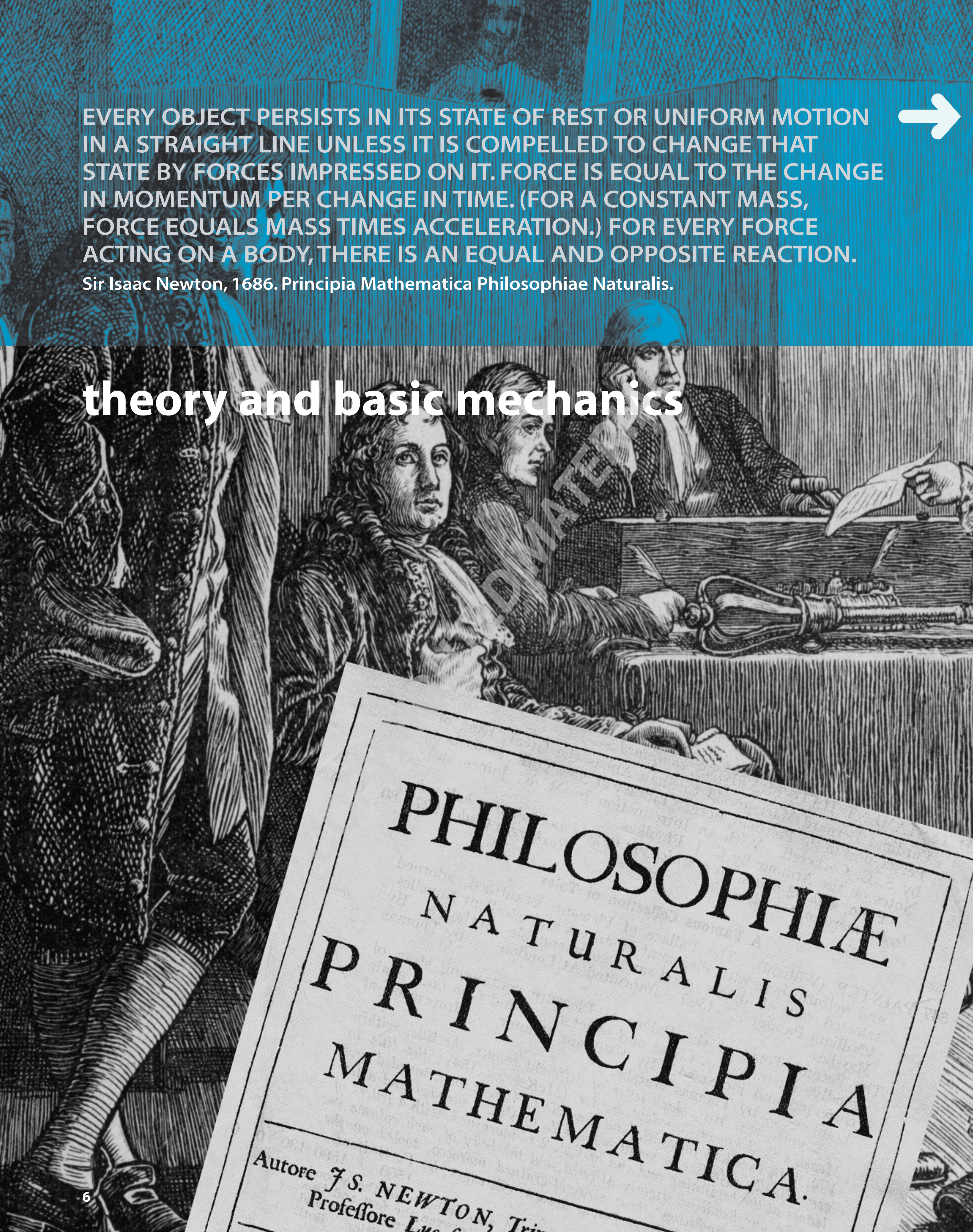
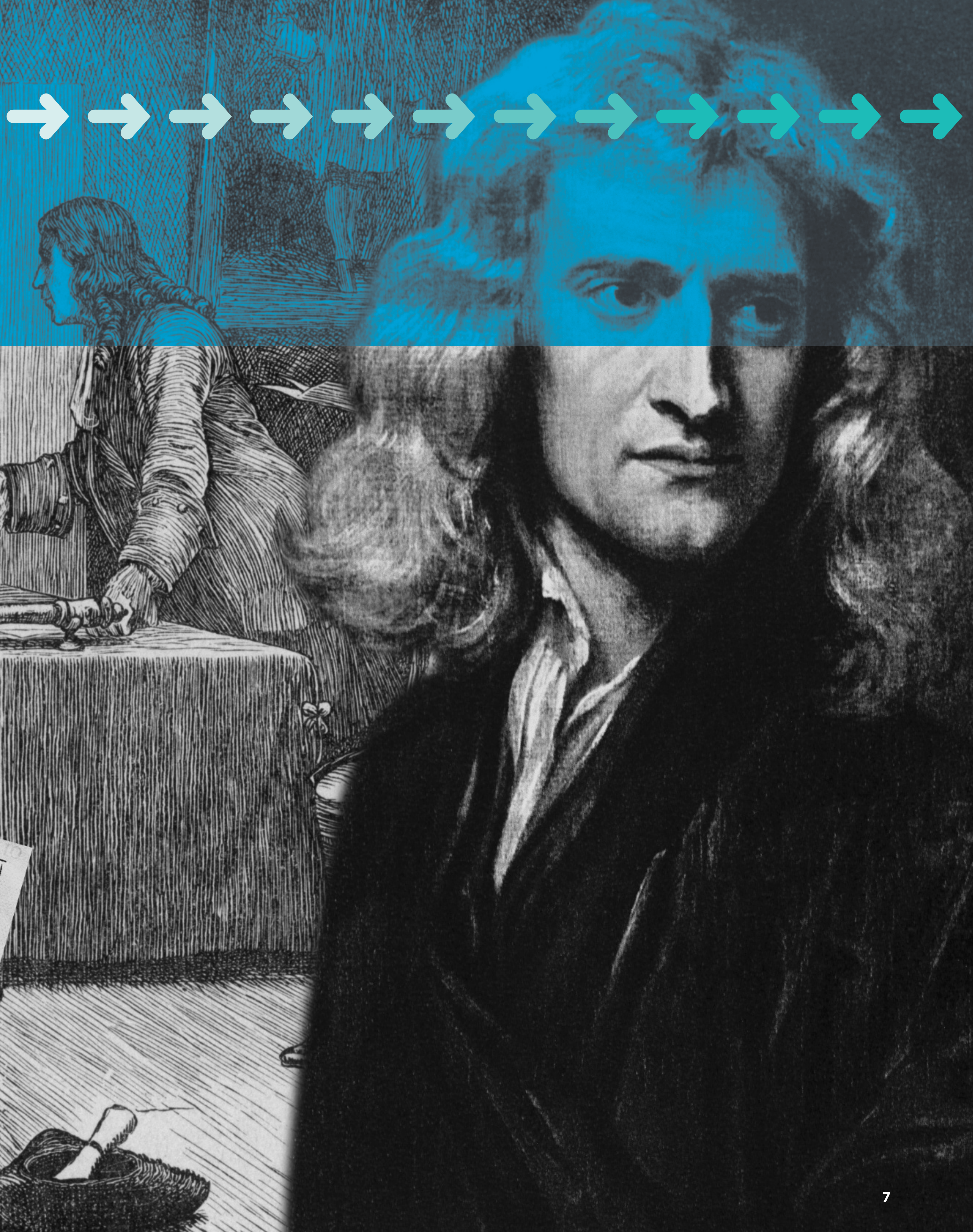
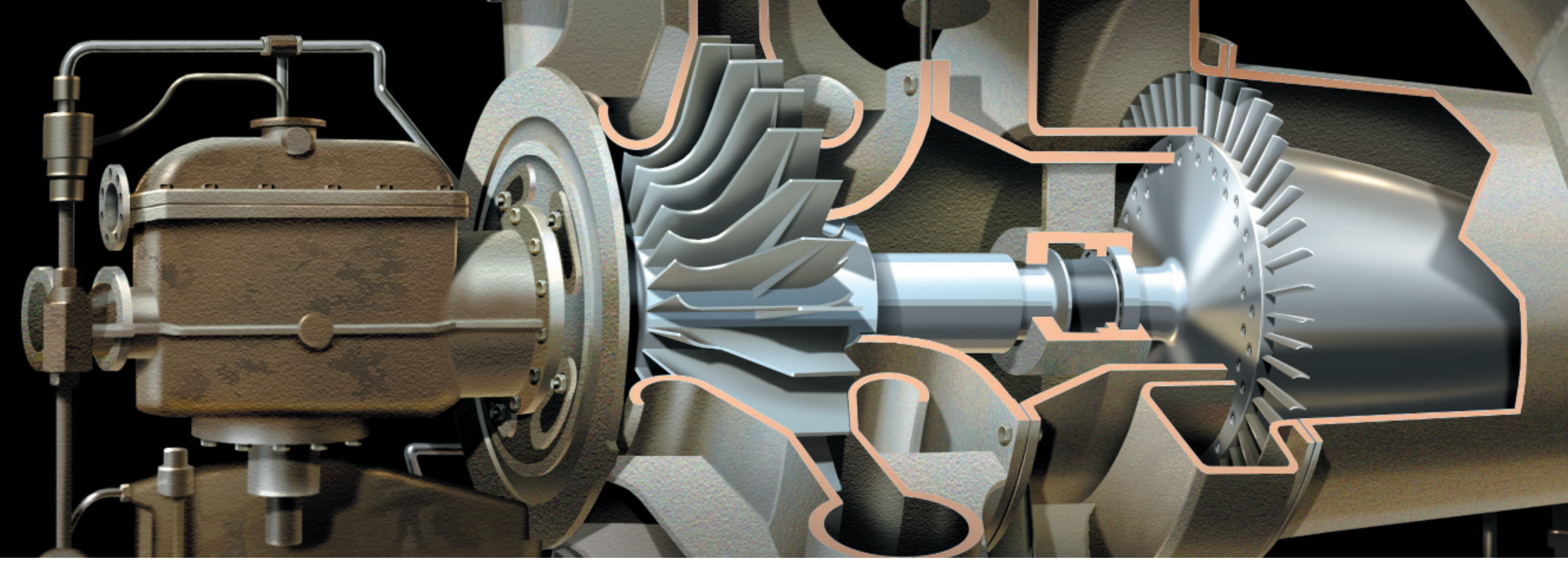
EVERY OBJECT PERSISTS IN ITS STATE OF REST OR UNIFORM MOTION IN A STRAIGHT LINE UNLESS IT IS COMPELLED TO CHANGE THAT STATE BY FORCES IMPRESSED ON IT. FORCE IS EQUAL TO THE CHANGE IN MOMENTUM PER CHANGE IN TIME. (FOR A CONSTANT MASS, FORCE EQUALS MASS TIMES ACCELERATION.) FOR EVERY FORCE ACTING ON A BODY, THERE IS AN EQUAL AND OPPOSITE REACTION.

