radio beacons. A route is a list of those points, a bit like a list of junctions, and a flight plan is the agreed route, height and speed that is filed before departure. The roads are invisible, yet they are why aircraft crossing a country seem to follow the same lines. Satellite navigation (How Flight Works 8) has made it easier to define points anywhere, so many routes are now defined by coordinates, not only by beacons on the ground.

Flight Levels: Layers, Not Heights

Aircraft at cruise are separated vertically, in layers. Above a certain height, the altitude is not measured against the local weather but against one agreed pressure setting, the standard 1013.25 hPa from How Flight Works 8. Every aircraft then uses the same reference, so their heights agree with each other even if they disagree with the real height above the sea. A height set this way is a **flight level**, the height in hundreds of feet: FL350 is 35,000 ft.

```
for fl in (100, 250, 350, 390):
    ft = fl * 100
    print("FL" + str(fl), "->", ft, "ft =", round(ft * 0.3048), "m")
# FL100 -> 10000 ft = 3048 m
# FL250 -> 25000 ft = 7620 m
# FL350 -> 35000 ft = 10668 m
# FL390 -> 39000 ft = 11887 m
```

Layers are usually 1,000 ft apart. In many regions a rule also gives opposite directions different layers: eastbound traffic takes odd levels and westbound traffic takes even ones, so two aircraft head-on cannot be at the same level by accident. Exercise 1 builds that rule in code. A long flight often steps up to a higher level as the fuel burns off and the aircraft gets lighter (How Flight Works 5 covers why thin air suits a jet).

Controllers, Radar and the Transponder

Air traffic control is the people and systems that keep aircraft apart and moving. A flight is handed from one controller to the next as it crosses sectors, each with its own radio frequency, in the same way a phone call hands over between masts. A controller gives instructions (a heading, a level, a speed), and the crew read them back so that any misheard word is caught, which is the same idea as the checklist and challenge-and-response in How Flight Works 8.

Controllers see the sky by radar. A **primary radar** sends out a radio pulse and listens for the echo from the aircraft's metal, which gives range and direction. A **secondary radar** asks the aircraft to answer: an on-board **transponder** replies with a code and, usually, its height, so the screen can label every dot. The echo has to travel out and back at the speed of light, which is very fast but not instant. The model below shows the round-trip delay.

```
C = 299792.458   # km/s
for km in (50, 150, 400):
    ms = 2 * km / C * 1000
    print(km, "km ->", round(ms, 2), "ms round trip")
# 50 km -> 0.33 ms round trip
# 150 km -> 1.0 ms round trip
```

```
# 400 km -> 2.67 ms round trip
```

A controller's screen refreshes every few seconds as the antenna sweeps round, so what you see is a recent picture, not live video. The transponder also lets nearby aircraft warn each other: many carry a collision-avoidance system that listens for other transponders and tells the crew to climb or descend. That system works between aircraft, with no controller needed, which is a good example of a safety layer added on top of another safety layer.

> **COMMON MISCONCEPTION**
>
> "Pilots fly wherever they like, and the controller only helps when there is a problem." In busy airspace every aircraft is on a plan, and controllers actively separate them all the time. A pilot may choose how to fly the aircraft, but not usually where, within the controlled system.

Sequencing Landings

The busiest part of the system is a runway. Aircraft behind each other must be spaced so that the one ahead has landed and left the runway, and so that the wake behind a large aircraft (the swirls from the wingtips, linked to How Flight Works 1 and 3) has died away. Controllers therefore build an orderly queue on approach, adjusting speeds and sometimes sending an aircraft round a holding pattern to slot it in. The spacing is measured in distance, and distance at a given speed is time. The model below turns a gap in nautical miles into the time between aircraft and the landings per hour a single runway can handle.

```
SPEED = 150.0   # knots on final approach
for gap in (3, 4, 5, 6):
    secs = gap / SPEED * 3600
    print(gap, "NM gap ->", round(secs), "s apart,", round(3600 / secs, 1), "landings pe
# 3 NM gap -> 72 s apart, 50.0 landings per hour
# 4 NM gap -> 96 s apart, 37.5 landings per hour
# 5 NM gap -> 120 s apart, 30.0 landings per hour
# 6 NM gap -> 144 s apart, 25.0 landings per hour
```

This is why a small change in the gap makes a large difference to capacity, and why bad weather, which makes controllers widen the gap, produces delays that ripple through the whole network. Exercise 2 puts a demand figure against these capacities. A flight that circles before landing is not in trouble; it is waiting for its place in a queue.

