Lesson CH:4

Newton's Laws of Motion

Mr. Gullo

September 2024

Table of Contents

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 m/s^2 downward.

Forces on an Inclined Plane

When objects rest on an inclined plane that makes an angle θ with the horizontal surface:

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

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

- $\vec{w}_{||}$ 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.

CINEC EDUCATION

Screenshot 2024-10-21 152424.png

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.

Screenshot 2024-10-21 152741.png

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?

Table of Contents

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

(b) $a_{\text{meas}} = a_{\text{astro}} + a_{\text{ship}}$, 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_{ship}:

$$\begin{aligned} -m_{\text{ship}} a_{\text{ship}} &= m_{\text{astro}} a_{\text{astro}} \\ m_{\text{ship}} a_{\text{ship}} &= -m_{\text{astro}} a_{\text{astro}} \\ a_{\text{ship}} &= -\frac{m_{\text{astro}} a_{\text{astro}}}{m_{\text{ship}}} \end{aligned}$$

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.

Table of Contents

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 $\mathrm{m/s^2}$ 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:

- $F_{\text{opposing}} = 800$ N
- $m_{\text{losing}} = 90.0$ kg
- $a = 1.20$ m/s² backward

Unknown:

- F_{friction} (force of friction)

Solution

net $F = F - f = ma$

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

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:

- $m_{\text{winning}} = 110$ kg
- $a = 1.20$ m/s² (same as losing player, in opposite direction)
- $F_{\text{friction}} = 692$ N (calculated in part a)

Unknown:

- F_{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?

Screenshot 2024-10-18 111640.png

CINEC EDUCATION

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?

Screenshot 2024-10-18 111809.png

Table of Contents

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)

Screenshot 2024-10-18 111908.png

Problem 17 - Solution (b)

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

Screenshot 2024-10-20 145707.png

$$T - 9f_1 = 9m_1 a \Rightarrow T = 9m_1 a + 9f_1$$

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: $T - 9f_1 = 9m_1 a$
- Solve for T and substitute known values

Table of Contents

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 1.75×10^4 N backward on the pavement, and the system experiences forces resisting motion that total 2400 N. If the acceleration is $0.150\ \mathrm{m/s^2}$, 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 1.75×10^4 N backward on the pavement, and the system experiences forces resisting motion that total 2400 N. If the acceleration is 0.150 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:

Screenshot 2024-10-18 111935.png

Problem 28 - Explanation

Explanation:

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

- 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