Sir Isaac Newton, 1686. Principia Mathematica Philosophiae Naturalis.

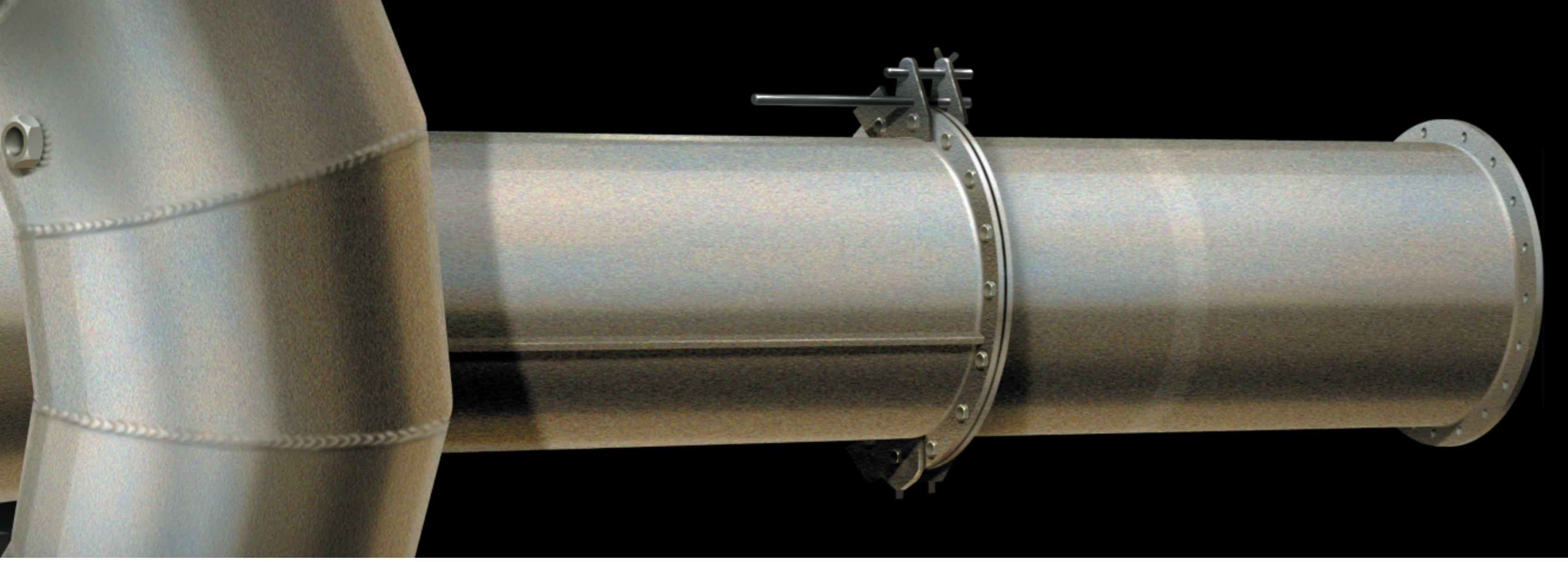
theory and basic mechanics







- How does a jet engine produce useful work, where does the energy come from to do it, and what is that work used for?
- How do the internals of a jet engine produce work? How does air move through the engine, and what happens to it as it does?
- Why do all large aircraft use jet engines instead of piston engines?
- What are the different types of jet engine, and what are their mechanical arrangements?