AIR TRAFFIC IDEA	WHAT IT DOES	COMPARED WITH
Airway	a defined route between points	a motorway or a network route
Flight level	a shared pressure-based layer	a lane, or a VLAN
Transponder code	identifies each aircraft on the screen	a device address
Holding pattern	waits for a place in the queue	a buffer in a router
Hand-off between sectors	passes a flight to the next controller	a phone call moving between masts

Great Circles: Why Flights Curve on a Map

The Earth is a sphere, nearly, and the shortest path between two points on a sphere is part of a **great circle**: the circle you get by cutting through the centre. On a globe, a string pulled tight between two cities lies along it. On a flat map, which has to stretch the globe, that shortest path usually looks like a curve bent towards the nearer pole. The route is not curving; the map is. The model below finds the great-circle distance and the starting direction for one long route.

```
from math import radians, degrees, sin, cos, asin, atan2, sqrt

def great_circle(lat1, lon1, lat2, lon2):
    p1, p2 = radians(lat1), radians(lat2)
    dl = radians(lon2 - lon1)
    a = sin((p2 - p1) / 2) ** 2 + cos(p1) * cos(p2) * sin(dl / 2) ** 2
    km = 2 * 6371 * asin(sqrt(a))
    y = sin(dl) * cos(p2)
    x = cos(p1) * sin(p2) - sin(p1) * cos(p2) * cos(dl)
    return km, (degrees(atan2(y, x)) + 360) % 360

km, brg = great_circle(40.64, -73.78, 51.47, -0.45)
print(round(km), "km, initial bearing", round(brg), "degrees")
# 5541 km, initial bearing 51 degrees
```

The starting direction is not the direction the aircraft keeps for the whole flight: on a great circle the heading changes steadily as the aircraft goes around the curve. Real routes also bend around restricted areas, take advantage of strong winds (How Flight Works 10 covers the jet streams), and follow the airways, so the shortest line is an ideal rather than a promise. Exercise 3 compares great-circle distances with a flat-grid guess.

From the Passenger Seat

A flight-tracking map shows your aircraft following a smooth curve over the ocean, and now you know why. The pilot's occasional announcement of the flight level is the layer the aircraft shares with its neighbours. A pause before landing, a turn out over the countryside or a wide loop is the controller fitting you into the line. You are part of a very large, orderly queue.

Challenges

EXERCISE 1

Write a function that says whether a flight level fits a track under the odd-for-east, even-for-west rule, then list the levels from FL290 to FL410 for tracks of 90, 270, 45 and 200 degrees. Why does the rule stop two head-on aircraft sharing a level?

View solution

EXERCISE 2

A runway has 36 aircraft per hour wanting to land. For gaps of 3, 4, 5 and 6 nautical miles at 150 knots, find the runway's capacity, the backlog after one hour, and the extra wait for the last aircraft. What does it show about small changes in spacing?

View solution

EXERCISE 3

For three long routes, compare the great-circle distance with a flat-grid distance that treats a degree of longitude as long as a degree of latitude. Which error is largest, and why is it largest on routes far from the equator?

View solution

QUICK REFERENCE

- **Airway:** a defined route between named points
- **Flight level:** height in hundreds of feet on the standard pressure setting; shared by all aircraft
- **Transponder:** answers radar with a code and height
- **Sequencing:** spacing is distance, which is time; wider gaps mean fewer landings per hour
- **Great circle:** the shortest path on a sphere, which looks curved on a flat map

COMING NEXT

How Flight Works 10 looks at weather, turbulence and safety: wind, jet streams, icing, thunderstorms, why turbulence is rarely dangerous, and how accident investigation made flying the safest transport.

How Flight Works

Chapter 10 · Weather and Safety

How Flight Works 9 described the invisible roads and the people who manage them. This chapter looks at the thing none of them control: the air itself. Weather is the main reason a flight is late, bumpy or rerouted, and it is also the reason the aviation industry built one of the most thorough safety cultures in the world. We will look at what the air does, then at how flying learned from its mistakes.

> **WHAT WAS RUN, AND WHAT TO TRUST**
>
> Every Python snippet in this chapter and in the three exercise solutions was executed, and the output in the comments is what Python printed. The figures (wind speeds, temperatures, flight counts, probabilities) are *round illustrative numbers*, not forecasts or statistics. I did **not** run a fresh web check for this chapter, so treat the descriptions as standard textbook material and check a meteorological or safety authority before quoting any of it. This is passenger-level explanation, not operating guidance.

