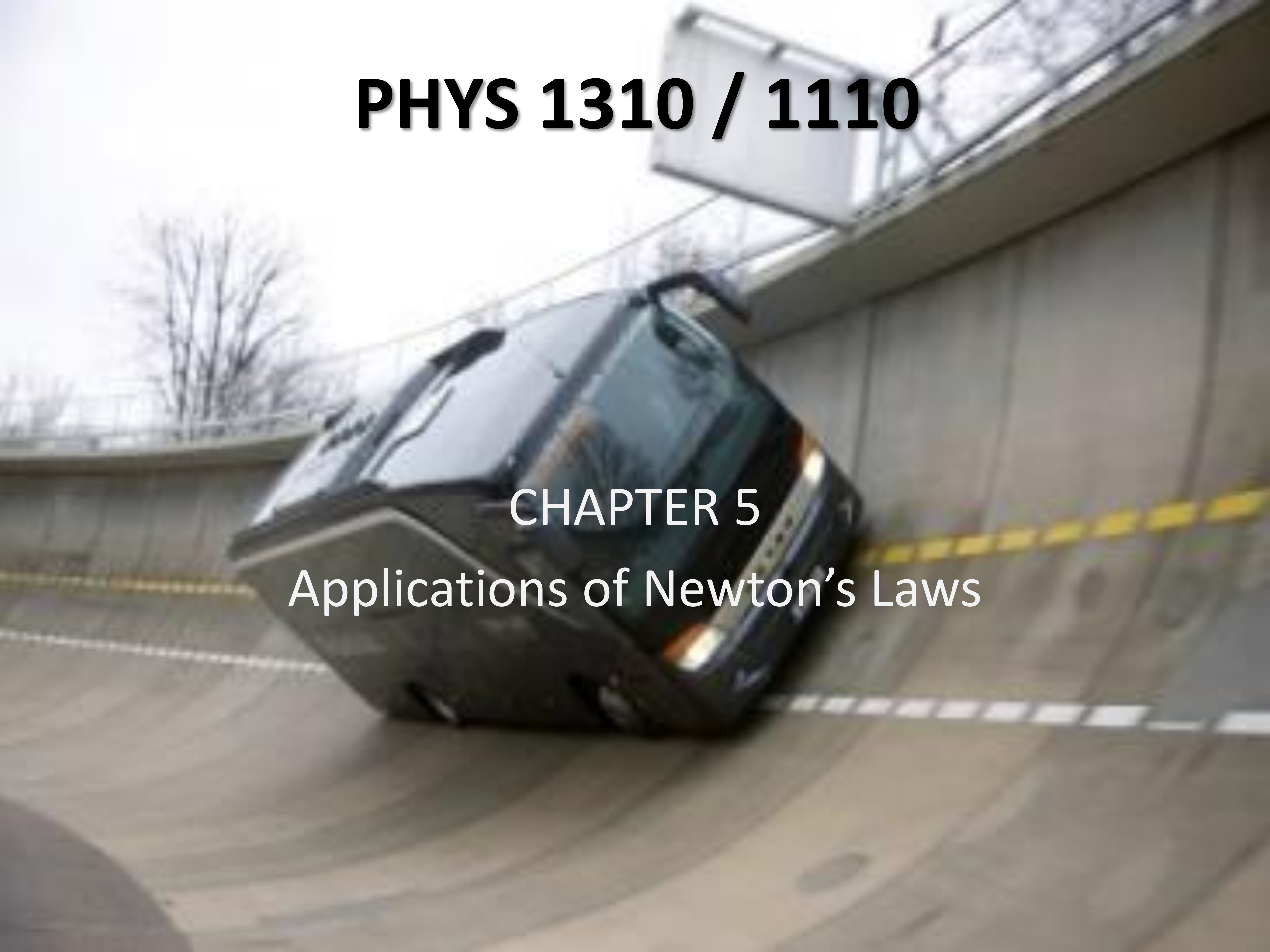


PHYS 1310 / 1110

CHAPTER 5
Applications of Newton’s Laws

CH5 in a Nutshell

- Newton's 1st: $$\sum F = 0$$ (equilibrium)
- Newton's 2nd: $$\sum F = ma$$ (dynamic)
- Force of Friction: $$f_s = \mu_s n$$ (static) $$f_k = \mu_k n$$ (kinetic)
- Force in circular motion: $$F = ma_{rad} = m\frac{v^2}{R} = m\left(\frac{4\pi^2 R}{T}\right)$$

Chapter Overview

- 5.1 Particles in Equilibrium
- 5.2 Dynamics of Particles
- 5.3 Friction Forces
- 5.4 Dynamics of Circular Motion
- 5.5 The Fundamental Forces of Nature

Chapter Objectives

- How to use Newton's first law to solve problems involving the forces that act on an object in **equilibrium**.
- How to use Newton's second law to solve problems involving the forces that act on an **accelerating** object.
- The nature of the different types of **friction forces** and how to solve problems that involve these forces.
- How to solve problems involving the forces that act on an object moving along a **circular path**.
- The relation between the four fundamental forces of nature.

Introduction

- Newton's three laws of motion can be stated very simply, but applying these laws to real-life situations requires analytical skills and problem-solving techniques.

- This chapter begins with equilibrium problems, in which we analyze the forces that act on an object that is at rest or moving with constant velocity.

- We'll then consider objects that are not in equilibrium, for which we'll have to deal with the relationship between forces and motion.

Using Newton's First Law When Forces Are in Equilibrium

- An object is in **equilibrium** when it is at rest or moving with constant velocity in an inertial frame of reference.

- The essential physical principle is Newton's first law:

Newton's first law:
Net force on an object ...

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

... must be *zero* for an **object in equilibrium.**

Sum of x-components of force on object must be zero.

$$\sum F_x = 0$$

Sum of y-components of force on object must be zero.

$$\sum F_y = 0$$

Problem-Solving Strategy for Equilibrium Situations (1 of 2)

- **Identify** the main concept: You must use Newton's first law.

- **Set up** the problem by using the following steps:

1. Draw a sketch of the physical situation.
2. Draw a free-body diagram for each object that is in equilibrium.
3. Ask yourself what is interacting with the object by contact or in any other way. If the mass is given, use $\boldsymbol{w = mg}$ to find the weight.
4. Check that you have only included forces that act <u>*on*</u> the object.
5. Choose a set of coordinate axes and include them in your free-body diagram.

Problem-Solving Strategy for Equilibrium Situations (2 of 2)

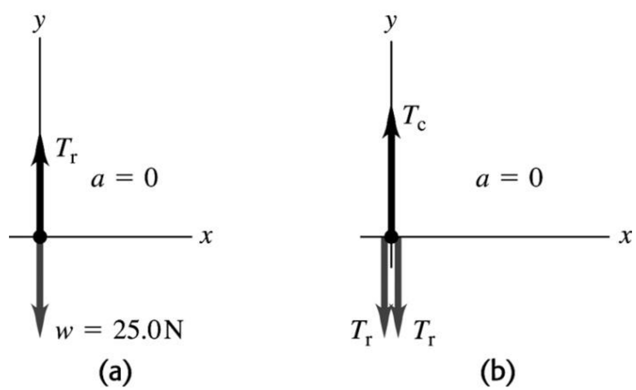
- **Execute** the solution as follows:

  1. Find the components of each force along each of the object's coordinate axes.
  2. Set the sum of all *x*-components of force equal to zero. In a separate equation, set the sum of all *y*-components equal to zero.
  3. If there are two or more objects, repeat all of the above steps for each object. If the objects interact with each other, use Newton's third law to relate the forces they exert on each other.
  4. Make sure that you have as many independent equations as the number of unknown quantities. Then solve these equations to obtain the target variables.

