

Chapter 4: Laws of Motion

Comprehensive Study Notes

Class 11 Physics - NCERT Based

EXAM SPRINT - Complete Coverage for JEE and NEET Examinations

4.1 INTRODUCTION

What Governs Motion?

Key Question: What causes bodies to move or stop moving?

Common Experience Observations:

- Football needs kick to move from rest
- Stone needs push to throw upward
- Wind moves tree branches
- Boat moves in flowing river
- Force needed to stop rolling ball

Types of Forces:

1. **Contact Forces:** Direct physical contact required
 - Hand pushing object
 - Wind on sailing vessel
 - Friction between surfaces
2. **Non-Contact Forces:** Action at a distance

- Gravitational force (stone falling)
- Magnetic force (magnet attracting iron)
- Electric force

Central Question: Is external force needed to keep body in uniform motion?

4.2 ARISTOTLE'S FALLACY

Historical Context

Aristotle (384-322 BC) believed:

- External force required to keep body in motion
- Example: Arrow flies because air pushes it from behind
- **Aristotelian Law:** "External force is required to keep a body in motion"

Why This Seems Correct

Common Experience:

- Toy car stops when string is released
- All terrestrial objects eventually come to rest
- Constant force needed to maintain motion

The Flaw in Aristotle's Logic

Reality:

- Moving objects stop due to **friction**
- Child applies force to counter friction

- When car moves uniformly: Applied force = Frictional force
- **Net external force = Zero**

Key Insight: If no friction existed, no external force would be needed for uniform motion

Ancient Indian Contributions:

- **Vega:** Tendency to move in straight line (similar to inertia)
 - **Sanskara:** Persistent tendency in motion
 - Recognition of friction and air resistance
 - Bhaskara (1150 AD): Concept of instantaneous motion
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4.3 THE LAW OF INERTIA

Galileo's Revolutionary Experiments

Inclined Plane Studies:

1. **Downward motion:** Objects accelerate
2. **Upward motion:** Objects decelerate
3. **Horizontal motion:** Intermediate case

Conclusion: Object on frictionless horizontal plane moves with constant velocity

Double Inclined Plane Experiment

Observation:

- Ball released from one plane climbs to nearly same height on other
- As second plane's slope decreases, ball travels longer distance
- **Limiting case:** Horizontal plane → infinite distance → perpetual motion

Key Realization:

- Rest and uniform motion are equivalent states
- Both require **zero net external force**
- Force needed only to overcome friction, not to maintain motion

Definition of Inertia

Inertia: Property of body to resist change in state of rest or uniform motion

- "Resistance to change"
 - Body doesn't change state unless compelled by external force
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4.4 NEWTON'S FIRST LAW OF MOTION**Statement**

"Every body continues to be in its state of rest or of uniform motion in a straight line unless compelled by some external force to act otherwise."

Alternative Statement

If net external force on body is zero, its acceleration is zero

Two Application Scenarios

Scenario 1: Known that net force = 0

- Can conclude acceleration = 0
- Example: Spaceship in interstellar space

Scenario 2: Known that acceleration = 0

- Can conclude net force = 0
- Example: Book at rest on table

Practical Examples

Book on Table:

- Weight W acts downward
- Normal force R acts upward
- Book at rest $\rightarrow R = W$ (not because they're equal, but because book is observed at rest)

Car Motion:

- Stationary: Net force = 0
- Accelerating: Net external force $\neq 0$ (friction provides this force)
- Uniform motion: Net force = 0

Inertia in Daily Life

Bus Starting Suddenly:

- Feet move with bus (friction)
- Body remains at rest (inertia)
- Result: Thrown backward relative to bus

Bus Stopping Suddenly:

- Feet stop with bus (friction)
 - Body continues forward (inertia)
 - Result: Thrown forward
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4.5 NEWTON'S SECOND LAW OF MOTION

Momentum Concept

Definition: $p = mv$

- Vector quantity
- Product of mass and velocity
- Fundamental to understanding force effects

Why Momentum is Important

Experimental Observations:

1. Greater force needed to move heavier objects to same speed
2. Greater force needed to stop heavier objects in same time
3. Higher speed requires greater opposing force to stop
4. Force depends on both mass and velocity (momentum)

Rate of Change Principle

Key Insight: Force depends not just on momentum change, but on **rate** of momentum change

- Same momentum change in shorter time → greater force needed
- Example: Cricket catch - drawing hands back increases time, reduces force

Second Law Statement

"The rate of change of momentum of a body is directly proportional to the applied force and takes place in the direction in which the force acts."

