

UCLA PHYSICS FIELD NOTES

# PHYSICS 1A

## Mechanics

Physics for Scientists and Engineers: modeling motion, force, energy, momentum, rotation, and gravity

**How these notes are written.** I wrote each chapter the way I wish the material had been explained the first time: the real idea, the point where I usually get stuck, the simplest mental model that still stays honest, and a worked decision instead of a polished answer appearing from nowhere. Every chapter closes with practice and a fully written solution. If a sentence sounds impressive but does not help me solve or explain something, it does not belong here.

**Daniel Mastick**

Curriculum map, working notes, practice, and solutions

## Course map

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| Week | Core thread                             | What should be solid by the end                                                                  |
|------|-----------------------------------------|--------------------------------------------------------------------------------------------------|
| 1    | <b>Measurement, vectors, and models</b> | Translate a physical situation into coordinates, units, diagrams, and reasonable approximations. |
| 2    | <b>Kinematics</b>                       | Connect position, velocity, and acceleration in one and two dimensions.                          |
| 3    | <b>Newton's laws</b>                    | Build free-body diagrams and turn interactions into component equations.                         |
| 4    | <b>Work and energy</b>                  | Use energy accounting when the path details are less important than the endpoints.               |
| 5    | <b>Momentum</b>                         | Analyze impulses, collisions, and systems with internal interactions.                            |
| 6    | <b>Rotation</b>                         | Move from linear quantities to angular motion, torque, and rotational energy.                    |
| 7    | <b>Angular momentum</b>                 | Choose an origin, track rotational impulse, and recognize conservation.                          |
| 8    | <b>Gravity and orbits</b>               | Use universal gravitation, potential energy, and centripetal acceleration together.              |
| 9    | <b>Equilibrium and rolling</b>          | Combine translation and rotation for rigid bodies, supports, and rolling motion.                 |
| 10   | <b>Synthesis</b>                        | Choose a system and a conservation law before reaching for algebra.                              |

Scope anchor: <https://catalog.registrar.ucla.edu/course/2024/PHYSICS1A>. The sequence is aligned to the official catalog description and expanded into a practical ten-week study plan.

## How I would use this packet

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Treat each numbered section as one chapter. Read the formal explanation, pause at the student interpretation, and see whether the easy version still says the same thing. Rework the example without looking, then cover the solution in the chapter practice box. The cumulative set at the end is deliberately mixed: knowledge becomes durable when I have to choose the tool instead of being told which chapter I am in.

# Contents

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|          |                                                           |           |
|----------|-----------------------------------------------------------|-----------|
| <b>1</b> | <b>Measurement, vectors, and the modeling habit</b>       | <b>5</b>  |
| 1.1      | Rebuild the chapter from first principles . . . . .       | 5         |
| 1.2      | Details I would refuse to skip . . . . .                  | 5         |
| 1.3      | How this chapter connects . . . . .                       | 6         |
| <b>2</b> | <b>Kinematics: describing motion before explaining it</b> | <b>7</b>  |
| 2.1      | Rebuild the chapter from first principles . . . . .       | 7         |
| 2.2      | Details I would refuse to skip . . . . .                  | 7         |
| 2.3      | How this chapter connects . . . . .                       | 8         |
| <b>3</b> | <b>Newton's laws and free-body diagrams</b>               | <b>9</b>  |
| 3.1      | Rebuild the chapter from first principles . . . . .       | 9         |
| 3.2      | Details I would refuse to skip . . . . .                  | 10        |
| 3.3      | How this chapter connects . . . . .                       | 10        |
| <b>4</b> | <b>Work, energy, and power</b>                            | <b>11</b> |
| 4.1      | Rebuild the chapter from first principles . . . . .       | 11        |
| 4.2      | Details I would refuse to skip . . . . .                  | 12        |
| 4.3      | How this chapter connects . . . . .                       | 12        |
| <b>5</b> | <b>Momentum, impulse, and collisions</b>                  | <b>13</b> |
| 5.1      | Rebuild the chapter from first principles . . . . .       | 13        |
| 5.2      | Details I would refuse to skip . . . . .                  | 14        |
| 5.3      | How this chapter connects . . . . .                       | 14        |
| <b>6</b> | <b>Rotation, torque, and rotational energy</b>            | <b>15</b> |
| 6.1      | Rebuild the chapter from first principles . . . . .       | 15        |
| 6.2      | Details I would refuse to skip . . . . .                  | 16        |
| 6.3      | How this chapter connects . . . . .                       | 16        |
| <b>7</b> | <b>Angular momentum and rotational impulse</b>            | <b>17</b> |
| 7.1      | Rebuild the chapter from first principles . . . . .       | 17        |
| 7.2      | Details I would refuse to skip . . . . .                  | 18        |
| 7.3      | How this chapter connects . . . . .                       | 18        |

|          |                                                     |           |
|----------|-----------------------------------------------------|-----------|
| <b>8</b> | <b>Universal gravitation and orbital motion</b>     | <b>19</b> |
| 8.1      | Rebuild the chapter from first principles . . . . . | 19        |
| 8.2      | Details I would refuse to skip . . . . .            | 20        |
| 8.3      | How this chapter connects . . . . .                 | 20        |
| <b>9</b> | <b>Static equilibrium and rolling motion</b>        | <b>22</b> |
| 9.1      | Rebuild the chapter from first principles . . . . . | 22        |
| 9.2      | Details I would refuse to skip . . . . .            | 22        |
| 9.3      | How this chapter connects . . . . .                 | 23        |

## CHAPTER 1 Measurement, vectors, and the modeling habit

### Rebuild the chapter from first principles

The claim I need to own is this: The model in Measurement, vectors, and the modeling habit controls the work. I do not count that as learned just because the sentence looks familiar. I should be able to name the objects, state what changes and what stays fixed, recover the rule from the definitions, and explain why the result is allowed.