This chapter provides answers to these initial questions – and, in doing so, inevitably raises more. For example, is it possible to achieve high thrust and high efficiency and a small, light engine, all at the same time?

One of the prerequisite skills of the engineer is to understand the fundamental and contradictory constraints of a jet engine and balance them appropriately for a given design specification. The ideas of balance and constraint are themes that will reappear frequently in the following chapters.

A gas turbine (the type of jet engine described in this book) used on a twin-engined aircraft

Hero's engine or 'aeolipile'. The word aeolipile derives from the Latin 'pila' meaning ball and Aeolus, the Greek god of the winds.

The theory of jet propulsion

Newton's third law of motion states that 'for every force acting on a body, there is an equal and opposite reaction'. The jet engine applies this principle by forcing a fluid, whether liquid or gaseous, in one direction so creating an equal reaction, 'thrust', that moves the engine (and the vehicle it is attached to) in the opposite direction.

The thrust of a jet engine operates on the engine itself – it does not push against the air behind it.

Simple jet engines

A rotating garden sprinkler is a simple, practical example of jet propulsion, rotating in reaction to the jets of water being forced through the nozzles. Hero's engine added heat to the equation. It was invented around the first century AD, perhaps as a toy, perhaps to open temple doors. Whatever the application, Hero's invention showed how the momentum of steam issuing from a number of jets could impart an equal and opposite reaction to the jets themselves – causing the engine to revolve.

The gas turbine

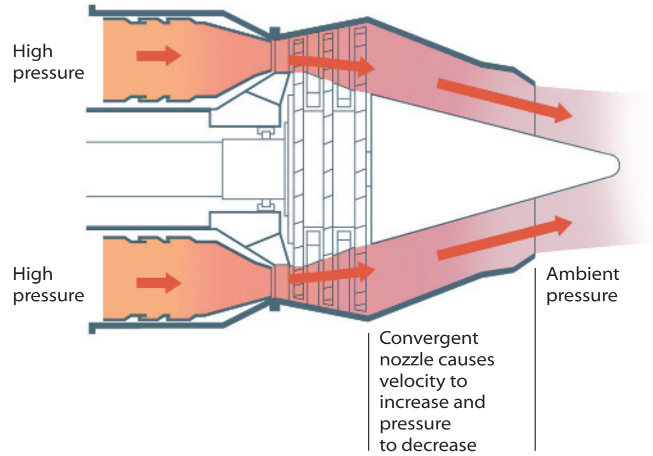
Most modern jet engines are gas turbines, which are heat engines, and like all heat engines burn fuel to convert their energy into something useful. For a gas turbine, that something useful is a fast moving jet of air propelling an aircraft forward, or powering a turbine driving a load such as an electrical generator, a compressor for a gas pipeline, or a ship's propeller, or water jet.

The gas turbine provides power for many applications: civil and military aircraft, naval and commercial ships, electricity production, gas compression, and oil pumping

Working cycle

The simplest gas turbine, a turbojet, is essentially a tube, open at both ends, with air continuously passing through it. The air enters through the intake, is compressed, mixed with fuel and heated in a combustor, expanded through a turbine, and finally the combustion gases are expelled from a rear nozzle to provide thrust. The turbine drives the compressor via a connecting shaft. This cycle of continuous combustion is known as the Brayton cycle. It defines a varying volume sequence with four distinct stages: compression, combustion, expansion, and exhaust.

The reduction in flow area causes the gases to speed up and reduce in pressure; this is sometimes called the Venturi effect



The pressure of the gases passing though the engine is always changing. First, pressure goes up in the compressor, it stays almost constant in the combustor (ideally there would be no pressure drop; in fact, it drops marginally), and then the pressure goes down as the combustion gases are expanded through the turbine. The pressure rise in the compressor is usually about twice as much as the pressure drop through the turbine that drives it, so the combustion gases arrive at the back of the engine with spare pressure to accelerate an exhaust jet rearwards.

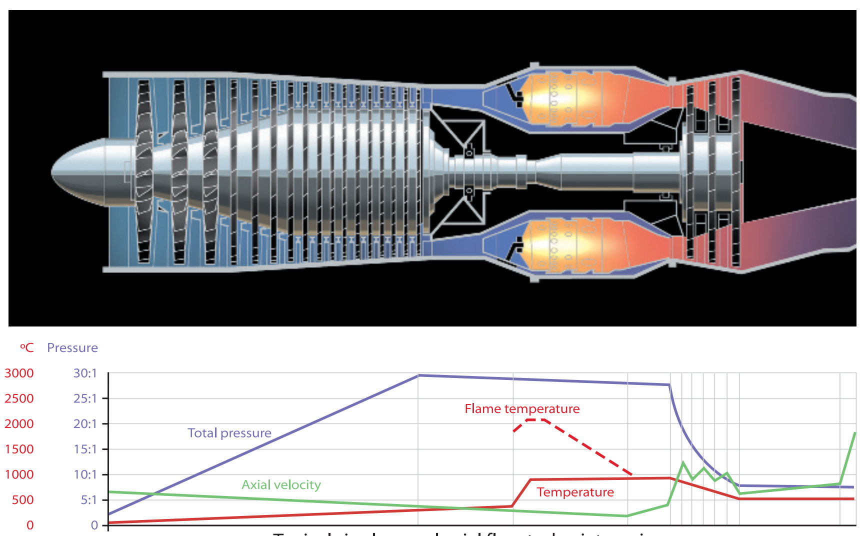
The relationship between pressure, volume, and temperature

The changes in pressure (and many of the changes in temperature) are caused by changes in the velocity of the air and combustion gases as they pass through the components of the gas turbine engine.