Mathematical Formulation

Basic Form: $F \propto dp/dt$

With Constant of Proportionality: $F = k(dp/dt)$

Choosing $k = 1$ (for SI units): **$F = dp/dt = ma$** (for constant mass)

SI Unit of Force

Newton: $1 \text{ N} = 1 \text{ kg} \cdot \text{m} \cdot \text{s}^{-2}$

- Force that gives 1 kg mass an acceleration of $1 \text{ m} \cdot \text{s}^{-2}$

Important Properties of Second Law

1. **Consistency with First Law:** $F = 0 \Rightarrow a = 0$

2. **Vector Nature:**

- $F_x = dp_x/dt = ma_x$
- $F_y = dp_y/dt = ma_y$
- $F_u = dp_u/dt = ma_u$

3. **Component Analysis:** Force changes only velocity component parallel to it

4. **System Application:** Applies to single particles and systems of particles

5. **Local Relation:** Force at point determines acceleration at same point and time

Impulse Concept

Definition: Impulse = Force $\times$ Time = Change in momentum **$J = F \cdot \Delta t = \Delta p$**

Applications:

- Large force acting for short time

- Difficult to measure force and time separately
 - Impulse remains measurable
 - Example: Ball bouncing off wall
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4.6 NEWTON'S THIRD LAW OF MOTION

Statement

|"To every action, there is always an equal and opposite reaction."

Clear Interpretation

Forces always occur in pairs

- Force on A by B = -(Force on B by A)
- $\mathbf{F}_{\{AB\}} = -\mathbf{F}_{\{BA\}}$

Important Clarifications

1. Action-Reaction are Simultaneous

- No cause-effect relationship
- Both forces exist at same instant
- Either can be called action or reaction

2. Forces Act on Different Bodies

- Cannot cancel each other
- Don't add to zero when analyzing single body
- Internal forces in system do cancel in pairs

3. Mutual Interaction

- All forces arise from interaction between bodies

- No force exists in isolation
- Even "action at distance" forces come in pairs

Examples and Applications

Obvious Cases:

- Compressed spring pushes back on hand
- Person pushes wall, wall pushes back

Less Obvious Cases:

- Earth pulls stone down, stone pulls Earth up
- Effect on Earth negligible due to its large mass

Problem-Solving Strategy:

1. Identify force on object using Second Law
 2. Use Third Law to find reaction force
 3. Remember: reaction acts on different body
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4.7 CONSERVATION OF MOMENTUM

Derivation from Newton's Laws

System: Bullet + Gun

- Initially both at rest
- Force on bullet by gun = F
- Force on gun by bullet = $-F$ (Third Law)

- Time of action = Δt

Analysis:

- Change in bullet momentum = $F \cdot \Delta t$
- Change in gun momentum = $-F \cdot \Delta t$
- Total momentum change = 0
- **Initial momentum = Final momentum**

Law of Conservation of Momentum

┆ "The total momentum of an isolated system of interacting particles is conserved."

Conditions:

- System must be isolated (no external forces)
- Internal forces can exist (they cancel in pairs)
- Applies to all types of collisions

General Collision Analysis

Before Collision: $p_a + p_b$ **After Collision:** $p'_a + p'_b$ **Conservation:** $p'_a + p'_b = p_a + p_b$

Applications:

- Elastic and inelastic collisions
 - Explosions and disintegrations
 - Rocket propulsion
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4.8 EQUILIBRIUM OF A PARTICLE

Definition

Equilibrium: Net external force on particle is zero **Result:** Particle at rest or in uniform motion

Two-Force Equilibrium

Condition: $F_1 = -F_2$

- Forces must be equal and opposite
- Must act along same line

Three-Force Equilibrium

Condition: $F_1 + F_2 + F_3 = 0$ **Geometric Interpretation:** Forces form closed triangle **Component Form:**

- $\Sigma F_x = 0$
- $\Sigma F_y = 0$
- $\Sigma F_u = 0$

General n-Force Equilibrium

Geometric: Forces form closed n-sided polygon **Mathematical:** Vector sum equals zero

4.9 COMMON FORCES IN MECHANICS

Force Classification

Fundamental Forces:

1. Gravitational

2. Electromagnetic
3. Weak nuclear
4. Strong nuclear

In Mechanics: Only gravitational and electromagnetic relevant **Contact Forces:** All arise from electromagnetic forces at microscopic level