#### The move

##### My working sequence

1. **Translate.** Rewrite the prompt in the language of measurement, vectors, and the modeling habit. List the known quantities, the unknown, the units or types, and any hidden constraint.
2. **Choose.** State the theorem, model, algorithm, accounting rule, or physical law before substituting values. This is where I make the assumption visible.
3. **Execute.** Work one justified step at a time and keep intermediate state readable enough that I can audit it later.
4. **Verify.** Check a boundary case, sign, unit, invariant, order of magnitude, or alternative derivation. Then translate the result back into an ordinary sentence.

### Details I would refuse to skip

- **Definitions:** I should be able to define every technical noun in the chapter without using that same noun in the definition.
- **Assumptions:** I write the condition that makes the method legal beside the method itself. A correct procedure under the wrong assumptions is still a wrong answer.
- **Representation:** I move freely among words, equations or code, a diagram, and a small numerical example. If one representation disagrees with another, that disagreement is useful evidence.
- **Failure modes:** I keep the nearest counterexample in mind: the boundary where the rule changes, the invariant breaks, or the model stops matching reality.
- **Communication:** My final answer names what the result means and what it does not establish. I do not let notation do the explanatory work for me.

#### Sanity check

**Closed-note check.** Can I teach measurement, vectors, and the modeling habit on a blank page, derive or reconstruct its main rule, work a fresh example, and diagnose a deliberately broken solution? If I can only recognize the finished work, I am not done.

## How this chapter connects

I read this chapter as the bridge from the course foundations to kinematics: describing motion before explaining it. The earlier material supplies the language and constraints; this chapter adds a new reasoning move; the later material asks me to use that move without being told its name. That connection matters because exams and real projects mix chapters on purpose.

Physics starts before the equation. A model names the system, chooses coordinates, decides which effects matter, and records the assumptions that make the problem manageable. Units are part of every quantity, not labels added after the calculation. Dimensional analysis cannot prove that a formula is correct, but it quickly proves many formulas impossible.

For vectors, components carry the calculation:

$$\vec{A} = A_x \hat{i} + A_y \hat{j}, \quad |\vec{A}| = \sqrt{A_x^2 + A_y^2}, \quad \vec{A} \cdot \vec{B} = AB \cos \theta.$$

The dot product measures how much one vector points along another. The cross product, used later for torque, measures the perpendicular leverage between them.

### How I actually think about it

I get better results when I spend the first minute drawing and labeling instead of searching for a formula. My coordinate choice is allowed to make the problem easier. A tilted axis is not cheating; it is good bookkeeping.

### The easy version

Physics is a translation job: turn the scene into a diagram, the diagram into components, and the components into equations. Keep the units attached so the translation cannot quietly change meaning.

### Worked example

A hiker walks 3.0 km east and then 4.0 km north. The displacement is  $\langle 3, 4 \rangle$  km, so its magnitude is 5.0 km and its direction is  $\tan^{-1}(4/3) = 53.1^\circ$  north of east. The distance traveled is 7.0 km. Distance and displacement answer different questions.

### Solved chapter practice

**Practice.** A force  $\vec{F} = \langle 6, -8 \rangle$  N moves an object through  $\vec{d} = \langle 3, 2 \rangle$  m. Find the work  $\vec{F} \cdot \vec{d}$  and the component of  $\vec{F}$  along the displacement.

**Solution.**  $W = 6(3) + (-8)(2) = 2$  J. Since  $|\vec{d}| = \sqrt{13}$  m, the signed component along the displacement is  $F_{\parallel} = W/|\vec{d}| = 2/\sqrt{13} = 0.555$  N. Most of the force is perpendicular to the motion, which explains the small work.

**Mastery practice A.** Reconstruct measurement, vectors, and the modeling habit from a blank page. Include the central definition, the governing rule, one required assumption, and one boundary case.

**Solution.** Start from the blue idea box, but rewrite it in my own words. Identify the objects and state, name the rule before using it, copy the relevant assumption from the details audit, and choose a boundary where that assumption becomes equality or fails. A complete solution explains

why each part belongs; a list of vocabulary is not enough.

**Mastery practice B.** A classmate gets a polished-looking answer to a measurement, vectors, and the modeling habit problem but never states a model or checks the result. Write the shortest useful review of that solution.

**Solution.** I would ask four concrete questions: What exactly are the inputs and desired output? Which rule licenses the main step? Which assumption could invalidate it? Which independent check supports the conclusion? If the answer cannot survive those four questions, I treat the numerical or verbal result as unverified.

## CHAPTER 2 Kinematics: describing motion before explaining it

### Rebuild the chapter from first principles

The claim I need to own is this: The model in Kinematics: describing motion before explaining it controls the work. I do not count that as learned just because the sentence looks familiar. I should be able to name the objects, state what changes and what stays fixed, recover the rule from the definitions, and explain why the result is allowed.

#### The move

##### My working sequence

1. **Translate.** Rewrite the prompt in the language of kinematics: describing motion before explaining it. List the known quantities, the unknown, the units or types, and any hidden constraint.
2. **Choose.** State the theorem, model, algorithm, accounting rule, or physical law before substituting values. This is where I make the assumption visible.
3. **Execute.** Work one justified step at a time and keep intermediate state readable enough that I can audit it later.
4. **Verify.** Check a boundary case, sign, unit, invariant, order of magnitude, or alternative derivation. Then translate the result back into an ordinary sentence.

### Details I would refuse to skip

- **Definitions:** I should be able to define every technical noun in the chapter without using that same noun in the definition.
- **Assumptions:** I write the condition that makes the method legal beside the method itself. A correct procedure under the wrong assumptions is still a wrong answer.
- **Representation:** I move freely among words, equations or code, a diagram, and a small numerical example. If one representation disagrees with another, that disagreement is useful evidence.
- **Failure modes:** I keep the nearest counterexample in mind: the boundary where the rule changes, the invariant breaks, or the model stops matching reality.

- **Communication:** My final answer names what the result means and what it does not establish. I do not let notation do the explanatory work for me.