- **Evaluate** your answer.

Example Problem

- (5.1) Two 25 N weights are suspended at opposite ends of a rope that passes over a light, frictionless pulley. The pulley is attached to a chain from the celling. (a) What is the tension in the rope? (b) What is the tension in the chain?



<u>IDENTIFY</u>: *$a = 0$* for each object. To each weight and to the pulley apply:

$$\sum F_y = ma_y$$

<u>SET UP</u>: Take +y upward. The pulley has negligible mass. Let $\boldsymbol{T_r}$ be the tension in the rope and let $\boldsymbol{T_c}$ be the tension in the chain.

<u>EXECUTE</u>: **(a)** The free-body diagram for each weight is the same and is given in Figure (a). gives: $\boldsymbol{T_r = w = 25\ N}$.

(b) The free-body diagram for the pulley is given in Figure (b). $\boldsymbol{T_c = 2T_r = 50\ N}$

<u>EVALUATE</u>: The tension is the same at all points along the rope.

Using Newton's Second Law: Dynamics of Particles

- In **dynamics** problems, we apply Newton’s second law to objects on which the net force is **not** zero.
- These objects are **not** in equilibrium and hence are accelerating:

Newton’s second law: If the *net* force on an object is not zero ...

$$\sum \vec{F} = m\vec{a}$$

... the object has *acceleration* in the same direction as the net force.

Mass of object

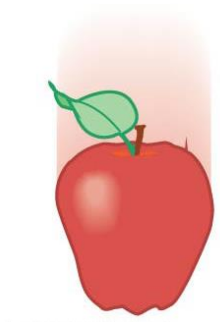
Each component of the net force on the object ...

$$\sum F_x = ma_x \qquad \sum F_y = ma_y$$

... equals the object’s mass times the corresponding acceleration component.

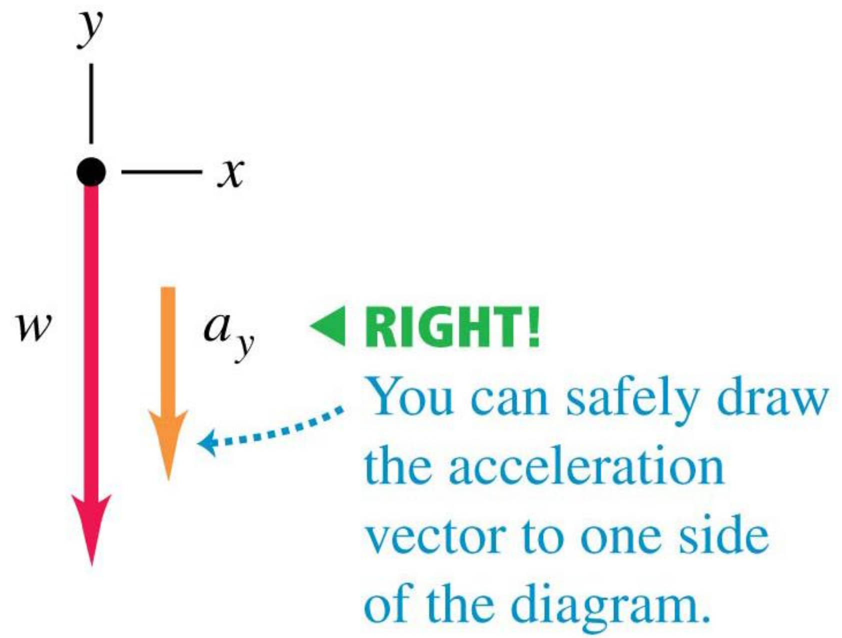
Setting Up Free Body Diagrams

- $m\vec{a}$ does **not** belong in a free-body diagram.

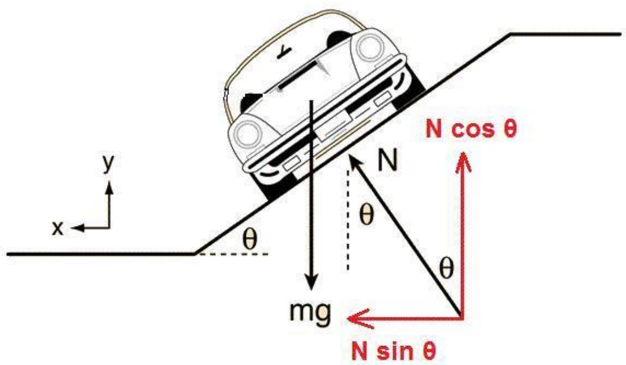


Only the force of gravity acts on this falling fruit.