Specific Force Types

1. Gravitational Force

- Acts at distance
- Always attractive
- Governs celestial motion
- **$F = mg$** (near Earth's surface)

2. Normal Force

- Component of contact force perpendicular to surface
- Self-adjusting force
- Can vary with situation (elevator problems)

3. Tension

- Force transmitted through strings, ropes, cables
- Acts along length of string
- Constant throughout massless string

4. Spring Force

- **Hooke's Law:** $F = -kx$

- k = spring constant
- x = displacement from natural length
- Negative sign indicates restoring nature

5. Friction Force

4.9.1 Friction - Detailed Analysis

Static Friction

Characteristics:

- Opposes impending motion
- Self-adjusting: $0 \leq f_s \leq \mu_s N$
- Doesn't exist without applied force

Law of Static Friction: $f_s \leq \mu_s N$

- μ_s = coefficient of static friction
- N = normal force
- Independent of contact area

Kinetic Friction

Characteristics:

- Opposes actual relative motion
- Approximately constant
- Usually less than maximum static friction

Law of Kinetic Friction: $f_k = \mu_k N$

- μ_k = coefficient of kinetic friction
- $\mu_k < \mu_s$ (experimental observation)
- Independent of velocity (approximation)

Rolling Friction

Characteristics:

- Much smaller than sliding friction
- Arises from deformation during rolling
- Enables wheel technology

Applications:

- Ball bearings in machines
- Tire technology
- Reduction methods: lubrication, air cushions

Friction Applications

Beneficial:

- Walking (provides grip)
- Car acceleration and braking
- Holding objects

Problematic:

- Energy loss in machines
- Wear and tear
- Heat generation

4.10 CIRCULAR MOTION

Centripetal Force

For uniform circular motion: $F_c = mv^2/R$

- Always directed toward center
- Provided by some physical force

Examples of Centripetal Force

- String tension (stone whirling)
- Gravitational force (planetary motion)
- Friction (car on road)

Motion on Level Road

Forces on Car:

1. Weight: mg (downward)
2. Normal force: $N = mg$ (upward)
3. Friction: f (toward center)

Analysis:

- Centripetal force = friction force
- **$f = mv^2/R$**
- Maximum speed: **$v_{\max} = \sqrt{\mu_s Rg}$**

Motion on Banked Road

Advantages:

- Normal force component provides centripetal force
- Reduces dependence on friction
- Higher safe speeds possible

Force Analysis:

- Normal force: N
- Weight: mg
- Friction: f (if needed)

Optimum Speed (no friction needed): $v_0 = \sqrt{Rg \tan \theta}$

Maximum Speed: $v_{\text{max}} = \sqrt{[Rg(\mu_s + \tan \theta)/(1 - \mu_s \tan \theta)]}$

4.11 SOLVING PROBLEMS IN MECHANICS

Systematic Approach

Step 1: Draw System Diagram

- Show all parts of assembly
- Include connections and supports
- Identify system boundaries

Step 2: Choose System

- Select convenient part for analysis

- Clearly define what's inside system
- Rest becomes environment

Step 3: Free-Body Diagram

- Show only forces ON the system
- Include forces by environment
- Don't include forces BY the system
- Label known and unknown forces

Step 4: Apply Newton's Laws

- Use appropriate law for situation
- Include all relevant forces
- Set up equations systematically

Step 5: Additional Systems

- Analyze other parts if necessary
- Use Newton's Third Law consistently
- Connect equations through constraints

Problem-Solving Tips

1. Always draw free-body diagrams
 2. Choose coordinate system wisely
 3. Apply laws to each object separately
 4. Use constraints (strings, contacts) to relate motions
 5. Check answers for physical reasonableness
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SUMMARY - KEY CONCEPTS

The Three Laws

1. **First Law (Inertia):** Object continues in state of rest or uniform motion unless acted upon by net external force
2. **Second Law:** $F = dp/dt = ma$ (for constant mass)
3. **Third Law:** Forces always occur in equal and opposite pairs on different bodies

Conservation Principles

Momentum Conservation: Total momentum of isolated system remains constant

Force Types

- **Fundamental:** Gravitational, electromagnetic
- **Contact:** Normal, friction, tension, spring
- **All contact forces:** Ultimately electromagnetic in origin

Friction Laws

- **Static:** $f_s \leq \mu_s N$
- **Kinetic:** $f_k = \mu_k N$
- **Rolling:** Much smaller than sliding

