Unit 3: Newtonian Mechanics – Newton's Laws

OBJECTIVES:

We will continue to reinforce the all topics explored previously.[1]

Big Idea 1: Objects and systems have properties such as mass and charge. Systems may have internal structure.

Enduring Understanding 1.A: The internal structure of a system determines many properties of the system.

> *Essential Knowledge 1.A.5: Systems have properties determined by the properties and interactions of their constituent atomic and molecular substructures. In AP Physics, when the properties of the constituent parts are not important in modeling the behavior of the macroscopic system, the system itself may be referred to as an object.*
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> > *Learning Objective 1.A.5.1: The student is able to model verbally or visually the properties of a system based on its substructure and to relate this to changes in the system properties over time as external variables are changed.*
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> > Learning Objective 1.A.5.2: The student is able to construct representations of how the properties of a system are determined by the interactions of its constituent substructures.
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> > Essential Knowledge 5.A.1: A system is an object or a collection of objects. The objects are treated as having no internal structure.

Essential Understanding 1.C: Objects and systems have properties of inertial mass and gravitational mass that are experimentally verified to be the same and that satisfy conservation principles.

> Essential Knowledge 1.C.1: Inertial mass is the property of an object or system that determines how its motion changes when it interacts with other objects or systems.
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> > Learning Objective 1.C.1.1: The student is able to **design an experiment** for collecting data to determine the relationship between the net force exerted on an object, its inertial mass, and its acceleration.
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> Essential Knowledge 1.C.2: Gravitational mass is the property of an object or a system that determines the strength of the gravitational interaction with other objects, systems, or gravitational fields.
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> a. The gravitational mass of an object determines the amount of force exerted on the object by a gravitational field.
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> b. Near the Earth's surface, all objects fall (in a vacuum) with the same acceleration, regardless of their inertial mass.
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> Essential Knowledge 1.C.3: Objects and systems have properties of inertial mass and gravitational mass that are experimentally verified to be the same and that satisfy conservation principles.
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> > Learning Objective 1.C.3.1: The student is able to **design a plan** for collecting data to measure gravitational mass and to measure inertial mass and to distinguish between the two experiments.

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[1] Specific objectives that are repeated here from previous topics are italicized.

Essential Knowledge 1.C.4: In certain processes, mass can be converted to energy and energy can be converted to mass according to $E = mc^2$, the equation derived from the theory of special relativity.[2]

Big Idea 2: Fields existing in space can be used to explain interactions.

Enduring Understanding 2.A: A field associates a value of some physical quantity with every point in space. Field models are useful for describing interactions that occur at a distance (long-range forces) as well as a variety of other physical phenomena.

Essential Knowledge 2.A.1: A vector field gives, as a function of position (and perhaps time), the value of a physical quantity that is described by a vector.

a. Vector fields are represented by field vectors indicating direction and magnitude.

b. When more than one source object with mass *or electric charge* is present, the field value can be determined by vector addition.

c. Conversely, a known vector field can be used to make inferences about the number, relative size, and location of sources.

Essential Knowledge 2.A.2: A scalar field gives, as a function of position (and perhaps time), the value of a physical quantity that is described by a scalar. *This should include electric potential.*

a. Scalar fields are represented by field values.

b. When more than one source object with mass *or charge* is present, the scalar field value can be determined by scalar addition.

c. Conversely, a known scalar field can be used to make inferences about the number, relative size, and location of sources.

Enduring Understanding 2.B: A gravitational field is caused by an object with mass.

Essential Knowledge 2.B.1: A gravitational field $\vec{g}$ at the location of an object with mass m causes a gravitational force of magnitude mg to be exerted on the object in the direction of the field.

a. On Earth, this gravitational force is called weight.

b. The gravitational field at a point in space is measured by dividing the gravitational force exerted by the field on a test object at that point by the mass of the test object and has the same direction as the force.

c. If the gravitational force is the only force exerted on the object, the observed free-fall acceleration of the object (in meters per second squared) is numerically equal to the magnitude of the gravitational field (in N/kg) at that location.