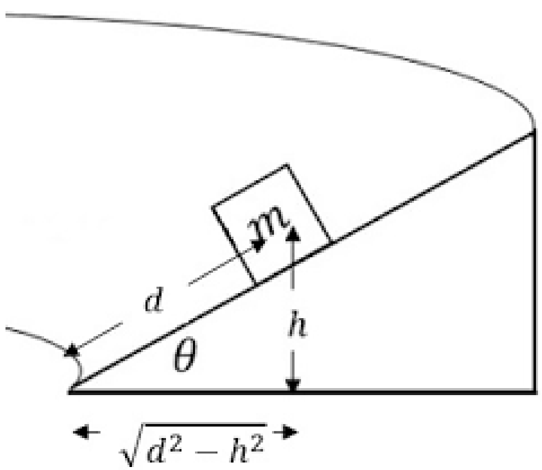
- Correct free-body diagram

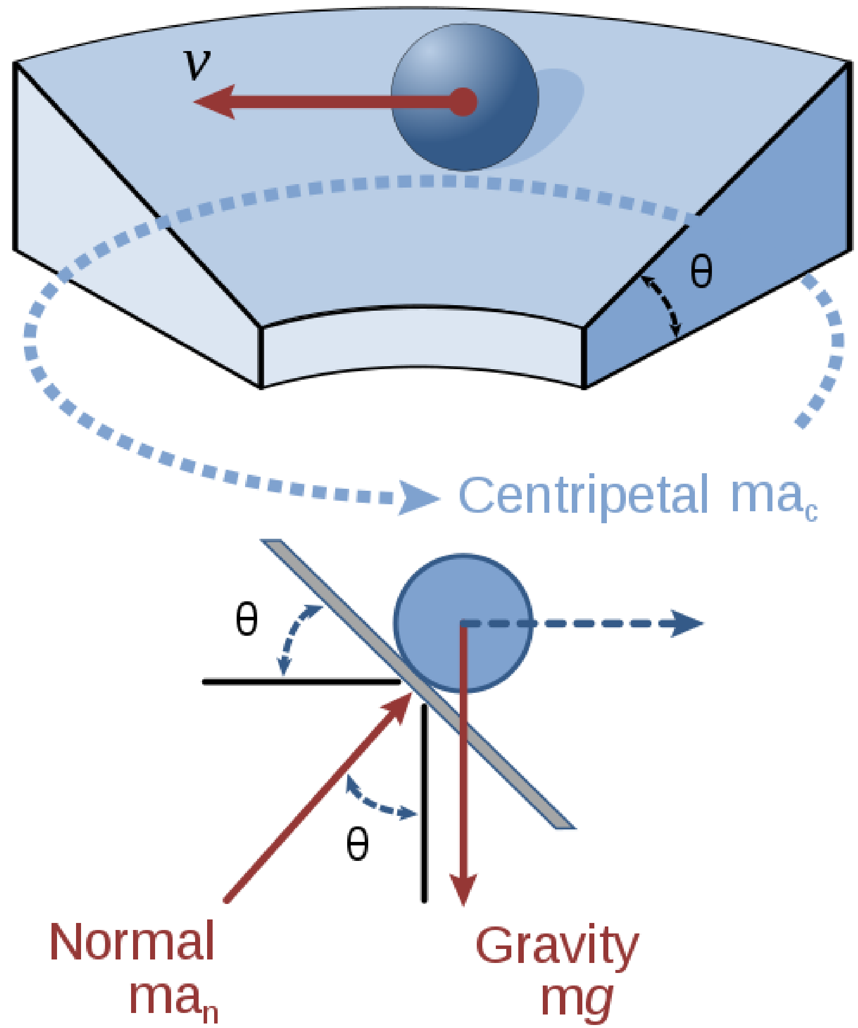


Setting up Dynamic FBD



Free Body Diagram





Problem-Solving Strategy for Dynamics Situations (1 of 2)

- **Identify** the relevant concept: You must use Newton's second law.
- **Set up** the problem by using the following steps:
  1. Draw a simple sketch of the situation that shows each moving object. For each object, draw a free-body diagram that shows all the forces acting **on** the object.
  2. Label each force. Usually, one of the forces will be the object's weight $\boldsymbol{w} = m\boldsymbol{g}$.
  3. Choose your *x*- and *y*-coordinate axes for each object, and show them in your free-body diagram.
  4. Identify any other equations you might need. If more than one object is involved, there may be relationships among their motions; for example, they may be connected by a rope.

Problem-Solving Strategy for Dynamics Situations (2 of 2)

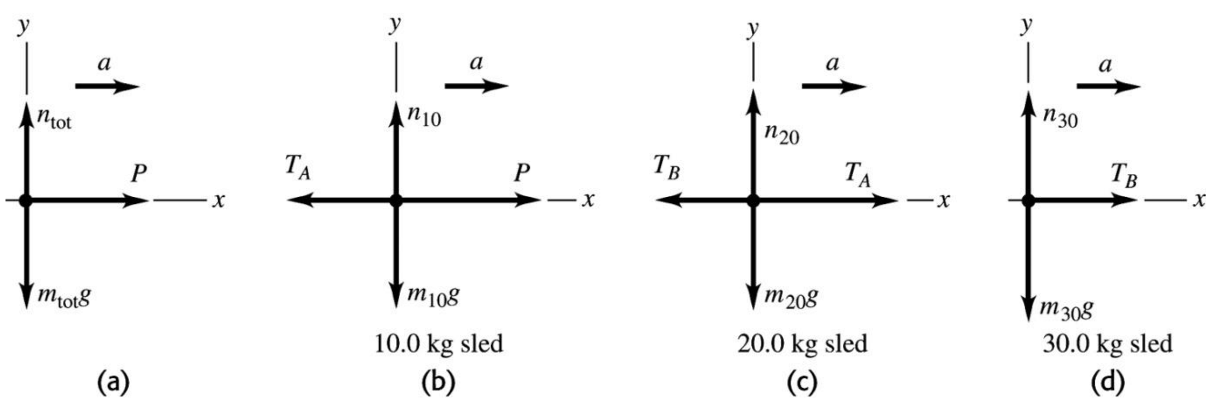
- **Execute** the solution as follows:
  1. For each object, determine the components of the forces along each of the object's coordinate axes.
  2. List all of the known and unknown quantities. In your list, identify the target variable or variables.
  3. For each object, write a separate equation for each component of Newton's second law. Write any additional equations that you identified in step 4 of "Set Up." (You need as many equations as there are target variables.)
  4. Do the easy part—the math! Solve the equations to find the target variable(s).
- **Evaluate** your answer.

Example Problem

- (5.14) Three sleds are being pulled horizontally on frictionless ice using ropes. The force of the pull is of magnitude 190 N. Find (a) the acceleration of the system, and (b) the tension in the ropes A and B.

IDENTIFY: Apply Newton's second law to the three sleds taken together as a composite object and to each individual sled. All three sleds have the same horizontal acceleration *a*.

SET UP: The free-body diagram for the three sleds taken as a composite object is given



Example continued

- **EXECUTE:** **(a)** for the three sleds as a composite object gives m_{tot} = 60 kg

$$\sum F_x = ma_x \quad \Rightarrow \quad a_x = \frac{F_x}{m_{tot}} = \frac{190\ N}{60\ kg} = \mathbf{3.17\ m/s^2}$$

- **EXECUTE:** **(b)** F = ma applied to the 10 kg sled yields $F_x - T_A = m_{10}a_x$

$$T_A = F_x - m_{10}a_x = (190\ N) - (10\ kg)\left(3.17\ \frac{m}{s^2}\right) = \mathbf{158\ N}$$

- **EXECUTE:** **(b)** F = ma applied to the 30 kg sled yields $F_x - T_A = m_{30}a_x$

$$T_B = F_x - m_{30}a_x = (190\ N) - (30\ kg)\left(3.17\ \frac{m}{s^2}\right) = \mathbf{95.1\ N}$$

EVALUATE: If we apply F = ma to the 20.0 kg sled and calculate *a* from T_A and T_B and found in part (b), we get

$$a = \frac{T_A - T_B}{m_{20}} = \frac{158\ N - 95.1\ N}{20\ kg} = \mathbf{3.15\ m/s^2}$$

Apparent Weight and Apparent Weightlessness

- When a passenger with mass m rides in an elevator with y-acceleration a_y, a scale shows the passenger's apparent weight to be:

$$n = m(g + a_y)$$

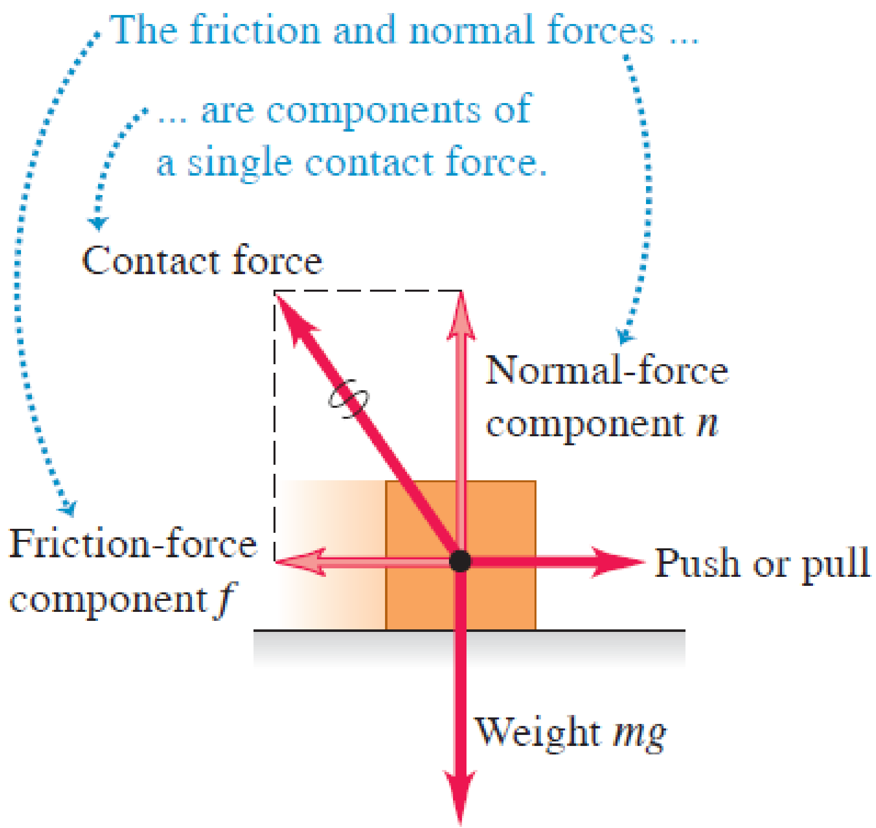
- The extreme case occurs when the elevator has a downward acceleration $a_y = -g$ … that is, when it is in free fall.
- In that case $n = 0$ and the passenger **seems** to be weightless.
- Similarly, an astronaut orbiting the earth with a spacecraft experiences **apparent weightlessness**.