Wind and the Jet Streams

An aircraft flies through the air, not over the ground, so a moving air mass carries it along. The speed relative to the ground is the speed through the air plus or minus the wind. High up, near the top of the weather layer, narrow rivers of very fast air called **jet streams** blow mostly from west to east, driven by the temperature difference between warm and cold regions and by the spin of the Earth. That is why a flight across an ocean from west to east is often shorter than the return. Exercise 1 explores the size of the effect, and the model below shows it for one route.

```
for wind in (0, 50, 100, 150):
    out = 480 - wind   # headwind outbound
    back = 480 + wind  # tailwind return
    t_out = 3000 / out
    t_back = 3000 / back
    print(wind, "kt wind ->", round(t_out, 2), "h out,", round(t_back, 2), "h back, roun
# 0 kt wind -> 6.25 h out, 6.25 h back, round trip 12.5 h
# 50 kt wind -> 6.98 h out, 5.66 h back, round trip 12.64 h
# 100 kt wind -> 7.89 h out, 5.17 h back, round trip 13.07 h
```

```
  # 150 kt wind -> 9.09 h out, 4.76 h back, round trip 13.85 h
```

Notice that the round trip gets longer, not equal: the wind costs more time against you than it gives back with you. Airline planners therefore choose routes day by day, bending them to catch a helping wind and to dodge a strong opposing one, which is one more reason the great-circle line from How Flight Works 9 is an ideal, not a promise.

Icing

Air cools as you climb, by roughly 2 degrees Celsius for every 1,000 ft in the standard model. Clouds high enough to be below freezing often hold **supercooled** water droplets: liquid, though colder than 0 degrees, because they have nothing to freeze onto. When an aircraft flies through them, the droplets freeze on contact with the leading edge of the wing and tail. Ice changes the shape of the aerofoil, adds weight and can bring the stall on sooner (How Flight Works 3). Aircraft therefore carry ice protection: heated edges, inflatable boots or fluid, and they are cleared of frost and snow on the ground before takeoff. The model below shows how temperature falls with height.

```
for ft in (0, 10000, 20000, 30000, 36000):
    t = 15 - 1.98 * ft / 1000 if ft < 36000 else -56.5
    print(ft, "ft ->", round(t, 1), "C")
# 0 ft -> 15.0 C
# 10000 ft -> -4.8 C
# 20000 ft -> -24.6 C
# 30000 ft -> -44.4 C
# 36000 ft -> -56.5 C
```

At cruise height the air is so cold that nearly all water is already ice crystals, which do not stick, so the worst icing is usually met in the climb and descent. Exercise 2 finds the band where supercooled droplets are most likely.

Thunderstorms

A thunderstorm is a tall column of rising and sinking air that can contain strong turbulence, heavy rain, hail, lightning and sudden changes in wind. Crews and controllers keep well away from the active cells, using the aircraft's weather radar to see rain ahead, and a route may bend a long way around a line of storms. Lightning is less of a danger than it sounds: an airliner's metal skin carries the current around the cabin, and the aircraft is designed and tested for strikes. A strike is usually a loud flash and a bang, followed by an inspection on the ground. Near the ground a storm can also produce a sudden downdraught and shear, so airports and crews treat that as a reason to wait or divert.

Turbulence

Turbulence is air that moves unevenly, so the wings feel a rapidly changing push. It has three common causes. *Convective* turbulence comes from rising warm air and storms; *mechanical* turbulence comes from wind blowing over hills and buildings; and **clear-air turbulence** appears near jet streams with no cloud to warn of it, so radar cannot see it. Pilots share reports so that following aircraft can change level.

It feels dramatic, but an aircraft is built for far more than turbulence delivers. The structure is designed and tested to carry loads well above anything normal flying produces, and the wings are made to flex. The real risk is to people who are not seated: a seatbelt is the single most effective protection, which is why crews ask you to keep it fastened when seated. The model below shows how a banked turn loads a wing, for comparison, because ordinary manoeuvring also adds weight on the wings (How Flight Works 4).

```
from math import cos, radians
for bank in (0, 30, 45, 60):
    print(bank, "degrees bank ->", round(1 / cos(radians(bank)), 2), "g in a level turn"
# 0 degrees bank -> 1.0 g in a level turn
# 30 degrees bank -> 1.15 g in a level turn
# 45 degrees bank -> 1.41 g in a level turn
# 60 degrees bank -> 2.0 g in a level turn
```

COMMON MISCONCEPTION

> "Turbulence can make a plane fall out of the sky." Air does not have holes, and a bump of a few seconds moves an aircraft a little, not a long way. It can feel as if you have dropped far because you are weightless for a moment, but the aircraft has barely moved. Turbulence is uncomfortable and occasionally injures people who are not belted in, but the structure is not at risk.