Learning Objective 2.B.1.1: The student is able to apply $\vec{F} = m\vec{g}$ to calculate the gravitational force on an object with mass to calculate the gravitational force on an object with mass m in a gravitational field of strength g in the context of the effects of a net force on objects and systems.

[2] We will revisit this.

Essential Knowledge 2.B.2: The gravitational field caused by a spherically symmetric object with mass is radial and, outside the object, varies as the inverse square of the radial distance from the center of that object.

a. The gravitational field caused by a spherically symmetric object is a vector whose magnitude outside the object is equal to $G\frac{M}{r^2}$.

b. Only spherically symmetric objects will be considered as sources of the gravitational field.

Learning Objective 2.B.2.1: The student is able to apply $g = G\frac{M}{r^2}$ to calculate the gravitational field due to an object with mass M, where the field is a vector directed toward the center of the object of mass M.

Learning Objective 2.B.2.2: The student is able to approximate a numerical value of the gravitational field (g) near the surface of an object from its radius and mass relative to those of the Earth or other reference objects.

Essential Understanding 2.E: Physicists often construct a map of isolines connecting points of equal value for some quantity related to a field and use these maps to help visualize the field.

Essential Knowledge 2.E.1: Isolines on a topographic (elevation) map describe the lines of approximately equal gravitational potential energy per unit mass (gravitational equipotential.) As the distance between two different isolines decreases, the steepness of the surface increases. [Contour lines on topographic maps are useful teaching tools for introducing the concept of equipotential lines. Students are encouraged to use the analogy in their answers when explaining gravitational *end electrical potential and potential difference*.]

Learning Objective 2.E.1.1: The student is able to construct or interpret visual representations of the isolines of equal gravitational potential energy per unit mass and refer to each line as a gravitational equipotential.

Big Idea 3: The interactions of an object with other objects can be described by forces.

Enduring Understanding 3.A.: All forces share certain common characteristics when considered by observers in inertial reference frames.

Essential Knowledge 3.A.2: Forces are described by vectors.

a. Forces are detected by their influence on the motion of an object.

b. Forces have magnitude and direction.

Learning Objective 3.A.2.1: The student is able to represent forces in diagrams or mathematically using appropriately labeled vectors with magnitude, direction, and units during the analysis of a situation.

Essential Knowledge 3.A.3: A force exerted on an object is always due to the interaction of that object with another object.

a. An object cannot exert a force on itself.

b. Even though an object is at rest, there may be forces exerted on that object by other objects.

c. The acceleration of an object, but not necessarily its velocity, is always in the direction of the net force exerted on the object by other objects.

> Learning Objective 3.A.3.1: The student is able to analyze a scenario and make claims (develop arguments, justify assertions) about the forces exerted on an object by other objects for different types of forces or components of forces.
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> Learning Objective 3.A.3.2: The student is able to challenge a claim that an object can exert a force on itself.
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> Learning Objective 3.A.3.3: The student is able to describe a force as an interaction between two objects and identify both objects for any force.
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> Learning Objective 3.A.3.4: The student is able to make claims about the force on an object due to the presence of other objects with the same property: mass, electric charge.

Essential Knowledge 3.A.4: If one object exerts a force on a second object, the second object always exerts a force of equal magnitude on the first object in the opposite direction.

> Learning Objective 3.A.4.1: The student is able to construct explanations of physical situations involving the interaction of bodies using Newton's third law and the representation of action-reaction pairs of forces.
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> Learning Objective 3.A.4.2: The student is able to use Newton's third law to make claims and predictions about the action-reaction pairs of force when two objects interact.
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> Learning Objective 3.A.4.3: The student is able to analyze situations involving interactions among several objects by using free-body diagrams that include the application of Newton's third law to identify forces.

Enduring Understanding 3.B: Classically, the acceleration of an object interacting with other objects can be predicted by using $\vec{a} = \frac{\vec{F}}{m}$.

