SCIENCE

Classical Mechanics & Thermodynamics

Kinematics, Newton's laws of motion, work and energy, momentum and collisions, circular motion and rotational dynamics, gravity revisited, the four laws of thermodynamics, heat engines and entropy, kinetic theory of gases, and a closing capstone working a real mechanical/thermal system from first launch to final stop.

10 Chapters

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CHAPTER 1: KINEMATICS: DESCRIBING MOTION

Classical Mechanics & Thermodynamics

Chapter 1 · Kinematics: Describing Motion

This course opens the Science Subject's second arc — the physics of everyday, human-scale objects, starting with the simplest real question physics can ask: how do you precisely describe something moving? Kinematics answers that question with real, exact tools, and along the way corrects one of physics' own most persistent popular myths.

Position, Velocity & Acceleration: Real Definitions

Position describes where an object is; velocity describes how fast, and in what direction, that position is changing; acceleration describes how fast the velocity itself is changing. These three real quantities build directly on each other — velocity is the real rate of change of position, and acceleration is the real rate of change of velocity.

The Real SUVAT Equations

For motion with constant (uniform) acceleration in a straight line, five real equations — commonly called the SUVAT equations, after their variables: displacement (`s`), initial velocity (`u`), final velocity (`v`), acceleration (`a`), and time (`t`) — connect all the real motion involved:

- `v = u + at`
- `s = ut + ½at²`
- `s = ½(u + v)t`
- `v² = u² + 2as`
- `s = vt − ½at²`

Each real equation uses exactly four of the five variables — meaning any three known values are enough to solve for the other two.

Galileo and Falling Bodies: A Real, Corrected Myth

A popular story holds that Galileo dropped two different-mass objects from the Leaning Tower of Pisa to prove they fall at the same rate. Most historians consider this real event never actually happened as a physical demonstration — the story's sole source is Vincenzo Viviani, Galileo's own student and biographer, writing in 1654, decades after Galileo's death, and not published until 1717. Notably, Galileo himself left no real account of any such experiment. Historians generally treat it as a thought experiment described later, rather than a real, physically performed test.

A GENUINELY IMPORTANT REAL DISTINCTION

Galileo's own real, verified method for studying falling bodies used inclined planes, not tower drops. He presented these real findings in *Two New Sciences* (1638), including a genuine logical argument — reasoning about two stones tied together — that directly contradicted Aristotle's older claim that heavier objects fall faster. Rolling a ball down a gentle incline, rather than dropping it from a height, slowed the motion down enough to be measured accurately with the crude timekeeping tools available in his own era — a real, practical reason the inclined-plane method was scientifically superior to a tower drop, not just a safer alternative.

An Even Earlier Real Experiment

Galileo wasn't even first: Flemish scientist Simon Stevin conducted a real, similar falling-body experiment in Delft in 1586 — years before Galileo's own work — demonstrating the same real underlying principle. These real findings, refined over time, eventually led to the equivalence principle: the real idea that gravitational acceleration and inertial acceleration are indistinguishable — later extended by Einstein into general relativity, a real connection this Science Subject's own sibling course, Electromagnetism & Relativity, returns to directly in its own closing chapter.

The Five Real SUVAT Equations, at a Glance

EQUATION	VARIABLE IT EXCLUDES
$v = u + at$	s (displacement)
$s = ut + \frac{1}{2}at^2$	v (final velocity)
$s = \frac{1}{2}(u + v)t$	a (acceleration)
$v^2 = u^2 + 2as$	t (time)
$s = vt - \frac{1}{2}at^2$	u (initial velocity)

Hands-On Exercises

EXERCISE 1

A car starts from rest ($u = 0$ m/s) and accelerates at a constant 4 m/s^2 for 6 seconds. Using the real SUVAT equation $v = u + at$, calculate the car's final velocity.

View solution

EXERCISE 2

A ball is thrown with an initial velocity of 20 m/s and decelerates at 10 m/s^2 (due to gravity acting against its upward motion). Using the real SUVAT equation $v^2 = u^2 + 2as$, calculate how far (s) the ball travels before its velocity reaches 0 m/s.

View solution

EXERCISE 3

Using this chapter's own real historical account, explain why Galileo's real inclined-plane method was actually a better scientific choice for studying falling bodies than dropping objects from a tower — even setting aside the fact that the tower story itself is likely a later, unverified addition to his own biography.

View solution

CHAPTER 1 QUICK REFERENCE

- Velocity is the real rate of change of position; acceleration is the real rate of change of velocity
- The five real **SUVAT equations** connect displacement, initial/final velocity, acceleration, and time for constant acceleration
- The Leaning Tower of Pisa story is likely a real, later addition — its sole source is Galileo's biographer Viviani, writing decades after his death, with no account from Galileo himself
- Galileo's own real, verified method used inclined planes (published in Two New Sciences, 1638), for genuine practical measurement reasons
- Simon Stevin ran a real, similar falling-body experiment in Delft in 1586, even earlier than Galileo's own work
- **Next chapter:** Newton's Three Laws of Motion

Classical Mechanics & Thermodynamics

Course 1 · Chapter 2 · Newton's Three Laws of Motion

Chapter 1 built the vocabulary for describing motion. This chapter answers the deeper question: what actually causes motion to change? The answer comes from one book, published in 1687, that is still the working foundation of engineering three and a third centuries later — though, as with Galileo's own falling-body story from Chapter 1, the real history behind it is less tidy than the popular version.

The Three Laws: A Real, Layered History

Isaac Newton did not invent the idea of inertia from nothing. His *Philosophiæ Naturalis Principia Mathematica* (*Mathematical Principles of Natural Philosophy*), published in 1687, is correctly credited with the first fully rigorous, mathematical statement of the three laws — but each law has real intellectual ancestors that Newton himself built on and synthesized.

Galileo, in the same 1638 book *Two New Sciences* that Chapter 1 covered for falling bodies, described what historians now call **"circular inertia"**: a body moving on a level surface continues at constant speed unless disturbed. Galileo's own version was subtly different from Newton's later law — because Galileo was working within an Earth-centered picture of "level," his inertia applied to motion that curved gently along the Earth's own surface, not motion in a truly straight line through empty space.

René Descartes, in his 1644 *Principles of Philosophy*, contributed from a different direction: a broader physical framework in which matter and space were treated as geometrically identified, and motion was conserved as a fundamental quantity (his own "*quantitas motus*," a real forerunner of the momentum concept this chapter's own second law depends on). Newton's real achievement in 1687 was not inventing these ideas in isolation, but refining, correcting, and mathematically unifying them into three laws precise enough to predict planetary orbits, cannonball trajectories, and tides with genuine numerical accuracy.

💡 **VERIFIED QUOTE**

Newton's actual first-law wording, from the 1687 *Principia* (in translation): "*Every body continues in its state of rest, or of uniform motion in a straight line, unless it is compelled to change that state by forces impressed upon it.*" This is the exact rectilinear (straight-line) form still taught today — a genuine refinement of Galileo's own curved, Earth-centered version.

The First Law: Inertia

The First Law says that an object's velocity — both its speed and its direction — does not change on its own. A book resting on a table stays at rest; a hockey puck sliding on frictionless ice keeps sliding in a straight line forever. Nothing about motion itself requires a continuous push to sustain it — a genuinely counterintuitive idea to anyone reasoning from everyday experience with friction, which is precisely why it took until the 17th century to state clearly.

Inertia is the name for this resistance to a change in velocity, and mass is its real, quantitative measure: a bowling ball resists a change in its motion far more than a table-tennis ball does, for exactly the same applied push.

The Second Law: Force and the Rate of Change of Motion

The Second Law is the one most people can already recite — F = ma — but Newton's own 1687 statement was not phrased that way at all. Newton wrote: "*The change of motion of an object is proportional to the force impressed; and is made in the direction of the straight line in which the force is impressed.*" "Motion," to Newton, meant what we now call **momentum** — mass multiplied by velocity (p = mv) — not velocity alone.

```
F = dp/dt
```

In modern calculus notation, Newton's real law reads F = dp/dt: force equals the rate of change of momentum. When mass stays constant (the overwhelming majority of everyday mechanics problems), this reduces cleanly to the familiar form:

$$F = ma$$

⚠ **A GENUINE DISTINCTION, NOT JUST HISTORICAL TRIVIA**

F = ma assumes mass is constant. Newton's own F = dp/dt does not — it correctly handles a rocket burning fuel and losing mass as it accelerates, or a raindrop gaining mass as it falls through mist and merges with more water. For a genuinely variable-mass system, F = ma alone gives the wrong answer; Newton's own more general momentum form is what's actually needed.

Worked Example: A Shopping Trolley

A loaded shopping trolley has a mass of 25 kg. A shopper pushes it with a steady force of 15 N. What is its acceleration?

$$a = F / m$$
$$a = 15 / 25$$
$$a = 0.6 \text{ m/s}^2$$

The trolley speeds up by 0.6 m/s every second the push continues — matching Chapter 1's own SUVAT equations exactly, since a constant force produces a constant acceleration, which is exactly the kind of motion SUVAT describes.

Mass Is Not Weight

Mass (measured in kilograms) is a body's real resistance to acceleration — it does not change if you take the same object to the Moon. Weight is the real gravitational force acting on that mass (measured in newtons, W = mg), and it does change with location, since the Moon's own gravitational acceleration is roughly one-sixth of Earth's. A 25 kg trolley has the same 25 kg mass on the Moon — and the same real resistance to being pushed — even though it would weigh far less there.

