AP PHYSICS 1

UNIT 5

Torque and Rotational Dynamics

10–15%
AP EXAM WEIGHTING

~15–20
CLASS PERIODS

Remember to go to **AP Classroom** to assign students the online **Progress Check** for this unit.

Whether assigned as homework or completed in class, the **Progress Check** provides each student with immediate feedback related to this unit's topics and science practices.

Progress Check 5

Multiple-choice: ~18 questions
Free-response: 4 questions

- Mathematical Routines
- Translation Between Representations
- Experimental Design and Analysis
- Qualitative/Quantitative Translation

UNIT 5

10–15% AP EXAM WEIGHTING | **~15–20** CLASS PERIODS

Torque and Rotational Dynamics

ESSENTIAL QUESTIONS

- Why does it matter where a door handle is placed?
- Why are long wrenches more effective?
- What do mobiles have in common with the Grand Canyon Skywalk?
- Why does a tightrope walker use a long pole?

Developing Understanding

Unit 5 reinforces the Unit 2 ideas of force and linear motion by introducing students to their rotational analogs—torque and rotational motion. Although these topics present more complex scenarios, the tools of analysis remain the same. The content and models explored in the first four units of the course set the foundation for Units 5 and 6. During their study of torque and rotational motion, students will be introduced to different ways of modeling forces. Throughout Units 5 and 6, students will compare and connect their understanding of linear and rotational motion, dynamics, energy, and momentum to develop holistic models to evaluate physical phenomena.

Building the Science Practices

2.A 2.C 2.D 3.B

In Unit 5, students will be introduced to new, but somewhat familiar, equations—and be expected to derive new expressions from those equations (**2.A**), just as they have in previous units. Those new expressions can help students compare physical quantities between scenarios (**2.C**), to make claims (**3.B**), and justify claims or predict values of variables using functional dependence (**2.D**). For example, students might be asked to determine the torque exerted on a system if the force exerted is doubled. Because using functional dependence to predict changes in quantities can be challenging, students may benefit from many opportunities to practice these important mathematical skills that will be tested in both the multiple-choice and free-response sections of the AP Physics 1 Exam.

Preparing for the AP Exam

The analysis of functional relationships is assessed on the fourth free-response question—the Qualitative/Quantitative Translation (QQT) question—as well as the multiple-choice section of the AP Physics 1 Exam. Therefore, students must be able to identify, work with, and predict new values from functional dependencies between variables. Students may also be asked to explain phenomena based on evidence obtained through application of functional relationships. Students who may struggle mathematically will benefit from scaffolded instruction to help them develop the mathematical understanding necessary to go from just calculating the value of a variable to determining how that value changes when the value of other variables in a related equation change.

UNIT AT A GLANCE

Topic	Suggested Skills
5.1 Rotational Kinematics	1.B Create quantitative graphs with appropriate scales and units, including plotting data. 2.A Derive a symbolic expression from known quantities by selecting and following a logical mathematical pathway. 2.D Predict new values or factors of change of physical quantities using functional dependence between variables. 3.A Create experimental procedures that are appropriate for a given scientific question. 3.C Justify or support a claim using evidence from experimental data, physical representations, or physical principles or laws.
5.2 Connecting Linear and Rotational Motion	1.C Create qualitative sketches of graphs that represent features of a model or the behavior of a physical system. 2.A Derive a symbolic expression from known quantities by selecting and following a logical mathematical pathway. 2.C Compare physical quantities between two or more scenarios or at different times and locations in a single scenario. 3.B Apply an appropriate law, definition, theoretical relationship, or model to make a claim.
5.3 Torque	1.A Create diagrams, tables, charts, or schematics to represent physical situations. 2.A Derive a symbolic expression from known quantities by selecting and following a logical mathematical pathway. 2.D Predict new values or factors of change of physical quantities using functional dependence between variables. 3.B Apply an appropriate law, definition, theoretical relationship, or model to make a claim.
5.4 Rotational Inertia	1.B Create quantitative graphs with appropriate scales and units, including plotting data. 2.B Calculate or estimate an unknown quantity with units from known quantities, by selecting and following a logical computational pathway. 2.C Compare physical quantities between two or more scenarios or at different times and locations in a single scenario. 3.A Create experimental procedures that are appropriate for a given scientific question. 3.B Apply an appropriate law, definition, theoretical relationship, or model to make a claim.

