JEE MAIN · PAPER 1 · PHYSICS

03 Laws of Motion

Formula & concept sheet

Force, momentum, friction and circular dynamics. Each idea is explained in plain words, then the formulas, then where it is used and how questions are framed around it.

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READ ALONGSIDE NCERT XI · Laws of Motion

HOW TO USE THIS SHEET

1. **Skim** — Read the Key ideas, then the formula cards.
2. **Memorise** — Learn the formulas and check every Trap box.
3. **Test** — Do the worked examples, then this chapter's PYQs.
4. **Revise** — Use the last-minute checklist before the exam.

Formula memorise · **Key idea** why it works · **Trap** marks lost here · **PYQ** how it is asked

Practise this chapter with real past-paper questions on Prep Vault. Written for revision, not as a first read.

CHAPTER 03

Laws of Motion

NCERT XI · Laws of Motion

Covers: Newton's laws · momentum and impulse · equilibrium · pulleys and blocks · friction · circular motion, banking · pseudo force.

1 Newton's laws, momentum, equilibrium

First law: a body stays at rest or in uniform motion unless a net force acts (inertia). **Second law:** the net force is the rate of change of momentum. **Third law:** forces come in equal and opposite pairs acting on **different** bodies at the same instant, so they never cancel each other.

SECOND LAW

$$\vec{F} = \frac{d\vec{p}}{dt} = m\vec{a}$$

constant mass; applied separately along each axis

IMPULSE

$$\vec{J} = \int \vec{F}\,dt = \Delta\vec{p}$$

$$F_{av} = \frac{\Delta p}{\Delta t}$$

area under the F–t graph

MOMENTUM CONSERVATION

$$\sum \vec{p}_{before} = \sum \vec{p}_{after}$$

when no external force acts; gun and bullet: $v_{gun} = -\frac{m}{M} v_{bullet}$

EQUILIBRIUM OF CONCURRENT FORCES

$\sum \vec{F} = 0$; for three forces $\frac{F_1}{\sin\alpha} = \frac{F_2}{\sin\beta} = \frac{F_3}{\sin\gamma}$

Lami's theorem: each angle lies opposite its force

APPARENT WEIGHT IN A LIFT

$N = m(g + a)$ accelerating up

$N = m(g - a)$ accelerating down

free fall: $N = 0$; the scale reads N, not mg

HOW IT IS ASKED

Force on a body from a given $x(t)$ or $v(t)$, impulse from an F–t graph, recoil of a gun, a lift with a spring balance, three strings holding a weight (Lami).

2 Blocks, strings and pulleys

Draw a free-body diagram for each body, take axes along the motion and write $\sum F = ma$ for each one. An inextensible string adds one more equation: the connected bodies have the same acceleration along the string.

ATWOOD MACHINE

$$a = \frac{(m_1 - m_2)g}{m_1 + m_2}$$

$$T = \frac{2m_1 m_2 g}{m_1 + m_2}$$

ideal pulley, massless string

TABLE AND HANGING MASS

$$a = \frac{m_2 g}{m_1 + m_2}$$

$$T = \frac{m_1 m_2 g}{m_1 + m_2}$$

m_1 on a smooth table, m_2 hanging

CONTACT FORCE

$$a = \frac{F}{m_1 + m_2}$$

$$N = \frac{m_2 F}{m_1 + m_2}$$

F pushes m_1, which pushes m_2

MOVABLE PULLEY

load moves half as far as the free end

$$a_{load} = \frac{a_{end}}{2}$$

the pulley takes two string segments, so the force on it is $2T$

SPRING FORCE

$$F = kx$$

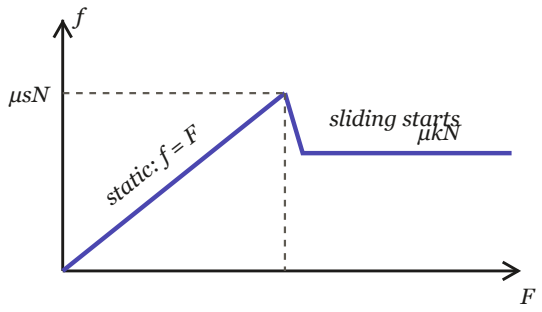
an ideal spring pulled by F at each end reads F, not $2F$

TRAP

Tension is the same along one ideal string over an ideal pulley, but **not** across different strings or over a pulley with mass. Write the constraint before you solve.