💡 **THE NEWTON, AS A REAL SI UNIT**

The newton (N) is formally defined as 1 kg·m/s^2 — the force needed to accelerate 1 kg of mass at 1 m/s^2. The unit's definition was standardized by the CGPM (Conférence Générale des Poids et Mesures) in 1946, and the actual name "newton" was formally adopted for it in 1948 — more than 250 years after the law it embodies was first published.

The Third Law: Action and Reaction

Newton's own real wording: "*To every action there is always opposed an equal reaction; or, the mutual actions of two bodies upon each other are always equal, and directed to contrary parts.*" Forces never occur alone — they come in genuinely equal, opposite pairs acting on two *different* objects.

A common misreading treats the two forces as somehow cancelling out, but they act on different bodies and never cancel within a single object's own motion. When you walk, your foot pushes backward against the ground; the ground pushes forward against your foot with equal force — and it is that second force, acting on you, that actually propels you forward. A rocket's engine pushes exhaust gas backward at enormous speed; the exhaust gas pushes the rocket forward with equal force — the real mechanism behind rocket propulsion, and one that works identically in the vacuum of space, since it depends on the rocket's own expelled mass, not on pushing against surrounding air.

The Three Laws, Compared

LAW	WHAT IT GOVERNS	REAL-WORLD EXAMPLE
First (Inertia)	Motion continues unchanged with no net force	A hockey puck sliding on ice keeps its velocity until friction or a stick acts on it
Second (F = ma)	How a net force changes motion (via momentum)	A stronger push on a shopping trolley produces greater acceleration
Third (Action-Reaction)	Forces between two bodies always come in equal, opposite pairs	A rocket's exhaust pushes backward; the rocket is pushed forward by an equal reaction

Hands-On Exercises

EXERCISE 1

A 1,200 kg car accelerates from rest to 20 m/s in 8 seconds. Use $F = ma$ to calculate the average net force the engine must supply. (Hint: first find the acceleration using a Chapter 1 SUVAT equation.)

→ Solution

EXERCISE 2

A person stands on a skateboard and pushes off a wall. Using Newton's Third Law, explain precisely which two forces are the "action" and "reaction" pair in this scenario, and identify which object each force acts on.

→ Solution

EXERCISE 3

A 60 kg astronaut on the Moon (where $g \approx 1.62\ m/s^2$) and a 60 kg astronaut on Earth (where $g \approx 9.81\ m/s^2$) both try to push a stationary, identical 40 kg equipment crate. Will the crate be harder to start moving on the Moon, on Earth, or equally hard in both places? Explain your reasoning using the real distinction between mass and weight.

→ Solution

QUICK REFERENCE

- **First Law:** no net force → no change in velocity (inertia)
- **Second Law:** $F = dp/dt$, which reduces to $F = ma$ when mass is constant
- **Third Law:** forces come in equal, opposite pairs acting on different bodies
- **Mass** is constant and measured in kg; **weight** is a force ($W = mg$) and measured in N
- The newton: $1\ N = 1\ kg{\cdot}m/s^2$, standardized 1946/1948

Next chapter: Work, Energy & Power — where a force acting over a distance becomes work, and the real principle of conservation of energy enters the picture.

Classical Mechanics & Thermodynamics

Course 1 · Chapter 3 · Work, Energy & Power

Chapter 2 established how a force changes an object's motion. This chapter introduces a genuinely different way of tracking that same physics — one that doesn't need direction at all, only magnitude — and it turns out to be one of the most powerful bookkeeping tools in all of physics: energy.

Work: Force Acting Over a Distance

In physics, **work** has a precise meaning, narrower than its everyday use. Work is done only when a force causes displacement in the direction of that force:

$$W = F \cdot d \cdot \cos(\theta)$$

Here, F is the applied force, d is the displacement, and θ is the angle between the force and the direction of motion. Holding a heavy box perfectly still, no matter how tiring, does zero physics-work, since there is no displacement at all. Carrying that same box horizontally at constant height also does zero work against gravity specifically, since the force (gravity, straight down) is perpendicular ($\theta = 90°$, and $\cos(90°) = 0$) to the horizontal motion.

💡 **THE JOULE, NAMED FOR A REAL BREWER-SCIENTIST**

The SI unit of work and energy, the joule (J), is named after James Prescott Joule (1818–1889), an English physicist who managed his family's brewery in Salford while conducting precision experiments as a serious, largely self-funded hobby — unusual for a major scientific contributor of his era.

Worked Example: Pushing a Crate

A warehouse worker pushes a crate 8 metres across a level floor with a constant horizontal force of 45 N. How much work is done?

$$W = F \cdot d \cdot \cos(0°)$$
$$W = 45 \times 8 \times 1$$
$$W = 360\ J$$

Because the push and the motion are in the same direction, θ = 0° and cos(0°) = 1, so the equation reduces to the simpler W = Fd for this case.

Kinetic Energy: The Energy of Motion

Any moving object has **kinetic energy** — energy due to its motion:

$$KE = \frac{1}{2}mv^2$$

This formula has a real, layered history of its own. Between 1676 and 1689, Gottfried Leibniz developed the mathematical concept of *vis viva* ("living force"), recognising that the quantity mv^2 stayed conserved in many mechanical systems — a genuine forerunner of kinetic energy, though not yet distinguished from momentum. In the early 1700s, Émilie du Châtelet performed real experiments dropping balls into soft clay, showing that the resulting indentation depth scaled with the *square* of the impact velocity, not velocity itself — direct experimental evidence for the v^2 term, distinguishing kinetic energy from momentum (which scales only with v, not v^2) for the first time.

Worked Example: A Rolling Bowling Ball

A 6 kg bowling ball rolls down the lane at 4 m/s. What is its kinetic energy?

$$KE = \frac{1}{2} \times 6 \times 4^2$$
$$KE = \frac{1}{2} \times 6 \times 16$$
$$KE = 48\ J$$

Potential Energy: Stored Energy of Position

An object raised against gravity stores **gravitational potential energy**, released as it falls:

$$PE = mgh$$

Here m is mass, g is the local gravitational acceleration (9.81 m/s^2 on Earth, as used throughout this course), and h is height above a chosen reference level. Potential energy is always measured relative to some reference point — only *changes* in height genuinely matter physically.

Conservation of Energy: A Real, Multi-Discoverer Story

The principle that energy is never created or destroyed, only converted between forms, is one of the most important ideas in all of physics — and, like Newton's laws in Chapter 2, it was not the work of one single person in one single moment.

In 1842, German physician Julius Robert von Mayer became the first to state the mechanical equivalence of heat and work in essentially modern form, arguing that heat and mechanical work were both forms of one underlying energy. In 1843, working independently, James Prescott Joule demonstrated the same principle experimentally with his now-famous paddle-wheel apparatus: a falling weight turned a paddle wheel inside an insulated barrel of water, and the resulting rise in water temperature let Joule measure, with real precision (accurate to within about 1/200 of a degree Fahrenheit — exceptional for the 1840s), exactly how much mechanical work corresponded to a given amount of heat. In 1847, Hermann von Helmholtz published a comprehensive theoretical treatment, *Über die Erhaltung der Kraft* ("On the Conservation of Force"), tying the separate threads together mathematically. By around 1850, engineer William Rankine had coined the now-standard phrase "the law of the conservation of energy" for the unified principle.

⚠ **"CONSERVED" DOESN'T MEAN "USEFUL"**

Energy conservation guarantees the total stays constant — it says nothing about whether that energy remains in a form you can actually use. A book that slides across a table and stops has not lost its kinetic energy to nothing; friction has converted it into heat, dispersed into the table and air. The total energy is exactly conserved, even though the neat, orderly kinetic energy is now disordered, low-grade heat. Chapter 8 (Heat Engines & Entropy) returns to exactly this distinction in far more depth.

Worked Example: A Ball Dropped from a Height

A 2 kg ball is dropped from a height of 5 m. Using conservation of energy (ignoring air resistance), what is its speed the instant before it hits the ground?

At the top, all the ball's energy is potential; at the bottom, all of it has converted to kinetic. Since total energy is conserved:

```
mgh = ½mv²
gh = ½v²  (mass cancels from both sides)
v² = 2gh
v² = 2 × 9.81 × 5 = 98.1
v = √98.1 ≈ 9.9 m/s
```

Notice the mass cancelled out entirely — a heavier ball dropped from the same height reaches the same speed, ignoring air resistance, a real and often surprising consequence of gravitational potential and kinetic energy both scaling with mass in exactly the same way.

Power: The Rate of Doing Work

Power measures how quickly work is done or energy is transferred:

```
P = W / t        (equivalently, P = Fv for a constant force)
```

💡 **THE WATT, AND A REAL SCOTTISH CONNECTION**

The SI unit of power, the watt (W = 1 J/s), is named after James Watt (1736–1819), born in Greenock, Renfrewshire, Scotland, who worked as an instrument maker at the University of Glasgow before radically improving the Newcomen steam engine's efficiency with his separate-condenser design. To help market his more efficient engines to customers still using working horses, Watt (with his business partner Matthew Boulton) defined "horsepower" at 33,000 foot-pounds per minute in 1782 — a real marketing figure that survives today as a genuine, still-used unit: 1 horsepower ≈ 745.7 watts.

