PHY131H1F Summer – Class 5

Today:
- Equilibrium
- Mass, Weight, Gravity
- Friction, Drag
- Rolling without slipping
- Examples of Newton's Second Law

Pre-class Reading Quiz. (Chapter 6)

Which of the following objects described below is in *dynamic equilibrium*?

A. A 100 kg barbell is held over your head.
B. A girder is lifted at constant speed by a crane.
C. A baseball is flying through the air and air resistance is negligible.
D. A girder is being lowered into place. It is slowing down.
E. A box in the back of a truck doesn't slide as the truck stops.

Pre-class Reading Quiz. (Chapter 6)

Which of the following types of friction is NOT part of your chapter 6 reading?

A. Drag
B. Internal friction
C. Kinetic friction
D. Rolling friction
E. Static friction

Last day I asked at the end of class:

A basketball and a tennis ball are in freefall.

1. Which, if either, has the larger **mass**?

ANSWER: The basketball.

2. Which, if either, experiences the larger **force of gravity**?

ANSWER: The basketball. ($F_g = mg$)

3. Which, if either, experiences the larger **acceleration**?

ANSWER: Neither. $a_y = -g$ for both.

4. Which, if either, has the larger **weight**?

ANSWER: Neither. They are both "weightless".

Preparation for Practicals next Tuesday:

- Take a ride on the Burton Tower elevators!
- All 4 elevators in the 14-storey tower of McLennan Physical Labs are equipped with a hanging spring-scale.
- It measures the upward force necessary to support a 500 g mass. (a.k.a. "weight")
- You may find that the measured weight of this object changes as you accelerate – check it out!

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

- An important problem solving technique is to identify when an object is in equilibrium.
- An object has zero acceleration if and only if the net force on it is zero.
- This is called "equilibrium".
- If an object is in **vertical equilibrium** (ie it is confined to a stationary horizontal surface) then $(F_{net})_y = 0$. The sum of y-components of all forces = 0.
- If an object is in **horizontal equilibrium** (ie freefall) then $(F_{net})_x = 0$.

Gravity for the universe

It was Newton who first recognized that **gravity is an attractive, long-range force between *any* two objects.** Somewhat more loosely, gravity is a force that acts on mass. When two objects with masses m_1 and m_2 are separated by distance r, each object pulls on the other with a force given by Newton's law of gravity, as follows:

$$F_{1\text{ on }2} = F_{2\text{ on }1} = \frac{Gm_1m_2}{r^2} \qquad \text{(Newton's law of gravity)}$$

(Sometimes called "Newton's 4th Law", or "Newton's Law of Universal Gravitation")

Gravity for Earthlings

If you happen to live on the surface of a large planet with radius R and mass M, you can write the gravitational force even more simply as

$$\vec{F}_G = (mg, \text{straight down}) \qquad \text{(gravitational force)}$$

where the quantity g is defined to be:

$$g = \frac{GM}{R^2}$$

Gravity: $F_G = mg$ is just a short form!

$$F_{1\text{ on }2} = F_{2\text{ on }1} = \frac{Gm_1m_2}{r^2}$$

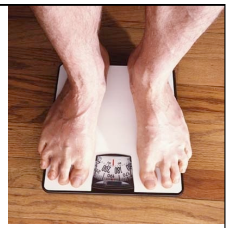
and

$$\vec{F}_G = (mg, \text{straight down})$$

are the same equation, with different notation!

The only difference is that in the second equation we have assumed that $m_2 = M$ (mass of the earth) and $r \approx R$ (radius of the earth).

Weight ≠ Weight ??!?



- Physics textbooks and physics teachers do not all agree on the definition of the word “weight”!
- Sometimes “weight” means the exact same thing as “force of gravity”. That is ***not*** how Randall Knight uses the word. (I will follow Knight’s definitions.)
- In Knight, “weight” means the magnitude of the *upward* force being used to support an object.
- If the object is at rest or moving at a constant velocity relative to the earth, then the object is in equilibrium. The upward supporting force exactly balances the downward gravitational force, so that weight = mg.

Weight - example

- When I stand on a scale in my bathroom it reads 185 pounds. 2.2 pounds = 9.8 Newtons, so this means the upward force on my feet when I am standing still is 185 lbs (9.8 N / 2.2 lbs) = 824 N.
- If I ride an elevator which is accelerating upward at 1.5 m/s^2, what is the upward force on my feet?
- [Take a wild guess first: **A:** 824 N, **B:** 950 N, **C:** 698 N, **D:** 0 N, **E:** –824 N]

Knight’s Definition of weight, page 161:

The **weight** of an object is the reading of a calibrated spring scale on which the object is stationary. Weight is the result of weighing. The weight of an object with vertical acceleration a_y is

$$w = mg\left(1 + \frac{a_y}{g}\right)$$

Spring scale on an elevator

You are attempting to pour out 1.0 kg of flour, using a kitchen scale on an elevator which is accelerating upward at 1.5 m/s^2.

The amount of flour you pour will be

A. too much.
B. too little.
C. the correct amount.

Pan balance on an elevator

You are attempting to pour out 1.0 kg of flour, using a pan balance on an elevator which is accelerating upward at 1.5 m/s^2.

The amount of flour you pour will be

A. too much.
B. too little.
C. the correct amount.

What is the equation for normal force?

A. $\vec{n} = mg$, upward
B. $\vec{n} = mg$, downward
C. $\vec{n} = mg\sin\theta$, perpendicular to surface
D. $\vec{n} = mg\cos\theta$, perpendicular to surface
E. There is no generally applicable equation for normal force.

Normal Force is Not always mg !