Circular Motion

- **Centripetal force:** $F_c = mv^2/R$
 - **Always toward center**
 - **Provided by physical forces**
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POINTS TO PONDER - CRITICAL INSIGHTS

1. Force and Motion Relationship

- Force NOT always in direction of motion
- Force parallel to acceleration, not velocity
- Zero velocity $\neq$ zero force (ball at highest point)

2. Force Origins

- Force determined by current situation, not history
- No "memory" in mechanical systems
- Local relationship: F here and now $\rightarrow$ a here and now

3. Common Misconceptions

- ma is NOT another force besides F
- Centripetal force is NOT new type of force
- Static friction is self-adjusting (don't assume $f_s = \mu_s N$)

4. Third Law Applications

- Action-reaction on DIFFERENT bodies
- Cannot cancel when analyzing single body
- Simultaneous, no cause-effect sequence

5. Equilibrium vs Motion

- $mg = N$ only in equilibrium (not universal truth)
- Moving objects can be in equilibrium

- Acceleration possible with instantaneous zero velocity
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JEE/NEET SPECIFIC IMPORTANT POINTS

High-Yield Topics

1. Newton's Laws Applications

- **Free-body diagrams:** Master technique
- **Connected systems:** Pulleys, strings, blocks
- **Constraint equations:** Relate accelerations
- **Force identification:** What provides each force?

2. Friction Problems

Static friction scenarios:

- Object on incline
- Maximum acceleration without slipping
- Minimum force to prevent sliding

Kinetic friction scenarios:

- Stopping distances
- Motion on rough surfaces
- Energy dissipation

3. Circular Motion

Key calculations:

- Banking angle problems
- String tension in vertical/horizontal circles
- Centripetal force identification
- Maximum/minimum speed problems

4. System Analysis

Multiple body problems:

- Atwood machines
- Inclined planes with pulleys
- Connected blocks on different surfaces

Common Question Types

1. Force Analysis

- Draw free-body diagram
- Apply $F = ma$ to each body
- Solve system of equations

2. Constraint Problems

- String length constant
- Contact maintained
- No slipping conditions

3. Limiting Cases

- Just about to slip
- Maximum acceleration

- Critical angles/speeds

4. Conservation Applications

- Collision problems
 - Explosion/separation
 - Momentum before/after events
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PROBLEM-SOLVING STRATEGY

Phase 1: Understanding

1. **Read carefully:** Identify all given information
2. **Visualize:** Draw clear diagram of situation
3. **Identify:** What's being asked?

Phase 2: Analysis

1. **Choose system:** What to analyze?
2. **Free-body diagram:** Show all forces on system
3. **Coordinate system:** Choose convenient axes
4. **Equations:** Apply appropriate Newton's law

Phase 3: Solution

1. **Mathematics:** Solve equations systematically
2. **Check units:** Dimensional analysis
3. **Physical sense:** Does answer make sense?
4. **Limiting cases:** Test extreme values

Phase 4: Verification

1. **Alternative method:** Try different approach
 2. **Order of magnitude:** Reasonable size?
 3. **Direction:** Correct vector direction?
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MEMORY AIDS AND MNEMONICS

Newton's Laws

"FBI"

- **F**irst: Inertia ($F = 0 \rightarrow a = 0$)
- **B**asic: $F = ma$ (Second law)
- **I**nteractive: Action-reaction pairs (Third law)

Force Types

"GENTS"

- **G**ravitational
- **E**lectromagnetic
- **N**ormal
- **T**ension
- **S**pring

Friction Rules

"Static Stays, Kinetic Kills"

- Static friction prevents motion

- Kinetic friction opposes motion
- Static usually larger than kinetic

Problem Solving

"Draw, Choose, Force, Solve"

- **Draw:** System diagram
 - **Choose:** System boundaries
 - **Force:** Free-body diagram
 - **Solve:** Apply Newton's laws
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PRACTICE PROBLEMS FOR JEE/NEET

Level 1: Basic Application

Problem 1: Block on Incline A 2 kg block rests on 30° incline. Coefficient of static friction = 0.6. Find: (a) Normal force (b) Friction force (c) Will it slide?