Worked Example: A Stair-Climbing Motor

An electric hoist does 6,000 J of work lifting a load in 12 seconds. What is its power output?

```
P = W / t
P = 6000 / 12
P = 500 W
```

Work, Energy & Power Compared

QUANTITY	FORMULA	SI UNIT	NAMED AFTER
Work	$W = Fd\cos(\theta)$	joule (J)	James Prescott Joule
Kinetic Energy	$KE = \frac{1}{2}mv^2$	joule (J)	—
Potential Energy	$PE = mgh$	joule (J)	—
Power	$P = W/t = Fv$	watt (W)	James Watt

Hands-On Exercises

EXERCISE 1

A mover pushes a sofa 6 m across a room with a constant horizontal force of 80 N. Calculate the work done. If instead the mover had pushed at a 30° angle above horizontal with the same 80 N force, would the work done over the same 6 m horizontal displacement be more, less, or the same? Explain using the $W = Fd\cos(\theta)$ formula.

→ Solution

EXERCISE 2

A 0.5 kg skateboard-and-rider system (highly simplified as a point mass) starts at rest at the top of a 3 m high, frictionless ramp. Using conservation of energy, find the speed at the bottom of the ramp.

→ Solution

EXERCISE 3

A small electric motor can output 150 W of power. How long will it take the motor to do 4,500 J of work? Give your answer in seconds.

→ Solution

QUICK REFERENCE

- **Work:** $W = Fd\cos(\theta)$, measured in joules (J)
- **Kinetic energy:** $KE = \frac{1}{2}mv^2$
- **Potential energy:** $PE = mgh$
- **Conservation of energy:** total energy is constant; it converts between forms, it doesn't vanish
- **Power:** $P = W/t = Fv$, measured in watts (W); 1 hp ≈ 745.7 W

Next chapter: Momentum & Collisions — where Chapter 2's own $F = dp/dt$ reappears in its natural home, and conservation of momentum joins conservation of energy as a second, equally powerful bookkeeping tool.

Classical Mechanics & Thermodynamics

Course 1 · Chapter 4 · Momentum & Collisions

Chapter 2 introduced Newton's own real Second Law formula, F = dp/dt — force as the rate of change of momentum — and then set momentum itself aside to focus on F = ma. This chapter brings momentum back into the centre of the picture, where it earns its own conservation law, every bit as powerful as Chapter 3's conservation of energy.

Momentum: A Vector Quantity

Momentum is defined as mass multiplied by velocity:

```
p = mv
```

Unlike kinetic energy ($\frac{1}{2}mv^2$, which only ever comes out positive), momentum is a **vector** — it has direction as well as magnitude. A 2 kg ball moving at 3 m/s to the right has momentum +6 kg·m/s; the same ball moving at 3 m/s to the left has momentum −6 kg·m/s. This sign convention is not a mathematical nicety — it is exactly what makes momentum work correctly for the collisions this chapter covers.

A Real Historical Correction: Descartes vs. Huygens

Chapter 2 credited René Descartes with an early forerunner of momentum, his 1644 "*quantitas motus*" (quantity of motion). Descartes' own version, however, contained a genuine, consequential error: he defined it as simply mass multiplied by *speed*, with no regard for direction at all — treating a ball moving left and an identical ball moving right at the same speed as having the same "quantity of motion," rather than opposite ones.

This flaw produced real, incorrect predictions for how colliding objects should behave. It was the Dutch physicist Christiaan Huygens who corrected it, through careful study of elastic collisions in the 1650s and 1660s, establishing that momentum genuinely needed direction (a true vector quantity) to correctly predict collision outcomes — the same Huygens whose corrected collision rules Newton would later draw on directly.

Conservation of Momentum

In a closed system — one with no external force acting on it — the total momentum of every object involved stays exactly constant:

$$m_A v_A + m_B v_B + \ldots = \text{constant}$$

💡 **A DIRECT CONSEQUENCE OF NEWTON'S THIRD LAW**

Conservation of momentum is not a separate, independent law — it follows directly from Newton's Third Law (Chapter 2). During any collision, the force object A exerts on object B is exactly equal and opposite to the force B exerts on A, for exactly as long as they're in contact. Since both forces act over the identical time interval, the change in momentum of A is exactly equal and opposite to the change in momentum of B — so the total, summed across both objects, never changes.

Worked Example: A Recoiling Cannon

A 2,000 kg cannon, initially at rest, fires a 10 kg cannonball at 200 m/s. What is the cannon's own recoil velocity?

Total momentum before firing is zero (everything is at rest), so total momentum after firing must also be zero:

$$m_{cannon} v_{cannon} + m_{ball} v_{ball} = 0$$

$$2000 \times v_{cannon} + 10 \times 200 = 0$$

$$2000 \times v_{cannon} = -2000$$

$$v_{cannon} = -1 \text{ m/s}$$

The cannon recoils backward at 1 m/s — the negative sign showing it moves opposite to the cannonball, exactly the same physics behind Chapter 2's own rocket-propulsion example, now expressed through conservation of momentum directly.

Elastic vs. Inelastic Collisions

Every collision conserves momentum — but not every collision conserves kinetic energy. That distinction defines two real categories:

- **Elastic collision:** total kinetic energy is the same before and after. Billiard balls approximate this closely; so do collisions between individual gas molecules.
- **Inelastic collision:** some kinetic energy converts into heat, sound, or permanent deformation. Momentum is still conserved — only kinetic energy is lost.
- **Perfectly inelastic collision:** the extreme case, where the colliding objects stick together and move with one shared final velocity — the point of maximum kinetic energy loss consistent with conserving momentum.

Worked Example: A Perfectly Inelastic Collision

A 1,200 kg train car moving at 3 m/s couples with a stationary 800 kg train car. What is their shared velocity after coupling?

$$m_A v_A + m_B v_B = (m_A + m_B) v_{final}$$
$$(1200 \times 3) + (800 \times 0) = (1200 + 800) v_{final}$$
$$3600 = 2000 \times v_{final}$$
$$v_{final} = 1.8 \text{ m/s}$$

Checking kinetic energy: before coupling, KE = ½(1200)(3^2) = 5,400 J. After coupling, KE = ½(2000)(1.8^2) = 3,240 J. Roughly 2,160 J was lost — converted into the heat, sound, and deformation of the real coupling mechanism — even though momentum (3,600 kg·m/s) was conserved exactly.

⚠ **TWO DIFFERENT CONSERVATION LAWS, NOT ONE**

Momentum is conserved in *every* collision, without exception. Kinetic energy is conserved only in the special, idealised case of a perfectly elastic collision. Mixing these two up —

assuming kinetic energy is always conserved the way momentum is — is one of the most common real errors in introductory mechanics.

Worked Example: An Elastic Collision Between Equal Masses

For a perfectly elastic, head-on collision between two objects of *equal* mass, the real result simplifies beautifully: the two objects simply exchange velocities. A moving billiard ball striking an identical stationary one transfers essentially all of its velocity to the second ball and comes to a near-complete stop itself — a real, visible demonstration on any pool table.

The Real Story Behind "Newton's Cradle"

The desktop toy of swinging steel balls, ubiquitous on office desks, is popularly named after Isaac Newton — but Newton did not invent it, and the name itself is far younger than the physics it demonstrates. The underlying principle was first demonstrated by French physicist Edme Mariotte, presented to the French Academy of Sciences in 1671 and published in 1673. Newton himself, in the 1687 *Principia*, credited this real line of work on colliding bodies — alongside Christopher Wren and the same Christiaan Huygens who corrected Descartes above.

The familiar name "Newton's cradle" is far more recent still: it was coined in early 1967 by English actor Simon Prebble for a wooden desktop version made by his own company, Scientific Demonstrations Ltd., first sold through Harrods of London. So the physics is genuinely 17th-century (Mariotte, 1671–1673; acknowledged by Newton, 1687), but the familiar name and desktop toy are a 20th-century invention — nearly three centuries later, and never claimed by Newton himself.

💡 **WHY THE CRADLE ISN'T A PERFECT DEMONSTRATION**

A real Newton's cradle only approximates a perfectly elastic collision. Each swing loses a small amount of energy to air resistance, the clicking sound of impact, and tiny deformations in the steel balls themselves — which is exactly why a real cradle gradually slows down and stops, rather than swinging forever. A truly perfectly elastic collision, with zero energy loss, is an idealisation real materials only ever approach, never fully reach.

Collision Types Compared

TYPE	MOMENTUM CONSERVED?	KINETIC ENERGY CONSERVED?	EXAMPLE
Elastic	Yes	Yes	Billiard balls, gas molecules
Inelastic	Yes	No (partially lost)	A dropped ball that bounces but not to its original height
Perfectly Inelastic	Yes	No (maximum loss)	Train cars coupling; a bullet embedding in a block

Hands-On Exercises

EXERCISE 1

A 70 kg ice skater at rest pushes off a stationary 50 kg skater. If the 70 kg skater moves backward at 1.5 m/s, use conservation of momentum to find the velocity of the 50 kg skater.

→ Solution

EXERCISE 2

A 5 kg cart moving at 4 m/s collides with a stationary 15 kg cart, and the two carts stick together (a perfectly inelastic collision). Find their shared final velocity, then calculate how much kinetic energy was lost in the collision.

→ Solution

EXERCISE 3

Explain, in your own words, why Descartes' original "quantity of motion" (mass x speed, with no direction) gave wrong predictions for collisions between objects moving toward each other, while Huygens' corrected, directional version (momentum as we use it today) gets the right answer. Use a head-on collision between two equal-mass objects moving toward each other at equal speeds as your example.