Frictional Forces (1 of 3)

- There is friction between the feet of this caterpillar (the larval stage of a butterfly of the family Papilionidae) and the surfaces over which it walks.
- Without friction, the caterpillar could not move forward or climb over obstacles.

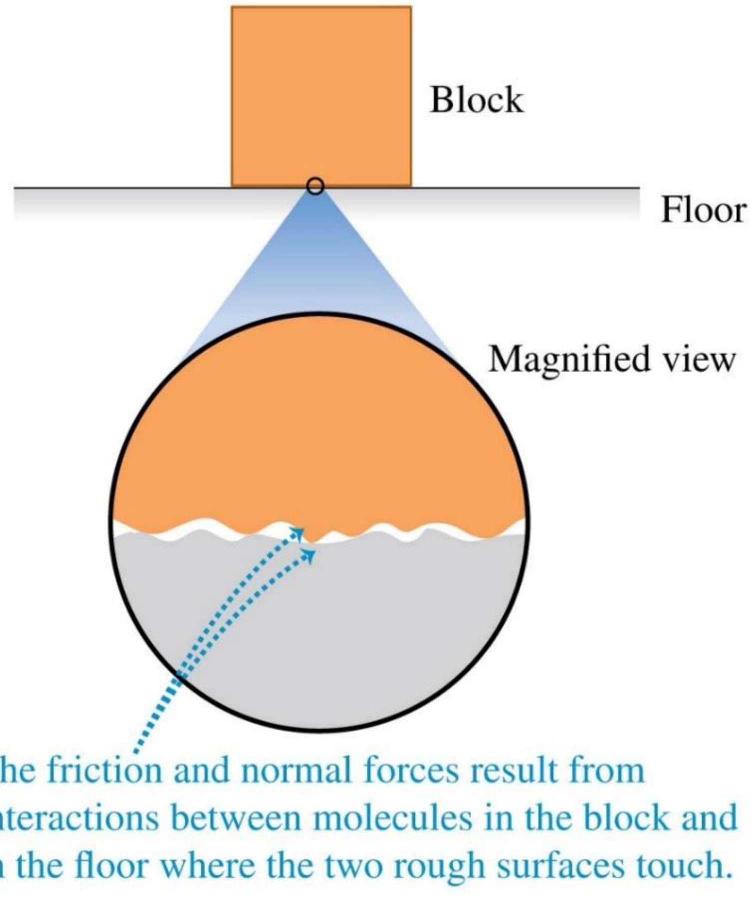
Frictional Forces (2 of 3)

- When an object rests or slides on a surface, the **friction force** is parallel to the surface.



Frictional Forces (3 of 3)

- Friction between two surfaces arises from interactions between molecules on the surfaces.



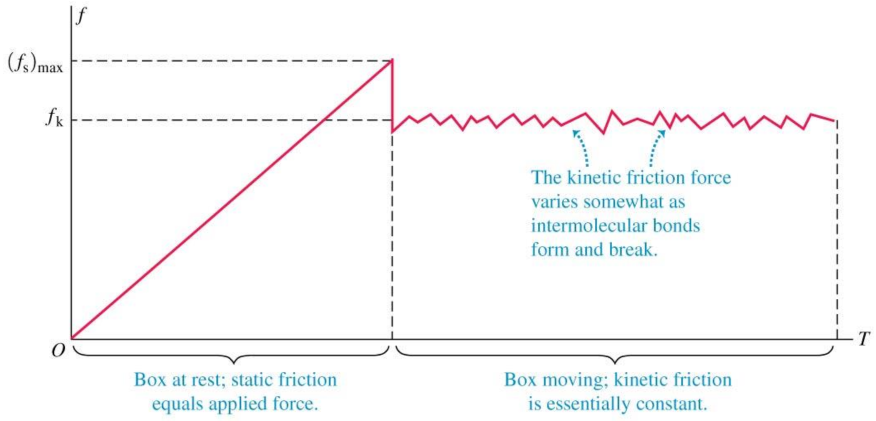
Kinetic "vs" Static Friction

- **Kinetic friction** acts when an object slides over a surface.

- The **kinetic friction force** is: $f_k = \mu_k n.$

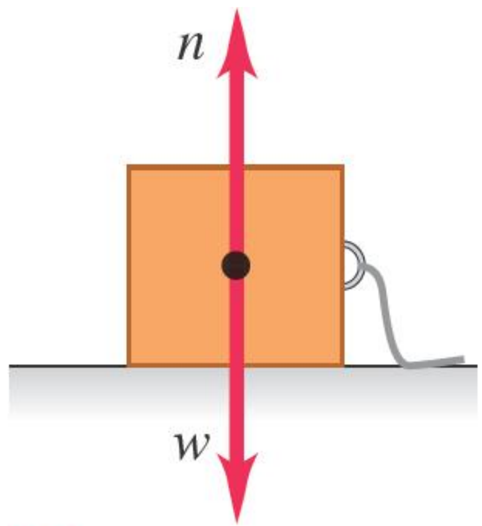
- The **static friction force** can vary between zero and its maximum value:

$$f_s \le \mu_s n.$$



Static Friction Followed by Kinetic Friction (1 of 5)

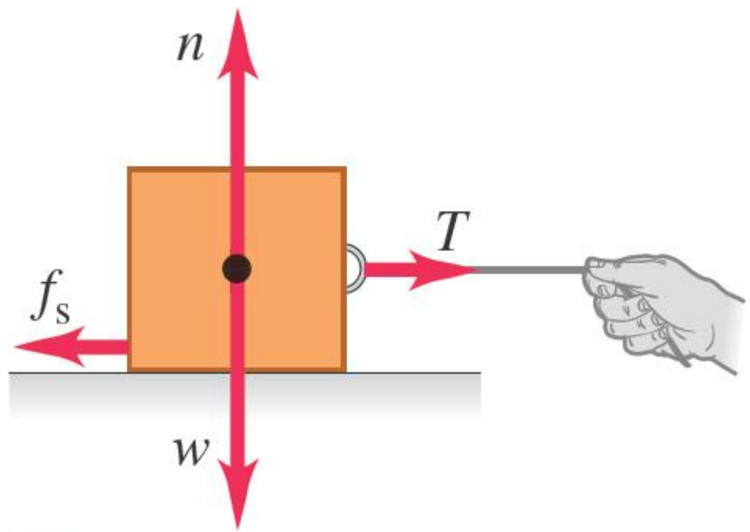
- Before the box slides, static friction acts. But once it starts to slide, kinetic friction acts.