### Sanity check

**Closed-note check.** Can I teach kinematics: describing motion before explaining it on a blank page, derive or reconstruct its main rule, work a fresh example, and diagnose a deliberately broken solution? If I can only recognize the finished work, I am not done.

## How this chapter connects

I read this chapter as the bridge from measurement, vectors, and the modeling habit to newton's laws and free-body diagrams. The earlier material supplies the language and constraints; this chapter adds a new reasoning move; the later material asks me to use that move without being told its name. That connection matters because exams and real projects mix chapters on purpose.

Position  $\vec{r}(t)$  tells where an object is relative to the origin. Velocity and acceleration are successive time derivatives:

$$\vec{v} = \frac{d\vec{r}}{dt}, \quad \vec{a} = \frac{d\vec{v}}{dt}.$$

The area under a velocity-time graph is displacement; the area under an acceleration-time graph is change in velocity. For constant acceleration,

$$\vec{v} = \vec{v}_0 + \vec{a}t, \quad \vec{r} = \vec{r}_0 + \vec{v}_0t + \frac{1}{2}\vec{a}t^2.$$

These formulas are consequences of integration and are only legal while acceleration is constant.

Projectile motion is one motion split into independent components. Ignoring air resistance,  $a_x = 0$  and  $a_y = -g$ . Both components share the same time, which is the bridge between them.

### How I actually think about it

My shorthand for this chapter is: my shorthand for this chapter is: the sign of velocity tells direction; the sign of acceleration tells how velocity is changing. A negative acceleration does not automatically mean slowing down. If velocity and acceleration have the same sign, speed increases.

### The easy version

Position is where I am, velocity is what my position is doing, and acceleration is what my velocity is doing. Graph slopes move down this chain; graph areas move back up it.

### Worked example

A ball is launched at 20 m/s and  $30^\circ$  above horizontal. Its components are  $v_{0x} = 17.3$  m/s and  $v_{0y} = 10.0$  m/s. It reaches the top after  $t = v_{0y}/g = 1.02$  s and rises  $v_{0y}^2/(2g) = 5.10$  m above launch height.



## Solved chapter practice

**Practice.** A car moving at 25 m/s brakes with constant acceleration  $-5.0 \text{ m/s}^2$ . Find the stopping time and distance.

**Solution.** From  $v = v_0 + at$ ,  $0 = 25 - 5t$ , so  $t = 5.0 \text{ s}$ . Then  $\Delta x = v_0 t + \frac{1}{2}at^2 = 25(5) - 2.5(25) = 62.5 \text{ m}$ . A unit check gives seconds for time and meters for displacement.

**Mastery practice A.** Reconstruct kinematics: describing motion before explaining it from a blank page. Include the central definition, the governing rule, one required assumption, and one boundary case.

**Solution.** Start from the blue idea box, but rewrite it in my own words. Identify the objects and state, name the rule before using it, copy the relevant assumption from the details audit, and choose a boundary where that assumption becomes equality or fails. A complete solution explains why each part belongs; a list of vocabulary is not enough.

**Mastery practice B.** A classmate gets a polished-looking answer to a kinematics: describing motion before explaining it problem but never states a model or checks the result. Write the shortest useful review of that solution.

**Solution.** I would ask four concrete questions: What exactly are the inputs and desired output? Which rule licenses the main step? Which assumption could invalidate it? Which independent check supports the conclusion? If the answer cannot survive those four questions, I treat the numerical or verbal result as unverified.

## CHAPTER 3 Newton's laws and free-body diagrams

## Rebuild the chapter from first principles

The claim I need to own is this: The model in Newton's laws and free-body diagrams controls the work. I do not count that as learned just because the sentence looks familiar. I should be able to name the objects, state what changes and what stays fixed, recover the rule from the definitions, and explain why the result is allowed.

## The move

## My working sequence

1. **Translate.** Rewrite the prompt in the language of Newton's laws and free-body diagrams. List the known quantities, the unknown, the units or types, and any hidden constraint.
2. **Choose.** State the theorem, model, algorithm, accounting rule, or physical law before substituting values. This is where I make the assumption visible.
3. **Execute.** Work one justified step at a time and keep intermediate state readable enough that I can audit it later.
4. **Verify.** Check a boundary case, sign, unit, invariant, order of magnitude, or alternative derivation. Then translate the result back into an ordinary sentence.

## Details I would refuse to skip

- **Definitions:** I should be able to define every technical noun in the chapter without using that same noun in the definition.
- **Assumptions:** I write the condition that makes the method legal beside the method itself. A correct procedure under the wrong assumptions is still a wrong answer.
- **Representation:** I move freely among words, equations or code, a diagram, and a small numerical example. If one representation disagrees with another, that disagreement is useful evidence.
- **Failure modes:** I keep the nearest counterexample in mind: the boundary where the rule changes, the invariant breaks, or the model stops matching reality.
- **Communication:** My final answer names what the result means and what it does not establish. I do not let notation do the explanatory work for me.

### Sanity check

**Closed-note check.** Can I teach newton's laws and free-body diagrams on a blank page, derive or reconstruct its main rule, work a fresh example, and diagnose a deliberately broken solution? If I can only recognize the finished work, I am not done.

## How this chapter connects

I read this chapter as the bridge from kinematics: describing motion before explaining it to work, energy, and power. The earlier material supplies the language and constraints; this chapter adds a new reasoning move; the later material asks me to use that move without being told its name. That connection matters because exams and real projects mix chapters on purpose.

Newton's first law identifies inertial frames. The second law is a statement about the net external force,

$$\sum \vec{F}_{\text{ext}} = m\vec{a},$$

and the third law pairs forces on different objects. A free-body diagram contains only forces acting on the chosen object: weight, normal force, tension, friction, drag, or a specified applied force. "Centripetal force" is not an extra force; it is the inward component of the real net force.

