Lecture Notes Chapter 4: Forces & Newton’s Laws

Introduction to Dynamics: Newton’s Laws of Motion

- The study of motion is kinematics, but kinematics only describes the way objects move – their velocity and their acceleration.
- Dynamics considers the forces that affect the motion of moving objects and systems.
- Galileo was instrumental in establishing observation as the absolute determinant of truth, rather than “logical” argument.

4.1 Development of Force Concept

- Dynamics is the study of the forces that cause objects and systems to move.
- Force is defined as a push or pull, which has both magnitude and direction, therefore it is a vector.
- Since force is a vector, it adds just like other vectors.

(b) Free-body diagram is a technique used to illustrate all the external forces acting on a body.

- The body is represented by a single isolated point (or free body), and only those forces acting on the body from the outside (external forces) are shown – these forces are the only ones shown, because only external forces acting on the body affect its motion.

Take-Home Experiment: Force Standards, p. 131

To investigate force standards and cause and effect, get two identical rubber bands.
Hang one rubber band vertically on a hook. Find a small household item that could be attached to the rubber band using a paper clip, and use this item as a weight to investigate the stretch of the rubber band.

Measure the amount of stretch produced in the rubber band with one, two, and four of these (identical) items suspended from the rubber band.

What is the relationship between the number of items and the amount of stretch?

How large a stretch would you expect for the same number of items suspended from two rubber bands?

What happens to the amount of stretch of the rubber band (with the weights attached) if the weights are also pushed to the side with a pencil?

4.2 Newton’s First Law of Motion: Inertia

- Define mass and inertia
- Understand Newton’s first law of motion.

Newton’s First Law of Motion

A body at rest remains at rest, or, if in motion, remains in motion at a constant velocity unless acted on by a net external force.

- We can think of this law as preserving the status quo of motion.
- This law states that there must be a cause (which is a net external force) for there to be any change in velocity (either a change in magnitude or direction).

An object sliding across a table or floor slows down due to the net force of friction acting on the object. If friction disappeared, would the object still slow down?

- The idea of cause and effect is crucial in accurately describing what happens in various situations.
- The object would not slow down at all if friction were completely eliminated.
- If we know enough about the friction, we can accurately predict how quickly the object will slow down. Friction is an external force.

Mass

The property of a body to remain at rest or to remain in motion with constant velocity is called inertia.

- Newton’s first law is often called the law of inertia.
- The inertial of an object is measured by its mass.
- Mass is a measure of the amount of matter in something.
- Unlike weight, mass does NOT vary with location.
CHECK YOUR UNDERSTANDING

Which has more mass: a kilogram of cotton balls or a kilogram of gold?

Solution: They are equal. A kilogram of one substance is equal in mass to a kilogram of another substance. The quantities that might differ between them are volume and density.

4.3 Newton’s Second Law of Motion: Concept of a System

- Define net force, external force, and system.
- Understand Newton’s second law of motion.
- Apply Newton’s second law to determine the weight of an object.

A change in motion is equivalent to a change in velocity.

- A change in velocity means, by definition, that there is an acceleration.
- Newton’s first law says that a net external force causes a change in motion; thus, a net external force causes acceleration.

What do we mean by an external force? An external force acts from outside the system of interest.

- Only external forces affect the motion of a system, according to Newton’s first laws.
- Different forces exerted on the same mass produce different accelerations. (The internal forces actually cancel.)
- **You must define the boundaries of the system before you can determine which forces are external.**

(a) The system of interest is the wagon plus the child in it.
- The two forces exerted by the other children are external forces.
- The force the child in the wagon exerts to hang onto the wagon is an internal force between elements of the system of interest.
- The weight \( W \) of the system and the support of the ground \( \mathbf{N} \) are assumed to cancel.

(b) All of external forces acting on the system add together to produce a net force, \( \mathbf{F}_{\text{net}} \).
The free-body diagram shows all of the forces acting on the system of interest.
- The dot represents the center of mass of the system.
- Each force vector extends from this dot.
- Because there are two forces acting to the right, we draw the vectors collinearly.

