Lecture 3: Forces—why objects move?

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The Laws of Motion

Kinematics: trajectory r(t)

Or more generally ... q(t) where the $q_i(t)$'s are "generalized coordinates" with number of components equal to "degree of freedom"

Dynamics: The cause this trajectory? Why the motion of an object will change? Two main factors.

- 1. Forces acting on the object
- 2. The mass of the object (Ex. Rocket or jet engine in a spacecraft)



Outline

- Review: circular motion in 2D
 - Non-uniform circular motion: \boldsymbol{a}_{c} and \boldsymbol{a}_{t}
 - Intuition about centripetal force in circular motion
 - Relative velocity, frame of reference, fictitious force.
- What is Force?
 - What cause change in velocity of an object
 - Fundamental force, Field force vs. Contact force
 - Normal force, Tension, Friction
 - Gravitational force, Weight
- Newton's Law and examples

What is Force?

Forces in everyday experience

- Push on an object to move it
- Throw or kick a ball
- May push on an object and not be able to move it

Forces are what cause any change in the velocity of an object.

Newton's definition: "a force is that which causes an acceleration"

Classes of Forces



1. Contact forces

 involve physical contact between two objects

2. Field forces

 act through empty space

Fundamental Forces

Gravitational force

- Between objects
- •Electromagnetic forces
 - Between electric charges
- Nuclear force
 - Between subatomic particles
- •Weak forces
 - Arise in certain radioactive decay processes

Note: These are all **field forces**.

Measuring forces by a spring



•A spring can be used to calibrate the magnitude of a force.

•Doubling the force causes double the reading on the spring.

 $F \propto \Delta x$

Newton's Law...in short

- First Law: A body moves with constant velocity (which may be zero) unless acted on by a force.
 - Force, inertial frame
- Second Law: The time rate of change of the momentum of a body equals the force acting on the body.
 - Momentum, mass is defined
- Third Law: The forces two bodies apply to each other are equal in magnitude and opposite in direction.
 - Postulates that momentum is conserved.

Newton's First Law

•If an object does not interact with other objects, it is possible to identify a reference frame in which the object has zero acceleration.

- This is also called the *law of inertia*.
- It defines a special set of reference frames called *inertial frames.*
 - We call this an *inertial frame of reference*.

Inertial Frames (กรอบอ้างอิงเลื่อย)

•Any reference frame that **moves with constant velocity** relative to an inertial frame is itself an inertial frame.

•A reference frame that moves with constant velocity relative to the distant stars is the best approximation of an inertial frame.

- Example: The frame of a "spinning turntable" is NOT an inertial frame
- The Earth is considered to be only approximately an inertial frame, because it has a small centripetal acceleration associated with its motion.

•If you accelerate relative to an object in an inertial frame, you are observing the object from an accelerated or **non-inertial reference frame.**

Newton's First Law – Alternative Statement

•In the absence of external forces, when viewed from an inertial reference frame, an object at rest remains at rest and an object in motion continues in motion with a constant velocity.

- Define "zero force"
- Also tells us that when no force acts on an object, the acceleration of the object is zero
- Can conclude that any isolated object is either at rest or moving at a constant velocity

•The First Law also allows the definition of *force* as *that which causes a change in the motion of an object.*

-SI unit of force is the **newton** (N): $1 \text{ N} = 1 \text{ kg} \cdot \text{m} / \text{s}^2$

ตัวอย่าง รถโดยสารประจำทางที่กำลังวิ่งอยู่ ต้องเบรกอย่างกระทันหัน ทำให้ผู้โดยสารที่ยืนอยู่พุ่งไปทางด้านหน้า แรงอะไรที่ทำให้ผู้โดยสารเคลื่อนที่ ดังกล่าว จงอธิบาย

ไม่มีแรงใดที่ทำให้ผู้โดยสารที่ยืนอยู่พุ่งไปทางด้านหน้า แต่เป็นเพราะการรักษาสภาพการเคลื่อนที่เดิมของตัวผู้โดยสารเอง (ตามกฏข้อที่หนึ่งของนิวตัน) เมื่อรถเบรกความเร็วของรถลดลง แต่ผู้โดยสารยังมีความเร็วเดิมในช่วงเวลาสั้นๆ

Another example: pendulum in a decelerating train

Newton's Second Law

•When viewed from an inertial reference frame, the acceleration of an object is directly proportional to the net force acting on it and inversely proportional to its mass.

- Force is the cause of *changes* in motion, as measured by the acceleration.
 - Remember, an object can have motion in the absence of forces.
 - Do not interpret force as the cause of motion.

$$\vec{a} \propto \frac{m}{m} \rightarrow \sum r = m\vec{a}$$

Inertia and Mass

•The tendency of an object to resist any attempt to change its velocity is called *inertia*.

•*Mass* is that property of an object that specifies how much resistance an object exhibits to changes in its velocity.

•Masses can be defined in terms of the accelerations produced by a given force acting on them:

$$\frac{m_1}{m_2} \equiv \frac{a_2}{a_1}$$

– Force is

– "a standard mass" \rightarrow other mass defined relative to thi

Gravitational Force

Every particle in the universe exerts an attractive force on every other particle.