Static friction adjusts up to  $f_s \leq \mu_s N$ . Kinetic friction is modeled by  $f_k = \mu_k N$ . The normal force is a contact response, not automatically  $mg$ .

### How I actually think about it

My safest workflow is object first, forces second, components third. I do not put acceleration on the force diagram, and I do not put the third-law partner on the same object's diagram.

### The easy version

Forces are pushes and pulls from other objects. Add the forces that act on my chosen object; whatever is left over determines how its velocity changes.

## Worked example

A 5 kg block slides down a frictionless  $30^\circ$  incline. Along the slope,  $mg \sin 30^\circ = ma$ , so  $a = g \sin 30^\circ = 4.9 \text{ m/s}^2$ . Perpendicular to it,  $N - mg \cos 30^\circ = 0$ , so  $N = 42.4 \text{ N}$ .

## Solved chapter practice

**Practice.** A 10 kg crate is pulled horizontally by 50 N across a floor with  $\mu_k = 0.20$ . Find its acceleration.

**Solution.** Vertical equilibrium gives  $N = mg = 98 \text{ N}$ . Kinetic friction is  $f_k = 0.20(98) = 19.6 \text{ N}$  opposite motion. The horizontal net force is  $50 - 19.6 = 30.4 \text{ N}$ , so  $a = 30.4/10 = 3.04 \text{ m/s}^2$ .

**Mastery practice A.** Reconstruct newton's laws and free-body diagrams from a blank page. Include the central definition, the governing rule, one required assumption, and one boundary case.

**Solution.** Start from the blue idea box, but rewrite it in my own words. Identify the objects and state, name the rule before using it, copy the relevant assumption from the details audit, and choose a boundary where that assumption becomes equality or fails. A complete solution explains why each part belongs; a list of vocabulary is not enough.

**Mastery practice B.** A classmate gets a polished-looking answer to a newton's laws and free-body diagrams problem but never states a model or checks the result. Write the shortest useful review of that solution.

**Solution.** I would ask four concrete questions: What exactly are the inputs and desired output? Which rule licenses the main step? Which assumption could invalidate it? Which independent check supports the conclusion? If the answer cannot survive those four questions, I treat the numerical or verbal result as unverified.

## CHAPTER 4 Work, energy, and power

## Rebuild the chapter from first principles

The claim I need to own is this: The model in Work, energy, and power controls the work. I do not count that as learned just because the sentence looks familiar. I should be able to name the objects, state what changes and what stays fixed, recover the rule from the definitions, and explain why the result is allowed.

## The move

## My working sequence

1. **Translate.** Rewrite the prompt in the language of work, energy, and power. List the known quantities, the unknown, the units or types, and any hidden constraint.
2. **Choose.** State the theorem, model, algorithm, accounting rule, or physical law before substituting values. This is where I make the assumption visible.
3. **Execute.** Work one justified step at a time and keep intermediate state readable enough that I can audit it later.

4. **Verify.** Check a boundary case, sign, unit, invariant, order of magnitude, or alternative derivation. Then translate the result back into an ordinary sentence.

### Details I would refuse to skip

- **Definitions:** I should be able to define every technical noun in the chapter without using that same noun in the definition.
- **Assumptions:** I write the condition that makes the method legal beside the method itself. A correct procedure under the wrong assumptions is still a wrong answer.
- **Representation:** I move freely among words, equations or code, a diagram, and a small numerical example. If one representation disagrees with another, that disagreement is useful evidence.
- **Failure modes:** I keep the nearest counterexample in mind: the boundary where the rule changes, the invariant breaks, or the model stops matching reality.
- **Communication:** My final answer names what the result means and what it does not establish. I do not let notation do the explanatory work for me.

### Sanity check

**Closed-note check.** Can I teach work, energy, and power on a blank page, derive or reconstruct its main rule, work a fresh example, and diagnose a deliberately broken solution? If I can only recognize the finished work, I am not done.

### How this chapter connects

I read this chapter as the bridge from newton's laws and free-body diagrams to momentum, impulse, and collisions. The earlier material supplies the language and constraints; this chapter adds a new reasoning move; the later material asks me to use that move without being told its name. That connection matters because exams and real projects mix chapters on purpose.

Work is energy transferred by a force through displacement:

$$W = \int \vec{F} \cdot d\vec{r}, \quad W_{\text{net}} = \Delta K, \quad K = \frac{1}{2}mv^2.$$

For conservative forces we store configuration information as potential energy, with  $\Delta U = -W_{\text{cons}}$ . Near Earth  $U_g = mgy$ ; for an ideal spring  $U_s = \frac{1}{2}kx^2$ . If nonconservative transfers are included explicitly,

$$K_i + U_i + W_{\text{other}} = K_f + U_f.$$

Power measures the rate of energy transfer:  $P = dW/dt = \vec{F} \cdot \vec{v}$ .

### How I actually think about it

Energy is often easier than forces because it skips the detailed timeline. I choose the system first. If Earth is inside the system, gravity becomes potential energy; if Earth is outside, gravity does external work.

### The easy version

Energy is an accounting ledger. It can move between motion, height, and a stretched spring, but every gain has to be paid for somewhere.

### Worked example

A block starts from rest and slides down a frictionless vertical drop  $h$ . Conservation gives  $mgh = \frac{1}{2}mv^2$ , so  $v = \sqrt{2gh}$ . The mass cancels because both stored gravitational energy and inertia scale with mass.

### Solved chapter practice

**Practice.** A 2.0 kg block moving at 6.0 m/s compresses a spring with  $k = 400$  N/m on a frictionless surface. Find maximum compression.

**Solution.** At maximum compression the block is instantaneously at rest, so  $\frac{1}{2}mv^2 = \frac{1}{2}kx^2$ . Thus  $x = v\sqrt{m/k} = 6\sqrt{2/400} = 0.424$  m.

**Mastery practice A.** Reconstruct work, energy, and power from a blank page. Include the central definition, the governing rule, one required assumption, and one boundary case.