How Flying Became the Safest Transport

Early aviation was dangerous, and many of its lessons were learnt the hard way. The change came from a habit: **every serious accident is investigated, and the findings are shared with the whole industry**. Investigators recover the aircraft, study the wreckage and read the data. The **flight data recorder** logs hundreds of parameters, such as speed, height and control positions, and the **cockpit voice recorder** keeps the last stretch of crew conversation. They are built to survive a crash and carry a locating beacon. The goal is to find causes, not to assign blame, so that people can speak freely and recommendations can be adopted everywhere.

Findings feed into design, training and rules. Examples that passengers never see include better-designed cockpits and alerts, collision-avoidance systems, wind-shear detection, and crew training that treats communication and teamwork as a skill, which came directly from studying how crews handle trouble. This is the same culture as the checklists in How Flight Works 8, extended to a whole industry. A support engineer will recognise it as a blameless post-incident review, done for every serious incident with its findings published for everyone.

The most useful picture is the Swiss-cheese idea: every safeguard has holes, but the holes are in different places, so a problem has to pass through every slice. Exercise 3 turns it into arithmetic.

WEATHER HAZARD	WHAT IT DOES	WHAT DEFENDS AGAINST IT
Strong wind	changes ground speed and path	route planning, fuel reserves
Icing	adds weight, spoils the aerofoil	heated edges, de-icing on the ground
Thunderstorm	strong turbulence, hail, shear	weather radar, routing around cells
Clear-air turbulence	sudden bumps with no cloud	pilot reports, seatbelts, a strong structure
Poor visibility	limits what the crew can see	instrument landing systems, trained crews

From the Passenger Seat

The seatbelt sign is the crew telling you where the air ahead is likely to be rough, and keeping your belt on is the single most useful thing you can do. A long detour on a flight tracker is a route around a storm or towards a helpful wind. A delay for de-icing on a winter morning is the system working as intended. When a jolt makes your stomach lurch, the aircraft is built for far more than that, and the people up front have seen it many times.

Challenges

EXERCISE 1

A 2000 NM trip is flown at 450 knots through the air. For winds of 0, 60 and 120 knots, compute the time with a headwind and with a tailwind, and the difference in minutes. Why is the saving with the tailwind smaller than the cost of the headwind?

View solution

EXERCISE 2

Using a fall of 1.98 C per 1,000 ft from 15 C at sea level, find the heights at which the temperature reaches 0 C, -20 C and -40 C, and the depth of the band between 0 C and -20 C. Why is icing more of a concern in a climb than at cruise?

View solution

EXERCISE 3

If each of N independent safeguards fails one time in ten, compute the chance that all fail together for N from 1 to 5, and how many of 40 million flights that would be. What real-world fact makes this model too optimistic?

View solution

QUICK REFERENCE

- **Jet stream:** fast, high-altitude air flowing mostly west to east; shortens eastbound flights

- **Icing:** supercooled droplets freeze on contact; defended by heating, boots and fluid
- **Thunderstorm:** avoided by routing around the cells, not flown through
- **Turbulence:** uncomfortable, rarely dangerous; keep the seatbelt fastened
- **Investigation:** every serious accident is studied and the lessons are shared industry-wide

COMING NEXT

How Flight Works 11 looks beyond the airliner: helicopters, gliders and soaring, balloons and airships, drones, electric aircraft and sustainable fuel, and the science fiction that came true.

How Flight Works

Chapter 11 · Beyond Airliners

So far we have followed the fixed-wing airliner, the machine that made flying ordinary. But it is only one answer to the question of how to stay up. How Flight Works 1 gave the four forces, and every aircraft in this chapter balances them in a different way: with a spinning wing, with no engine at all, with a bag of warm air, or with a battery. We will also look at what may come next, and at the science fiction that got there first.

> **WHAT WAS RUN, AND WHAT TO TRUST**
>
> Every Python snippet in this chapter and in the three exercise solutions was executed, and the output in the comments is what Python printed. The figures (rotor sizes, glide ratios, temperatures, battery and fuel energy) are *round illustrative numbers*, not product data or forecasts. I did **not** run a fresh web check for this chapter, so treat the descriptions as standard textbook material and check a manufacturer or regulator before quoting any of it. This is passenger-level explanation, not operating guidance.

