

# Lesson CH:4

## Newton's Laws of Motion

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# Newton's Three Laws of Motion

- **First Law: The Law of Inertia**

$$\sum \vec{F} = \vec{0} \Rightarrow \vec{v} = \text{constant}$$

If no net force, velocity remains constant (including zero).

- **Second Law: Force, Mass, and Acceleration**

$$\vec{F} = m\vec{a} \quad \text{or} \quad \vec{a} = \frac{\vec{F}}{m}$$

Net force equals mass times acceleration.

- **Third Law: Action and Reaction**

$$\vec{F}_{A \text{ on } B} = -\vec{F}_{B \text{ on } A}$$

Forces between objects are equal and opposite.

Note:  $\vec{F}$  is force,  $m$  is mass,  $\vec{a}$  is acceleration,  $\vec{v}$  is velocity.

# Newton's Second Law in Detail

- Acceleration ( $\vec{a}$ ) is defined as a change in velocity, either in magnitude or direction, or both.
- Newton's second law of motion states that the acceleration of a system is directly proportional to and in the same direction as the net external force acting on the system, and inversely proportional to its mass.
- In equation form:

$$\vec{a} = \frac{\vec{F}_{\text{net}}}{m}$$

- Often written in the more familiar form:

$$\vec{F}_{\text{net}} = m\vec{a}$$

- $\vec{F}_{\text{net}}$  represents the net external force acting on the system.
- $m$  is the mass of the system.

# Weight and Free Fall

- Weight ( $\vec{w}$ ) is defined as the force of gravity acting on an object of mass  $m$ .
- The object experiences an acceleration due to gravity  $\vec{g}$ :

$$\vec{w} = m\vec{g}$$

- If the only force acting on an object is due to gravity, the object is in free fall.
- On Earth, the acceleration due to gravity is approximately  $9.8 \text{ m/s}^2$  downward.

# Forces on an Inclined Plane

When objects rest on an inclined plane that makes an angle  $\theta$  with the horizontal surface:

- The weight of the object can be resolved into components that act perpendicular ( $\vec{w}_\perp$ ) and parallel ( $\vec{w}_\parallel$ ) to the surface of the plane.
- These components can be calculated using:

$$w_\parallel = |\vec{w}| \sin(\theta) = mg \sin(\theta)$$

$$w_\perp = |\vec{w}| \cos(\theta) = mg \cos(\theta)$$

- $\vec{w}_\parallel$  is the component causing the object to slide down the plane.
- $\vec{w}_\perp$  is the component balanced by the normal force from the plane.

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# Tension and Normal Force

- Tension ( $\vec{T}$ ) is the pulling force that acts along a stretched flexible connector, such as a rope or cable.
- When a rope supports the weight of an object at rest:

$$|\vec{T}| = mg$$

- Normal force ( $\vec{N}$ ) is the supporting force applied by a surface to an object that is at rest on the surface.
- On a horizontal, non-accelerating surface:

$$|\vec{N}| = mg$$

- The normal force is always perpendicular to the surface.



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# Problem-Solving Strategy

To solve problems involving Newton's laws of motion:

- ① Draw a sketch of the problem.
- ② Identify known and unknown quantities, and the system of interest.
- ③ Draw a free-body diagram:
  - Represent the object as a dot.
  - Draw vectors for all forces acting on the object.
  - Resolve non-horizontal/vertical vectors into components.
- ④ Apply Newton's second law in the horizontal and vertical directions:
  - If no acceleration in a direction:  $F_{\text{net}} = 0$
  - If acceleration present:  $F_{\text{net}} = ma$
- ⑤ Solve the resulting equations.
- ⑥ Check your answer: Is it reasonable? Are the units correct?

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## Problem 4

- Since astronauts in orbit are apparently weightless, a clever method of measuring their masses is needed to monitor their mass gains or losses to adjust diets. One way to do this is to exert a known force on an astronaut and measure the acceleration produced. Suppose a net external force of 50.0 N is exerted and the astronaut's acceleration is measured to be  $0.893 \text{ m/s}^2$ .
- (a) Calculate her mass.
- (b) By exerting a force on the astronaut, the vehicle in which they orbit experiences an equal and opposite force. Discuss how this would affect the measurement of the astronaut's acceleration. Propose a method in which recoil of the vehicle is avoided.