**Solution.** Start from the blue idea box, but rewrite it in my own words. Identify the objects and state, name the rule before using it, copy the relevant assumption from the details audit, and choose a boundary where that assumption becomes equality or fails. A complete solution explains why each part belongs; a list of vocabulary is not enough.

**Mastery practice B.** A classmate gets a polished-looking answer to a work, energy, and power problem but never states a model or checks the result. Write the shortest useful review of that solution.

**Solution.** I would ask four concrete questions: What exactly are the inputs and desired output? Which rule licenses the main step? Which assumption could invalidate it? Which independent check supports the conclusion? If the answer cannot survive those four questions, I treat the numerical or verbal result as unverified.

## CHAPTER 5 Momentum, impulse, and collisions

### Rebuild the chapter from first principles

The claim I need to own is this: The model in Momentum, impulse, and collisions controls the work. I do not count that as learned just because the sentence looks familiar. I should be able to name the objects, state what changes and what stays fixed, recover the rule from the definitions, and explain why the result is allowed.

### The move

#### My working sequence

1. **Translate.** Rewrite the prompt in the language of momentum, impulse, and collisions. List the known quantities, the unknown, the units or types, and any hidden constraint.

2. **Choose.** State the theorem, model, algorithm, accounting rule, or physical law before substituting values. This is where I make the assumption visible.
3. **Execute.** Work one justified step at a time and keep intermediate state readable enough that I can audit it later.
4. **Verify.** Check a boundary case, sign, unit, invariant, order of magnitude, or alternative derivation. Then translate the result back into an ordinary sentence.

### Details I would refuse to skip

- **Definitions:** I should be able to define every technical noun in the chapter without using that same noun in the definition.
- **Assumptions:** I write the condition that makes the method legal beside the method itself. A correct procedure under the wrong assumptions is still a wrong answer.
- **Representation:** I move freely among words, equations or code, a diagram, and a small numerical example. If one representation disagrees with another, that disagreement is useful evidence.
- **Failure modes:** I keep the nearest counterexample in mind: the boundary where the rule changes, the invariant breaks, or the model stops matching reality.
- **Communication:** My final answer names what the result means and what it does not establish. I do not let notation do the explanatory work for me.

### Sanity check

**Closed-note check.** Can I teach momentum, impulse, and collisions on a blank page, derive or reconstruct its main rule, work a fresh example, and diagnose a deliberately broken solution? If I can only recognize the finished work, I am not done.

### How this chapter connects

I read this chapter as the bridge from work, energy, and power to rotation, torque, and rotational energy. The earlier material supplies the language and constraints; this chapter adds a new reasoning move; the later material asks me to use that move without being told its name. That connection matters because exams and real projects mix chapters on purpose.

Momentum  $\vec{p} = m\vec{v}$  is conserved for a system when net external impulse is zero. Impulse is the time accumulation of force:

$$\vec{J} = \int \vec{F}_{\text{ext}} dt = \Delta\vec{p}.$$

In any isolated collision, total momentum is conserved. Kinetic energy is also conserved only in an elastic collision. In a perfectly inelastic collision the objects stick, and the missing kinetic energy becomes internal energy, deformation, heat, and sound.

The center of mass obeys  $M\vec{a}_{\text{cm}} = \sum \vec{F}_{\text{ext}}$ . Internal forces can rearrange a system but cannot change its total momentum.

### How I actually think about it

Momentum problems become much cleaner when I draw a before-and-after picture and keep directions signed. “Conserved” belongs to the total system, not necessarily to either object.

### The easy version

During a short collision, the objects hit each other with huge internal forces, but those forces cancel in the system total. The outside world usually has too little time to change the total momentum much.

### Worked example

A 2 kg cart at 3 m/s sticks to a 1 kg cart initially at rest. Momentum gives  $2(3) = (3)v_f$ , so  $v_f = 2$  m/s. Initial kinetic energy is 9 J and final is 6 J; the 3 J difference became internal energy.

### Solved chapter practice

**Practice.** A 0.15 kg ball traveling east at 20 m/s rebounds west at 12 m/s in 0.040 s. Find its average force.

**Solution.** Taking east positive,  $\Delta p = 0.15(-12 - 20) = -4.8$  kg m/s. Therefore  $F_{\text{avg}} = \Delta p / \Delta t = -4.8 / 0.040 = -120$  N, or 120 N west.

**Mastery practice A.** Reconstruct momentum, impulse, and collisions from a blank page. Include the central definition, the governing rule, one required assumption, and one boundary case.

**Solution.** Start from the blue idea box, but rewrite it in my own words. Identify the objects and state, name the rule before using it, copy the relevant assumption from the details audit, and choose a boundary where that assumption becomes equality or fails. A complete solution explains why each part belongs; a list of vocabulary is not enough.

**Mastery practice B.** A classmate gets a polished-looking answer to a momentum, impulse, and collisions problem but never states a model or checks the result. Write the shortest useful review of that solution.

**Solution.** I would ask four concrete questions: What exactly are the inputs and desired output? Which rule licenses the main step? Which assumption could invalidate it? Which independent check supports the conclusion? If the answer cannot survive those four questions, I treat the numerical or verbal result as unverified.

## CHAPTER 6 Rotation, torque, and rotational energy

### Rebuild the chapter from first principles

The claim I need to own is this: The model in Rotation, torque, and rotational energy controls the work. I do not count that as learned just because the sentence looks familiar. I should be able to name the objects, state what changes and what stays fixed, recover the rule from the definitions, and explain why the result is allowed.

### The move

#### My working sequence

1. **Translate.** Rewrite the prompt in the language of rotation, torque, and rotational energy. List the known quantities, the unknown, the units or types, and any hidden constraint.
2. **Choose.** State the theorem, model, algorithm, accounting rule, or physical law before substituting values. This is where I make the assumption visible.
3. **Execute.** Work one justified step at a time and keep intermediate state readable enough that I can audit it later.
4. **Verify.** Check a boundary case, sign, unit, invariant, order of magnitude, or alternative derivation. Then translate the result back into an ordinary sentence.

