Week 5

Friction (Chapter 5, section 8)
& Circular Motion (Chapter 6, sections 1-2)

Lecture Quiz 1

You have a machine which can accelerate pucks on frictionless ice. Starting from rest, the puck travels a distance x in time t when force F is applied. If force $3F$ is applied, the distance the puck travels in time t is:

- **A.** x
- **B.** 1.5x
- **C.** $3x$
- **D.** 4.5x
- **E.** $9x$

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.

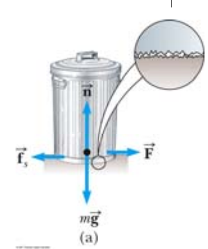
- Friction is proportional to the normal force
  - $f_s \le \mu_s n$ and $f_k = \mu_k n$
    - μ is the **coefficient of friction**
  - These equations relate the magnitudes of the forces, they are not vector equations
  - For static friction, the equals sign is valid only at *impeding* motion, the surfaces are on the verge of slipping
  - Use the inequality if the surfaces are not on the verge of slipping

Forces of Friction, final

- 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

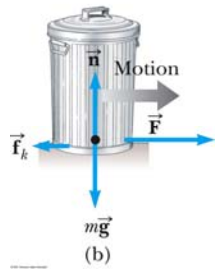
Static Friction

- Static friction acts to keep the object from moving
- If $\vec{F}$ increases, so does $\vec{f}_s$
- If $\vec{F}$ decreases, so does $\vec{f}_s$
- $f_s \le \mu_s n$
  - Remember, the equality holds when the surfaces are on the verge of slipping



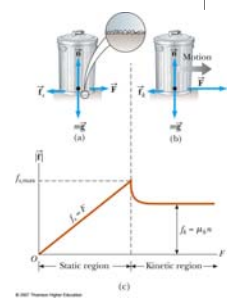
Kinetic Friction

- The force of kinetic friction acts when the object is in motion
- Although μ_k can vary with speed, we shall neglect any such variations
- $f_k = \mu_k n$



Explore Forces of Friction

- Vary the applied force
- Note the value of the frictional force
  - Compare the values
- Note what happens when the can starts to move



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

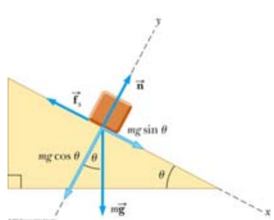
Note: All values are approximate. In some cases, the coefficient of friction can exceed 1.0.

Friction in Newton's Laws Problems

- Friction is a force, so it simply is included in the $\sum \vec{F}$ in Newton's Laws
- The rules of friction allow you to determine the direction and magnitude of the force of friction

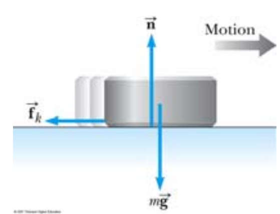
Friction Example, 1

- The block is sliding down the plane, so friction acts up the plane
- This setup can be used to experimentally determine the coefficient of friction
- $\mu = \tan \theta$
  - 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

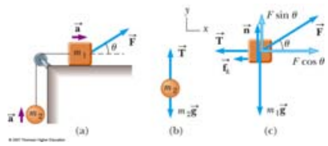


Friction, Example 2

- Draw the free-body diagram, including the force of kinetic friction
  - Opposes the motion
  - Is parallel to the surfaces in contact
- Continue with the solution as with any Newton's Law problem
- This example gives information about the motion which can be used to find the acceleration to use in Newton's Laws



Friction, Example 3



- Friction acts only on the object in contact with another surface
- Draw the free-body diagrams
- Apply Newton's Laws as in any other multiple object system problem

Clicker Question

Two blocks with different masses, M1=1kg, and M2=2kg,, slide with the same constant speed on a smooth surface, then move onto a surface having friction coefficient μ_k.

Which stops in the shorter time?

A. M_1
B. M_2
C. Both stop in the same time
D. Cannot be determined

Lecture Quiz 2

- Two people, each of 70 kg mass, are riding in an elevator. One is standing on the floor. The other is hanging on a rope suspended from the ceiling. Compare the force F1 the floor exerts on the first person to the force F2 the rope exerts on the second person. Which statement is correct?

A. They are equal and opposite in direction.
B. They are equal and have the same direction.
C. F1 is greater than F2 , but they have the same direction.
D. F1 is greater than F2 , but they have opposite directions.
E. F1 is less than F2 , but they have the same direction.

Uniform Circular Motion, Acceleration

- A particle moves with a constant speed in a circular path of radius r with an acceleration:

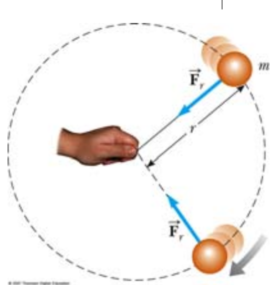
$$a_c = \frac{v^2}{r}$$

  - The centripetal acceleration, $\vec{\mathbf{a}}_c$ is directed toward the center of the circle
- The centripetal acceleration is always perpendicular to the velocity