# Problem 4 - Solution

Solution:

$$(a) \quad m = \frac{\text{net}F}{a} = \frac{50.0 \text{ N}}{0.893 \text{ m/s}^2} = 56.0 \text{ kg}$$

$$(b) \quad a_{\text{meas}} = a_{\text{astro}} + a_{\text{ship}}, \text{ where: } a_{\text{ship}} = \frac{m_{\text{astro}} a_{\text{astro}}}{m_{\text{ship}}}$$

- If the force could be exerted on the astronaut by another source (other than the spaceship), then the spaceship would not experience a recoil.

# Derivation of Ship's Acceleration

- 1) Newton's Third Law: Force on astronaut equals negative force on ship

$$F_{\text{on astro}} = -F_{\text{on ship}}$$

- 2) Express forces using Newton's Second Law ( $F = ma$ ):

$$m_{\text{astro}} a_{\text{astro}} = -m_{\text{ship}} a_{\text{ship}}$$

- 3) Rearrange to isolate  $a_{\text{ship}}$ :

$$-m_{\text{ship}} a_{\text{ship}} = m_{\text{astro}} a_{\text{astro}}$$

$$m_{\text{ship}} a_{\text{ship}} = -m_{\text{astro}} a_{\text{astro}}$$

$$a_{\text{ship}} = -\frac{m_{\text{astro}} a_{\text{astro}}}{m_{\text{ship}}}$$

- 4) Drop negative sign for magnitude:

$$a_{\text{ship}} = \frac{m_{\text{astro}} a_{\text{astro}}}{m_{\text{ship}}}$$

- Interpretation: Ship's acceleration is proportional to astronaut's mass and acceleration, inverse to ship's mass.

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# Problem 16

A rugby player is being pushed backward by an opposing player who is exerting a force of 800 N on him. The mass of the losing player plus equipment is 90.0 kg, and he is accelerating at  $1.20 \text{ m/s}^2$  backward.

- (a) What is the force of friction between the losing player's feet and the grass?
- (b) What force does the winning player need to exert on the ground to move forward at the same acceleration if his mass plus equipment is 110 kg?
- (c) Draw a sketch of the situation showing the system of interest used to solve each part.



## Problem 16 - Part (a)

### Question

What is the force of friction between the losing player's feet and the grass?

### Knowns and Unknowns

#### Knowns:

- $F_{\text{opposing}} = 800 \text{ N}$
- $m_{\text{losing}} = 90.0 \text{ kg}$
- $a = 1.20 \text{ m/s}^2$  backward

#### Unknown:

- $F_{\text{friction}}$  (force of friction)

### Solution

$$\text{net } F = F - f = ma$$

$$f = F - ma = 800 \text{ N} - (90.0 \text{ kg})(1.20 \text{ m/s}^2) = \underline{692 \text{ N}}$$

## Problem 16 - Part (b)

### Question

What force does the winning player exert on the ground to move forward if his mass plus equipment is 110 kg?

### Knowns and Unknowns

#### Knowns:

- $m_{\text{winning}} = 110 \text{ kg}$
- $a = 1.20 \text{ m/s}^2$  (same as losing player, in opposite direction)
- $F_{\text{friction}} = 692 \text{ N}$  (calculated in part a)

#### Unknown:

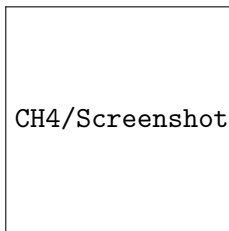
- $F_{\text{ground}}$  (force exerted on the ground)

### Solution

$$F = ma + f = (110\text{kg} + 90.0\text{kg})(1.20 \text{ m/s}^2) + 692 \text{ N} = 932 \text{ N}$$

## Problem 16 - Solution (c)

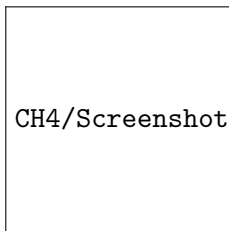
- (c) Draw a sketch of the situation showing the system of interest used to solve each part.
- (a) What is the force of friction between the losing player's feet and the grass?



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## Problem 16 - Solution (c)

- (c) Draw a sketch of the situation showing the system of interest used to solve each part.
- (b) What force does the winning player exert on the ground to move forward if his mass plus equipment is 110 kg?