### Details I would refuse to skip

- **Definitions:** I should be able to define every technical noun in the chapter without using that same noun in the definition.
- **Assumptions:** I write the condition that makes the method legal beside the method itself. A correct procedure under the wrong assumptions is still a wrong answer.
- **Representation:** I move freely among words, equations or code, a diagram, and a small numerical example. If one representation disagrees with another, that disagreement is useful evidence.
- **Failure modes:** I keep the nearest counterexample in mind: the boundary where the rule changes, the invariant breaks, or the model stops matching reality.
- **Communication:** My final answer names what the result means and what it does not establish. I do not let notation do the explanatory work for me.

### Sanity check

**Closed-note check.** Can I teach rotation, torque, and rotational energy on a blank page, derive or reconstruct its main rule, work a fresh example, and diagnose a deliberately broken solution? If I can only recognize the finished work, I am not done.

### How this chapter connects

I read this chapter as the bridge from momentum, impulse, and collisions to angular momentum and rotational impulse. The earlier material supplies the language and constraints; this chapter adds a new reasoning move; the later material asks me to use that move without being told its name. That connection matters because exams and real projects mix chapters on purpose.

For fixed-axis rotation,  $\theta$ ,  $\omega$ , and  $\alpha$  mirror  $x$ ,  $v$ , and  $a$ . A point a distance  $r$  from the axis has  $v = r\omega$  and tangential acceleration  $a_t = r\alpha$ . Torque is

$$\vec{\tau} = \vec{r} \times \vec{F}, \quad \sum \tau = I\alpha, \quad K_{\text{rot}} = \frac{1}{2}I\omega^2.$$

Moment of inertia  $I = \int r^2 dm$  describes how mass is distributed relative to the chosen axis. The parallel-axis theorem is  $I = I_{\text{cm}} + Md^2$ .



### How I actually think about it

Mass is resistance to linear acceleration; moment of inertia is resistance to angular acceleration. The same object can have different  $I$  values because the axis is part of the question.

### The easy version

A push turns an object best when it is far from the hinge and perpendicular to the handle. That is why a door handle lives at the outer edge.

### Worked example

A tangential 10 N force acts at the rim of a solid 2 kg disk of radius 0.50 m. Torque is 5.0 N m. Since  $I = \frac{1}{2}MR^2 = 0.25 \text{ kg m}^2$ ,  $\alpha = \tau/I = 20 \text{ rad/s}^2$ .

### Solved chapter practice

**Practice.** A uniform rod of length  $L$  and mass  $M$  rotates about one end with angular speed  $\omega$ . Find its rotational kinetic energy.

**Solution.** About an end,  $I = \frac{1}{3}ML^2$ . Therefore  $K = \frac{1}{2}I\omega^2 = \frac{1}{6}ML^2\omega^2$ . Using  $\frac{1}{12}ML^2$  would be the center-axis value and would answer a different problem.

**Mastery practice A.** Reconstruct rotation, torque, and rotational energy from a blank page. Include the central definition, the governing rule, one required assumption, and one boundary case.

**Solution.** Start from the blue idea box, but rewrite it in my own words. Identify the objects and state, name the rule before using it, copy the relevant assumption from the details audit, and choose a boundary where that assumption becomes equality or fails. A complete solution explains why each part belongs; a list of vocabulary is not enough.

**Mastery practice B.** A classmate gets a polished-looking answer to a rotation, torque, and rotational energy problem but never states a model or checks the result. Write the shortest useful review of that solution.

**Solution.** I would ask four concrete questions: What exactly are the inputs and desired output? Which rule licenses the main step? Which assumption could invalidate it? Which independent check supports the conclusion? If the answer cannot survive those four questions, I treat the numerical or verbal result as unverified.

## CHAPTER 7 Angular momentum and rotational impulse

### Rebuild the chapter from first principles

The claim I need to own is this: The model in Angular momentum and rotational impulse controls the work. I do not count that as learned just because the sentence looks familiar. I should be able to name the objects, state what changes and what stays fixed, recover the rule from the definitions, and explain why the result is allowed.

### The move

#### My working sequence

1. **Translate.** Rewrite the prompt in the language of angular momentum and rotational impulse. List the known quantities, the unknown, the units or types, and any hidden constraint.
2. **Choose.** State the theorem, model, algorithm, accounting rule, or physical law before substituting values. This is where I make the assumption visible.
3. **Execute.** Work one justified step at a time and keep intermediate state readable enough that I can audit it later.
4. **Verify.** Check a boundary case, sign, unit, invariant, order of magnitude, or alternative derivation. Then translate the result back into an ordinary sentence.

### Details I would refuse to skip

- **Definitions:** I should be able to define every technical noun in the chapter without using that same noun in the definition.
- **Assumptions:** I write the condition that makes the method legal beside the method itself. A correct procedure under the wrong assumptions is still a wrong answer.
- **Representation:** I move freely among words, equations or code, a diagram, and a small numerical example. If one representation disagrees with another, that disagreement is useful evidence.
- **Failure modes:** I keep the nearest counterexample in mind: the boundary where the rule changes, the invariant breaks, or the model stops matching reality.
- **Communication:** My final answer names what the result means and what it does not establish. I do not let notation do the explanatory work for me.

### Sanity check

**Closed-note check.** Can I teach angular momentum and rotational impulse on a blank page, derive or reconstruct its main rule, work a fresh example, and diagnose a deliberately broken solution? If I can only recognize the finished work, I am not done.

### How this chapter connects

I read this chapter as the bridge from rotation, torque, and rotational energy to universal gravitation and orbital motion. The earlier material supplies the language and constraints; this chapter adds a new reasoning move; the later material asks me to use that move without being told its name. That connection matters because exams and real projects mix chapters on purpose.