Helicopters: the Spinning Wing

A helicopter's rotor is a set of long, narrow wings that spin around a mast. Each blade is an aerofoil (How Flight Works 3), so the rotor makes lift even when the helicopter is standing still, which is what lets it hover, rise straight up and land in a small space. The price is complexity. The blade moving forward meets faster air than the blade moving back, so the lift would be uneven; the rotor head changes each blade's angle of attack as it goes round to even it out, and that same control tilts the rotor to move the machine forwards, backwards or sideways. The pilot has a lever that changes the angle of every blade together to climb or descend, and a stick that tilts the disc (How Flight Works 4 gave the three axes of control).

A single main rotor would also twist the body the other way, so most helicopters add a small **tail rotor**, or use two main rotors turning in opposite directions. The history is slow: the idea is old, but a practical helicopter had to wait for light engines and a way to control the blades, in the 1930s and 1940s. A key idea is **disc loading**, the weight carried per square metre swept by the rotor. A larger disc moves more air more slowly for the same weight and takes less power, which is why helicopters have long blades. Exercise 1 explores it.

```
from math import pi
for radius in (2, 5, 8):
    area = pi * radius ** 2
    print(radius, "m radius -> disc area", round(area, 1), "m2, loading", round(1000 * 9
# 2 m radius -> disc area 12.6 m2, loading 780.7 N/m2 for 1000 kg
# 5 m radius -> disc area 78.5 m2, loading 124.9 N/m2 for 1000 kg
# 8 m radius -> disc area 201.1 m2, loading 48.8 N/m2 for 1000 kg
```

Gliders and Soaring

A glider is an aeroplane with no engine, and How Flight Works 2 showed that gliding came before powered flight. Its long, thin wing has a high **glide ratio**: the distance it travels forward for every unit of height lost. A modern sailplane can manage 40 or more to one, so from 1,500 m it can travel tens of kilometres in still air. It stays up by finding air that rises faster than it sinks. **Thermals** are columns of warm air rising from sun-heated ground; ridges deflect wind upwards on a hillside; and **mountain waves** form downwind of high ground. A glider circles in a thermal to climb, then glides to the next. The stall and the wing shape from How Flight Works 3 matter a great deal here, because the glider must fly slowly and tightly in rising air without stalling.

```
for ratio in (10, 20, 40, 60):
    print(ratio, ":1 glide ->", round(ratio * 1500 / 1000, 1), "km from 1500 m")
# 10 :1 glide -> 15.0 km from 1500 m
# 20 :1 glide -> 30.0 km from 1500 m
# 40 :1 glide -> 60.0 km from 1500 m
# 60 :1 glide -> 90.0 km from 1500 m
```

This also answers a worry: if an airliner loses power, it does not fall like a stone. It becomes a heavy glider with a ratio of well over ten to one, which gives its crew many minutes and many kilometres to find a runway. Exercise 2 adds a headwind and a thermal.

Balloons and Airships

A balloon does not use a wing at all. It floats for the same reason a cork floats in water: it displaces air that weighs more than the balloon and its load. A hot-air balloon heats the air inside, which expands and becomes less dense than the cool air outside, and the difference in weight is the lift. A gas balloon uses a gas lighter than air. Balloons have no engine and no steering except height: they go where the wind at each level takes them, so a pilot climbs or descends to find a wind going the right way. The model below shows how the lift grows as the air inside is heated.

```
for inside in (343, 373, 393):
    out = 353 / 288
    inn = 353 / inside
    lift = out - inn
    print(inside, "K inside ->", round(lift, 3), "kg per m3, 2800 m3 lifts", round(lift
# 343 K inside -> 0.197 kg per m3, 2800 m3 lifts 550 kg
# 373 K inside -> 0.279 kg per m3, 2800 m3 lifts 782 kg
# 393 K inside -> 0.327 kg per m3, 2800 m3 lifts 917 kg
```

Air density in the model is about 353 divided by the temperature in kelvin, and the outside air is taken as 288 K (15 degrees Celsius). Note how little lift each cubic metre gives: a balloon has to be enormous. An **airship** adds engines and rudders to a lighter-than-air envelope, so it can be steered; the great rigid airships of the early twentieth century carried passengers across oceans in comfort before the type faded, overtaken by the faster, cheaper aeroplane described in How Flight Works 6. Modern airships and balloons survive in niche roles such as observation, advertising and lifting heavy loads.