3 Friction

Friction opposes **relative sliding** between surfaces. **Static** friction adjusts itself to the applied force up to a limit $\mu_s N$; once sliding starts, **kinetic** friction is the constant $\mu_k N$, a little smaller. It depends on the normal force and the surfaces, not on the contact area.



Static friction matches the applied force up to $\mu_s N$; once sliding, it is the constant $\mu_k N$.

LAWS OF FRICTION

$f_s \le \mu_s N, \quad f_k = \mu_k N$

$\mu_s > \mu_k$

rolling friction is smaller than sliding friction

ANGLE OF REPOSE

$\tan\theta = \mu_s$

the steepest slope on which a block stays at rest

SMOOTH INCLINE

$a = g\sin\theta$

normal force $N = mg\cos\theta$ if nothing else pushes across the slope

ROUGH INCLINE, SLIDING DOWN

$a = g(\sin\theta - \mu_k\cos\theta)$

it slides only if $\tan\theta > \mu_s$

ROUGH INCLINE, MOVING UP

$a = g(\sin\theta + \mu\cos\theta)$

deceleration, since friction acts down the slope

LEAST FORCE TO SLIDE A BLOCK

$F_{min} = \dfrac{\mu mg}{\sqrt{1+\mu^2}}$

applied at angle ϕ above the horizontal with $\tan\phi = \mu$; pulling lifts part of the weight: $N = mg - F\sin\phi$

BLOCK ON A BLOCK (SMOOTH FLOOR)

$a_{max} = \mu g$

pull lower block M: $F_{max} = \mu(M+m)g$

pull upper block m: $F_{max} = \mu mg\,\dfrac{M+m}{M}$

limit of no slipping between them

AT REST ON AN INCLINE

$f = mg\sin\theta$

static friction balances the slope component; it is not $\mu_s N$ unless about to slip

SLIDING TO A STOP

$s = \dfrac{u^2}{2\mu g},\ t = \dfrac{u}{\mu g}$

on a rough horizontal surface; independent of mass

PUSH OR PULL AT AN ANGLE

$N = mg \mp F\sin\phi$

$a = \dfrac{F\cos\phi - \mu N}{m}$

minus for a pull (lifts the block), plus for a push

TRAP

Static friction is **self-adjusting**: write $\mu_s N$ only at the point of slipping. Friction does not depend on contact area, a favourite statement question.

HOW IT IS ASKED

Largest force before blocks slip, whether a block slides down an incline of given angle, speed or distance after sliding, and statement questions on the laws of friction.

4 Circular dynamics and banking

Centripetal force is not a new force: it is the **net real force towards the centre** (tension, gravity, friction or normal force). Choose the radial direction, resolve along it and set the sum equal to mv^2/r.

CENTRIPETAL FORCE

$$F = \frac{mv^2}{r} = m\omega^2 r$$

directed towards the centre

LEVEL ROAD

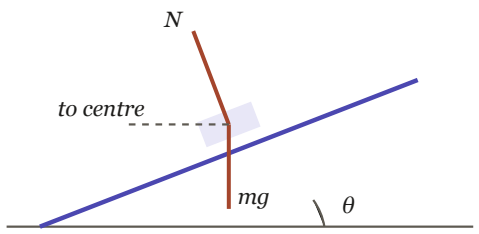
$$v_{max} = \sqrt{\mu r g}$$

friction supplies the force; independent of mass

BANKED ROAD, NO FRICTION

$$\tan\theta = \frac{v^2}{rg}$$

also the lean angle of a cyclist on a turn



Horizontal part of N supplies the centripetal force; vertical part balances mg.

BANKED ROAD WITH FRICTION

$$v_{max} = \sqrt{rg\,\frac{\mu + \tan\theta}{1 - \mu\tan\theta}}$$

$$v_{min} = \sqrt{rg\,\frac{\tan\theta - \mu}{1 + \mu\tan\theta}}$$

at v_{min} friction acts up the slope; v_{min} needs $\tan\theta > \mu$

CONICAL PENDULUM

$$\tan\theta = v^2/(rg) = \omega^2 r/g$$

$$T = 2\pi\sqrt{\ell\cos\theta/g}$$

$r = \ell\sin\theta$, with θ the angle from the vertical

VERTICAL CIRCLE (STRING)