The fundamental laws of compressible flow state that when a gas or fluid is flowing at subsonic speeds through a convergent space (such as a venturi tube), its speed will increase, and its static pressure will decrease. If the gas or fluid flows through a divergent duct, its speed will slow, and its static pressure will increase. This helps to explain the shape of the exhaust and of the passages through the stator and rotor blades of both compressor and turbine.

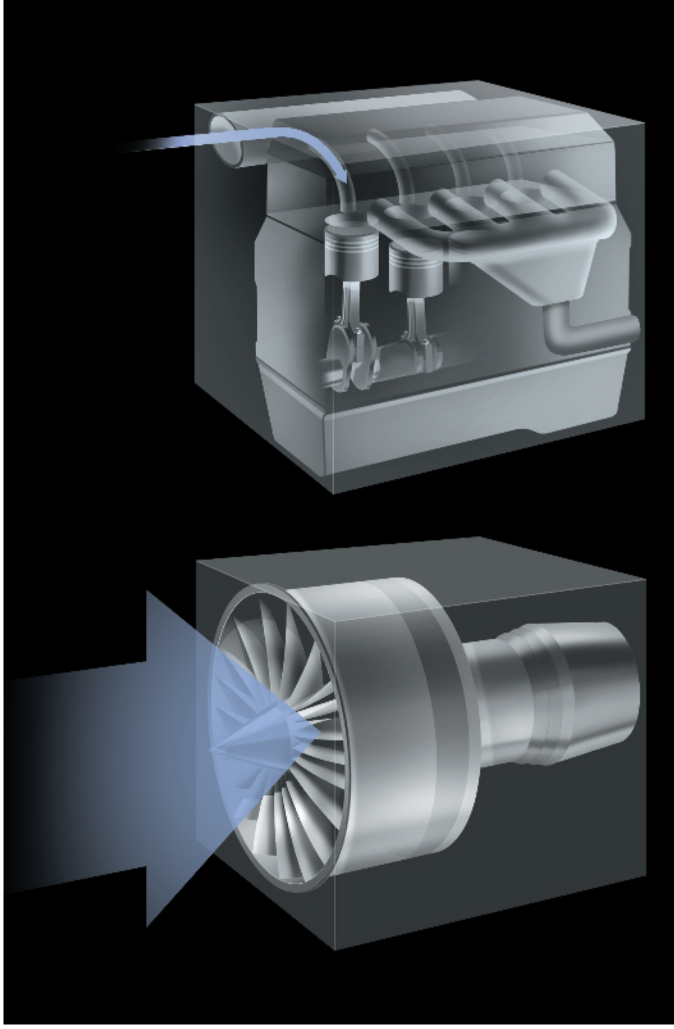
Boyle's law states that if the temperature of a confined gas is not changed, the pressure will increase in direct relationship to a decrease in volume – and vice versa. Charles's law describes how when a gas under constant pressure is allowed to expand, an increase in temperature will cause an increase in volume – as happens in the combustor of a gas turbine.

In the compressors and turbines, pressure, temperature, and volume are all changing, so Boyle's and Charles's laws need to be applied together as the Universal Gas Law.



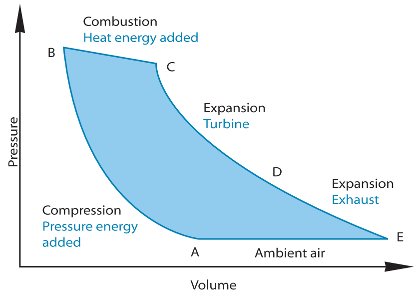
Typical single-spool axial flow turbo-jet engine

The variation of temperature, pressure, and velocity through a simple turbojet

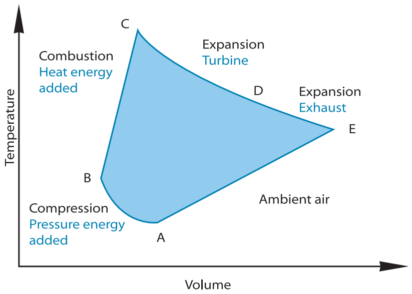


A comparison between a typical piston engine and a typical gas turbine of the same size shows that the gas turbine produces 20 times more power due to the increased airflow through the engine

Pressure - volume diagram

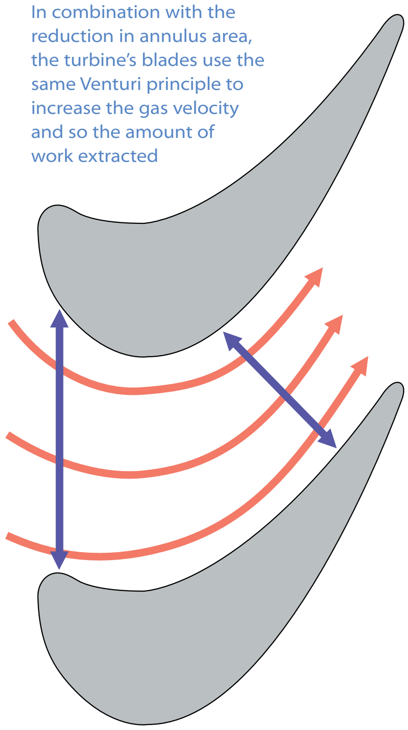


Brayton cycle



Temperature, pressure, and volume vary through the gas turbine cycle of compression, combustion, and expansion through the turbines and exhaust

In combination with the reduction in annulus area, the turbine's blades use the same Venturi principle to increase the gas velocity and so the amount of work extracted



Producing useful work

The fundamental laws of thermodynamics show that the power required for a given pressure ratio or extracted for a given expansion ratio are directly proportional to the entry temperature. The turbine entry temperature can be five times that of the compressor entry temperature; therefore, the turbine needs a much lower expansion ratio to drive the compressor than the compressor needs to do its work. The difference becomes available to produce thrust when exhausted from the nozzle.

In short, for a simple gas turbine, the hotter the engine is run, the greater the spare pressure and the higher the jet velocity.

The advantages of a gas turbine

Studies (» 288[a]) suggest that the core of a gas turbine can be about twenty times as powerful as the same size piston engine. This is because the continuous cycle and large, open flowpath of a gas turbine can admit 70 times as much air as an equivalently sized piston engine over the same time period. This would suggest that 70 times more fuel could be burnt, leading to 70 times as much energy released in the gas turbine. However, not all the air is used for complete combustion with the fuel. With the assumption that one third of the oxygen in the air passing through a gas turbine is used for combustion, (whereas a piston engine uses nearly all of the oxygen) the energy release rate is about 23 times (70/3) higher than a piston engine of the same size. The ratio of energy release rate varies with size; a comparison of large engines will give different energy release rates from a comparison of small engines.

Being able to move more air through an engine and therefore burn more fuel means that gas turbines can be very powerful for a given size. However, a gas turbine is costly to manufacture because expensive combustor and turbine materials are needed to withstand continuously high temperature. Gas temperatures and pressures can be higher in a piston engine but only at certain points in the cycle; overall, the average temperature in a piston engine is much lower, so the materials used can be cheaper.