(c) A larger net external force produces a larger acceleration \( (a' > a) \) when an adult pushes the child.

Acceleration is directly proportional to and in the same direction as the net (total) external force acting on a system.

The same force exerted on systems of different masses produces different accelerations.

(a) A basketball player pushes on a basketball to make a pass. (The effect of gravity on the ball is ignored.)
(b) The same player exerts an identical force on a stalled SUV and produces a far smaller acceleration (even if friction is negligible).
(c) The free-body diagrams are identical, permitting direction comparison of the two situations.

The acceleration of an object depends only on the net external force and the mass of the object. Combining the two proportionalities just given yields Newton’s second law of motion.
Newton’s Second Law of Motion

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, Newton’s second law of motion is
  \[ a = \frac{F_{\text{net}}}{m} \]
- This is often written in the more familiar form
  \[ F_{\text{net}} = ma \]
- When only the magnitude of force and acceleration are considered, this equation is simply
  \[ F_{\text{net}} = ma \]

Although these last two equations are really the same, the first gives more insight into what Newton’s second law means.

- The law is a cause and effect relationship among three quantities that is not simply based on their definitions.
- The validity of the second law is completely based on experimental verification.

Units of Force

\[ 1\text{N} = 1\text{ kg} \cdot \text{m/s}^2 = 0.225\text{ lb}. \]

Weight and the Gravitation Force

When an object is dropped, it accelerates toward the center of Earth.

- Newton’s second law states that a net force on an object is responsible for its acceleration.
- If air resistance is negligible, the net force on a falling object is the gravitational force, commonly called its weight \( w \).

Weight can be denoted as a vector \( \mathbf{w} \) because it has a direction; down is, by definition, the direction of gravity, and hence weight is a downward force. The magnitude of weight is denoted as \( w \).

Galileo was instrumental in showing that, in the absence of air resistance, all objects fall with the same acceleration \( g \). Using Galileo’s result and Newton’s second law, we can derive an equation for weight.
• Consider an object with mass \( m \) falling downward toward Earth. It experiences only the downward force of gravity, which has magnitude \( w \).

• Newton’s second law states that the magnitude of the net external force on an object is \( F_{\text{net}} = ma \).

• Since the object experiences only the downward force of gravity, \( F_{\text{net}} = w \). The acceleration of an object due to gravity is \( g \), or \( a = g \). Substituting these into Newton’s second law gives

\[
F_{\text{net}} = ma = mg
\]

When the net external force on an object is its weight, we say that it is in free-fall. That is, the only force acting on the object is the force of gravity.

In the real world, when objects fall downward toward Earth, they are never truly in free-fall because there is always some upward force from the air action on the object.

The acceleration due to gravity \( g \) varies slightly over the surface of Earth, so that the weight of an object depends on location and is not an intrinsic property of the object.

The broadest definition of weight is that the weight of an object is the gravitational force on it from the nearest large body, such as Earth, the Moon, the Sun, and so on.

It is important to be aware that weight and mass are very different physical quantities, although they are closely related.

• Mass is the quantity of matter (how much “stuff”) and does not vary in classical physics.

• Weight is the gravitational force and DOES vary depending on gravity.

EXAMPLE 4.1 What Acceleration Can a Person Produce when Pushing a Lawn Mower?

Suppose that the net external force (push minus friction) exerted on a lawn mower is 51 N (about 11 lb) parallel to the ground. The mass of the mower is 24 kg. What is its acceleration?

Solution:

The magnitude of the acceleration \( a \) is

\[
a = \frac{F_{\text{net}}}{m}
\]

Entering known values gives

\[
a = \frac{51 \text{ N}}{24 \text{ kg}}
\]
Substituting the units $\text{kg} \cdot \text{m/s}^2$ for $N$ yields

\[
N = \frac{51 \text{ kg} \cdot \text{m/s}^2}{24 \text{ kg}} = 2.1 \text{ m/s}^2
\]

Discussion:

The direction of the acceleration is the same direction as that of the net force, which is parallel to the ground. The force exerted by the person pushing the mower must be greater than the friction opposing the motion (since we know the mower moves forward) and the vertical forces must cancel if there is to be no acceleration in the vertical direction (the mower is moving only horizontally).