The force that each exerts on the other is directed along the line joining the particles.







5.5 The Gravitational Force

Example





 $= 1.4 \times 10^{-8}$ N

5.5 The Gravitational Force



Definition of Weight

The weight of an object on or above the earth is the gravitational force that the earth exerts on the object. The weight always acts downwards, toward the center of the earth.

On or above another astronomical body, the weight is the gravitational force exerted on the object by that body.

SI Unit of Weight: newton (N)

5.5 The Gravitational Force

Relation Between Mass and Weight

$$W = G \frac{M_E m}{r^2}$$

$$W = mg$$

$$g = G \frac{M_E}{r^2}$$

Object of mass m \overrightarrow{W} RE

Mass of earth = $M_{\rm E}$

5.5 The Gravitational Force

On the earth's surface:

$$g = G \frac{M_E}{R_E^2}$$

= $(6.67 \times 10^{-11} \,\mathrm{N \cdot m^2/kg^2}) \frac{(5.98 \times 10^{24} \,\mathrm{kg})}{(6.38 \times 10^6 \,\mathrm{m})^2}$
= 0.80 m/a²

 $= 9.80 \text{ m/s}^2$

Newton's Third Law

•The action force is equal in magnitude to the reaction force and opposite in direction.

- One of the forces is the action force, the other is the reaction force. (It doesn't matter which is considered which).
- The action and reaction forces must act on different objects and be of the same type.



Action-Reaction example

•The normal force (table on monitor) is the reaction of the force the monitor exerts on the table.

 Normal means perpendicular, in this case

•The action (Earth on monitor) force is equal in magnitude and opposite in direction to the reaction force, the force the monitor exerts on the Earth.



Forces on the Object

•In a free body diagram, you want the forces acting on a particular object.

Model the object as a particle

•The normal force and the force of gravity are the forces that act on the monitor.





Analysis Models Using Newton's Second Law

•Assumptions

- Objects can be modeled as particles.
- Interested only in the external forces acting on the object
 - Can neglect reaction forces
- Initially dealing with frictionless surfaces
- Masses of strings or ropes are negligible.
 - The force the rope exerts is away from the object and parallel to the rope.
 - When a rope attached to an object is pulling it, the magnitude of that force is the **tension** in the rope.

Normal Force

Section 5.7

•is the (contact) force that prevents an object from falling through the floor due to its weight!

•The normal force is **not** always equal to the gravitational force of the object.

•Think of a scale (ตาซั่ง)



How the scale works: apparent weight

The apparent weight of an object is the reading of the scale. It is equal to the normal force the man exerts on the scale.



(a) No acceleration ($\vec{v} = constant$)

(b) Upward acceleration

(c) Downward acceleration

(d) Free-fall

Inclined Planes

•Forces acting on the object:

- The normal force acts perpendicular to the plane.
- The gravitational force acts straight down.

•Choose the coordinate system with x along the incline and y perpendicular to the incline.

•net force to the x-direction and a particle in equilibrium to the v-direction.



Tension force

Cables and ropes transmit forces through *tension*.







(b)





A massless rope will transmit tension undiminished from one end to the other.

If the rope passes around a massless, frictionless pulley, the tension will be transmitted to the other end of the rope undiminished.

Example: Equilibrium

- •Traffic light has a weight Mg, find tension T_1 and T_2 in the cables which make angle
- Assume cables don't break
 - Nothing is moving, so acceleration is zero
 - Model as a particle in equilibrium = zero net force
- Geometry method
- Algebraic method (component)



Example : Atwood's Machine

•Forces acting on the objects:

- Tension (same for both objects, one string)
- Gravitational force

•Each object has the same acceleration since they are connected.

•The tension is the same on both sides of the pulley as long as you assume a massless, frictionless pulley.

•Find *a* and *T* ?



Example: multiple objects

- •Free-body diagram for **each** object
 - One cord, so tension is the same for both objects
 - Connected, so acceleration is the same for both objects
- Find *a* and *T*
 - Under what condition does the block slide down the slope?

 Next question: what if there is friction between the block and the incline?

Forces of Friction

•When an object is in motion on a surface or through a viscous medium, there will be a resistance to the motion.

- This is due to the interactions between the object and its environment.
- •This resistance is called the *force of friction*.

Forces of Friction, cont.

•Friction is proportional to the normal force.

$$f_s \leq f_{s,max}$$
 and $f_{s,max} = \mu_s N$
 $f_k = \mu_k N$

$\boldsymbol{\mu}$ is the **coefficient of friction**

- These equations relate the magnitudes of the forces; they are not vector equations.
- For static friction, the equals sign is valid only at *impeding* motion, the surfaces are on the verge of slipping.
- Use the inequality for static friction if the surfaces are not on the verge of slipping.

•The coefficient of friction depends on the surfaces in contact.

•The force of static friction is generally greater than the force of kinetic friction.

•The direction of the frictional force is opposite the direction of motion and parallel to the surfaces in contact.