Aircraft climbing just after take-off

The gas turbine as an aero engine

For an aero engine, the thrust transmitted to the airframe can be given by the mass flow of air passing through the engine multiplied by the increase in speed of that air.

Air approaches the engine at the flight speed V_{flight} and is ejected faster from the rear nozzle at a speed of V_{jet}. If the mass flow is W, then the thrust F is given by the equation

$$F = W(V_{jet} - V_{flight})$$

This is known as momentum thrust; this equation applies when the nozzle is not choked, and V_{jet}, therefore, is less than Mach one – the speed of sound.

For an unchoked nozzle, there are two ways to increase thrust at given flight speed and altitude. The mass flow W passing through the engine can become larger or V_{jet} can be increased. To increase the mass flow, the engine must have a larger frontal area; it will be bigger, heavier, and produce more drag. On the other hand, a higher V_{jet} makes the engine noisier and increases the fuel consumption needed to obtain a given thrust. The task of the aero engine designer is to obtain a compromise between these two factors.

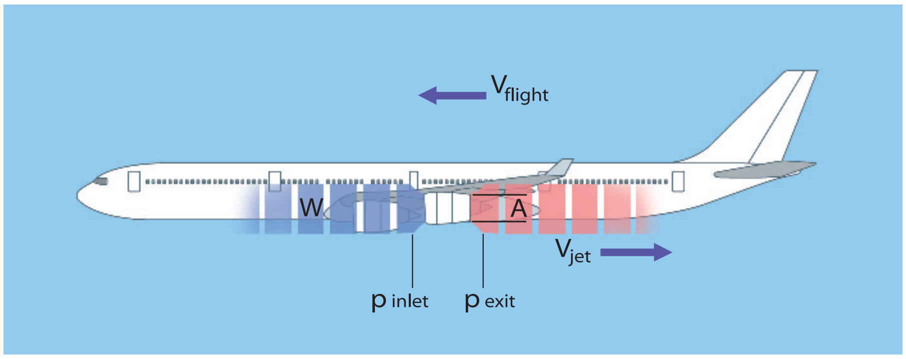
When the nozzle becomes choked, V_{jet} is fixed at Mach one, and, in order to calculate F, a new term, pressure thrust, is added to the equation

$$F = W(V_{jet} - V_{flight}) + A(p_{exit} - p_{inlet})$$

where A is the jet exit area of the exhaust nozzle, p_{exit} is the static pressure at the nozzle exit, and p_{inlet} the static pressure at engine inlet. With V_{jet} fixed at Mach one, the new term for pressure thrust allows thrust to be increased by raising p_{exit}. This is achieved through a higher total pressure in the jet pipe. Although V_{jet} is fixed at the speed of sound, by running the engine hotter, the speed of sound can be increased, V_{jet} goes up and momentum thrust increases.

The first task of the aero engine is to accelerate the aircraft down the runway. A big engine like the Trent 500 swallows and ejects 1,000kg or one tonne of air every second during take-off. At sea level, one cubic metre of air has a mass of about one kilogram, so the engine is ingesting about 1,000 cubic metres of air every second. If this volume of air were a cylinder the diameter of the intake, stretching out in front of the engine, it would extend for 200 metres – and would be consumed by the engine in one second.

Air is required to provide propulsion for aero engines – the mass of air does not change through the engine, though it does gain energy through the addition of fuel



The next task for the engine is to make the aircraft lift off. For example, an Airbus A340-600 aircraft weighs 368 tonnes; each of its four Trent 500 engines produces about twenty-five tonnes of thrust at take-off, giving a total output of 100 tonnes of thrust. Vertical take-off, therefore, is not an option but because the aircraft is going forwards, air passes over the wings and can be turned downwards to create lift. At take-off, a wing gives more than one tonne of lift per square metre – the A340 has 437 square metres of wing, so it can get airborne and climb. The engines do not provide direct lift, but are required to push the aircraft through the air, overcoming the drag of the airframe and the lift-induced drag from the wings.

Flight speed increases until engine thrust equals drag. The aircraft can now cruise with constant lift from the wings. It slowly gains height as fuel is consumed and the aircraft becomes lighter. Then, engine thrust is decreased by reducing fuel flow; the aircraft slows down, descends, and lands. This is a typical cruise profile for a civil airliner.

The turbojet – and its limitations

The first jets to fly were turbojets with a single compressor and turbine. The turbojet is a simple, classic design, and, in only a few years, proved to be a fast, powerful engine. However, the turbojet has now largely been superseded because later developments of the gas turbine have proved more efficient for the majority of air travel.

When an engine has reached a steady running condition, the energy input to the engine from fuel is almost exactly equal to the extra jet kinetic energy output (relative to the engine) and the extra jet thermal energy output. Light and sound energy emission and heat loss across the engine is negligible. About half the energy input goes out as extra jet kinetic energy. This proportion is called the thermal efficiency. A thermal efficiency of 100 per cent would mean that all the energy was being turned into jet kinetic energy with no wasted heat; this is a theoretical ideal, impossible to achieve. Conversely, a fire that does no work has zero thermal efficiency by this definition. Some modern gas turbines can achieve a thermal efficiency of about 45 per cent. Another measure of performance is propulsive efficiency; this is the work done to propel the aircraft divided by the work done by the engine to accelerate the jet of air.

The part of the fuel energy that goes out as jet kinetic energy will vary with V_{jet}^2 because the jet kinetic energy is given by

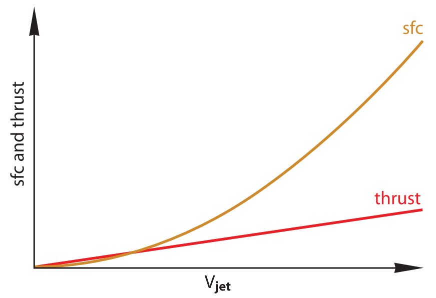
$$KE = \tfrac{1}{2}WV_{jet}^2$$

But thrust is given by the equation

$$F = W(V_{jet} - V_{flight}) + A(p_{exit} - p_{inlet})$$

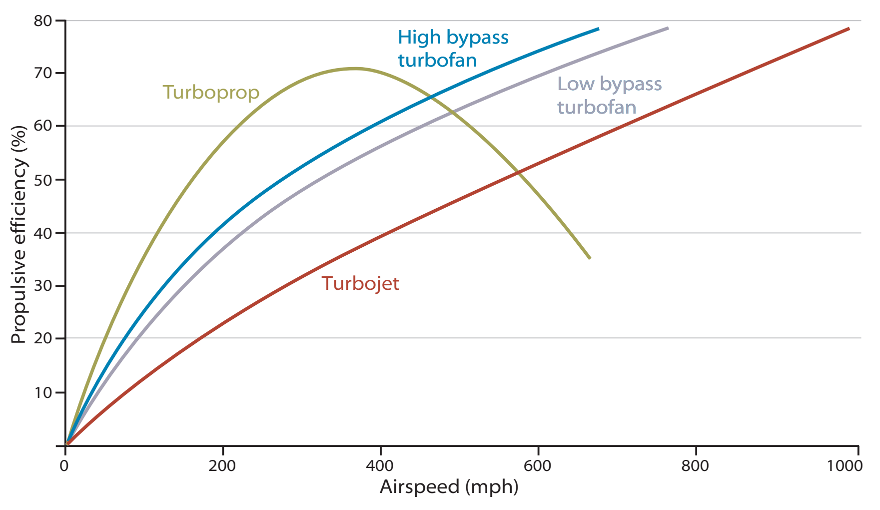
So, thrust will increase in proportion to V_{jet}, but fuel consumption varies with V_{jet}^2.