top: $v \geq \sqrt{gr}$

bottom: $v \geq \sqrt{5gr}$

at the top the tension can fall to zero

TENSION AT AN ANGLE

$$T - mg\cos\theta = \frac{mv^2}{r}$$

θ from the downward vertical; $T_{bottom} - T_{top} = 6mg$

CONVEX BRIDGE OR HILL

$$N = mg - \frac{mv^2}{r}$$

the car leaves the surface at $v = \sqrt{gr}$

CONCAVE DIP

$$N = mg + \frac{mv^2}{r}$$

the road pushes harder than the weight at the bottom of a dip

ROTOR (WALL OF DEATH)

$$\mu N = mg,\ N = m\omega^2 r$$

$$\omega_{min} = \sqrt{\frac{g}{\mu r}}$$

friction holds the rider up

SPEED IN A VERTICAL CIRCLE

$$v^2 = u^2 - 2gr(1 - \cos\theta)$$

from the lowest point, θ measured from the downward vertical

ROD ROTATING ABOUT ONE END

$$T(x) = \frac{M\omega^2}{2L}\,(L^2 - x^2)$$

tension at distance x from the axis; largest at the pivot

SIMPLE PENDULUM, RELEASE ANGLE

extreme point: $a = g\sin\theta_0$

lowest point: $a = 2g(1 - \cos\theta_0)$

at the extreme the speed is zero, so only the tangential part is left; the two are equal when $\theta_0 \approx 53^\circ$

HOW IT IS ASKED

Banking angle or the safe speed range, the speed ratio for equal centripetal force at different radii, the minimum speed at the top of a vertical circle, tension at a given angle, or the acceleration of a pendulum bob at two positions.

5 Pseudo force

In a frame that accelerates with $\vec{a}$, add a **pseudo force** $-m\vec{a}$ to every body and then use Newton's laws as usual. Use either the ground frame or the accelerating frame, never both together.

PSEUDO FORCE

$\vec{F}_{ps} = -m\vec{a}_{frame}$

opposite to the frame's acceleration

PENDULUM IN AN ACCELERATING CAR

$\tan\theta = \dfrac{a}{g}$

$g_{eff} = \sqrt{g^2 + a^2}$

the bob hangs along the effective gravity

ROTATING FRAME

$F_{cf} = m\omega^2 r$ outward

the centrifugal force exists only in the rotating frame

KEY IDEA

In a lift accelerating up, g is replaced by $g + a$ for everything inside it: a pendulum is faster, a floating block displaces more water, a spring balance reads more.

6 Worked examples

ATWOOD MACHINE

$m_1 = 3\ \text{kg}$ and $m_2 = 2\ \text{kg}$ hang over an ideal pulley, $g = 10\ \text{m s}^{-2}$. Find a and T.

$a = \dfrac{(3-2)10}{5} = 2\ \text{m s}^{-2}; T = \dfrac{2\cdot 3\cdot 2\cdot 10}{5} = 24\ \text{N}$

ROUGH INCLINE

A block slides down a 37° incline with $\mu_k = 0.25$ ($\sin 37^\circ = 0.6$, $\cos 37^\circ = 0.8$). Its acceleration?

$a = 10(0.6 - 0.25\times 0.8) = 4\ \text{m s}^{-2}$

BANKED ROAD

A frictionless road of radius $100\ \text{m}$ is banked for $20\ \text{m s}^{-1}$. Find the angle ($g = 10$).

$\tan\theta = \dfrac{20^2}{100\times 10} = 0.4$, so $\theta \approx 21.8^\circ$

VERTICAL CIRCLE

A ball on a $0.5\ \text{m}$ string is whirled in a vertical circle. Least speed at the bottom?

$v = \sqrt{5gr} = \sqrt{5\times 10\times 0.5} = 5\ \text{m s}^{-1}$

LIFT

A $60\ \text{kg}$ person stands on a scale in a lift accelerating upwards at $2\ \text{m s}^{-2}$. Scale reading?

$N = m(g+a) = 60\times 12 = 720\ \text{N}$

TWO STRINGS

A $100\ \text{N}$ weight hangs from two strings, each 30° from the vertical. Tension in each?

$2T\cos 30^\circ = 100$, so $T = \dfrac{100}{\sqrt{3}} \approx 57.7\ \text{N}$

7 Last-minute checklist

- Draw a free-body diagram for every body and name each force by what causes it.
- Pick axes along the acceleration. Write the constraint (string, pulley) as its own equation.
- Friction: decide first whether the body moves; use $\mu_s N$ only at the limit.
- Circular motion: sum the forces along the radius and set it equal to mv^2/r.
- Pseudo force: stay in one frame for the whole problem.

Now test it. Practise this chapter with past-paper and bank questions on Prep Vault. **Practice this chapter →**