1 No applied force, box at rest. No friction: $f_s = 0$

Static Friction Followed by Kinetic Friction (2 of 5)

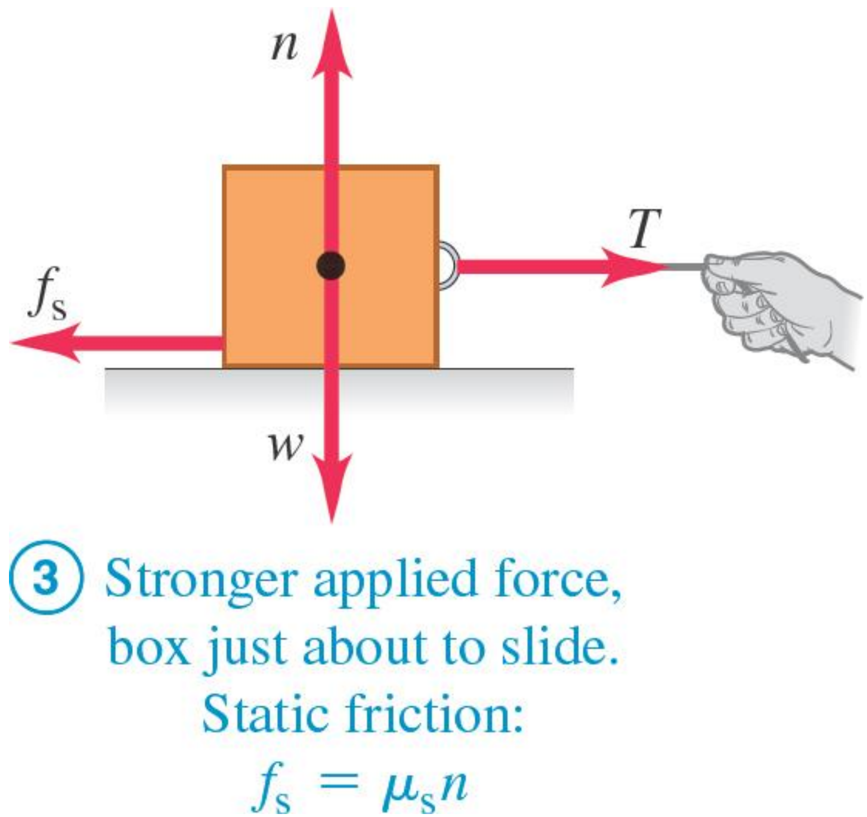
- The applied force must be greater than the static friction force before the box can slide. ($T < f_s$)



(2) Weak applied force, box remains at rest. Static friction: $f_s < \mu_s n$

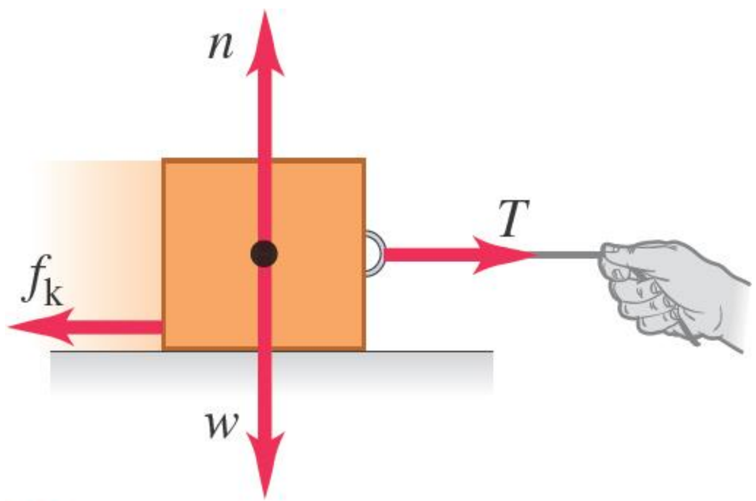
Static Friction Followed by Kinetic Friction (3 of 5)

- When T ≥ f_s the box begins to slide.



Static Friction Followed by Kinetic Friction (4 of 5)

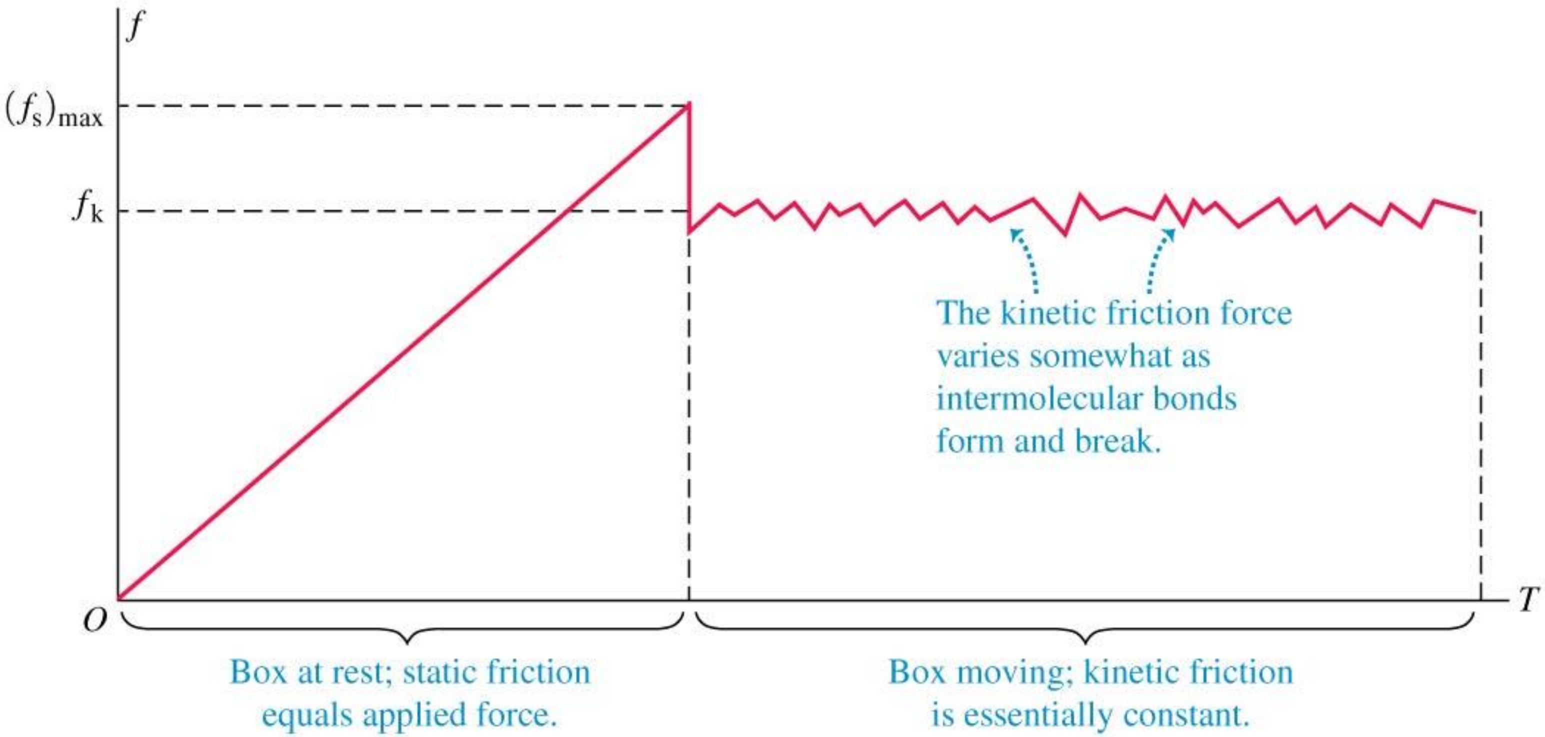
- Once the box starts to slide, kinetic friction acts… ($f_k < f_s$).