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# Problem 17

Two teams of nine members each engage in a tug of war. Each of the first team's members has an average mass of 68 kg and exerts an average force of 1350 N horizontally. Each of the second team's members has an average mass of 73 kg and exerts an average force of 1365 N horizontally.

- (a) What is the acceleration of the two teams?
- (b) What is the tension in the section of rope between the teams?

## Problem 17 - Solution (a)

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## Problem 17 - Solution (b)

(b) What is the tension in the section of rope between the teams?

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$$T - 9f_1 = 9m_1a \Rightarrow T = 9m_1a + 9f_1$$



# Problem 17 - Explanation

Explanation:

- (a) We use Newton's Second Law for the entire system:  $F = Ma$
- The net force is the difference between the forces of the two teams
  - We divide by the total mass to find acceleration
- (b) We consider the forces on one team
- Use Newton's Second Law:  $T - 9f_1 = 9m_1a$
  - Solve for  $T$  and substitute known values

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## Problem 28

Commercial airplanes are sometimes pushed out of the passenger loading area by a tractor.

- (a) An 1800-kg tractor exerts a force of  $1.75 \times 10^4$  N backward on the pavement, and the system experiences forces resisting motion that total 2400 N. If the acceleration is  $0.150 \text{ m/s}^2$ , what is the mass of the airplane?
- (b) Calculate the force exerted by the tractor on the airplane, assuming 2200 N of the friction is experienced by the airplane.
- (c) Draw two sketches showing the systems of interest used to solve each part, including the free-body diagrams for each.

## Problem 28 - Solution (a)

**Question:** An 1800-kg tractor exerts a force of  $1.75 \times 10^4$  N backward on the pavement, and the system experiences forces resisting motion that total 2400 N. If the acceleration is  $0.150 \text{ m/s}^2$ , what is the mass of the airplane?

**Solution:** net  $F = Ma = (m_a + m_t)a = F - f$ , so that:  $m_a = \frac{F-f}{a} - m_t$

$$m_a = \frac{1.75 \times 10^4 \text{ N} - 2400 \text{ N}}{0.150 \text{ m/s}^2} - 1800 \text{ kg} = \underline{9.89 \times 10^4 \text{ kg}}$$

## Problem 28 - Solution (b)

**Question:** Calculate the force exerted by the tractor on the airplane, assuming 2200 N of the friction is experienced by the airplane.

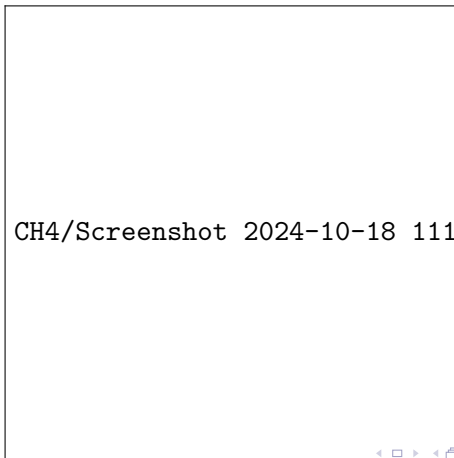
**Solution:** net  $F = F' - f' = m_a a$

$$F' = m_a a + f' = (9.89 \times 10^4 \text{ kg})(0.150 \text{ m/s}^2) + 2200 \text{ N} = \underline{1.70 \times 10^4 \text{ N}}$$

## Problem 28 - Solution (c)

**Question:** Draw two sketches showing the systems of interest used to solve each part, including the free-body diagrams for each.

**Solution:**



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## Problem 28 - Explanation

Explanation:

We use Newton's Second Law for the entire system:  $F = Ma$

- Substitute the given force, friction, and acceleration
- Solve for the airplane's mass

We use Newton's Second Law for just the airplane:  $F' - f' = m_{\text{airplane}}a$

- Solve for  $F'$  and substitute known values

# Conclusion

- We've explored various applications of Newton's Laws of Motion:
  - Measuring mass in weightless environments
  - Analyzing forces in sports (rugby and tug of war)
  - Calculating forces in aircraft towing
- Key takeaways:
  - Newton's Second Law ( $F = ma$ ) is crucial for solving these problems
  - Consider all forces acting on a system
  - Break down complex situations into simpler components
  - Pay attention to vector directions and sign conventions
- Practice solving homework problems to reinforce your understanding of Newton's Laws