Force and Translational Dynamics

AP Physics 1

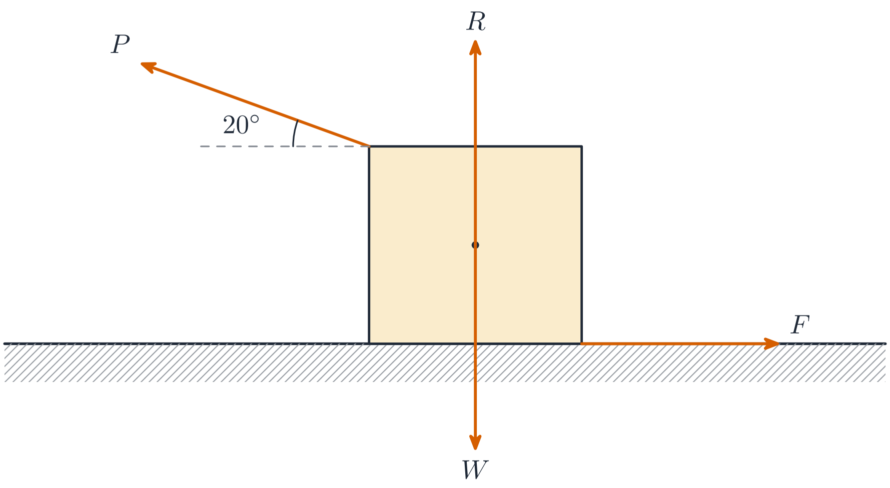
Systems and Center of Mass

A **system** 系统 is the object or group of objects you choose to analyze. A system can be treated as a single point at its **center of mass** 质心–the average position of its mass. External forces change the motion of the center of mass; internal forces (between parts of the system) do not.

This is why a wrench spinning across a table still has its center of mass move in a straight line: the spinning is internal, and only the (near-zero) external force matters for the center of mass. For two masses m_1, m_2 on a line at positions x_1, x_2, the center of mass sits at $x_{\text{cm}} = \dfrac{m_1 x_1 + m_2 x_2}{m_1 + m_2}$ –always closer to the heavier mass.

Forces and Free-Body Diagrams

A **force** 力 is a push or pull –a vector, measured in newtons (N). A **free-body diagram** 受力图 shows one object as a dot with arrows for **every** force acting **on** it (weight 重力, normal, tension 张力, friction, applied), each labelled and pointing the right way. Draw it before any dynamics problem; it is where most marks are won or lost.

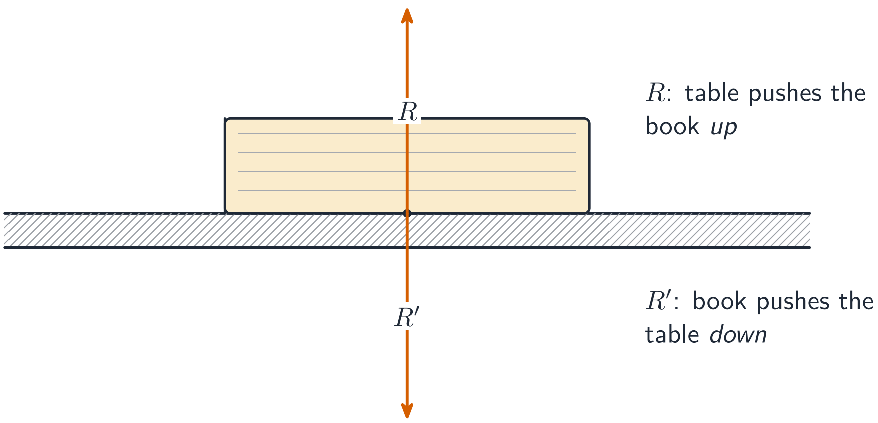


A free-body diagram shows every force acting on one object

Two rules keep free-body diagrams honest: draw only forces acting **on** the chosen object (not forces it exerts on other things), and draw only **real, physical** forces (a rope, a surface, gravity, a hand) –never an "*ma*" arrow, which is the *result* of the forces, not a force itself.

Newton's Third Law

Newton's third law 牛顿第三定律: if object A pushes on object B, then B pushes back on A with a force **equal in size and opposite in direction**. These two forces act on **different** objects, so they never cancel each other. Identify third-law pairs by the "A on B / B on A" wording.



A Newton's third-law pair: equal and opposite forces on two different objects

A classic trap: the weight of a book and the normal force from the table are **not** a third-law pair –they act on the **same** object (the book). The partner of the book's weight is the pull the book exerts on the Earth; the partner of the table's push is the push the book makes on the table.

Newton's First Law

Newton's first law 牛顿第一定律 (the law of **inertia** 惯性): an object's velocity stays constant unless a **net force** 合力 acts on it. So zero net force means constant velocity (including rest) –the object is in **translational equilibrium** 平衡. Inertia is the tendency to resist changes in motion, measured by mass.