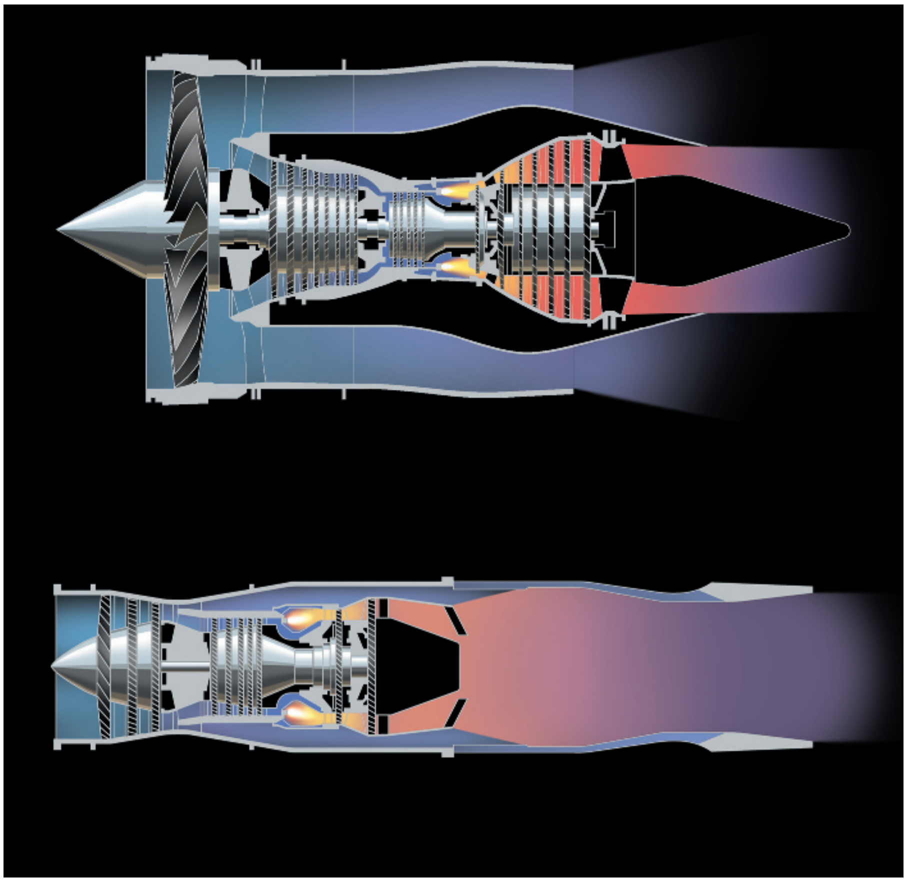
Therefore, although thrust increases with increasing jet velocity, fuel consumption increases more quickly. This is the tragedy of the turbojet: a high jet velocity, which can be in excess of 1,000 metres per second for simple turbojets, produces high fuel consumption for a given thrust and can be unacceptably noisy.



Specific fuel consumption (sfc) increases sharply with V_{jet} compared to the linear increase of thrust

The variation of propulsive efficiency with speed and engine type





Top: a high bypass ratio three-shaft civil engine

Bottom: a two-shaft military engine with a low bypass ratio and afterburning

The advantages of a turbofan

There are good reasons for an engine to have a high compression pressure ratio and a high turbine entry temperature. However, if all the spare pressure that this generates at the exit of the engine is only used to accelerate the core airflow, the high jet velocity is noisy and does not give the highest possible amount of thrust for a given amount of fuel. The solution – proposed by Frank Whittle (» 26) – is to add an additional low-pressure turbine downstream of the core turbine; this powers a fan to drive additional air outside the core of the engine, through a bypass duct.

The low-pressure turbine, which may consist of several turbine stages joined together, extracts energy from the moving exhaust gases so that, by the time these gases reach the final core nozzle, their pressure and temperature are much lower. As a result, the core jet accelerates to a much more modest velocity, sufficiently greater than the flight speed to create thrust but not so much greater that it creates more noise and uses more fuel.

The low-pressure, or LP, turbine of a Trent 500 extracts 80,000 horsepower from exhaust gases, which it then transmits along a shaft to the large fan at the front of the engine. This fan gives a small pressure rise to a large amount of air, which is then split: some goes through the core of the engine in the same way as a turbojet, while the remainder goes through the bypass duct. Because the fan pressure ratio of the single-stage fan is low, the bypass jet velocity is only slightly greater than the flight velocity.

So, a turbofan engine gets its thrust by accelerating a large mass of air to a modest jet velocity. Since thrust is proportional to V_{jet} but fuel consumption goes with V^2_{jet}, the turbofan gives about twice as much thrust for the same fuel consumption as a turbojet of the same core size. It is also much quieter and so may be used at commercial airports. This could be described as the triumph of the turbofan.