Drones

A drone is an aircraft with no pilot on board. Most small ones are **multirotors**: several fixed-pitch propellers, each turned by its own electric motor. They have no tilting rotor head or tail rotor. Instead a computer changes the speed of each motor hundreds of times a second to pitch, roll and yaw, which is the same fly-by-wire idea as in How Flight Works 8, taken to its extreme: a multirotor is so unstable that no human could fly it without the computer. Larger drones use wings for efficiency and rotors to take off, and military and survey aircraft fly for many hours. Because they share the sky with crewed aircraft, drones come with rules about

height, distance from airports and registration, much like the airways in How Flight Works 9. A web developer will recognise the pattern: small, cheap, networked, and a lot of software.

Electric Aircraft and Sustainable Fuel

Electric motors are simple, quiet and efficient, which suits flight, but a battery stores far less energy per kilogram than liquid fuel, and a battery does not get lighter as the energy is used, whereas an aircraft burning fuel does. That explains why electric aircraft today are small, light and fly short trips such as training and local flights. Larger aircraft may use hydrogen, or a hybrid mix. The comparison below makes the gap concrete.

```
for kg in (200, 500, 1000):
    kwh = kg * 250 / 1000
    print(kg, "kg battery ->", round(kwh), "kWh,", round(kwh / 60, 1), "h at 60 kW")
# 200 kg battery -> 50 kWh, 0.8 h at 60 kW
# 500 kg battery -> 125 kWh, 2.1 h at 60 kW
# 1000 kg battery -> 250 kWh, 4.2 h at 60 kW
```

The other route is **sustainable aviation fuel**: a fuel made from sources such as waste oils or captured carbon that can be burned in existing engines, often blended with ordinary fuel. It does not need new aircraft or airports, which is its appeal. Its supply and cost are the open questions. Exercise 3 compares battery and fuel directly.

> **COMMON MISCONCEPTION**
>
> "A helicopter that loses its engine falls straight down." Not so: the rotor can keep spinning as the helicopter descends, like a sycamore seed, and the pilot can use that spin to slow down for a landing, a technique called autorotation. It is practised in training, and it is why a helicopter is not a rock with a propeller.

The Science Fiction That Came True

Fiction has often run ahead of engineering. Jules Verne imagined a great flying machine with lifting rotors in the nineteenth century. Writers dreamt of rocket-powered flight, jet packs,

personal flying cars, silent electric air taxis and pilotless transport long before the technology existed, and some of those ideas have since arrived in some form: jet engines, rockets, drones and autopilots. Others are still waiting, and the jet pack and the mass-market flying car have been "ten years away" for a very long time because the physics of this chapter punishes them: a small disc carrying a heavy person needs a great deal of power, and a battery cannot supply it for long. The ideas that came true are the ones that respected the four forces.

AIRCRAFT	HOW IT STAYS UP	STRENGTH	LIMIT
Airliner	fixed wing, jet engines	speed, range	needs a long runway
Helicopter	spinning wing	hovers, lands anywhere	slow, costly, complex
Glider	long wing, rising air	no fuel, quiet	depends on the weather
Balloon	air lighter than its surroundings	simple, silent	goes where the wind goes
Multirotor drone	several small propellers	stable, cheap	short flights
Electric aeroplane	fixed wing, battery	quiet, efficient	battery weight

From the Passenger Seat

You are unlikely to meet most of these from an airliner window, but you may see them. A glider on a summer afternoon circling under a line of small clouds is in a thermal. A helicopter hovering over a city is held up by its spinning wing and a great deal of power. A balloon at sunrise is drifting with the wind at its own height. And the next time you cross an ocean, remember that the engine you hear has a quiet competitor under development, and a very patient one: the battery.

Challenges

EXERCISE 1

An aircraft of 1500 kg has a rotor of radius 3, 5 or 8 m. Compute the disc area and disc loading for each, and explain why a larger disc needs less power for the same weight.

View solution

EXERCISE 2

A glider with a glide ratio of 40 starts from 1500 m at 100 km/h. Find the still-air distance, the distance over the ground with headwinds of 0, 25 and 50 km/h, the sink rate, and the net climb in a 2 m/s thermal.

View solution

EXERCISE 3

Compare a battery at 250 Wh per kg with fuel at 12,000 Wh per kg for 500 kWh of energy. Then allow for efficiency of 90 percent for a motor and 35 percent for an engine. How big is the gap?