Worked example. A 1200 kg car cruises at a steady 25 m/s on a level road. What is the net force on it? Because the velocity is constant, the acceleration is zero, so by the first law the **net** force is zero –the forward drive force exactly balances drag and friction. "Steady speed" always means balanced forces.

Newton's Second Law

Newton's second law 牛顿第二定律 relates net force to acceleration:

$$\vec{a} = \frac{\sum \vec{F}}{m}, \qquad \text{i.e.} \qquad \sum \vec{F} = m\vec{a}.$$

Apply it **one axis at a time**: add the force components along each axis and set the sum equal to ma for that axis. Acceleration points the same way as the net force.

Worked example. A 4.0 kg box is pulled along the floor by a horizontal force of 18 N. Friction on the box is 6.0 N. Find its acceleration. Along the direction of motion the net force is $18 - 6.0 = 12$ N, so

$$a = \frac{\sum F}{m} = \frac{12}{4.0} = 3.0 \text{ m/s}^2.$$

Worked example (incline 斜面). A block of mass m slides down a frictionless ramp tilted at angle θ. Find its acceleration. Resolve gravity into components along and perpendicular to the ramp; only the along-ramp part, $mg \sin\theta$, drives the motion, so

$$a = \frac{mg \sin\theta}{m} = g \sin\theta.$$

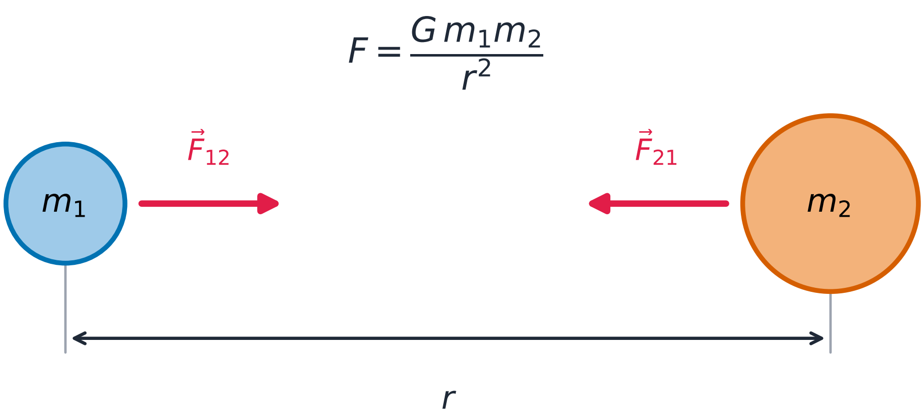
The steeper the ramp, the larger $\sin\theta$ and the faster it accelerates; at $\theta = 90°$ it is free fall.

Gravitational Force

Near a planet's surface, the **gravitational force** (weight) is $F_g = mg$, directed down, where g is the **gravitational field strength** 重力场强度. More generally, **Newton's law of gravitation** 万有引力定律 gives the attraction between any two masses:

$$F_g = \frac{Gm_1m_2}{r^2},$$

directed along the line joining them, weaker as the distance r grows (an inverse-square law). Doubling the separation quarters the force.



Two masses attract each other with equal, opposite, inverse-square forces along the line joining them

Worked example. A 2.0 kg object weighs 19.6 N on Earth ($g = 9.8$ m/s^2). On the Moon $g_{\text{Moon}} = 1.6$ m/s^2. Its mass is unchanged (2.0 kg), but its weight becomes $F_g = mg = 2.0 \times 1.6 = 3.2$ N. Mass measures inertia; weight is a force that depends on where you are.

Kinetic and Static Friction

Friction 摩擦力 acts along a surface, opposing relative sliding (or the tendency to slide):

- **Kinetic friction 动摩擦** (while sliding): $f_k = \mu_k N$.
- **Static friction 静摩擦** (while not yet sliding): $f_s \le \mu_s N$ –it adjusts up to a maximum to prevent motion.

Here N is the **normal force 法向力** (surface push, perpendicular to the surface) and μ is the **coefficient of friction 摩擦系数**.