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UNIT AT A GLANCE *(cont'd)*

Topic	Suggested Skills
5.5 Rotational Equilibrium and Newton's First Law in Rotational Form	**1.C** Create qualitative sketches of graphs that represent features of a model or the behavior of a physical system. **2.A** Derive a symbolic expression from known quantities by selecting and following a logical mathematical pathway. **2.B** Calculate or estimate an unknown quantity with units from known quantities, by selecting and following a logical computational pathway. **3.B** Apply an appropriate law, definition, theoretical relationship, or model to make a claim.
5.6 Newton's Second Law in Rotational Form	**1.A** Create diagrams, tables, charts, or schematics to represent physical situations. **2.A** Derive a symbolic expression from known quantities by selecting and following a logical mathematical pathway. **2.C** Compare physical quantities between two or more scenarios or at different times and locations in a single scenario. **3.C** Justify or support a claim using evidence from experimental data, physical representations, or physical principles or laws.

Go to **AP Classroom** to assign the **Progress Check** for Unit 5.
Review the results in class to identify and address any student misunderstandings.

SAMPLE INSTRUCTIONAL ACTIVITIES

The sample activities on this page are optional and are offered to provide possible ways to incorporate various instructional approaches in the classroom. Teachers do not need to use these activities or instructional approaches and are free to alter or edit them. The examples below were developed in partnership with teachers from the AP community to share ways that they approach teaching some of the topics in this unit. Please refer to the Instructional Approaches section beginning on p. 153 for more examples of activities and strategies.

Activity	Topic	Sample Activity
1	5.3	**Predict and Explain** Spin a bike wheel (preferably with the tire removed so that it will roll on its metal rims) and release it from rest on the floor or a long table. Have students predict what will happen to the wheel's linear velocity (it will increase) and its angular velocity (it will decrease) as the wheel "peels out." Then, explain why this happens using a force diagram.
2	5.3	**Create a Plan** Have students design a walkway (of given mass) that is to be suspended from a ceiling. Have them determine the amount of force the two supports (one on each end) must be able to provide as a person (of given mass) walks across the walkway.
3	5.3	**Desktop Experiment Task** Take a hard-boiled egg and a raw egg without identifying marks or labels. Give students the task to determine which one is which. To give them a starting point, have students place the eggs on a level surface and give each egg a spin. Once each egg is spinning lightly, have students touch each egg on the top to stop it. Students should conclude that the raw egg is noticeably more difficult to start or stop.
4	5.4	**Desktop Experiment Task** Have students allow a yo-yo to fall and unroll. Then, have them use a meterstick and stopwatch to determine its downward acceleration. Next, have them measure its mass and the radius of its axle and use that information to determine the yo-yo's rotational inertia using rotational dynamics.
5	5.6	**Create a Plan** Have students complete the necessary research to determine the rotational inertia of a human body in different configurations (e.g., arms outstretched, arms pulled in). Then, obtain footage of an ice skater spinning and pulling in their arms. Have students analyze the footage to see if angular momentum is conserved.
6	5.6	**Desktop Experiment Task** Set a meter stick on a pivot that is not set at the center of mass of the meterstick. Hang two objects off the meterstick so that the two object–meterstick system is in equilibrium. Have students observe and collect data to allow them to determine the mass of the meterstick.

TOPIC 5.1

Rotational Kinematics

Required Course Content

LEARNING OBJECTIVE

5.1.A

Describe the rotation of a system with respect to time using angular displacement, angular velocity, and angular acceleration.

ESSENTIAL KNOWLEDGE

5.1.A.1

Angular displacement is the measurement of the angle, in radians, through which a point on a rigid system rotates about a specified axis.

Relevant equation:

$$\Delta\theta = \theta - \theta_0$$

5.1.A.1.i

A rigid system is one that holds its shape but in which different points on the system move in different directions during rotation. A rigid system cannot be modeled as an object.

5.1.A.1.ii

One direction of angular displacement about an axis of rotation—clockwise or counterclockwise—is typically indicated as mathematically positive, with the other direction becoming mathematically negative.

5.1.A.1.iii

If the rotation of a system about an axis may be well described using the motion of the system's center of mass, the system may be treated as a single object. For example, the rotation of Earth about its axis may be considered negligible when considering the revolution of Earth about the center of mass of the Earth–Sun system.

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SUGGESTED SKILLS

1.B Create quantitative graphs with appropriate scales and units, including plotting data.

2.A Derive a symbolic expression from known quantities by selecting and following a logical mathematical pathway.

2.D Predict new values or factors of change of physical quantities using functional dependence between variables.

3.A Create experimental procedures that are appropriate for a given scientific question.

3.C Justify or support a claim using evidence from experimental data, physical representations, or physical principles or laws.

LEARNING OBJECTIVE

5.1.A

Describe the rotation of a system with respect to time using angular displacement, angular velocity, and angular acceleration.