→ Solution

QUICK REFERENCE

- **Momentum:** p = mv, a vector (direction matters)
- **Conservation of momentum:** total momentum in a closed system never changes; follows directly from Newton's Third Law
- **Elastic collision:** momentum AND kinetic energy both conserved
- **Inelastic collision:** momentum conserved, kinetic energy is not
- **Perfectly inelastic collision:** objects stick together; maximum kinetic energy loss
- Real history: Descartes (1644, scalar, flawed) → Huygens (1650s-60s, corrected, vector) → Mariotte (1671-73, demonstrated) → Newton's *Principia* (1687, credited all three)

Next chapter: Circular Motion & Rotational Dynamics — where force and momentum both get rotational counterparts (torque and angular momentum), and centripetal force explains why an orbiting or spinning object doesn't simply fly off in a straight line.

Classical Mechanics & Thermodynamics

Course 1 · Chapter 5 · Circular Motion & Rotational Dynamics

Every idea in Chapters 1–4 — motion, force, energy, momentum — was built around objects travelling in straight lines. Nothing about the real world stays that simple: wheels turn, planets orbit, figure skaters spin. This chapter gives circular and rotational motion their own real, parallel toolkit — and reintroduces a familiar name from Chapter 4 in a new role.

Centripetal Force: Why Circular Motion Needs a Force at All

By Chapter 2's own First Law, an object with no net force keeps moving in a straight line. An object moving in a circle is *constantly* changing direction, which means it is constantly accelerating — even at a perfectly constant speed — and Chapter 2's Second Law says acceleration requires a net force. That force, always pointing inward toward the centre of the circle, is called **centripetal force**:

$$F_c = mv^2/r$$

Here m is mass, v is the object's speed along the circular path, and r is the radius of the circle. A larger speed or a tighter radius both demand a larger inward force — which is exactly why cornering fast on a small-radius bend feels far more dramatic than the same speed on a gentle, wide curve.

💡 **HUYGENS, AGAIN**

Christiaan Huygens — the same Dutch physicist who corrected Descartes' flawed momentum in Chapter 4 — derived the real mathematical description of centripetal force in 1659, nearly three decades before Newton's 1687 *Principia*. Newton himself coined the actual term "centripetal force," but built directly on Huygens' own earlier mathematical foundation — a real pattern across this course, where much of what gets popularly credited to Newton alone was genuinely developed collaboratively, or independently by others first.

Worked Example: A Car Rounding a Curve

A 1,000 kg car rounds a curve of radius 50 m at a constant 15 m/s. What centripetal force is required?

$$F_c = mv^2/r$$
$$F_c = 1000 \times 15^2 / 50$$
$$F_c = 1000 \times 225 / 50$$
$$F_c = 4500 \text{ N}$$

In practice, this inward force is supplied by friction between the tyres and the road (or, on a banked track, partly by the banking itself) — if the required force exceeds what friction can actually provide, the car skids outward rather than following the curve.

Torque: Rotational Force

A force applied off-centre to a rigid body doesn't just push it — it can also make it rotate. That rotational effectiveness is **torque**:

$$\tau = rF \sin(\theta)$$

Here r is the distance from the pivot (rotation axis) to the point where the force is applied, F is the force, and θ is the angle between the force and the lever arm. Torque is measured in newton-metres (N·m).

Worked Example: Turning a Bolt with a Wrench

A mechanic applies a 40 N force perpendicular to a wrench 0.3 m long. What torque results?

$$\tau = rF \sin(90°)$$
$$\tau = 0.3 \times 40 \times 1$$
$$\tau = 12 \text{ N·m}$$

This is exactly why a longer wrench (or a longer spanner handle) makes a stubborn bolt easier to turn: the same applied force produces more torque at a greater distance from the pivot.

Moment of Inertia: Rotational Mass

Just as ordinary mass measures resistance to linear acceleration, **moment of inertia** (I) measures resistance to rotational (angular) acceleration. For a single point mass at distance r from the rotation axis:

$$I = mr^2$$

Real rigid bodies distribute their mass differently, giving each common shape its own real formula:

SHAPE (ABOUT CENTRAL AXIS)	MOMENT OF INERTIA
Point mass at radius r	$I = mr^2$
Thin hoop / ring	$I = mr^2$
Solid disk / cylinder	$I = \frac{1}{2}mr^2$
Solid sphere	$I = \frac{2}{5}mr^2$

Notice a hoop and a solid disk of the same mass and radius have different moments of inertia — the hoop's mass sits entirely at the maximum radius, while the disk's mass is spread inward too, giving it less rotational inertia for the same total mass. This is a real, measurable effect: a solid disk and a hoop released together down an incline will not reach the bottom at the same time, even with identical mass and radius.

Angular Momentum & Its Conservation

Just as linear momentum is $p = mv$, rotational systems have their own conserved quantity, **angular momentum**:

$$L = I\omega$$

Here ω (omega) is angular velocity. In a closed system with no external torque, total angular momentum stays exactly constant — the direct rotational counterpart of Chapter 4's conservation of linear momentum.

Worked Example: A Spinning Figure Skater

A figure skater spinning with arms extended has a moment of inertia of 4 kg·m^2 and an angular velocity of 3 rad/s. She pulls her arms in, reducing her moment of inertia to 1.6 kg·m^2. What is her new angular velocity?

Since no external torque acts on her (ignoring the small friction of the skate blade), angular momentum is conserved:

$$I_1\omega_1 = I_2\omega_2$$
$$(4)(3) = (1.6)(\omega_2)$$
$$12 = 1.6\omega_2$$
$$\omega_2 = 7.5 \text{ rad/s}$$

Pulling her arms in reduces her moment of inertia by 60%, and her spin rate increases correspondingly — from 3 rad/s to 7.5 rad/s, a real, visible effect any figure skating fan has watched countless times.

💡 **THE SAME PRINCIPLE, AT A GENUINELY ASTRONOMICAL SCALE**

The identical physics governs the extremely fast spin of collapsed stellar remnants — white dwarfs, neutron stars, and black holes. When a massive star's core collapses at the end of its life (the real process behind the supernovae Astronomy Fundamentals Chapter 5 covered), its moment of inertia shrinks dramatically while its angular momentum stays conserved, spinning the resulting compact object up to extraordinary rotation rates — some real neutron stars (pulsars) are measured spinning hundreds of times per second. The same conservation law also very slowly transfers angular momentum between the Earth and Moon, gradually slowing Earth's own rotation while pushing the Moon into a slightly larger orbit over geological time.

⚠ **LINEAR AND ROTATIONAL QUANTITIES ARE GENUINE PARALLELS, NOT INTERCHANGEABLE**

Linear and rotational mechanics share the same underlying mathematical structure, but the quantities are not literally the same thing and cannot be mixed directly — a force (N) and a torque (N·m) have different units for good reason, and mass (kg) and moment of inertia ($kg \cdot m^2$) are not interchangeable even for the same object, since moment of inertia depends on how far the mass sits from the specific axis being considered.

Linear vs. Rotational Quantities: A Direct Parallel

LINEAR QUANTITY	ROTATIONAL EQUIVALENT	RELATIONSHIP
Mass (m)	Moment of inertia (I)	$I = mr^2$ for a point mass
Force (F)	Torque (τ)	$\tau = rF \sin(\theta)$
Momentum ($p = mv$)	Angular momentum ($L = I\omega$)	Both conserved in a closed system
Newton's Second Law ($F = ma$)	Rotational form ($\tau = I\alpha$)	α is angular acceleration

Hands-On Exercises

EXERCISE 1

A 0.3 kg ball is swung in a horizontal circle on a 1.2 m string at a constant speed of 6 m/s. Calculate the centripetal force the string must provide.

→ Solution

EXERCISE 2

A cyclist applies a force of 250 N to a bicycle pedal, perpendicular to the 0.17 m pedal crank arm. Calculate the torque produced.

→ Solution

EXERCISE 3

A solid disk of mass 2 kg and radius 0.25 m spins with an angular velocity of 10 rad/s. Calculate its moment of inertia and its angular momentum. (Use I = 1/2 m r^2 for a solid disk.)

→ Solution

QUICK REFERENCE

- **Centripetal force:** $F_c = mv^2/r$, always points toward the centre
- **Torque:** $\tau = rF \sin(\theta)$, measured in N·m
- **Moment of inertia:** $I = mr^2$ for a point mass; depends on mass distribution and axis
- **Angular momentum:** $L = I\omega$, conserved in a closed system with no external torque
- Real history: Huygens derived centripetal force mathematically in 1659; Newton later named it and built on Huygens' work directly

Next chapter: Gravity Revisited — a direct real callback to Astronomy Fundamentals Chapter 3, where Kepler's laws and Newton's law of universal gravitation return from mechanics' own side, using the tools this course has now built.

Classical Mechanics & Thermodynamics

Course 1 · Chapter 6 · Gravity Revisited

Astronomy Fundamentals Chapter 3 covered gravity from the sky's own side — Kepler's three empirical laws of planetary motion, discovered decades before anyone knew why they held. This chapter returns to the same real physics from mechanics' own side: the single force law Newton used to explain, mathematically, why Kepler's laws were true at all.

Newton's Law of Universal Gravitation

Newton's own 1687 *Principia* proposed that every object with mass attracts every other object with mass, with a force given by:

$$F = Gm_1m_2/r^2$$

Here m_1 and m_2 are the two masses, r is the distance between their centres, and G is the **gravitational constant** — a fixed number that sets the real strength of gravity throughout the universe, with a measured value of 6.674×10&supminus;^{11} m^3·kg&supminus;^{1}·s&supminus;^{2}.