Turbofan types

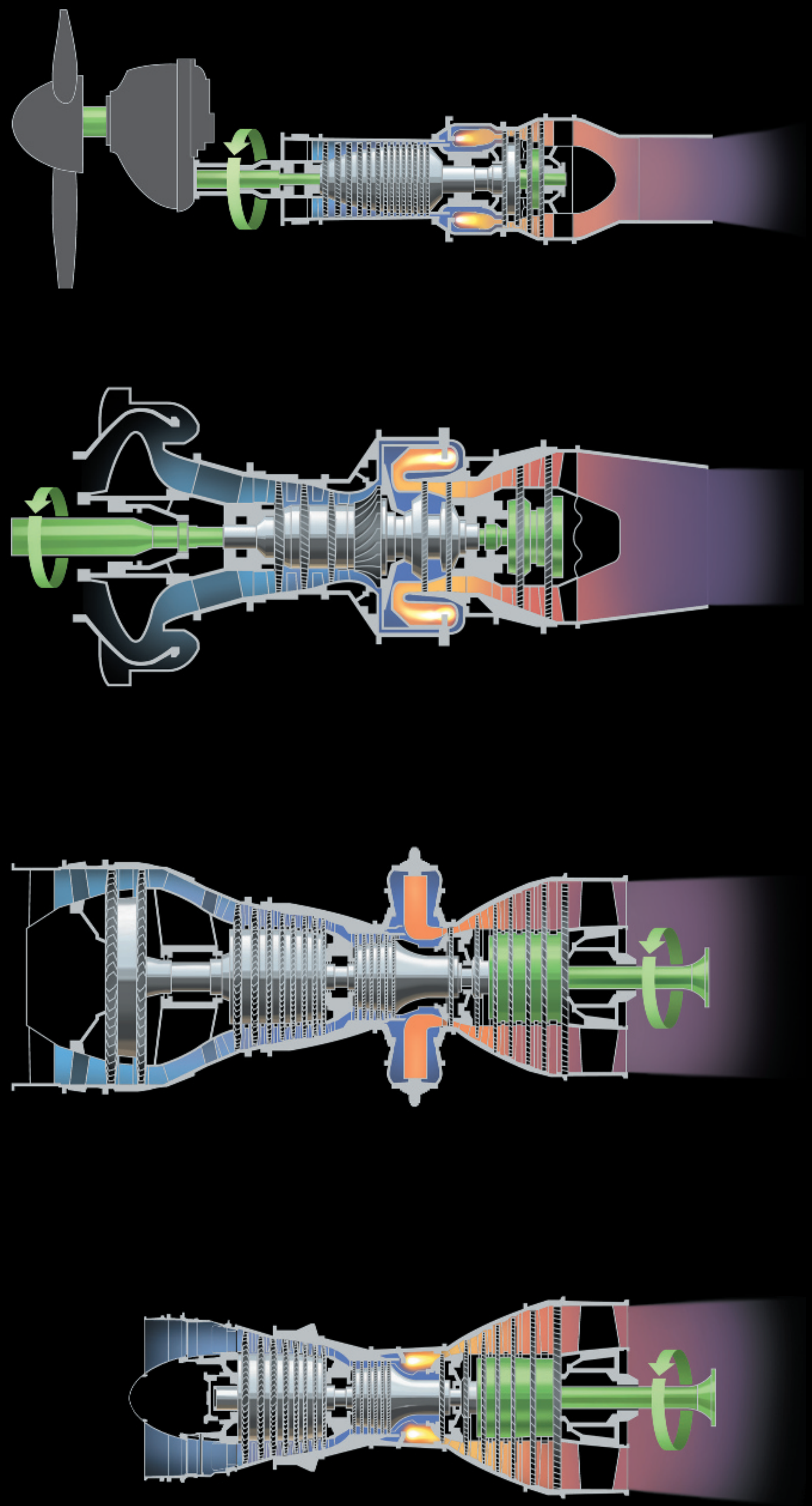
The core is sometimes called a gas generator because it generates a useful, continuous flow of hot, high-pressure gas at exit from the core turbines. This hot, high-pressure gas can become the single, very high-speed exhaust of a turbojet, or it can be expanded to drive an LP turbine. In a conventional turbofan, the LP turbine is used to drive the fan. The bypass air may then eject from a separate bypass nozzle, or from an integrated nozzle shared with the core flow.

The Trent and the EUROJET EJ200 are both turbofans but are very different in design as they are intended for very different applications. The Eurofighter Typhoon, powered by the EJ200, can fly nearly three times faster then the commercial airliners powered by the Trent (» 75), and so the three-stage EJ200 fan has a higher pressure ratio than the single-stage Trent fan. Coupled with the low bypass ratio this gives the higher jet velocity necessary for higher flight speed.

A low bypass engine with a three-stage fan is the correct choice for the Typhoon because its mission is not always to fly at maximum speed; it must also cruise, loiter, and intercept as a single aircraft system. This contrasts with an interceptor, where a pure turbojet may be the better choice for its typical, high-speed mission. In situations where thrust is more important than noise or fuel consumption, aircraft can use afterburning – burning extra fuel in the exhaust for short periods to gain extra thrust.

Turboshafts and turboprops

Turboshaft and turboprop engines are gas turbine engines where all the useful power output is transmitted by a shaft. Engines that drive an unducted fan or a propeller



Top: the geared turboprop

Upper middle: a reverse flow turboshaft as used on helicopters

Lower middle: a three-shaft industrial engine with two booster compressor stages running off the LP turbine. The radial DLE combustors seen here are more typically a feature on engines without booster stages.

Bottom: a marine engine with a conventional aero-derivative combustor

are called turboprops, while the engines that power helicopters are called turboshafts because the helicopter rotor is quite separate from the engine. Turboshafts also drive ships' propellers, generators in power stations, oil pipeline pumps, and natural gas compressors.

A turboprop engine uses the LP turbine to drive a large propeller though a speed reduction gearbox. For a given engine weight, a turboprop, with its large propeller, accelerates more air than a turbofan to a lower velocity, and hence delivers more thrust for a given fuel consumption. Turboprops are lighter than turbofans of the same size because they do not need a nacelle around the propeller. However, the low jet velocity means that as flight speed increases, thrust lapses quickly. This is a factor in preventing the use of turboprops in high-speed applications.

A helicopter turboshaft engine uses LP turbine power to drive a shaft to turn the main rotor. Helicopter rotors are much larger than propeller blades because, without wings to generate lift, a helicopter needs to generate a lot of thrust for lift off.

The Industrial Trent uses LP turbine power to turn a two-stage LP compressor and extracts enough power to drive a 40-50MW external generator or other loads such as a oil pump or a gas pipeline compressor. Marine and industrial engines are similar to the aircraft engines from which they are often derived, but may have heavier components because weight is less important than, for example, low emissions. Marine engines and industrial engines running offshore have special coatings to cope with the salt in sea spray and the sulphur in marine fuel.

An Airbus A340-600 with four Trent 500 engines

Mechanical arrangements

Most gas turbine engines have axial (rather than radial, or centrifugal) compressors and turbines. Axial compressors and turbines consist of sets of rotor blades radiating from rotating discs, interspersed with stationary blades fixed at their outer circumference in the engine casings. In a compressor, the stationary blades are called stators; in a turbine, they are called nozzle guide vanes. The air passing though the compressor rotors and stators is compressed. The task of the compressor is to achieve that compression as efficiently as possible.

Air passes though the open flowpath of an axial compressor at about 150 metres per second, but aviation fuel only burns at a few metres per second. Therefore, prior to combustion, the compressor exit air has to be slowed down before fuel is added through injectors into the combustor flametube.