View solution

QUICK REFERENCE

- **Helicopter:** a spinning wing; hovers, lifts straight up, needs a tail rotor or a second rotor
- **Glider:** high glide ratio; climbs in thermals, ridge lift and mountain waves
- **Balloon:** floats because the gas inside is lighter than the air displaced
- **Drone:** software holds an unstable multirotor steady
- **Electric aircraft:** efficient motor, but heavy batteries limit range
- **Sustainable fuel:** a drop-in fuel for existing engines

COMING NEXT

How Flight Works 12 is the final chapter: a passenger's guide to a whole flight, from taxi to landing, and what each sound and sensation means, with a recap of the course.

How Flight Works

Chapter 12 · Passenger Guide

This is the last chapter, and it is the one you can use on your next trip. Instead of one idea at a time, we walk through a whole flight in order, from the gate to the arrivals hall, and explain the sounds, bumps and announcements as they happen. Almost every one of them is something you met earlier in the course: the four forces from How Flight Works 1, the wing from How Flight Works 3, the controls from How Flight Works 4, the engines from How Flight Works 5, the airways of How Flight Works 9 and the weather of How Flight Works 10. Now they all happen at once.

> **WHAT WAS RUN, AND WHAT TO TRUST**
>
> Every Python snippet in this chapter and in the three exercise solutions was executed, and the output in the comments is what Python printed. The figures (accelerations, times, fuel rates, descent distances) are *round illustrative numbers*, not data for any real aircraft or airline. I did **not** run a fresh web check for this chapter, so treat the descriptions as standard textbook material; real flights vary a great deal, and your crew's announcements always win. This is passenger-level explanation, not operating guidance.

Pushback and Taxi

The aircraft is pushed backwards by a small tug, because a jet engine cannot safely reverse out of a gate. A few minutes later you hear the engines start with a rising whine, and you may feel a gentle lurch. Out on the taxiway you will notice thumps and a bumpy rumble: those are the joints in the concrete and the nose wheel, not the engines. Hydraulic pumps and the air-conditioning make a hum that comes and goes. You often wait in a queue here. The controller is sequencing the aircraft for the runway, the same sequencing described in How Flight Works 9, and a gap in the queue is like a gap between requests on a busy server.

Takeoff

The pilots line up and hold the brakes while the engines spool up, and then the push in your back begins. The takeoff run is the plain physics of acceleration: a steady push builds speed, and

the distance grows with the square of the speed. The snippet below shows the pattern, and Exercise 1 repeats it for three other speeds.

```
ACCEL = 2.5   # m/s^2, a round figure
for v in (50, 65, 80):
    print(v, "m/s after", round(v / ACCEL), "s over", round(v ** 2 / (2 * ACCEL)), "m")
# 50 m/s after 20 s over 500 m
# 65 m/s after 26 s over 845 m
# 80 m/s after 32 s over 1280 m
```

At a speed the crew has calculated for the weight of the aircraft, they pull back gently. The wing, now moving fast enough, makes more lift than the aircraft weighs (How Flight Works 1), and you feel the wheels stop rumbling as the nose lifts. A moment later comes a thump from under the floor: the landing gear retracting and the doors closing. Once airborne the engines throttle back slightly, which feels like a loss of power but is only the crew reducing thrust from the takeoff setting to the climb setting. It is normal, and it happens on almost every flight.

Climb

The climb is where the aircraft burns fuel fastest, and it is a busy time for the controllers. You may feel the flaps and slats (How Flight Works 3) being drawn in, a series of small changes in the engine note and a gentle swaying as the aircraft turns onto its route. Your ears pop because the cabin is pressurised: the cabin air is held at the equivalent of a mountain-top height of about two thousand metres, rather than the thin air outside. Somewhere in the first quarter hour the seat belt sign goes off, and the cabin crew start their work.

Cruise

At cruise the aircraft flies level at a flight level and speed set by the plan and by air traffic control (How Flight Works 9), and the autopilot does most of the flying, with the pilots monitoring (How Flight Works 8). From the window you may see the wing flexing slightly in rough air; that is by design, because a wing that bends absorbs gusts. Turbulence feels dramatic from the seat, but as How Flight Works 10 explained, it is mostly a comfort problem, and the seat belt advice is

about injury, not about the aircraft. The air outside is far colder than a freezer, and the cabin is warm because hot air from the engines is cooled and mixed to a comfortable temperature. A long cruise is mostly quiet, which is the point of the whole machine.

Descent and Approach

The descent often starts a long way out. The engines are near idle, so the aircraft glides down a gentle slope, with a little power added. A common rule of thumb gives about 3 nautical miles of ground distance for every 1,000 feet of height to lose, and Exercise 2 puts it in code. This is why the captain's announcement often arrives well before the city appears. The approach is a sequence of turns and speed reductions that line the aircraft up with the runway, and the flaps and slats come out again so the wing makes enough lift at the lower speed (How Flight Works 3). You will hear a rumble as they extend and a whoosh as the gear comes down.