4 Box sliding at constant speed. Kinetic friction: $f_k = \mu_k n$

Static Friction Followed by Kinetic Friction (5 of 5)

- Before the box slides, static friction acts. But once it starts to slide, kinetic friction acts.



Some Approximate Coefficients of Friction

Materials	**Coefficient of Static Friction,**	**Coefficient of Kinetic Friction,**
Steel on steel	0.74	0.57
Aluminum on steel	0.61	0.47
Copper on steel	0.53	0.36
Brass on steel	0.51	0.44
Zinc on cast iron	0.85	0.21
Copper on cast iron	1.05	0.29
Glass on glass	0.94	0.40
Copper on glass	0.68	0.53
Teflon on Teflon	0.04	0.04
Teflon on steel	0.04	0.04
Rubber on concrete (dry)	1.0	0.8
Rubber on concrete (wet)	**0.30**	**0.25**

Static Friction and Windshield Wipers

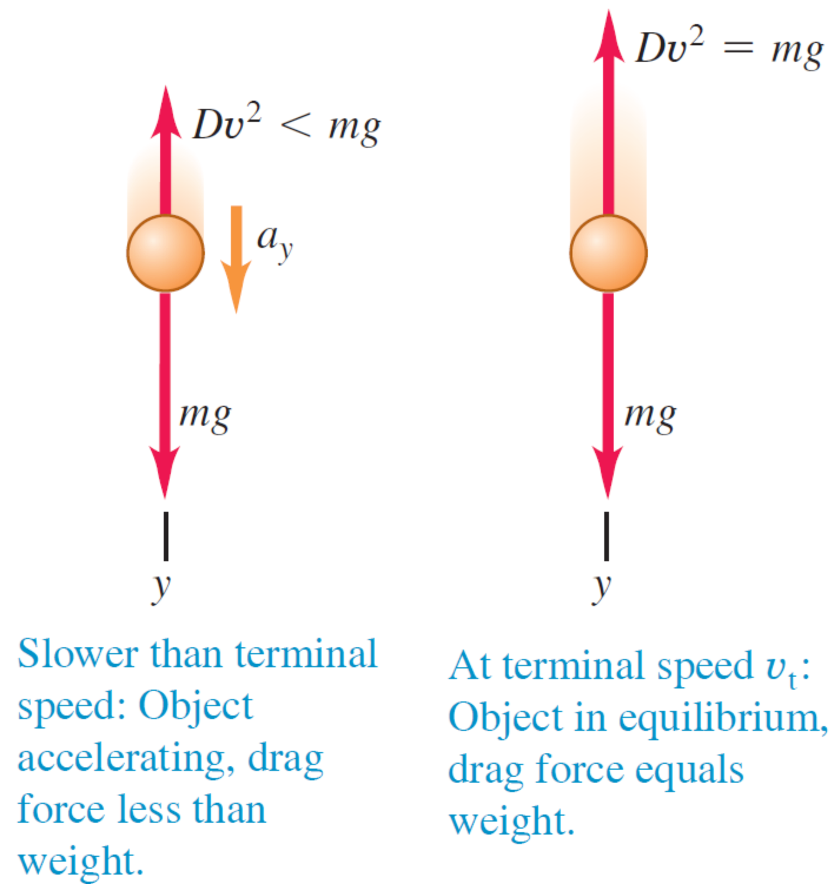
- The squeak of windshield wipers on dry glass is a “stick-slip” phenomenon.
- The moving wiper blade sticks to the glass momentarily, then slides when the force applied to the blade by the wiper motor overcomes the maximum force of static friction.
- When the glass is wet from rain or windshield cleaning solution, friction is reduced and the wiper blade doesn’t stick.

Fluid Resistance and Terminal Speed

(1 of 2)

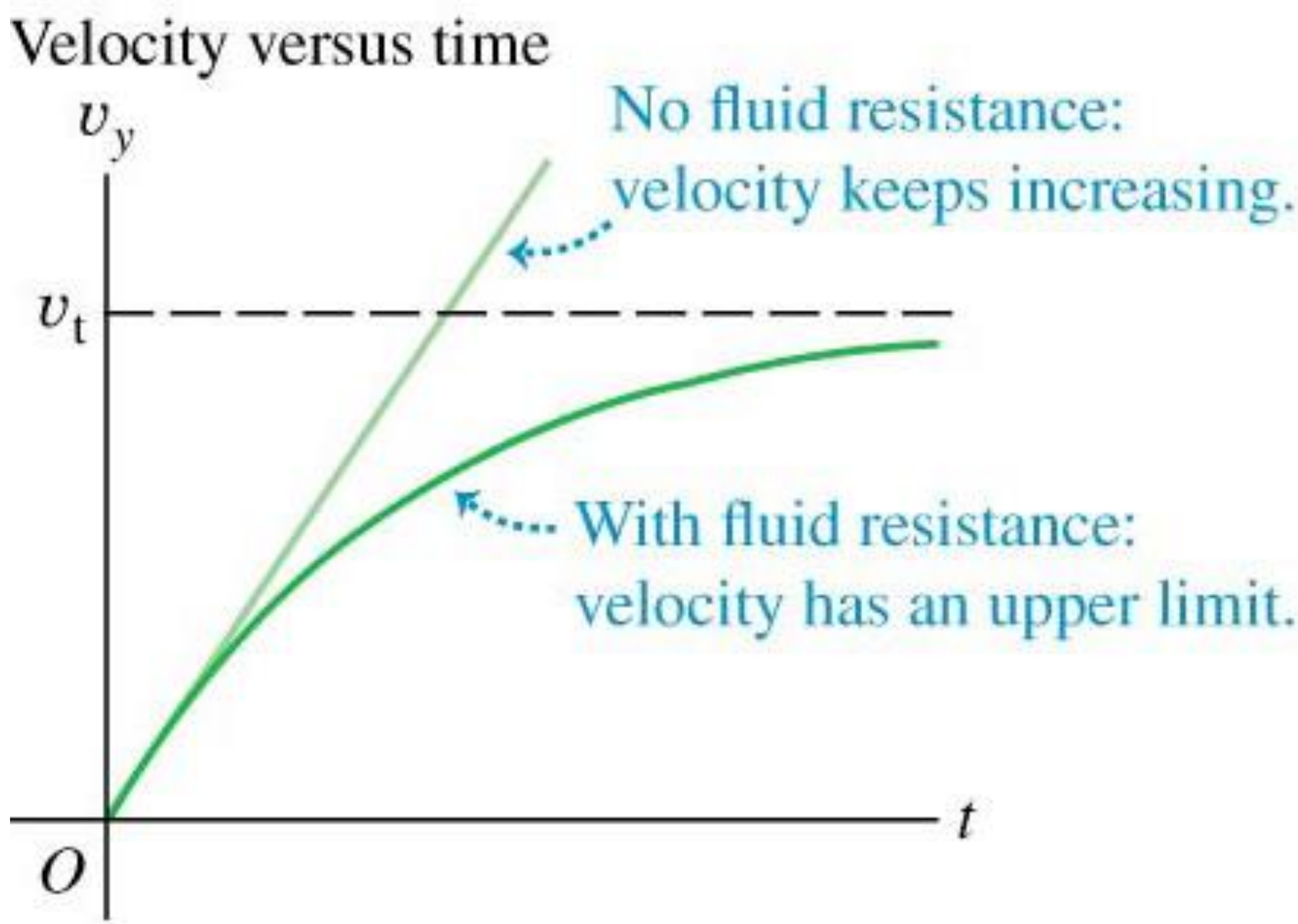
- The **fluid resistance** acting on an object depends on the speed of the object.
- A falling object reaches its **terminal speed** when the resisting force equals the weight of the object.
- The figures at the right illustrate the effects of air drag.