•The coefficients of friction are nearly independent of the area of contact.

Some Coefficients of Friction

TABLE 5.1

Coefficients of Friction

	μ_s	μ_k
Rubber on concrete	1.0	0.8
Steel on steel	0.74	0.57
Aluminum on steel	0.61	0.47
Glass on glass	0.94	0.4
Copper on steel	0.53	0.36
Wood on wood	0.25 - 0.5	0.2
Waxed wood on wet snow	0.14	0.1
Waxed wood on dry snow		0.04
Metal on metal (lubricated)	0.15	0.06
Teflon on Teflon	0.04	0.04
Ice on ice	0.1	0.03
Synovial joints in humans	0.01	0.003

Note: All values are approximate. In some cases, the coefficient of friction can exceed 1.0.

•Static friction acts to keep the object from moving. So that as long as the object is not moving, $f_s = F$ For small applied forces, the magnitude of the force of static friction equals the magnitude of the applied force. When the magnitude of the applied force exceeds the magnitude of the maximum force of static friction, the trash can breaks free and accelerates to the right.

Example: how to measure coefficients of friction

•The block is sliding down the plane, so friction acts up the plane. How does the friction force relate to θ ?

•This setup can be used to experimentally determine the coefficient of friction.

• μ = tan θ

- For μ_s , use the angle where the block just slips.
- For μ_k , use the angle where the block slides down at a constant speed.

Example 2

•A tire of mass *m* is sliding on ice with kinetic coefficient of friction μ_k If its initial speed is v_0 , how far does the tire slide before it stops? Plot the graph of v(t)

•Draw the free-body diagram, including the force of kinetic friction.

- **Opposes** the motion
- parallel to the surfaces in contact
- What is *a*?

Friction, Example 3

•Draw the free-body diagrams.

•Apply Newton's Laws as in any other multiple object system problem.

•Drag the block with a Force **F** so the system *is moving,* what is *a*, *T*, *f*?

•What type of friction force is this?

Analysis Model Summary

•Particle under a net force

- If a particle experiences a non-zero net force, its acceleration is related to the force by Newton's Second Law.
- May also include using a particle under constant acceleration model to relate force and kinematic information.
- •Particle in equilibrium
 - If a particle maintains a constant velocity (including a value of zero), the forces on the particle balance and Newton's Second Law becomes.

$$\sum \vec{F} = 0$$

Summary

Dynamics studies the causes of motion. In Physics, we cover the **Newtonian Mechanics (Force laws)** which is quite *intuitive*.

Newton's laws address the issue of how to find an expression for *a*(*t*) from our knowledge about *forces* acting on the object...

...which we then use to solve for *r(t)* through

$$\vec{a} = \frac{d^2}{dt^2} \vec{r}$$

We call this **"Equation of Motion"** (สมการการเคลื่อนที่) which is practically a set of differential equations.

- Upon further insight (in the next Lecture 4), you'll realize we are actually going backward here in the description of dynamics. Concept of Energy and momentum are more *fundamental than forces*.
 - Sometimes we don't know the value of the force
 - or the forces can just gets very complicated. e.g. Tensional force in a pendulum, normal force etc.
 - It's also nice to exploit *symmetry* and *conserved quantities* in the system

Fxtra nrohlems (from David Morin's book)

Figure 2.1

Example (A plane and masses): Mass M_1 is held on a plane with inclination angle θ , and mass M_2 hangs over the side. The two masses are connected by a massless string which runs over a massless pulley (see Fig. 2.1). The coefficient of friction (assume the kinetic and static coefficients are equal) between M_1 and the plane is μ . Mass M_1 is released. Assuming that M_2 is sufficiently large so that M_1 gets pulled up the plane, what is the acceleration of the system? What is the tension in the string?

Ans:

$$a = \frac{g(M_2 - \mu M_1 \cos \theta - M_1 \sin \theta)}{M_1 + M_2}$$
, and $T = \frac{M_1 M_2 g}{M_1 + M_2} (1 + \mu \cos \theta + \sin \theta)$

b) What exactly is the condition for M_1 to get pulled up the plane?

Ans: we must have
$$M_2 > M_1(\mu \cos \theta + \sin \theta)$$

c) On the other hand, what is the condition for M1 to move down the plane? And what is the corresponding *a* and *T*?

Ans: we must have
$$M_2 < M_1(\sin \theta - \mu \cos \theta)$$
.
 $a = \frac{g(M_2 + \mu M_1 \cos \theta - M_1 \sin \theta)}{M_1 + M_2}$, and $T = \frac{M_1 M_2 g}{M_1 + M_2}(1 - \mu \cos \theta + \sin \theta)$.

d) And lastly what is the condition for the blocks stay at rest

Ans:
$$M_1(\sin\theta - \mu\cos\theta) < M_2 < M_1(\sin\theta + \mu\cos\theta)$$

2.2. FREE-BODY DIAGRAMS

Example (An Atwood's machine): Consider the pulley system in Fig. 2.5. What are the accelerations of the two masses? What is the tension in the string?

II-7