ESSENTIAL KNOWLEDGE

5.1.A.2

Average angular velocity is the average rate at which angular position changes with respect to time.

Relevant equation:

$$\omega_{avg} = \frac{\Delta\theta}{\Delta t}$$

5.1.A.3

Average angular acceleration is the average rate at which the angular velocity changes with respect to time.

Relevant equation:

$$\alpha_{avg} = \frac{\Delta\omega}{\Delta t}$$

5.1.A.4

Angular displacement, angular velocity, and angular acceleration around one axis are analogous to linear displacement, velocity, and acceleration in one dimension and demonstrate the same mathematical relationships.

5.1.A.4.i

For constant angular acceleration, the mathematical relationships between angular displacement, angular velocity, and angular acceleration can be described with the following equations:

$$\omega = \omega_0 + \alpha t$$

$$\theta = \theta_0 + \omega_0 t + \frac{1}{2}\alpha t^2$$

$$\omega^2 = \omega_0^2 + 2\alpha(\theta - \theta_0)$$

5.1.A.4.ii

Graphs of angular displacement, angular velocity, and angular acceleration as functions of time can be used to find the relationships between those quantities.

BOUNDARY STATEMENT

Descriptions of the directions of rotation for a point or object are limited to clockwise and counterclockwise with respect to a given axis of rotation.

TOPIC 5.2

Connecting Linear and Rotational Motion

Required Course Content

LEARNING OBJECTIVE

5.2.A

Describe the linear motion of a point on a rotating rigid system that corresponds to the rotational motion of that point, and vice versa.

ESSENTIAL KNOWLEDGE

5.2.A.1

For a point at a distance r from a fixed axis of rotation, the linear distance s traveled by the point as the system rotates through an angle $\Delta\theta$ is given by the equation $\Delta s = r\Delta\theta$.

5.2.A.2

Derived relationships of linear velocity and of the tangential component of acceleration to their respective angular quantities are given by the following equations:

$s = r\theta$

$v = r\omega$

$a_T = r\alpha$

5.2.A.3

For a rigid system, all points within that system have the same angular velocity and angular acceleration.

BOUNDARY STATEMENT

Descriptions of the directions of rotation for a point or object are limited to clockwise and counterclockwise with respect to a given axis of rotation.

SUGGESTED SKILLS

1.C Create qualitative sketches of graphs that represent features of a model or the behavior of a physical system.

2.A Derive a symbolic expression from known quantities by selecting and following a logical mathematical pathway.

2.C Compare physical quantities between two or more scenarios or at different times and locations in a single scenario.

3.B Apply an appropriate law, definition, theoretical relationship, or model to make a claim.

SUGGESTED SKILLS

1.A
Create diagrams, tables, charts, or schematics to represent physical situations.

2.A
Derive a symbolic expression from known quantities by selecting and following a logical mathematical pathway.

2.D
Predict new values or factors of change of physical quantities using functional dependence between variables.

3.B
Apply an appropriate law, definition, theoretical relationship, or model to make a claim.

TOPIC 5.3
Torque

Required Course Content

LEARNING OBJECTIVE	ESSENTIAL KNOWLEDGE
5.3.A Identify the torques exerted on a rigid system.	**5.3.A.1** Torque results only from the force component perpendicular to the position vector from the axis of rotation to the point of application of the force. **5.3.A.2** The lever arm is the perpendicular distance from the axis of rotation to the line of action of the exerted force.
5.3.B Describe the torques exerted on a rigid system.	**5.3.B.1** Torques can be described using force diagrams. **5.3.B.1.i** Force diagrams are similar to free-body diagrams and are used to analyze the torques exerted on a rigid system. **5.3.B.1.ii** Similar to free-body diagrams, force diagrams represent the relative magnitude and direction of the forces exerted on a rigid system. Force diagrams also depict the location at which those forces are exerted relative to the axis of rotation. **5.3.B.2** The magnitude of the torque exerted on a rigid system by a force is described by the following equation, where θ is the angle between the force vector and the position vector from the axis of rotation to the point of application of the force. $\tau = rF_{\perp} = rF\sin\theta$

BOUNDARY STATEMENT

While AP Physics 1 expects students to mathematically manipulate the magnitude of torque using vector conventions, the direction of torque is beyond the scope of the course.

TOPIC 5.4

Rotational Inertia

Required Course Content

LEARNING OBJECTIVE

5.4.A

Describe the rotational inertia of a rigid system relative to a given axis of rotation.

ESSENTIAL KNOWLEDGE

5.4.A.1

Rotational inertia measures a rigid system's resistance to changes in rotation and is related to the mass of the system and the distribution of that mass relative to the axis of rotation.