Essential Knowledge 3.B.1: If an object of interest interacts with several other objects, the net force is the vector sum of the individual forces.

Learning Objective 3.B.1.1: The student is able to predict the motion of an object subject to forces exerted by several objects using an application of Newton's second law in a variety of physical situations with acceleration in one dimension.

Learning Objective 3.B.1.2: The student is able **to design a plan** to collect and analyze data for motion (static, constant, or accelerating) from force measurements and carry out an analysis to determine the relationship between the net force and the vector sum of the individual forces.

Learning Objective 3.B.1.3: The student is able to re-express a free-body diagram representation into a mathematical representation and solve the mathematical representation for the acceleration of the object.

Learning Objective 3.B.1.4: The student is able to predict the motion of an object subject to forces exerted by several objects using an application of Newton's second law in a variety of physical situations.

Essential Knowledge 3.B.2: Free-body diagrams are useful tools for visualizing forces being exerted on a single object and writing the equations that represent a physical situation.

a. An object can be drawn as if it was extracted from its environment and the interactions with the environment identified.

b. A force exerted on an object can be represented as an arrow whose length represents the magnitude of the force and whose direction shows the direction of the force.

c. A coordinate system with one axis parallel to the direction of the acceleration simplifies the translation from the free-body diagram to the algebraic representation.

Learning Objective 3.B.2.1: The student is able to create and use free-body diagrams to analyze the physical situations to solve problems with motion qualitatively and quantitatively.

Essential Knowledge 3.B.3: *This objective deals with restoring force and simple harmonic motion. We will mention restoring force here but won't cover the bulk of this objective until a later unit.*

Enduring Understanding 3.C: At the macroscopic level, forces can be categorized as either long-range (action-at-a-distance) forces or contact forces.

Essential Knowledge 3.C.1: Gravitational force describes the interaction of one object that has mass with another object that has mass.

a. The gravitational force is always attractive.

b. The magnitude of force between two spherically symmetric objects of mass m_1 and m_2 is… $G\frac{m_1 m_2}{r^2}$ where r is the center-to-center distance between the objects.

c. In a narrow range of heights above the Earth's surface, the local gravitational field, g, is approximately constant.

Essential Knowledge 3.C.4: Contact forces result from the interaction of one object touching another object, and they arise from inter-atomic electric forces. These forces include tension, friction, normal, spring, *and buoyant*.

Learning Objective 3.C.4.1: The student is able to make claims about various contact forces between objects based on the microscopic cause of those forces.

Learning Objective 3.C.4.2: The student is able to explain contact forces (tension, friction, normal, buoyant, spring) as arising from inter-atomic electric forces and that they therefore have certain directions.

Enduring Understanding 3.G: Certain types of forces are considered fundamental.

Essential Knowledge 3.G.1: Gravitational forces are exerted at all scales and dominate at the largest distance and mass scales.

Learning Objective 3.G.1.1: The student is able to articulate situations when the gravitational force is the dominant force and when the electromagnetic, weak, and strong forces can be ignored.

Learning Objective 3.G.1.2: The student is able to connect the strength of the gravitational force between two objects to the spatial scale of the situation and the masses of the objects involved and compare that strength to other types of forces.

Essential Knowledge 3.G.2: Electromagnetic forces are exerted at all scales and can dominate at the human scale. (more later)

Essential Knowledge 3.G.3: The strong force is exerted at nuclear scales and dominates the interactions of nucleons.

Learning Objective 3.G.3.1: The student is able to identify the strong force as the force that is responsible for holding the nucleus together.

Big Idea 4: Interactions between systems can result in changes in those systems.

Enduring Understanding 4.A: The acceleration of the center of mass of a system is related to the net force exerted on the system, where $\vec{a} = \frac{\vec{F}}{m}$.

Essential Knowledge 4.A.1: The linear motion of a system can be described by the displacement, velocity, and acceleration of its center of mass.

Learning Objective 4.A.1.1: The student is able to use representations of the center of mass of an isolated two-object system to analyze the motion of the system qualitatively and semi-quantitatively.