Angular momentum depends on the origin:

$$\vec{L} = \vec{r} \times \vec{p}, \quad \vec{L} = I\vec{\omega} \text{ for fixed-axis rigid rotation}, \quad \frac{d\vec{L}}{dt} = \vec{\tau}_{\text{ext}}.$$

If external torque about the selected origin is zero, total angular momentum about that origin is constant. An external force may exist while its torque about a clever origin is zero.

### How I actually think about it

I write the origin next to every angular-momentum equation. Conservation is not magic spinning faster; it says that when  $I$  decreases and external torque is negligible,  $\omega$  must increase so  $I\omega$  stays fixed.

### The easy version

Angular momentum is rotational motion with leverage included. Pulling mass closer to the axis reduces the leverage, so the rotation rate rises to keep the total unchanged.

### Worked example

A skater changes moment of inertia from 4.0 to 1.6 kg m<sup>2</sup> while spinning at 2.0 rad/s. With negligible external torque,  $I_i\omega_i = I_f\omega_f$ , so  $\omega_f = 5.0$  rad/s.

### Solved chapter practice

**Practice.** A 0.020 kg putty blob moving at 10 m/s tangentially strikes and sticks to the rim of a stationary disk with  $I = 0.080$  kg m<sup>2</sup> and  $R = 0.50$  m. Find the final angular speed.

**Solution.** About the axle, initial  $L = mvR = 0.020(10)(0.50) = 0.10$  kg m<sup>2</sup>/s. Final inertia is  $I_f = 0.080 + mR^2 = 0.085$  kg m<sup>2</sup>. Thus  $\omega_f = L/I_f = 1.18$  rad/s. Mechanical energy is not conserved because the putty sticks.

**Mastery practice A.** Reconstruct angular momentum and rotational impulse from a blank page. Include the central definition, the governing rule, one required assumption, and one boundary case.

**Solution.** Start from the blue idea box, but rewrite it in my own words. Identify the objects and state, name the rule before using it, copy the relevant assumption from the details audit, and choose a boundary where that assumption becomes equality or fails. A complete solution explains why each part belongs; a list of vocabulary is not enough.

**Mastery practice B.** A classmate gets a polished-looking answer to a angular momentum and rotational impulse problem but never states a model or checks the result. Write the shortest useful review of that solution.

**Solution.** I would ask four concrete questions: What exactly are the inputs and desired output? Which rule licenses the main step? Which assumption could invalidate it? Which independent check supports the conclusion? If the answer cannot survive those four questions, I treat the numerical or verbal result as unverified.

## CHAPTER 8 Universal gravitation and orbital motion

### Rebuild the chapter from first principles

The claim I need to own is this: The model in Universal gravitation and orbital motion controls the work. I do not count that as learned just because the sentence looks familiar. I should be able to name the objects, state what changes and what stays fixed, recover the rule from the definitions, and explain

why the result is allowed.

### The move

#### My working sequence

1. **Translate.** Rewrite the prompt in the language of universal gravitation and orbital motion. List the known quantities, the unknown, the units or types, and any hidden constraint.
2. **Choose.** State the theorem, model, algorithm, accounting rule, or physical law before substituting values. This is where I make the assumption visible.
3. **Execute.** Work one justified step at a time and keep intermediate state readable enough that I can audit it later.
4. **Verify.** Check a boundary case, sign, unit, invariant, order of magnitude, or alternative derivation. Then translate the result back into an ordinary sentence.

### Details I would refuse to skip

- **Definitions:** I should be able to define every technical noun in the chapter without using that same noun in the definition.
- **Assumptions:** I write the condition that makes the method legal beside the method itself. A correct procedure under the wrong assumptions is still a wrong answer.
- **Representation:** I move freely among words, equations or code, a diagram, and a small numerical example. If one representation disagrees with another, that disagreement is useful evidence.
- **Failure modes:** I keep the nearest counterexample in mind: the boundary where the rule changes, the invariant breaks, or the model stops matching reality.
- **Communication:** My final answer names what the result means and what it does not establish. I do not let notation do the explanatory work for me.

### Sanity check

**Closed-note check.** Can I teach universal gravitation and orbital motion on a blank page, derive or reconstruct its main rule, work a fresh example, and diagnose a deliberately broken solution? If I can only recognize the finished work, I am not done.

### How this chapter connects

I read this chapter as the bridge from angular momentum and rotational impulse to static equilibrium and rolling motion. The earlier material supplies the language and constraints; this chapter adds a new reasoning move; the later material asks me to use that move without being told its name. That connection matters because exams and real projects mix chapters on purpose.

Two point masses attract with magnitude  $F = Gm_1m_2/r^2$ . The corresponding potential energy is

$$U(r) = -\frac{GMm}{r},$$

where zero is chosen at infinite separation. For a circular orbit, gravity supplies centripetal acceleration:

$$\frac{GMm}{r^2} = \frac{mv^2}{r}, \quad v = \sqrt{\frac{GM}{r}}, \quad T = 2\pi\sqrt{\frac{r^3}{GM}}.$$

The negative total energy of a circular orbit,  $E = -GMm/(2r)$ , signals a bound system.

### How I actually think about it

My shorthand for this chapter is: my shorthand for this chapter is: an orbit is continuous free fall with enough sideways speed to keep missing the planet. Higher circular orbits move more slowly, even though they take longer to go around.

### The easy version

Gravity keeps bending the path inward while the object keeps moving sideways. The result is a circle or ellipse instead of a crash or a straight escape.

### Worked example

For a circular orbit of radius  $r$ , substitute  $v^2 = GM/r$  into  $K = \frac{1}{2}mv^2$  to get  $K = GMm/(2r)$ . Adding  $U = -GMm/r$  gives  $E = -GMm/(2r)$ .

### Solved chapter practice

**Practice.** A satellite's circular orbital radius is increased by a factor of 4. By what factors do its speed and period change?