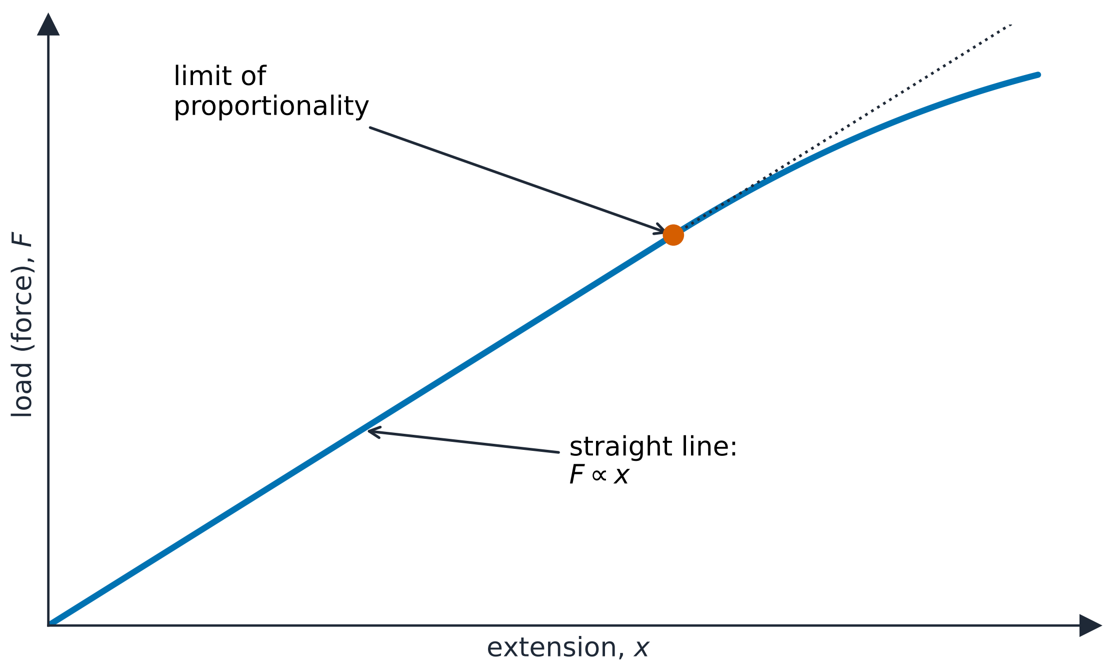
Worked example. A 5.0 kg crate sits on a level floor with $\mu_s = 0.40$. Will a horizontal push of 15 N move it? On a level floor $N = mg = 5.0 \times 9.8 = 49$ N, so the largest static friction is $f_{s,\text{max}} = \mu_s N = 0.40 \times 49 = 19.6$ N. The 15 N push is smaller than 19.6 N, so friction rises to match it and the crate stays still.

Spring Forces

An ideal spring exerts a **restoring force 回复力** proportional to its stretch or compression –**Hooke's law 胡克定律**:

$$F_s = -kx,$$

where k is the **spring constant 弹簧常数** (stiffness) and x is the displacement from the spring's natural length. The minus sign means the force points back toward equilibrium.



Hooke's law: extension is proportional to load up to the limit of proportionality

Worked example. A spring with $k = 200$ N/m hangs vertically and a 0.50 kg mass is hung on it. How far does it stretch at rest? At rest the spring force balances the weight,

$kx = mg$, so

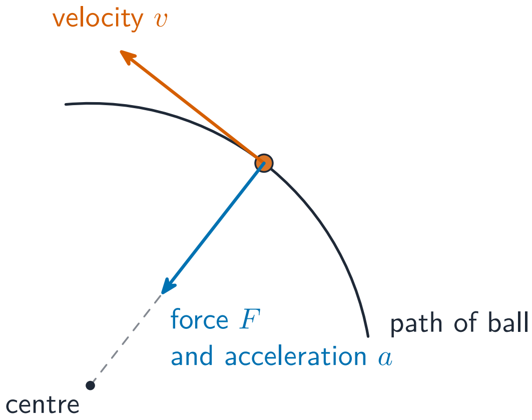
$$x = \frac{mg}{k} = \frac{0.50 \times 9.8}{200} = 0.025 \text{ m} = 2.5 \text{ cm}.$$

Circular Motion

An object moving in a circle at constant speed still **accelerates**, because its velocity direction keeps changing. This **centripetal acceleration** 向心加速度 points toward the center:

$$a_c = \frac{v^2}{r}.$$

It is produced by a **net inward (centripetal) force** 向心力 $F_c = \frac{mv^2}{r}$ –supplied by whatever real force points inward (tension, gravity, friction, normal). There is no separate outward force; "centrifugal" is only an apparent effect.



The velocity points along the tangent; the centripetal force and acceleration point to the centre

Worked example. A 0.30 kg ball on a string is whirled in a horizontal circle of radius 0.80 m at 4.0 m/s. Find the tension in the string. The tension supplies the whole centripetal force:

$$T = \frac{mv^2}{r} = \frac{0.30 \times 4.0^2}{0.80} = 6.0 \text{ N}.$$

If the string can take at most 6.0 N, this is the fastest the ball can go at that radius – spin any faster and the string breaks.

Exam tips

- Always draw a **free-body diagram** first: only real forces **on** the chosen object (weight, normal, tension, friction, applied) —never an "ma" arrow.
- Apply $\sum F = ma$ **one axis at a time**; on an incline resolve gravity into $mg \sin\theta$ (along) and $mg \cos\theta$ (perpendicular).
- A **Newton's third-law pair** acts on **two different objects** —a book's weight and the table's normal force are *not* a pair (both act on the book).

- **Static friction** adjusts up to $\mu_s N$ (use it to test whether motion starts); once sliding, use **kinetic** friction $f_k = \mu_k N$.
- Circular motion needs a **net inward (centripetal) force** mv^2/r supplied by a real force —there is no outward ”centrifugal” force.