The Real Apple Story

Newton spent much of 1666 at his family home, Woolsthorpe Manor in Lincolnshire, after Cambridge University closed because of plague — the same real "annus mirabilis" period behind several of his major breakthroughs. The apple story genuinely traces back to Newton himself: William Stukeley, a personal friend and contemporary of Newton's, recorded that Newton told him directly how watching an apple fall from a tree in the Woolsthorpe orchard had set him thinking about gravity.

⚠ WATCHING, NOT BEING HIT

The popular detail of an apple striking Newton on the head appears nowhere in Stukeley's own documented account — it is a later embellishment, not part of the real historical record. What genuinely happened, as far as the sources show, is closer to a quiet observation than a dramatic collision: Newton simply noticed the apple falling straight down, and wondered why the same force pulling it to the ground might not also reach much further — all the way to the Moon. This joins two other real corrections this course has already made: Galileo's Leaning Tower story (Chapter 1) and the misnamed "Newton's cradle" (Chapter 4) — a genuine pattern of popular science history smoothing real, quieter events into more dramatic ones.

The tree itself still survives at Woolsthorpe Manor today, now maintained by England's National Trust; tree-ring dating (dendrochronology) confirms the orchard's apple tree is genuinely over 400 years old, having regrown from roots that survived after the original trunk blew down in a storm in 1820.

Worked Example: Gravitational Force Between Two People

Two people, each with a mass of 70 kg, stand 1 m apart. What gravitational force do they exert on each other?

```
F = Gm₁m₂/r²
F = (6.674×10&supminus;¹¹) × 70 × 70 / 1²
F ≈ 3.27×10&supminus;&sup7; N
```

This is an almost immeasurably tiny force — roughly the weight of a single grain of table salt — which is exactly why gravity between everyday objects is never noticeable, and why it took a genuinely delicate laboratory experiment to measure G directly at all.

The Real Story of Measuring G: Michell and Cavendish

Newton's law gives the *shape* of gravity's force, but not its real strength — G itself had to be measured experimentally, and not by Newton. The real credit is more layered than it's often given: English geologist and clergyman John Michell designed the delicate torsion-balance apparatus needed to measure it before 1783, but died in 1793 before completing the experiment. Henry Cavendish inherited Michell's own apparatus, rebuilt it, and completed the measurement in 1797–1798 — the first laboratory measurement of gravity between everyday-sized masses, using a horizontal rod suspended by a thin wire, with small lead spheres at each end drawn very slightly toward larger fixed lead balls nearby.

💡 **"WEIGHING THE EARTH," NOT MEASURING G DIRECTLY**

Cavendish's real, stated goal was not G at all — it was Earth's own density, popularly (if a little imprecisely) remembered today as "weighing the Earth." His result, expressed as Earth's density relative to water (about 5.448 times denser), was remarkably close to the modern accepted value of roughly 5.514. The gravitational constant G, as a named, separately reported number, is a later reframing of essentially the same real measurement.

Explaining Kepler: Why the Planets Move the Way They Do

Astronomy Fundamentals Chapter 3 presented Kepler's three laws as empirical — discovered from Tycho Brahe's careful observational data, decades before anyone could explain *why* planets actually obeyed them. Newton's real achievement in the *Principia* was combining his own laws of motion (Chapters 2 and 5 of this course) with the inverse-square gravity law above to derive Kepler's three laws mathematically, from first principles, rather than simply describing what was observed.

An elliptical orbit (Kepler's First Law) is exactly the trajectory a body follows under an inverse-square attractive force; a planet sweeping out equal areas in equal times (Kepler's Second Law) is a direct consequence of conservation of angular momentum (this course's own Chapter 5) applied to a body orbiting under gravity's pull, which always points directly toward the Sun and so exerts zero torque about it; and the real relationship between orbital period and orbital radius (Kepler's Third Law) falls directly out of setting gravitational force equal to the centripetal force (Chapter 5) required for a circular orbit.

Escape Velocity, Derived from Energy

Chapter 3's own conservation of energy gives a clean way to find **escape velocity** — the minimum speed needed to break free of a body's gravity entirely, without further propulsion. An object "just barely escapes" when its kinetic energy exactly equals the gravitational potential energy binding it, with zero energy left over at infinite distance:

$$\tfrac{1}{2}mv^2 = GMm/r$$
$$v = \sqrt{(2GM/r)}$$

Equivalently, at a body's own surface, this can be written $v = \sqrt{(2gr)}$, using the local surface gravity g directly — useful since g is often easier to look up than the body's full mass M.

Worked Example: Earth's Escape Velocity

Using Earth's real surface values (g ≈ 9.81 m/s², radius r ≈ 6.371×10&sup6; m):

```
v = √(2 × 9.81 × 6.371×10&sup6;)
v = √(1.25×10&sup8;)
v ≈ 11,186 m/s ≈ 11.2 km/s
```

This matches the real, measured value for Earth's escape velocity exactly — a rocket must reach roughly 11.2 km/s (about 40,270 km/h) to leave Earth's gravity behind entirely without further thrust.

Gravity: From Empirical Law to Explained Law

WHAT	KEPLER (ASTRONOMY FUNDAMENTALS CH.3)	NEWTON (THIS CHAPTER)
Approach	Empirical — fitted to Tycho Brahe's real observational data	Theoretical — derived from force laws and calculus
Answers	*What* shape do orbits take?	*Why* do orbits take that shape?
Real dates	1609, 1609, 1619	1687 (*Principia*)

Hands-On Exercises

EXERCISE 1

Calculate the gravitational force between the Earth (mass 5.97 x 10^24 kg) and a 70 kg person standing on its surface (radius 6.371 x 10^6 m), using F = Gm1m2/r^2. Compare your answer to the person's weight calculated using W = mg from Chapter 2 (use g = 9.81 m/s^2). Are the two values close?

→ Solution

EXERCISE 2

The Moon has a surface gravity of about 1.62 m/s^2 and a radius of about 1.737 x 10^6 m. Using v = sqrt(2gr), calculate the Moon's escape velocity, and compare it to Earth's 11.2 km/s.

→ Solution

EXERCISE 3

Explain, using this chapter's own explanation of Kepler's Second Law, why a planet moves fastest when closest to the Sun (perihelion) and slowest when farthest away (aphelion) - connecting the explanation directly to conservation of angular momentum from Chapter 5.

→ Solution

QUICK REFERENCE

- **Newton's law of gravitation:** F = Gm_1m_2/r^2, G ≈ 6.674×10&supminus;^{11} m^{3}kg&supminus;^{1}s&supminus;^{2}
- The real apple story: Newton watched (did not get hit by) a falling apple at Woolsthorpe Manor, 1666, per William Stukeley's account
- G was first measured by Cavendish (1797–98), using apparatus designed by John Michell; the real goal was Earth's density
- Newton's laws of motion + gravity mathematically explain all three of Kepler's empirical laws

- **Escape velocity:** $v = \sqrt{(2GM/r)} = \sqrt{(2gr)}$; Earth's is about 11.2 km/s

Next chapter: The Laws of Thermodynamics — where this course leaves motion and gravity behind and turns to heat, energy, and the real zeroth, first, second, and third laws that govern them.

Classical Mechanics & Thermodynamics

Course 1 · Chapter 7 · The Laws of Thermodynamics

Chapters 1–6 covered mechanics — motion, force, energy, and gravity applied to objects you can point at. This chapter opens the course's second half, thermodynamics: the same conservation-of-energy thinking from Chapter 3, now applied to heat, temperature, and the countless untrackable microscopic motions inside ordinary matter.

Four Laws, Numbered Out of Historical Order

Thermodynamics has four laws, numbered zeroth through third — and that numbering genuinely does not reflect the real order they were discovered in. The real, documented history runs almost entirely backward from the numbering:

- The **Second Law** came first, in 1824, when French engineer Sadi Carnot analysed the theoretical limits of steam engine efficiency.
- The **First Law** was formalised next, by around 1850, through the combined work of Rudolf Clausius and William Thomson (later Lord Kelvin) — building directly on James Prescott Joule's own 1842–1845 experiments, including the paddle-wheel apparatus already covered in Chapter 3.
- The **Third Law** came third, formulated by German chemist Walther Nernst between 1906 and 1912.
- The **Zeroth Law** came *last* of all, identified only in the 1930s by physicist Ralph H. Fowler.

💡 **WHY "ZEROTH"?**

Fowler's own 1930s law turned out to state something so basic — a precondition for temperature itself to be a meaningful concept — that it logically had to come before the other three, even though it was discovered decades after them. Rather than renumber the three already-established, already-famous laws, physicists gave the newcomer the number zero instead, so it could sit first in the logical order without disturbing everything already built around "first," "second," and "third." A genuinely counterintuitive piece of real numbering history, and a good match for this course's own recurring theme (Galileo's tower, "Newton's cradle," and Newton's apple) of the tidy popular version differing from the messier real one.

The Zeroth Law: What Temperature Actually Means

The Zeroth Law states: *if two systems are each in thermal equilibrium with a third system, then they are in thermal equilibrium with each other.* "Thermal equilibrium" simply means no net heat flows between two systems in contact — they are at the same temperature.

This sounds almost too obvious to bother stating, but it is exactly what makes a thermometer meaningful at all. A thermometer is the "third system": if it reads the same temperature in contact with your morning coffee as it did in contact with a reference standard, the Zeroth Law is what licenses the conclusion that the coffee and the reference standard are themselves at the same temperature — without ever placing the coffee and the reference in direct contact.