EXAMPLE 4.2 What Rocket Thrust Accelerates This Sled? (p. 136)

Prior to manned space flights, rocket sleds were used to test aircraft, missile equipment, and physiological effects on human subjects at high speeds. They consisted of a platform that was mounted on one or two rails and propelled by several rockets. Calculate the magnitude of force exerted by each rocket, called its thrust $T$, for the four-rocket propulsion system in the figure below. The sled’s initial acceleration is $49 \text{ m/s}^2$, the mass of the system is $2100 \text{ kg}$, and the force of friction opposing the motion is known to be $650 \text{ N}$.

- A sled experiences a rocket thrust that accelerates it to the right.
- Each rocket creates an identical thrust $T$.
- As in other situations where there is only horizontal acceleration, the vertical forces cancel – the ground exerts an upward force $N$ on the system that is equal in magnitude and opposite in direction to its weight, $W$.
- The system here is the sled, its rockets, and rider, so none of the forces between these objects are considered.
- The arrow representing friction ($f$) is drawn larger than scale.
Strategy: Although there are forces acting vertically and horizontally, we assume the vertical forces cancel since there is not vertical acceleration.

Solution:

- Since we have defined the direction of the force and acceleration as acting “to the right,” we need to consider only the magnitudes of these quantities in the calculations. \[ F_{\text{net}} = ma \], where \[ F_{\text{net}} = 4T - f \] (while the engine thrusts add, friction opposes the thrust).
- Substituting this into Newton’s second law gives \[ F_{\text{net}} = ma = 4T - f \].
- Then \[ 4T = ma + f \].
- Substituting known values yields \[ T = \frac{1.0 \times 10^5 \text{ N}}{4} = 2.6 \times 10^4 \text{ N} \]

Newton’s second law of motion is more than a definition; it is a relationship among acceleration, force, and mass. It can help us make predictions. Each of those physical quantities can be defined independently, so the second law tells us something basic and universal about nature.

4.4 Newton’s Third Law of Motion: Symmetry in Forces

- Understand Newton’s third law of motion.
- Apply Newton’s third law to define systems and solve problems of motion.

Whenever one body exerts a force on a second body, the first body experiences a force that is equal in magnitude and opposite in direction to the force that it exerts.

This law represents a certain symmetry in nature: Forces always occur in pairs, and one body cannot exert a force on another without experiencing a force itself.

- We sometimes refer to this law loosely as “action-reaction,” where the force exerted is the action and the force experienced as a consequence is the reaction.
- Newton’s third law has practical uses in analyzing the origin of forces and understanding which forces are external to a system.

Consider a swimmer pushing off from the side of a pool as illustrated in the figure below.

- She pushes against the pool wall with her feet and accelerates in the direction opposite to that of her push.
- The wall has exerted an equal and opposite force back on the swimmer. You might think that two equal and opposite forces would cancel, but they do not because they act on different systems.
In this case, there are two systems that we could investigate: the swimmer or the wall.

- If we select the swimmer to be the system of interest, as in the figure, then $F_{\text{wall on feet}}$ is an external force on this system and affects its motion.
- The swimmer moves in the direction of $F_{\text{wall on feet}}$.
- In contrast, the force $F_{\text{wall on feet}}$ acts on the wall and not on our system of interest. Thus $F_{\text{wall on feet}}$ does not directly affect the motion of the system and does not cancel $F_{\text{wall on feet}}$.
- Note that the swimmer pushes in the direction opposite to that in which she wishes to move. The reaction to her push is thus in the desired direction.

![Diagram of swimmer and wall with forces](image)

4.5 Normal, Tension, and Other Examples of Forces

- Define normal and tension forces.
- Apply Newton’s laws of motion to solve problems involving a variety of forces.
- Use trigonometric identities to resolve weight into components.

4.6 Problem-Solving Strategies

4.7 Further Applications of Newton’s Laws of Motion

4.8 Extended Topic: The Four Basic Forces – An Introduction

- Understand the four basic forces that underline the processes in nature.