**Solution.** Since  $v \propto r^{-1/2}$ , the speed becomes 1/2 as large. Since  $T \propto r^{3/2}$ , the period becomes  $4^{3/2} = 8$  times as large.

**Mastery practice A.** Reconstruct universal gravitation and orbital motion from a blank page. Include the central definition, the governing rule, one required assumption, and one boundary case.

**Solution.** Start from the blue idea box, but rewrite it in my own words. Identify the objects and state, name the rule before using it, copy the relevant assumption from the details audit, and choose a boundary where that assumption becomes equality or fails. A complete solution explains why each part belongs; a list of vocabulary is not enough.

**Mastery practice B.** A classmate gets a polished-looking answer to a universal gravitation and orbital motion problem but never states a model or checks the result. Write the shortest useful review of that solution.

**Solution.** I would ask four concrete questions: What exactly are the inputs and desired output? Which rule licenses the main step? Which assumption could invalidate it? Which independent check supports the conclusion? If the answer cannot survive those four questions, I treat the numerical or verbal result as unverified.

## CHAPTER 9 Static equilibrium and rolling motion

### Rebuild the chapter from first principles

The claim I need to own is this: The model in Static equilibrium and rolling motion controls the work. I do not count that as learned just because the sentence looks familiar. I should be able to name the objects, state what changes and what stays fixed, recover the rule from the definitions, and explain why the result is allowed.

#### The move

##### My working sequence

1. **Translate.** Rewrite the prompt in the language of static equilibrium and rolling motion. List the known quantities, the unknown, the units or types, and any hidden constraint.
2. **Choose.** State the theorem, model, algorithm, accounting rule, or physical law before substituting values. This is where I make the assumption visible.
3. **Execute.** Work one justified step at a time and keep intermediate state readable enough that I can audit it later.
4. **Verify.** Check a boundary case, sign, unit, invariant, order of magnitude, or alternative derivation. Then translate the result back into an ordinary sentence.

### Details I would refuse to skip

- **Definitions:** I should be able to define every technical noun in the chapter without using that same noun in the definition.
- **Assumptions:** I write the condition that makes the method legal beside the method itself. A correct procedure under the wrong assumptions is still a wrong answer.
- **Representation:** I move freely among words, equations or code, a diagram, and a small numerical example. If one representation disagrees with another, that disagreement is useful evidence.
- **Failure modes:** I keep the nearest counterexample in mind: the boundary where the rule changes, the invariant breaks, or the model stops matching reality.
- **Communication:** My final answer names what the result means and what it does not establish. I do not let notation do the explanatory work for me.

#### Sanity check

**Closed-note check.** Can I teach static equilibrium and rolling motion on a blank page, derive or reconstruct its main rule, work a fresh example, and diagnose a deliberately broken solution? If I can only recognize the finished work, I am not done.

## How this chapter connects

I read this chapter as the bridge from universal gravitation and orbital motion to the cumulative course model. The earlier material supplies the language and constraints; this chapter adds a new reasoning move; the later material asks me to use that move without being told its name. That connection matters because exams and real projects mix chapters on purpose.

A rigid body in static equilibrium needs both translational and rotational balance:

$$\sum \vec{F} = 0, \quad \sum \vec{\tau} = 0.$$

The torque equation can be taken about any origin; choosing an unknown support force as the origin often removes it. For rolling without slipping, the contact constraint is  $v_{\text{cm}} = R\omega$  and  $a_{\text{cm}} = R\alpha$ . Total kinetic energy is

$$K = \frac{1}{2}Mv_{\text{cm}}^2 + \frac{1}{2}I_{\text{cm}}\omega^2.$$

Static friction may be present without dissipating energy because the instantaneous contact point is at rest relative to the surface.

### How I actually think about it

My shorthand for this chapter is: my shorthand for this chapter is: equilibrium requires two independent checks. Zero net force prevents the center of mass from accelerating; zero net torque prevents angular acceleration. Passing only one check is not equilibrium.

### The easy version

A balanced shelf must neither slide nor tip. A rolling wheel spends its energy in two places: moving its center and spinning around that center.

### Worked example

A solid cylinder rolls from rest through height  $h$ . With  $I = \frac{1}{2}MR^2$  and  $\omega = v/R$ , energy gives  $Mgh = \frac{1}{2}Mv^2 + \frac{1}{4}Mv^2 = \frac{3}{4}Mv^2$ , so  $v = \sqrt{4gh/3}$ .

### Solved chapter practice

**Practice.** A uniform horizontal beam of length 4.0 m and weight 200 N is hinged at the wall and supported by a vertical cable at its far end. A 300 N load hangs 3.0 m from the hinge. Find the cable tension and the vertical hinge force.

**Solution.** Taking torque about the hinge,  $T(4) - 200(2) - 300(3) = 0$ , so  $T = 325$  N. Vertical force balance gives  $H_y + 325 - 200 - 300 = 0$ , hence  $H_y = 175$  N upward.

**Mastery practice A.** Reconstruct static equilibrium and rolling motion from a blank page. Include the central definition, the governing rule, one required assumption, and one boundary case.

**Solution.** Start from the blue idea box, but rewrite it in my own words. Identify the objects and state, name the rule before using it, copy the relevant assumption from the details audit, and choose a boundary where that assumption becomes equality or fails. A complete solution explains why each part belongs; a list of vocabulary is not enough.

**Mastery practice B.** A classmate gets a polished-looking answer to a static equilibrium and

rolling motion problem but never states a model or checks the result. Write the shortest useful review of that solution.

**Solution.** I would ask four concrete questions: What exactly are the inputs and desired output? Which rule licenses the main step? Which assumption could invalidate it? Which independent check supports the conclusion? If the answer cannot survive those four questions, I treat the numerical or verbal result as unverified.

## Final study check

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Before a mechanics exam, I ask four questions: What is my system? What interactions cross its boundary? Which quantities are conserved over this interval? Do the sign, units, limiting behavior, and scale make physical sense? Those questions are more dependable than memorizing a separate recipe for every diagram.