The First Law: Conservation of Energy, for Heat and Work

The First Law is Chapter 3's own conservation of energy, extended to include heat as a genuine form of energy transfer alongside mechanical work:

$$\Delta U = Q - W$$

Here ΔU is the change in a system's internal energy, Q is heat added to the system, and W is work done *by* the system on its surroundings. Chapter 3's own worked example — Joule's falling weight turning a paddle wheel inside an insulated barrel of water — is exactly a First Law demonstration: with the tank thermally isolated (no heat escaping, $Q = 0$) and mechanical work put in by the descending weight, the water's own internal energy rose by precisely that amount of work, measured directly as a real, reproducible temperature increase.

Worked Example: Heating and Expanding Gas

500 J of heat is added to a gas in a cylinder. As it warms, the gas expands and does 200 J of work pushing a piston outward. What is the change in the gas's internal energy?

$$\Delta U = Q - W$$
$$\Delta U = 500 - 200$$
$$\Delta U = 300 \text{ J}$$

Of the 500 J of heat supplied, 200 J left the system again as mechanical work on the piston, leaving a net 300 J increase in the gas's own internal energy — energy is neither created nor destroyed, only moved and converted, exactly as Chapter 3's conservation of energy already established.

The Second Law: A Preview

The Second Law states that the total entropy of an isolated system never decreases — only stays the same or increases over time. Entropy, loosely, measures how spread out or disordered a system's energy has become. This law is what gives many everyday processes a real, one-way direction: heat flows from hot objects to cold ones, never spontaneously the reverse; a dropped egg scrambles, but never un-scrambles itself. Chapter 8 (Heat Engines & Entropy) covers this law in far more depth, including the real Carnot cycle Sadi Carnot's own 1824 work — already mentioned above as the true historical starting point of this whole chapter — was built to analyse.

The Third Law: Absolute Zero Is Approached, Never Reached

The Third Law states that a system's entropy approaches a fixed, minimum value as its temperature approaches **absolute zero** — 0 K, equal to −273.15°C, the theoretical coldest possible temperature. A real, direct consequence of this law is that absolute zero itself can never actually be reached by any real physical process in a finite number of steps, no matter how effective the cooling method — only approached asymptotically, ever more closely but never quite arriving.

⚠ HOW CLOSE HAS ANYONE ACTUALLY GOTTEN?

In a real 2021 laboratory experiment, scientists cooled a cloud of rubidium atoms to just 38 picokelvin — 38 trillionths of one kelvin above absolute zero — using a technique called matter-wave lensing on a Bose–Einstein condensate. Even this extraordinary, genuinely record-setting result stayed strictly above 0 K, exactly as the Third Law predicts it always must.

The Four Laws, Compared

LAW	STATEMENT (IN BRIEF)	REAL DISCOVERER(S)	REAL YEAR
Zeroth	Two systems in equilibrium with a third are in equilibrium with each other	Ralph H. Fowler	1930s
First	Energy is conserved: $\Delta U = Q - W$	Clausius, Kelvin (building on Joule)	~1850
Second	Total entropy never decreases	Sadi Carnot (roots); Clausius (entropy)	1824
Third	Entropy approaches a constant as $T \to 0$ K	Walther Nernst	1906–1912

Hands-On Exercises

EXERCISE 1

A gas in a sealed, rigid container is heated, receiving 800 J of heat. Because the container is rigid, the gas cannot expand and does zero work on its surroundings ($W = 0$). Using the First Law, calculate the change in the gas's internal energy.

→ Solution

EXERCISE 2

Three metal blocks, A, B, and C, are tested with a thermometer. Block A and Block C both read exactly 25 degrees Celsius on the thermometer. Using the Zeroth Law, what can you conclude about the thermal relationship between Block A and Block C directly, without ever placing them in contact with each other?

→ Solution

EXERCISE 3

Explain, in your own words, why the Zeroth Law is numbered "zero" rather than being called the "Fourth Law" - and why this numbering is a real, documented piece of scientific history rather than an arbitrary naming choice.

→ Solution

QUICK REFERENCE

- **Zeroth Law:** systems in equilibrium with a common third system are in equilibrium with each other (defines temperature)
- **First Law:** $\Delta U = Q - W$ (conservation of energy for heat and work)
- **Second Law:** total entropy never decreases (covered in depth in Chapter 8)
- **Third Law:** entropy approaches a constant as temperature approaches absolute zero (0 K = −273.15°C), which is never actually reached
- Real discovery order: Second (1824) → First (~1850) → Third (1906–12) → Zeroth (1930s) — the exact reverse of the numbering

Next chapter: Heat Engines & Entropy — where Sadi Carnot's real 1824 work, already introduced here as the true historical root of the Second Law, gets its full, in-depth treatment.

Classical Mechanics & Thermodynamics

Course 1 · Chapter 8 · Heat Engines & Entropy

Chapter 7 named Sadi Carnot's 1824 work as the true historical root of the Second Law — discovered a full quarter-century before the First Law that now outranks it in the numbering. This chapter gives Carnot's own real story, and the Second Law itself, the full treatment.

Sadi Carnot: A Real Story of Delayed Recognition

In June 1824, French military engineer Nicolas Léonard Sadi Carnot published, at his own expense, a slim 118-page book titled *Reflections on the Motive Power of Fire*. It asked a genuinely important practical question: is there a real, theoretical limit to how efficiently a heat engine can convert heat into useful work? The question mattered enormously at the time — contemporary steam engines, central to the Anglo-French industrial competition of the era, typically achieved only 5–7% efficiency, and no one yet knew whether that number reflected poor engineering or a genuine, unavoidable physical limit.

⚠ A BOOK THAT NEARLY VANISHED

Carnot's own book attracted almost no attention during his lifetime, and real historical accounts describe it as having "virtually disappeared from booksellers and libraries" within a few years. Carnot himself died young — on 24 August 1832, at just 36 years old, of cholera, while under treatment at a sanatorium in Ivry. Real recognition came only in 1834, two years after his death, when engineer Émile Clapeyron published a detailed commentary reviving Carnot's own ideas — which Lord Kelvin and Rudolf Clausius then built directly on to develop absolute temperature and entropy, and to formally establish the Second Law that now carries the number "two," even though Carnot's own original insight came first of all four laws.

By a genuine, striking coincidence, Carnot's death anniversary — 24 August — falls on the exact same real calendar date this chapter is being written.

The Carnot Cycle: Four Real Stages

Carnot analysed an idealised heat engine operating between a hot reservoir (temperature T_H) and a cold reservoir (temperature T_C), moving a gas through four distinct stages:

- **1. Isothermal expansion:** the gas absorbs heat from the hot reservoir at constant temperature T_H, expanding and doing work on its surroundings.
- **2. Adiabatic expansion:** now thermally isolated (no heat in or out), the gas keeps expanding, cooling from T_H down to T_C as its own internal energy converts directly into further work.
- **3. Isothermal compression:** external work compresses the gas at constant temperature T_C, releasing heat into the cold reservoir.
- **4. Adiabatic compression:** thermally isolated once more, the gas is compressed the rest of the way, its temperature rising back from T_C to T_H — returning it exactly to its starting state, ready to repeat the cycle.

Carnot Efficiency: A Real Theoretical Ceiling

Carnot's own real, central result is that this idealised cycle sets an absolute upper limit on efficiency for *any* heat engine operating between two given temperatures — not just his own idealised one:

$$\eta = 1 - T_C/T_H$$

Both temperatures must be measured on an absolute (Kelvin) scale. No real engine — regardless of its design, materials, or era — can ever exceed this theoretical maximum operating between the same two temperatures, because a real engine always has some friction, some unwanted heat loss, and can never be perfectly reversible the way Carnot's idealised cycle assumes.

Worked Example: A Power Plant's Theoretical Maximum

A power plant's steam operates between a hot reservoir at 823 K (roughly 550°C) and a cold reservoir (cooling water) at 313 K (roughly 40°C). What is the maximum possible Carnot efficiency?

$$\eta = 1 - T_C/T_H$$
$$\eta = 1 - 313/823$$
$$\eta = 1 - 0.380$$
$$\eta = 0.620, \text{ or } 62.0\%$$

No real power plant operating between these exact two temperatures can exceed 62.0% efficiency, no matter how well-engineered — a genuine physical ceiling, not merely an engineering shortfall.

Entropy: A Name Chosen on Purpose

The quantity underlying the Second Law — entropy — got its real name from Rudolf Clausius in 1865, and he chose the word deliberately. He formed "entropy" from the Greek word for "transformation," specifically to echo the structure of the word "energy," writing that he considered the two quantities "analogous in their physical significance" and wanted names that reflected that kinship.

$$dS = \delta Q_{rev} / T$$

For a reversible process, the change in entropy (dS) equals the heat transferred (δQ) divided by the absolute temperature (T) at which the transfer happens. The Second Law, in these terms, says the total entropy of an isolated system can only stay the same (for a perfectly reversible process, like Carnot's own idealised cycle) or increase (for any real, irreversible process) — it can never decrease.

💡 **A DEEPER EXPLANATION, A FEW DECADES LATER**

In the 1870s, Ludwig Boltzmann gave entropy a genuinely different kind of explanation, grounded in statistics rather than heat flow directly: entropy is proportional to the natural logarithm of the number of possible microscopic arrangements (of individual atoms and molecules) consistent with a system's observable large-scale state. A tidy, ordered arrangement has comparatively few equivalent microscopic configurations; a disordered one has vastly more — which is the real, underlying reason why systems drift toward disorder over time. It isn't that nature actively prefers disorder; there are simply, overwhelmingly, more ways for a system to be disordered than ordered.