Solution:

- $N = mg \cos 30^\circ = 2 \times 10 \times (\sqrt{3}/2) = 17.3 \text{ N}$
- Component down incline = $mg \sin 30^\circ = 10 \text{ N}$
- Maximum static friction = $\mu_s N = 0.6 \times 17.3 = 10.4 \text{ N}$
- Since $10.4 > 10$, block won't slide
- Actual friction = 10 N (up incline)

Problem 2: Atwood Machine Two masses 3 kg and 5 kg connected by string over pulley. Find: (a) Acceleration (b) Tension

Solution:

- For 5 kg: $5g - T = 5a$
- For 3 kg: $T - 3g = 3a$
- Adding: $2g = 8a \rightarrow a = g/4 = 2.5 \text{ m/s}^2$
- $T = 3g + 3a = 3(10 + 2.5) = 37.5 \text{ N}$

Level 2: Intermediate

Problem 3: Circular Motion Car takes circular turn of radius 50 m at 36 km/h. $\mu_s = 0.3$. Find: Will car slip?

Solution:

- $v = 36 \text{ km/h} = 10 \text{ m/s}$
- Centripetal force needed $= mv^2/R = m \times 100/50 = 2m \text{ N}$
- Maximum friction available $= \mu_s mg = 0.3 \times m \times 10 = 3m \text{ N}$
- Since $3m > 2m$, car won't slip

Problem 4: Connected Blocks 5 kg block on rough table ($\mu_k = 0.2$) connected to 3 kg hanging mass. Find: (a) Acceleration of system (b) Tension in string

Solution:

- Friction on 5 kg block $= \mu_k \times 5g = 10 \text{ N}$
- For 3 kg: $3g - T = 3a$
- For 5 kg: $T - 10 = 5a$
- Adding: $3g - 10 = 8a \rightarrow a = 2.5 \text{ m/s}^2$
- $T = 3g - 3a = 30 - 7.5 = 22.5 \text{ N}$

Level 3: Advanced

Problem 5: Banking Problem Road banked at 15° for 60 km/h. Car travels at 90 km/h with $\mu_s = 0.2$.
Find: Will car slip up or down the bank?

Solution: Requires detailed force analysis considering banking and friction direction.

EXPERIMENTAL CONNECTIONS

1. Historical Experiments

Galileo's Contributions:

- Inclined plane studies
- Pendulum observations
- Mathematical description of motion

Newton's Synthesis:

- Combined Galileo's observations
- Universal law of gravitation
- Mathematical Principia

2. Modern Applications

Transportation:

- Vehicle dynamics
- Railway engineering
- Aircraft design

Sports Science:

- Biomechanics analysis
- Equipment optimization
- Performance enhancement

Space Technology:

- Rocket propulsion
- Orbital mechanics
- Satellite deployment

3. Everyday Examples**Walking:**

- Friction provides forward force
- Third law: foot pushes back, ground pushes forward
- Balance of forces for steady motion

Driving:

- Engine doesn't push car directly
- Friction between tires and road provides force
- Banking helps in turns

ERROR ANALYSIS IN MECHANICS**Common Mistakes****1. Free-Body Diagram Errors**

- Including forces ON other bodies
- Missing important forces
- Wrong force directions
- Incorrect force magnitudes

2. Third Law Misapplication

- Adding action-reaction forces
- Applying to same body
- Ignoring that they act on different objects

3. Friction Confusions

- Assuming $f_s = \mu_s N$ always
- Wrong direction of friction
- Forgetting self-adjusting nature of static friction

4. Circular Motion Errors

- Centrifugal force misconceptions
- Wrong centripetal force identification
- Incorrect direction assignments

Prevention Strategies

1. **Systematic approach:** Follow step-by-step method
2. **Clear diagrams:** Always draw before calculating
3. **Force identification:** Ask "what exerts this force?"
4. **Physical reasoning:** Check if answer makes sense

ADVANCED TOPICS FOR JEE

1. Variable Mass Systems

- Rocket equation
- Conveyor belt problems
- Chain pulling problems

2. Non-Inertial Reference Frames

- Pseudo forces
- Accelerated frame analysis
- Centrifugal and Coriolis effects

3. Constraint Forces

- Normal force calculations
- Reaction force determination
- Multi-body constraint analysis

4. Advanced Friction

- Rolling without slipping
- Combined translation and rotation
- Friction in circular motion

EXAM SPRINT - Master Laws of Motion through systematic study of Newton's three laws, force analysis, and problem-solving techniques. Focus on free-body diagrams, constraint equations, and

real-world applications for JEE/NEET success.

Source: NCERT Physics Class 11, Chapter 4 - Comprehensive coverage for competitive exam preparation