Uniform Circular Motion, Force

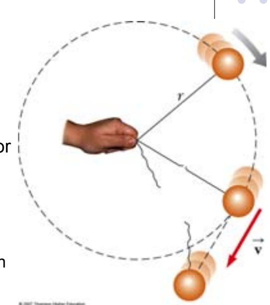
- A force, $\vec{\mathbf{F}}_r$, is associated with the centripetal acceleration
- The force is also directed toward the center of the circle
- Applying Newton's Second Law along the radial direction gives

$$\sum F = ma_c = m\frac{v^2}{r}$$



Uniform Circular Motion, cont

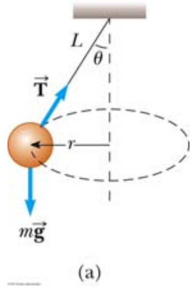
- A force causing a centripetal acceleration acts toward the center of the circle
- It causes a change in the direction of the velocity vector
- If the force vanishes, the object would move in a straight-line path ***tangent*** to the circle
  - See various release points in the active figure



Conical Pendulum

- The object is in equilibrium in the vertical direction and undergoes uniform circular motion in the horizontal direction
  - $\sum F_y = 0 \rightarrow T \cos \theta = mg$
  - $\sum F_x = T \sin \theta = m a_c$
- v is independent of m

$$v = \sqrt{Lg \sin\theta \tan\theta}$$



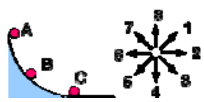
Motion in a Horizontal Circle

- The speed at which the object moves depends on the mass of the object and the tension in the cord
- The centripetal force is supplied by the tension

$$v = \sqrt{\frac{Tr}{m}}$$

Clicker Question

A small ball is released from rest at position A and rolls down a vertical circular track under the influence of gravity.



When the ball reaches position B, which of the indicated directions most nearly corresponds to the direction of the normal force on the ball?

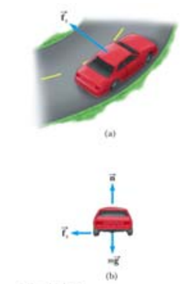
A. 1
B. 2
C. 3
D. 4
E. 5

Horizontal (Flat) Curve

- The force of static friction supplies the centripetal force
- The maximum speed at which the car can negotiate the curve is

$$v = \sqrt{\mu_s g r}$$

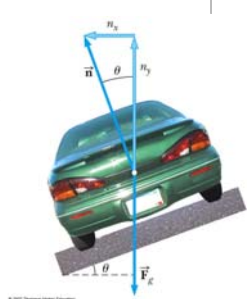
  - Note, this does not depend on the mass of the car



Banked Curve

- These are designed with friction equaling zero
- There is a component of the normal force that supplies the centripetal force

$$\tan\theta = \frac{v^2}{rg}$$



Banked Curve, 2

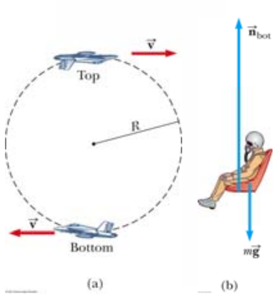
- The banking angle is independent of the mass of the vehicle
- If the car rounds the curve at less than the design speed, friction is necessary to keep it from sliding down the bank
- If the car rounds the curve at more than the design speed, friction is necessary to keep it from sliding up the bank

Loop-the-Loop

- This is an example of a vertical circle
- At the bottom of the loop (b), the upward force (the normal) experienced by the object is greater than its weight

$$\sum F = n_{bot} - mg = \frac{mv^2}{r}$$

$$n_{bot} = mg\left(1 + \frac{v^2}{rg}\right)$$

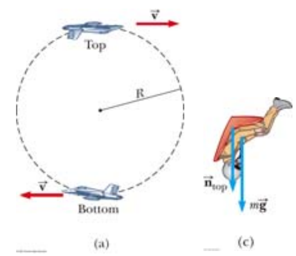


Loop-the-Loop, Part 2

- At the top of the circle (c), the force exerted on the object is less than its weight

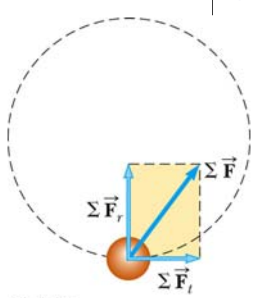
$$\sum F = n_{top} + mg = \frac{mv^2}{r}$$

$$n_{top} = mg\left(\frac{v^2}{rg} - 1\right)$$



Non-Uniform Circular Motion

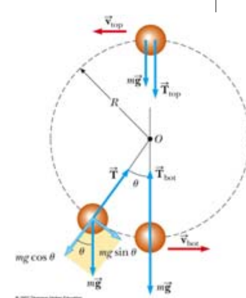
- The acceleration and force have tangential components
- $\vec{\mathbf{F}}_r$ produces the centripetal acceleration
- $\vec{\mathbf{F}}_t$ produces the tangential acceleration
- $\sum \vec{\mathbf{F}} = \sum \vec{\mathbf{F}}_r + \sum \vec{\mathbf{F}}_t$



Vertical Circle with Non-Uniform Speed

- The gravitational force exerts a tangential force on the object
  - Look at the components of F_g
- The tension at any point can be found

$$T = mg\left(\frac{v^2}{Rg} + \cos\theta\right)$$



Top and Bottom of Circle

- The tension at the bottom is a maximum

$$T = mg\left(\frac{v_{bot}^2}{Rg} + 1\right)$$

- The tension at the top is a minimum

$$T = mg\left(\frac{v_{top}^2}{Rg} - 1\right)$$

- If $T_{top} = 0$, then $v_{top} = \sqrt{gR}$