Essential Knowledge 4.A.2: The acceleration is equal to the rate of change of velocity with time, and velocity is equal to the rate of change of position with time.

a. The acceleration of the center of mass of a system is directly proportional to the net force exerted on it by all objects interacting with the system and inversely proportional to the mass of the system.

b. Force and acceleration are both vectors, with acceleration in the same direction as the net force.

> Learning Objective 4.A.2.1: The student is able to make predictions about the motion of a system based on the fact that acceleration is equal to the change in velocity per unit time, and velocity is equal to the change in position per unit time.
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> Learning Objective 4.A.2.2: The student is able to evaluate using given data whether all the forces on a system or whether all the parts of a system have been identified. (quantitative)
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> Learning Objective 4.A.2.3: The student is able to create mathematical models and analyze graphical relationships for acceleration, velocity, and position of the center of mass of a system and use them to calculate properties of the motion of the center of mass of a system.

Essential Knowledge 4.A.3: Forces that systems exert on each other are due to interactions between objects in the systems. If the interacting objects are parts of the same system, there will be no change in the center-of-mass velocity of that system.

> Learning Objective 4.A.3.1: The student is able to apply Newton's second law to systems to calculate the change in the center-of-mass velocity when an external force is exerted on the system.
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> Learning Objective 4.A.3.2: The student is able to use visual or mathematical representations of the forces between objects in a system to predict whether or not there will be a change in the center-of-mass velocity of that system.

PROCEDURE:

1. Phase 1: Force, free-body diagrams, fundamental forces, contact forces v. field forces, gravitational force, gravitational field, and mass (inertial, gravitational, and resting)

- **Notes: I – IV**
- **Lab: Inertial v Gravitational Mass**
- **Homework 1:**
    - ***Some commonly-used values: Earth's mass: 5.98E24 kg; Earth's radius: 6.38E6 m***
    - ***I want to emphasize that gravitational acceleration and gravitational field are numerically the same value. Consider that when a question asks for gravitational acceleration so that you're reinforcing the concept of gravitational field.***
    - **Page 125+ Conceptual Questions 9, 10, 12, 13, and 26 and Problems 18, 19, 21, 23, 24a, 26, 27, 30**

2. Phase 2: Newton's first law, static equilibrium, the effect of internal forces, Newton's second law, normal force, tension force

- **Notes: Up through tension**
- **Lab: Newton's Second Law**
- **<u>Homework 2</u>: This is long…Start early. Chapter 4 Conceptual Questions 1-4, 14-17, 21, 24 and Problems 1-3, 5, 10, 11, 12[3], 34, 47, 48, 50, 55, 57, 63, 64, 67, 71, 73, 108[4] (Note the footnotes for problems 12 and 108.) ALSO FOR EXTRA CREDIT: #8 done on a half sheet of paper that you can turn in separately at the start of class.**

3. Phase 3: Newton's second law (continued), friction, terminal velocity

- **Notes: Finish Roman numeral VI**
- **<u>Homework 3</u>: Chapter 4 Conceptual Questions 11[5], 18-20, 22, 25, 27 and Problems 35-38, 40[6], 43, 51, 53, 59 (Note the footnote for conceptual question 11 and problem 40.)**

4. Phase 4: Newton's third law, kinematic connections

- **Notes: Roman numeral VII**
- **<u>Homework 4</u>: Chapter 4 Conceptual Questions 6-8[7] and Problems 4, 6, 25[8], 41, 44, 65, 69, 112, 114 (conceptual only), 115**

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[3] When doing problem 12, consider how that can be.
[4] For problem 108, only explain. Don't do computations.
[5] For conceptual question 11, identify for each case whether the acceleration is greater than, less than, or equal to $9.8 m/s^2$.
[6] For problem 40, only say WHY a, b, and c will be different from each other, and rank them from high to low.
[7] Conceptual question 8 is important.
[8] For problem 25, think again about force vs. field. Note that m (object in the field) changes from c to d.