Landing and Arrival

A firm touchdown is often deliberate, because it gets the wheels turning and the brakes working. Wheel brakes, spoilers on the top of the wing that dump lift (How Flight Works 3) and reverse thrust that redirects engine air forward all slow the aircraft, so the loud roar after landing is the engines being used to brake and not an emergency. The aircraft turns off the runway, taxis to the gate and shuts down. A timeline makes the shape of the whole flight clear.

```
from datetime import datetime, timedelta
clock = datetime(2026, 1, 1, 9, 0)
for name, minutes in (("Pushback and taxi", 12), ("Takeoff and climb", 18), ("Cruise", 7
    clock += timedelta(minutes=minutes)
    print(name, "ends at", clock.strftime("%H:%M"))
# Pushback and taxi ends at 09:12
# Takeoff and climb ends at 09:30
# Cruise ends at 10:40
# Descent ends at 10:55
# Approach and landing ends at 11:10
```

YOU NOTICE	WHAT IS HAPPENING	WHERE IT CAME FROM
Thump under the floor after takeoff	landing gear retracting	this chapter
Engines quieter just after liftoff	thrust reduced from takeoff to climb setting	How Flight Works 5
Ears popping	cabin pressure changing with height	this chapter
Wing flexing in rough air	the wing absorbing gusts, by design	How Flight Works 10
Rumble before landing	flaps, slats and gear extending	How Flight Works 3
Roar after touchdown	reverse thrust and spoilers braking	How Flight Works 3

COMMON MISCONCEPTION

"If the engines go quiet during descent, something has failed." Not so: in descent the engines are deliberately near idle, and the aircraft glides down a planned slope. A quieter cabin on the way down is the sign of a normal descent, and the tone returns as power is added on the approach.

Recap: the Course in a Few Lines

You can now explain the whole of flight in plain language. The four forces of lift, weight, thrust and drag are balanced by a wing that turns the air downward (How Flight Works 1). The Wright brothers solved control, not just power (How Flight Works 2), and the wing's shape, camber and angle of attack decide lift and stall (How Flight Works 3). Pitch, roll and yaw are the three axes of control (How Flight Works 4), and engines grew from propellers to fans (How Flight Works 5). War sped the whole story up (How Flight Works 6), and the sound barrier ended in Concorde and a quieter economic reality (How Flight Works 7). Cockpits turned into software, with checklists as the reliability tool (How Flight Works 8), and the sky is shared through invisible roads (How Flight Works 9). Weather and turbulence are managed, and the way accidents are investigated made flying the safest transport (How Flight Works 10). The same forces carry helicopters, gliders, balloons and drones (How Flight Works 11). And now the whole flight fits together.

Where to Go Next

If the history held your interest, the other science courses on the site that explain how a large machine works follow the same pattern. For the spaceward end of the story there is a whole course on space exploration, and for the old maps and great sea voyages that came before flight, the Age of Exploration courses. Best of all, the next time you are in a window seat, watch the wing, listen for the changes, and see how many of them you can name.

Challenges

EXERCISE 1

An aircraft accelerates at 2.5 m/s^2 and lifts off at 120, 140 or 160 knots (1 knot is 0.5144 m/s). Find the time and the runway distance for each, and explain why a faster liftoff needs much more runway.

View solution

EXERCISE 2

Use the rule of 3 nautical miles per 1,000 feet to find how far out the descent must begin from 24,000, 30,000 and 36,000 feet, levelling off at 3,000 feet, and estimate the time at 7.5 nautical miles per minute.

View solution

EXERCISE 3

Total the time and fuel of a short flight from five phases (taxi, takeoff and climb, cruise, descent, approach and taxi in), and find the share of fuel for each. Which phase burns fuel fastest, and which burns most in total?

View solution

QUICK REFERENCE

- **Takeoff:** distance grows with the square of the speed; the thump after liftoff is the gear
- **Climb:** highest fuel rate; ears pop as cabin pressure adjusts

- **Cruise:** autopilot flies, the crew monitors; wing flex and turbulence are normal
- **Descent:** engines near idle; about 3 nautical miles per 1,000 feet
- **Landing:** spoilers, brakes and reverse thrust; the roar is braking

COURSE COMPLETE

That is the end of How Flight Works. You now know why anything flies, how it is controlled and powered, who shares the sky with it, and what every sound on your next flight means. Thank you for reading, and enjoy the view.