(a) Free-body diagrams for falling with air drag



Fluid Resistance and Terminal Speed

(2 of 2)

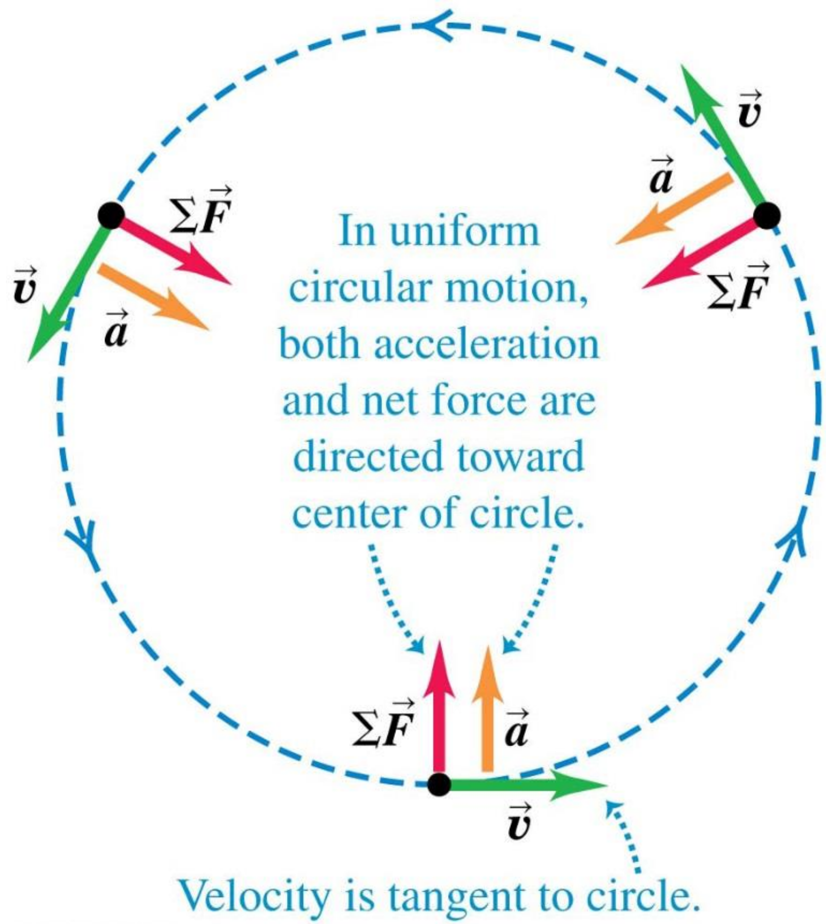


Dynamics of Circular Motion

- If a particle is in uniform circular motion, both its acceleration and the net force on it are directed toward the center of the circle.

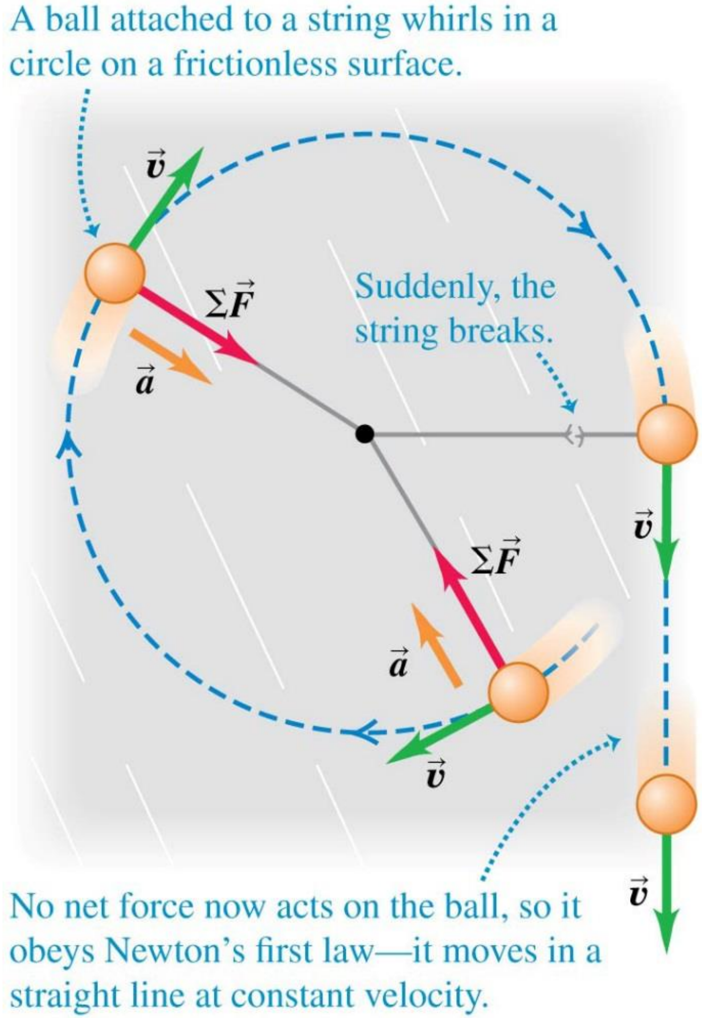
- The net force on the particle is:

$$F_{net} = \mathrm{m}a_{rad} = \frac{mv^2}{R}$$



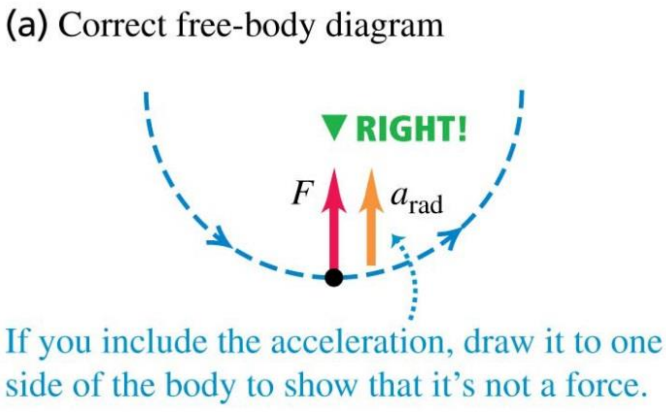
What If the String Breaks?

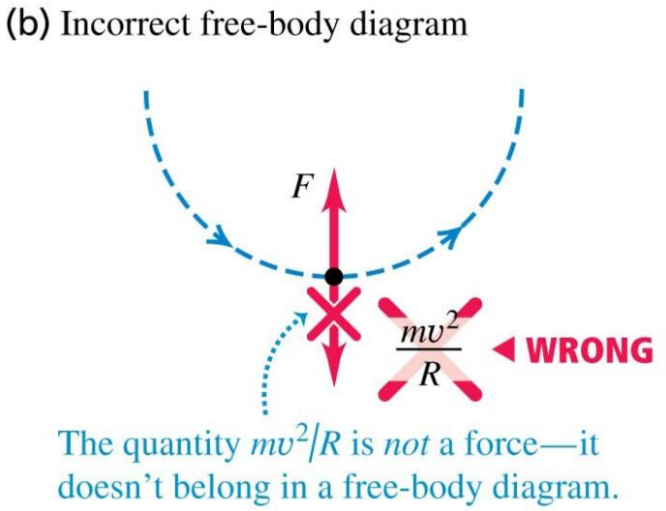
- If the string breaks, no net force acts on the ball, so it obeys Newton's first law and moves in a straight line.