Once the air/fuel mix is ignited, the flametube provides the necessary protection from the high-speed airflow for flame stability. The rest of the compressor air is fed into the combustor downstream of the stable, primary combustion zone, mixing with the air inside, to give a lower exit temperature profile into the turbine system.

The turbine nozzle guide vanes accelerate and deflect the combustion gases. These high-speed gases move through the turbine rotors pushing them around. In this way, a turbine can generate torque to drive a compressor or fan. The task of a turbine is to do this for the least pressure drop, and to survive for as long as possible at the extreme, continuous temperatures found in the hot end of gas turbine engines.

The pressure built up after the fan and compressor, and left over at turbine exit, accelerates the bypass and core jets through nozzles (or a single, combined nozzle) to obtain thrust. This is transmitted by the engine mounts to the aircraft. If the engine is a turboprop or turboshaft, the last turbine stages drive a load instead of a fan.

The rotating turbine and compressor discs, either individually or joined together into a drum, are attached to the shafts that connect the turbines to the compressors or the power turbine to its load. These shafts are supported by bearings fixed into the engine structure. At the front of the engine, where metal and air temperatures are comparatively cool, ball bearings provide axial location. The rear bearings are typically roller bearings that locate the shafts radially, but allow differential thermal expansion of the shafts and casings in an axial direction.

Multi-shaft layouts

The simplest arrangement of a jet engine has a single compressor, driven via a shaft by a single turbine. In practice, this layout is only used for the smaller turbojets; larger, more complex layouts require a multi-shaft approach.

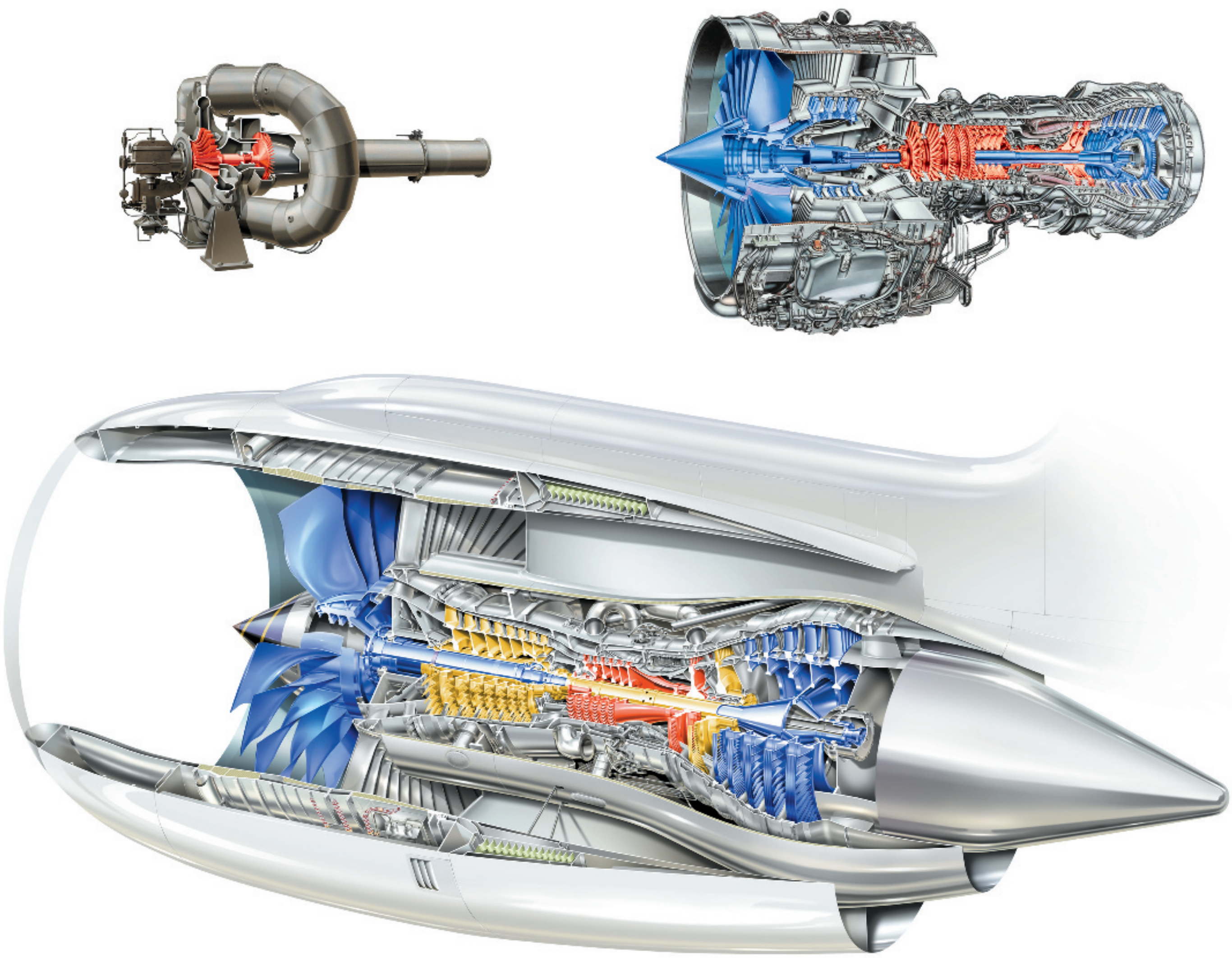
As the air is compressed on its way towards the combustion chamber, the annulus area of the compressor reduces, and the compressor blades become smaller. In the interests of efficiency, the smaller blades at the rear of the compressor need to rotate at a higher speed than the fan at the front.

This is done by splitting both the compressor and turbine into two: an LP compressor is connected via a shaft to an LP turbine; an HP compressor is connected via a second shaft running outside the LP shaft to a high-pressure (HP) turbine. This two-shaft engine layout is the optimum engine architecture for engines up to 25,000-35,000lb thrust.

Larger turbofans can benefit from three shafts; in this configuration, there is a fan (LP), an intermediate (IP) compressor, and an HP compressor all running on separate shafts connected to respective LP, IP, and HP turbines.

The separation of the fan and first compressor stages allows the shaft speeds and thus fan and blade velocities to be optimised more closely to the ideal operating conditions of each stage.

The three-shaft layout adds a level of mechanical complexity to the overall engine layout but reduces the reliance on variable geometry compressor features. The main benefit is that high thrust can be developed from a shorter, lighter engine than an equivalently rated two-shaft layout.



The growth in complexity of shaft arrangements as engine thrust and size increase is shown with the first working gas turbine, Whittle's single-shaft W1, the two-shaft V2500[*1] (25,000 to 35,000lbs), and the three-shaft Trent (53,000 to 95,000lbs). Red indicates the HP spool, yellow, the IP spool, and blue, the LP spool.

In theory, there is no difference between theory and practice;
experience suggests that in practice, there is.

experience