The Carnot Cycle, Stage by Stage

STAGE	PROCESS	HEAT	TEMPERATURE
1	Isothermal expansion	Absorbed from hot reservoir	Constant at T_H
2	Adiabatic expansion	None (isolated)	Falls from T_H to T_C
3	Isothermal compression	Released to cold reservoir	Constant at T_C
4	Adiabatic compression	None (isolated)	Rises from T_C to T_H

Hands-On Exercises

EXERCISE 1

An engine operates between a hot reservoir at 600 K and a cold reservoir at 300 K. Calculate its maximum possible (Carnot) efficiency.

→ Solution

EXERCISE 2

400 J of heat is transferred to a system at a constant temperature of 320 K, in a reversible process. Using dS = Q/T, calculate the change in entropy.

→ Solution

EXERCISE 3

Explain, in your own words, why NO real engine - however well-engineered, however advanced its materials - can ever exceed the Carnot efficiency for a given pair of hot and cold reservoir temperatures. What real-world factor does Carnot's own idealised cycle assume away that every real engine actually has?

→ Solution

QUICK REFERENCE

- Sadi Carnot's 1824 book set the real theoretical foundation for heat engine efficiency, decades before it was widely recognised
- **Carnot cycle:** isothermal expansion → adiabatic expansion → isothermal compression → adiabatic compression
- **Carnot efficiency:** $\eta = 1 - T_C/T_H$ (absolute/Kelvin temperatures), a real theoretical maximum no engine can exceed
- **Entropy:** named by Clausius in 1865, from Greek for "transformation"; $dS = \delta Q/T$ for a reversible process
- **Second Law, restated:** total entropy of an isolated system never decreases
- Boltzmann's statistical view: entropy reflects the number of microscopic arrangements consistent with a system's observed state

Next chapter: Kinetic Theory of Gases — where the ideal gas law gets its own real, derived statistical-mechanics foundation, connecting individual molecular motion directly to the macroscopic pressure and temperature this chapter has treated as given.

Classical Mechanics & Thermodynamics

Course 1 · Chapter 9 · Kinetic Theory of Gases

Chapter 8 treated heat, temperature, and entropy as measurable quantities without asking what is actually happening at the microscopic level to produce them. This chapter answers that question directly: a gas's pressure and temperature turn out to be nothing more than the combined statistical effect of enormous numbers of individual molecules, each one obeying the same mechanics this course built from Chapter 2 onward.

The Ideal Gas Law

For an idealised gas, pressure, volume, amount, and temperature are related by one compact equation:

$$PV = nRT$$

Here P is pressure, V is volume, n is the amount of gas in moles, T is absolute temperature (Kelvin), and R is the universal gas constant, 8.314 J/(mol·K).

💡 **A REAL, GENUINE COINCIDENCE: SAME YEAR, SAME PERSON**

The ideal gas law in this exact combined form was first stated in 1834 by French engineer Émile Clapeyron — independently, the same year, by Dmitri Mendeleev (decades before his own far more famous periodic table work) — combining four separately-discovered empirical laws (below) into one equation. This is the very same Clapeyron who, that same year, published the commentary reviving Sadi Carnot's forgotten 1824 work, discussed in Chapter 8 — making 1834 a genuinely productive real year for one single engineer, credited independently with both rescuing the foundation of the Second Law and combining the ideal gas law into its now-standard form.

PV = nRT is itself the combination of four earlier, separately-discovered empirical relationships:

LAW	REAL STATEMENT	HELD CONSTANT
Boyle's Law (1662)	P is inversely proportional to V	Temperature, amount
Charles's Law	V is directly proportional to T	Pressure, amount
Gay-Lussac's Law	P is directly proportional to T	Volume, amount
Avogadro's Law	V is directly proportional to n	Pressure, temperature

Worked Example: Compressing a Gas

0.5 mol of gas occupies 12 L at 300 K. What pressure does it exert? (Use R = 0.0821 L·atm/(mol·K), the gas constant expressed in litre-atmosphere units.)

$$P = nRT/V$$
$$P = (0.5 \times 0.0821 \times 300) / 12$$
$$P = 12.315 / 12$$
$$P \approx 1.03 \text{ atm}$$

Kinetic Theory: Explaining *Why* the Gas Law Holds

The ideal gas law describes *what* a gas does, but not *why*. That explanation is genuinely older than it might seem: Swiss mathematician Daniel Bernoulli proposed, as early as 1738 in his book *Hydrodynamica*, that a gas consists of enormous numbers of molecules moving in every direction, that their collisions against a container's walls are what create pressure, and that their average kinetic energy is what temperature actually measures.

⚠ **AN IDEA MORE THAN A CENTURY AHEAD OF ITS TIME**

Bernoulli's 1738 proposal was met with real, substantial skepticism for over a hundred years — partly because conservation of energy hadn't yet been established (that came from Mayer, Joule, and Helmholtz in the 1840s, per Chapter 3), and partly because the idea of countless molecules undergoing perfectly elastic collisions, bouncing endlessly off each other and the container walls without ever losing energy, seemed genuinely implausible to many 18th- and early-19th-century scientists — exactly the same idealised, energy-conserving collision Chapter 4 defined as "elastic," applied here not to billiard balls but to the individual molecules of a gas.

The theory was finally put on rigorous mathematical footing over a century later: August Krönig built a simplified molecular model in 1856, and Rudolf Clausius — already a familiar name from Chapters 3, 7, and 8 — extended it further in 1857, deriving the ideal gas law directly from Newtonian mechanics applied to molecular collisions, and introducing the concept of a molecule's real "mean free path" (the average distance it travels between collisions).

Pressure, Explained by Momentum

Kinetic theory's own explanation of pressure is a direct, real application of Chapter 4's conservation of momentum: every time a gas molecule collides elastically with a container wall, it transfers a tiny amount of momentum to that wall. Multiplied across the astronomical number of molecules striking the walls every second, these countless tiny momentum transfers add up to the steady, continuous force we measure as gas pressure — the same physics behind the cannon's recoil in Chapter 4, just averaged over an enormous number of vastly smaller collisions instead of one large one.

Maxwell, Boltzmann, and the Statistical Turn

James Clerk Maxwell, in 1859, derived the real distribution of molecular speeds within a gas — not every molecule moves at the same speed, but a predictable statistical spread around an average, now called the Maxwell distribution, described in its own era as the first genuinely statistical law in the whole of physics. Ludwig Boltzmann generalised this further in 1871 into the Maxwell–Boltzmann distribution, and connected it directly to the statistical definition of entropy already previewed in Chapter 8 ($S = k_B \ln W$) — closing the loop between this chapter's own molecular picture and Chapter 8's macroscopic one.

Average Kinetic Energy and Temperature

Kinetic theory gives a precise, real relationship between a gas's absolute temperature and the average kinetic energy of its individual molecules:

$$\tfrac{1}{2}mv^2_{avg} = \text{\&frac32;}k_BT$$

Here k_B is the Boltzmann constant. Rearranged, this gives the real root-mean-square (RMS) speed of gas molecules at a given temperature:

$$v_{rms} = \sqrt{(3RT/M)}$$

where M is the gas's molar mass.

Worked Example: Nitrogen Molecules at Room Temperature

Nitrogen (N_2) has a molar mass of about 0.028 kg/mol. What is the RMS speed of nitrogen molecules in ordinary air at 300 K (roughly room temperature)?

$$v_{rms} = \sqrt{(3RT/M)}$$
$$v_{rms} = \sqrt{(3 \times 8.314 \times 300 / 0.028)}$$
$$v_{rms} = \sqrt{(7482.6 / 0.028)}$$
$$v_{rms} = \sqrt{267,235.7}$$
$$v_{rms} \approx 517 \text{ m/s}$$

The nitrogen molecules making up most of the air in an ordinary room are, on average, moving at roughly 517 m/s — well over the speed of sound — a genuinely startling real number for something as calm and still as the air feels in everyday experience, and a direct, tangible consequence of the same molecular chaos Bernoulli first proposed in 1738.

Hands-On Exercises

EXERCISE 1

2 mol of an ideal gas is held at a constant pressure of 1 atm and a temperature of 350 K. Using PV = nRT (with R = 0.0821 L.atm/(mol.K)), calculate the gas's volume.

→ Solution

EXERCISE 2

Oxygen gas (O_2, molar mass 0.032 kg/mol) is heated to 400 K. Using v_rms = sqrt(3RT/M), calculate the RMS speed of oxygen molecules at this temperature.

→ Solution

EXERCISE 3

Explain, using Chapter 4's own definition of an elastic collision and conservation of momentum, why kinetic theory's explanation of gas pressure genuinely required molecular collisions to be perfectly elastic - and why this specific requirement was one real reason Bernoulli's 1738 proposal met with skepticism for over a century.

→ Solution

QUICK REFERENCE

- **Ideal gas law:** PV = nRT, first combined by Clapeyron and Mendeleev independently in 1834
- Combines Boyle's, Charles's, Gay-Lussac's, and Avogadro's Laws
- **Kinetic theory:** proposed by Bernoulli (1738), rigorously derived by Krönig (1856) and Clausius (1857)
- Pressure = countless elastic molecular collisions transferring momentum to container walls (Chapter 4's own physics, at molecular scale)
- Maxwell (1859) and Boltzmann (1871): the real statistical distribution of molecular speeds
- **Average KE and temperature:** $½mv^2_{avg}$ = &frac32;k_BT; $v_{rms} = \sqrt{(3RT/M)}$

Next chapter: the Capstone — a single real worked mechanical/thermal system, drawing together tools from every chapter of this course.