Avoid Using "Centrifugal Force"

- Figure (a) shows the correct free-body diagram for an object in uniform circular motion.
- Figure (b) shows a common error.
- In an inertial frame of reference, there is no such thing as “centrifugal force”.

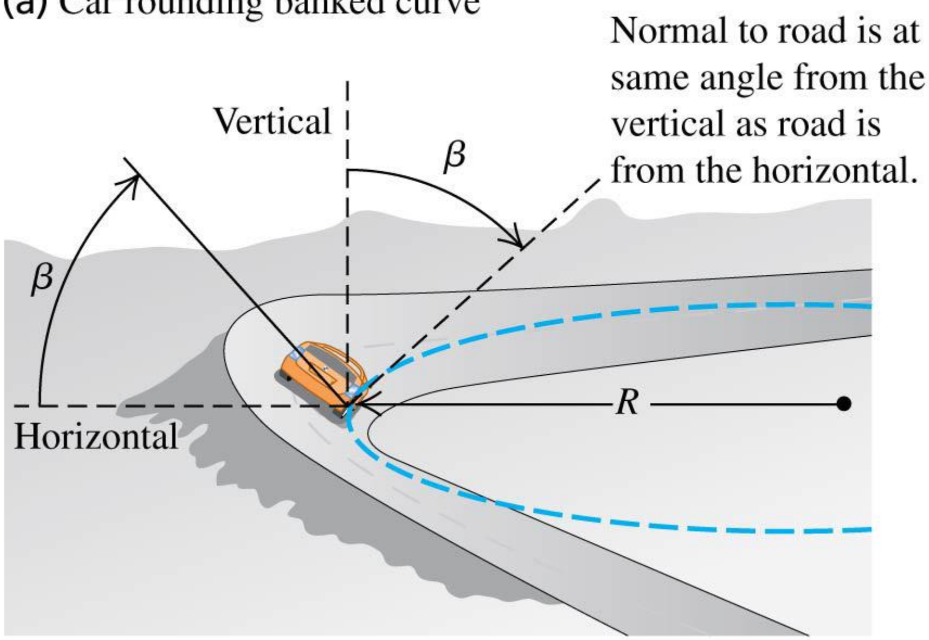




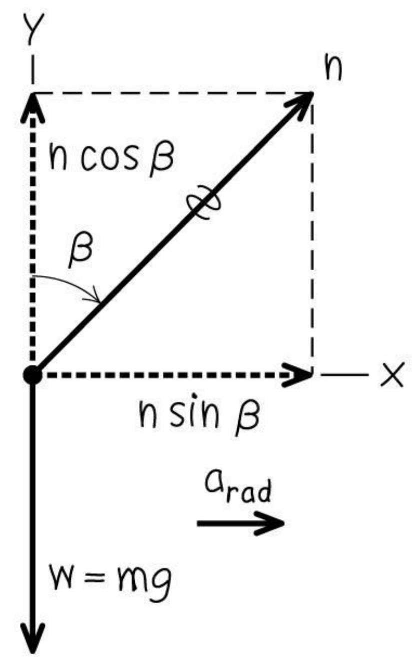
A Car Rounds a Banked Curve

- At what angle should a curve be banked so a car can make the turn even with no friction?
- Follow **Example 5.22**.

(a) Car rounding banked curve

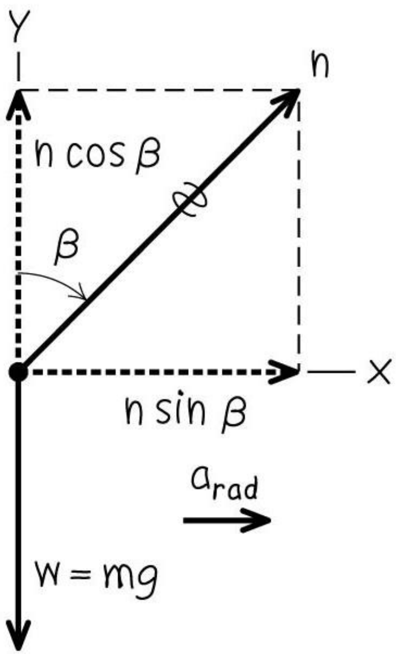


(b) Free-body diagram for car



Banked Curve…

(b) Free-body diagram for car



- The centripetal acceleration of the car in the x-direction: $\mathbf{a_{rad} = v^2/R}$, and none in y-direction. From Newton's second law:

$$\sum F_x = n\sin\beta = \mathrm{m}a_{rad}$$

$$\sum F_y = n\cos\beta\ - \mathrm{mg} = 0$$

- From second equation, n = mg/cosβ
- Plugging into first equation, we get

$$\left(\frac{mg}{cos\beta}\right)\sin\beta = \ \mathrm{m}a_{rad} \quad \Rightarrow \quad g\ tan\beta = \ a_{rad} = \frac{v^2}{R}$$

- Thus, we arrive at an expression for banked angle:

$$\beta = \ \tan^{-1}\left(\frac{a_{rad}}{g}\right) = \ \tan^{-1}\left(\frac{v^2}{gR}\right)$$

5.5 The Fundamental Forces of Nature

- According to current understanding, all forces are expressions of four (4) distinct **fundamental** forces:
  - **gravitational interactions**
  - **electromagnetic interactions**
  - the **strong interaction**
  - the **weak interaction**

Force	Direction	Range	Rel. strength	Acts on...
Electromagnetic	Attractive / repulsive	∞ $1/r^2$	$1/137$	Charged particles
Gravitational	Attractive	∞ $1/r^2$	10^{-38}	Particles w/ mass
Strong nuclear	Attractive < 3fm Repulsive < 0.5fm	3 fm	1	Quarks Gluons
Weak nuclear		10^{-18} m	10^{-6}	Quarks Leptons

Check out: https://www.youtube.com/watch?v=DjiD85iU1sU

FYI: Fundamental Forces…

- Physicists have taken steps to unify all force interactions into a “**Standard model**”.

$$Z = \int D(fields)e^{i\int d^4x \overbrace{\sqrt{-g}}^{\text{gravity}}\left(R - \underbrace{F_{\mu\nu}F^{\mu\nu}}_{\text{electromagnetic}} - \overbrace{G_{\mu\nu}G^{\mu\nu}}^{\text{strong force}} - \underbrace{W_{\mu\nu}W^{\mu\nu}}_{\text{weak force}} + \overbrace{\sum_i \Psi_i \mathfrak{D}\psi_i + D_\mu H^\dagger D^\mu \underset{\substack{\uparrow \\ \textbf{Higg's Boson} \\ \textbf{(2012)}}}{\boldsymbol{H}} - V(H) - \lambda_{ij}\Psi_i H\psi_j}^{\text{matter}}\right)}$$

- What about the **5th force** of nature?
  - Discovered by Fermi lab in 2021, it might help us explain what is “Dark” matter and energy??
  - It might give us an insight into why the Universe is expanding???

Check out: https://www.youtube.com/watch?v=jnqiTeNcsus