5.4.A.2

The rotational inertia of an object rotating a perpendicular distance r from an axis is described by the equation

$$I = mr^2.$$

5.4.A.3

The total rotational inertia of a collection of objects about an axis is the sum of the rotational inertias of each object about that axis:

$$I_{tot} = \sum I_i = \sum m_i r_i^2$$

LEARNING OBJECTIVE

5.4.B

Describe the rotational inertia of a rigid system rotating about an axis that does not pass through the system's center of mass.

ESSENTIAL KNOWLEDGE

5.4.B.1

A rigid system's rotational inertia in a given plane is at a minimum when the rotational axis passes through the system's center of mass.

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SUGGESTED SKILLS

1.B Create quantitative graphs with appropriate scales and units, including plotting data.

2.B Calculate or estimate an unknown quantity with units from known quantities, by selecting and following a logical computational pathway.

2.C Compare physical quantities between two or more scenarios or at different times and locations in a single scenario.

3.A Create experimental procedures that are appropriate for a given scientific question.

3.B Apply an appropriate law, definition, theoretical relationship, or model to make a claim.

LEARNING OBJECTIVE

5.4.B

Describe the rotational inertia of a rigid system rotating about an axis that does not pass through the system's center of mass.

ESSENTIAL KNOWLEDGE

5.4.B.2

The parallel axis theorem uses the following equation to relate the rotational inertia of a rigid system about any axis that is parallel to an axis through its center of mass:

$$I' = I_{cm} + Md^2$$

BOUNDARY STATEMENT

AP Physics 1 only expects students to calculate the rotational inertia for systems of five or fewer objects arranged in a two-dimensional configuration.

Students do not need to know the rotational inertia of extended rigid systems, as these will be provided within the exam. Students should have a qualitative understanding of the factors that affect rotational inertia; for example, how rotational inertia is greater when mass is farther from the axis of rotation, which is why a hoop has more rotational inertia than a solid disk of the same mass and radius.

TOPIC 5.5

Rotational Equilibrium and Newton's First Law in Rotational Form

Required Course Content

LEARNING OBJECTIVE

5.5.A

Describe the conditions under which a system's angular velocity remains constant.

ESSENTIAL KNOWLEDGE

5.5.A.1

A system may exhibit rotational equilibrium (constant angular velocity) without being in translational equilibrium, and vice versa.

5.5.A.1.i

Free-body and force diagrams describe the nature of the forces and torques exerted on an object or rigid system.

5.5.A.1.ii

Rotational equilibrium is a configuration of torques such that the net torque exerted on the system is zero.

Relevant equation:

$$\sum \tau_i = 0$$

5.5.A.1.iii

The rotational analog of Newton's first law is that a system will have a constant angular velocity only if the net torque exerted on the system is zero.

5.5.A.2

A rotational corollary to Newton's second law states that if the torques exerted on a rigid system are not balanced, the system's angular velocity must be changing.

BOUNDARY STATEMENT

AP Physics 1 does not expect students to simultaneously analyze rotation in multiple planes.

SUGGESTED SKILLS

1.C Create qualitative sketches of graphs that represent features of a model or the behavior of a physical system.

2.A Derive a symbolic expression from known quantities by selecting and following a logical mathematical pathway.

2.B Calculate or estimate an unknown quantity with units from known quantities, by selecting and following a logical computational pathway.

3.B Apply an appropriate law, definition, theoretical relationship, or model to make a claim.

SUGGESTED SKILLS

1.A
Create diagrams, tables, charts, or schematics to represent physical situations.

2.A
Derive a symbolic expression from known quantities by selecting and following a logical mathematical pathway.

2.C
Compare physical quantities between two or more scenarios or at different times and locations in a single scenario.

3.C
Justify or support a claim using evidence from experimental data, physical representations, or physical principles or laws.

TOPIC 5.6

Newton's Second Law in Rotational Form

Required Course Content

LEARNING OBJECTIVE

5.6.A
Describe the conditions under which a system's angular velocity changes.

ESSENTIAL KNOWLEDGE

5.6.A.1
Angular velocity changes when the net torque exerted on the object or system is not equal to zero.

5.6.A.2
The rate at which the angular velocity of a rigid system changes is directly proportional to the net torque exerted on the rigid system and is in the same direction. The angular acceleration of the rigid system is inversely proportional to the rotational inertia of the rigid system.

Relevant equation:

$$\alpha_{\text{sys}} = \frac{\sum \tau}{I_{\text{sys}}} = \frac{\tau_{\text{net}}}{I_{\text{sys}}}$$

5.6.A.3
To fully describe a rotating rigid system, linear and rotational analyses may need to be performed independently.