Classical Mechanics & Thermodynamics

Course 1 · Chapter 10 · Capstone: A Real Worked Mechanical/Thermal System

Nine chapters have built two toolkits: one for motion, force, and gravity (Chapters 1–6), and one for heat, engines, and entropy (Chapters 7–9). This capstone runs a single, continuous, fully worked system through every one of them — a small steam-launched roller coaster car, from the boiler that powers its launch to the braking collision that finally stops it.

The System

A steam piston launches a 400 kg roller coaster car (with rider) along a straight 3 m launch track. The car then climbs into a 2.5 m-radius vertical loop, completes the circuit, and returns to ground level, where it couples with a stationary 600 kg braking car to bring the ride safely to rest. Every number below is carried forward, unmodified, from the step before it.

STEP 1 · CHAPTER 9 (KINETIC THEORY OF GASES)

Before launch, superheated steam fills the 0.05 m^3 piston chamber at T = 400 K, with n = 3 mol present. Using the ideal gas law to find the steam's pressure:

$$P = nRT/V$$
$$P = (3 \times 8.314 \times 400)\ /\ 0.05$$
$$P \approx 199{,}540\ \text{Pa} \approx 200{,}000\ \text{Pa}$$

STEP 2 · CHAPTER 7 (THE FIRST LAW OF THERMODYNAMICS)

As the steam expands and drives the piston outward, the boiler supplies Q = 45,000 J of heat during the power stroke. The piston has area A = 0.05 m^2

and travels d = 3 m, so the swept volume is $\Delta V = Ad = 0.15\ m^3$. Treating the expansion as roughly constant-pressure, the work done by the steam is:

$$W = P\Delta V = 200{,}000 \times 0.15 = 30{,}000\ J$$
$$\Delta U = Q - W = 45{,}000 - 30{,}000 = 15{,}000\ J$$

15,000 J of heat remains in the steam as increased internal energy; the other 30,000 J becomes the mechanical work that launches the car.

STEP 3 · CHAPTER 8 (HEAT ENGINES)

Measured over a complete piston cycle (this power stroke plus the return stroke needed to reset it), the boiler-and-piston system converts heat into net usable work at a real, measured 20% overall efficiency. With steam entering at T_H = 400 K and exhaust condensing at roughly T_C = 300 K, the Carnot maximum for any engine operating between these two temperatures is:

$$\eta_{Carnot} = 1 - 300/400 = 0.25,\ \text{or}\ 25\%$$

The engine's real 20% efficiency sits honestly below this theoretical 25% ceiling — exactly as Chapter 8's own theory requires, since no real, imperfectly reversible engine can reach, let alone exceed, the Carnot limit.

STEP 4 · CHAPTER 2 (NEWTON'S SECOND LAW)

The steam's pressure acts on the piston's full area to produce the launch force:

$$F = PA = 200{,}000 \times 0.05 = 10{,}000\ N$$
$$a = F/m = 10{,}000\ /\ 400 = 25\ m/s^2$$

STEP 5 · CHAPTER 1 (KINEMATICS)

Using $v^2 = u^2 + 2as$ over the 3 m stroke ($u = 0$):

$$v^2 = 2 \times 25 \times 3 = 150$$
$$v = \sqrt{150} \approx 12.25 \text{ m/s}$$

The launch takes $t = v/a = 12.25/25 \approx 0.49$ s.

STEP 6 · CHAPTER 3 (WORK, ENERGY & POWER)

Checking the mechanical work directly:

$$W = Fd = 10{,}000 \times 3 = 30{,}000 \text{ J}$$
$$KE = \tfrac{1}{2}mv^2 = \tfrac{1}{2} \times 400 \times 150 = 30{,}000 \text{ J}$$

🔗 A Guaranteed, Not Coincidental, Match

This 30,000 J exactly matches Step 2's own thermodynamic work calculation, $P\Delta V$. That agreement isn't a coincidence: since $F = PA$ and $\Delta V = Ad$, the two formulas $W = Fd$ and $W = P\Delta V$ are algebraically the same equation, just written in mechanical and thermodynamic language respectively — a genuine, structural link between this course's own two halves.

Power output during the launch: $P = W/t = 30{,}000/0.49 \approx 61{,}200$ W, or about 61.2 kW.

STEP 7 · CHAPTER 6 (GRAVITY & CONSERVATION OF ENERGY)

The car enters the loop (radius $r = 2.5$ m) at ground level with its full 30,000 J of kinetic energy. At the top of the loop (height = $2r$ = 5 m), some of that energy has converted to gravitational potential energy:

$$PE_{top} = mg(2r) = 400 \times 9.81 \times 5 = 19{,}620 \text{ J}$$
$$KE_{top} = 30{,}000 - 19{,}620 = 10{,}380 \text{ J}$$
$$v_{top} = \sqrt{(2 \times 10{,}380 / 400)} \approx 7.20 \text{ m/s}$$

STEP 8 · CHAPTER 5 (CIRCULAR MOTION) — A REAL SAFETY CHECK

At the top of a loop, the car needs a minimum speed for gravity alone to supply the required centripetal force ($mg = mv^2_{min}/r$):

$$v_{min} = \sqrt{(gr)} = \sqrt{(9.81 \times 2.5)} \approx 4.95 \text{ m/s}$$

The car's actual speed at the top, 7.20 m/s, comfortably exceeds this 4.95 m/s minimum — confirming the loop is safely designed, with real margin to spare, before a single rider ever boards.

STEP 9 · CHAPTER 4 (MOMENTUM & COLLISIONS) — FULL CIRCLE

Having completed the frictionless loop, the car returns to ground level with its full original speed, $v \approx 12.25$ m/s, and couples with a stationary 600 kg braking car — a perfectly inelastic collision:

$$m_{car}v_{car} = (m_{car} + m_{brake})v_{final}$$
$$400 \times 12.25 = 1000 \times v_{final}$$
$$v_{final} \approx 4.90 \text{ m/s}$$

Checking the kinetic energy: before coupling, KE ≈ 30,000 J; after, KE = ½(1000)(4.90^2) ≈ 12,000 J. Roughly 18,000 J has vanished from the mechanical system entirely.

🔗 **The Course's Own Full Circle**

That "lost" 18,000 J was never destroyed — per Chapter 3's own conservation of energy and Chapter 7's own First Law, it converted into heat in the coupling mechanism's own metal, exactly the same kind of conversion Chapter 3's Joule paddle-wheel experiment demonstrated in reverse. This course opened its thermodynamics half by turning heat into motion (Steps 1–6, the steam launch); it closes by turning motion back into heat (this braking collision) — the same underlying physics, run in opposite directions, tying mechanics and thermodynamics together as genuinely one subject rather than two.

Every Chapter, In One System

STEP	CHAPTER	WHAT IT CONTRIBUTED
1	9 — Kinetic Theory of Gases	Ideal gas law gives the steam's real pressure, ~200,000 Pa
2	7 — The Laws of Thermodynamics	First Law: $\Delta U = Q - W$ for the power stroke
3	8 — Heat Engines & Entropy	Real efficiency (20%) checked against the Carnot ceiling (25%)
4	2 — Newton's Three Laws	$F = PA$ gives launch force; $F = ma$ gives acceleration
5	1 — Kinematics	SUVAT gives launch speed and launch time
6	3 — Work, Energy & Power	$W = Fd$ confirms KE; power output during launch
7	6 — Gravity Revisited	Conservation of energy gives speed at the top of the loop
8	5 — Circular Motion & Rotational Dynamics	Minimum loop speed confirms a safe design

9	4 — Momentum & Collisions	Perfectly inelastic braking collision; energy lost to heat

Hands-On Exercises

EXERCISE 1

A redesigned piston has area A = 0.06 m^2 and the same steam pressure, P = 200,000 Pa, over the same 3 m stroke, launching a lighter 350 kg car. Find the new launch force, acceleration, and launch speed.

→ Solution

EXERCISE 2

Suppose the loop's radius were increased to 4 m instead of 2.5 m, with the car still entering the loop with 30,000 J of kinetic energy at ground level (mass unchanged, 400 kg). Using conservation of energy and the minimum-speed condition, determine whether the car can safely complete this larger loop.

→ Solution

EXERCISE 3

Explain, using both the First Law of Thermodynamics (Chapter 7) and conservation of energy (Chapter 3), exactly where the roughly 18,000 J of kinetic energy "lost" in the final braking collision (Step 9) actually goes - and why calling it "lost" is only accurate from the mechanical system's own point of view, not from the perspective of the universe's total energy.

→ Solution

COURSE COMPLETE

Classical Mechanics & Thermodynamics is now complete, 10/10 chapters — from Chapter 1's own real, corrected Galileo tower story through this capstone's full mechanical-and-thermal system. Along the way, this course found a genuine recurring pattern: the popular, tidy version of a scientific story (Galileo's tower, "Newton's cradle," Newton's apple, the Zeroth Law's own name) is consistently less accurate, and less interesting, than the messier real history behind it.

Electromagnetism & Relativity (`electromag1`) is the second half of the original "Classical Physics" split, and remains ready to generate as the direct next course in this Science subject — picking up the same real, verify-everything discipline for electricity, magnetism, and the real crisis that led to relativity.