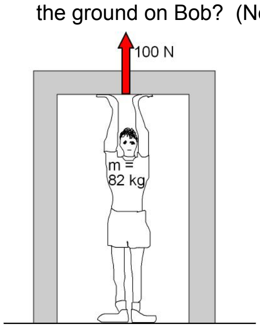
- Gravity, F_G, has an equation for it which predicts the correct magnitude (it's always mg here on Earth).
- Normal force, Tension and Static friction are all self-adjusting forces: ***there is no equation for these!!***
- Normal force is whatever is needed to keep the object from crashing through the surface.
- Tension is whatever is needed to keep the string or rope from breaking.
- Static friction is whatever is needed to keep the object from slipping along the surface.
- In all these cases, you must draw a free-body diagram and figure out by using equilibrium and Newton's 2nd law what the needed force is.

Getting the piano on the truck

- A piano has a mass of 225 kg.

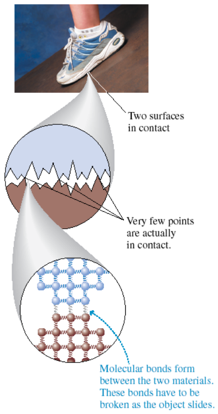
1. What force is required to push the piano upwards at a constant velocity as you lift it into the truck?
2. What force is required to push the piano up a frictionless ramp at a constant velocity into the truck? Assume the ramp is 3.00 m long and the floor of the truck is 1.00 m high? What is the normal force of the ramp on the piano?

Bob stands under a low concrete arch, and presses upwards on it with a force of 100 N. Bob's mass is 82 kg. He is in equilibrium. What is the total **normal force** of the ground on Bob? (Note that 82 × 9.8 = 800.)



A. 800 N, upward
B. 800 N, downward
C. 900 N, upward
D. 700 N, upward
E. 900 N, downward

FIGURE 6.19 An atomic-level view of friction.

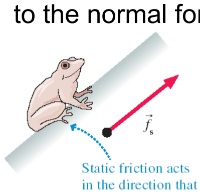


Which is true? “Friction

A. always causes objects to slow down.”
B. always causes objects to speed up.”
C. can cause objects to speed up or slow down, depending on the situation.”

“Static Friction” $\vec{f}_s$

- When two flat surfaces are in contact but are not moving relative to one another, they tend to resist slipping. They have “locked” together. This creates a force perpendicular to the normal force, called static friction.

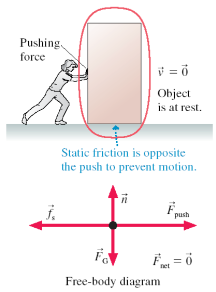


There is no general equation for f_s.

The direction of f_s is whatever is required to prevent slipping.

Static Friction

FIGURE 6.11 Static friction keeps an object from slipping.



The box is in static equilibrium, so the static friction must exactly balance the pushing force:

$$f_s = F_{push}$$

This is not a general, "all-purpose" equation. It is found from looking at the free body diagram and applying horizontal equilibrium, since $a_x = 0$.

Static Friction

There's a limit to how big f_s can get. If you push hard enough, the object slips and starts to move. In other words, the static friction force has a *maximum* possible size $f_{s\,max}$.

- The two surfaces don't slip against each other as long as $f_s \leq f_{s\,max}$.
- A static friction force $f_s > f_{s\,max}$ is not physically possible. Many experiments have shown the following approximate relation usually holds:

$$f_{s\,max} = \mu_s n$$

where n is the magnitude of the normal force, and the proportionality constant μ_s is called the "coefficient of static friction".

A wooden block weighs 100 N, and is sitting stationary on a smooth horizontal concrete surface. The coefficient of static friction between wood and concrete is 0.2. A 5 N horizontal force is applied to the block, pushing toward the right, but the block does not move. What is the force of static friction of the concrete on the block?

A. 100 N, to the left
B. 20 N, to the left
C. 5 N, to the left
D. 20 N, to the right
E. 5 N, to the right

A wooden block weighs 100 N, and is sitting stationary on a smooth horizontal concrete surface. The coefficient of static friction between wood and concrete is 0.2. A horizontal force is applied to the block, pushing toward the right. What is the maximum pushing force you can apply and have the block remain stationary?

A. 200 N
B. 100 N
C. 20 N
D. 10 N
E. 5 N

"Kinetic Friction" $\vec{f}_k$

- Also called "sliding friction"
- When two flat surfaces are in contact and sliding relative to one another, heat is created, so it slows down the motion (kinetic energy is being converted to thermal energy).

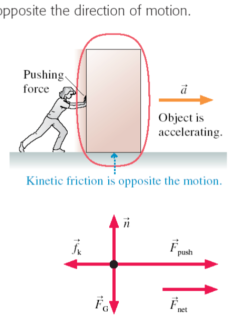
$$f_k = \mu_k n$$

where n is the normal force.

The direction of f_k is opposite the direction of motion.

Kinetic Friction

FIGURE 6.13 The kinetic friction force is opposite the direction of motion.



The kinetic friction force is proportional to the magnitude of the normal force. Many experiments show the following approximate relation:

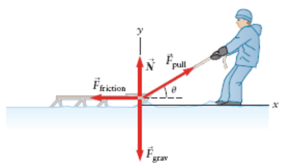
$$f_k = \mu_k n$$

where n is the magnitude of the normal force, and the proportionality constant μ_k is called the "coefficient of kinetic friction".

A wooden block weighs 100 N, and is sliding to the right on a smooth horizontal concrete surface at a speed of 5 m/s. The coefficient of kinetic friction between wood and concrete is 0.1. A 5 N horizontal force is applied to the block, pushing toward the right. What is the force of kinetic friction of the concrete on the block?

A. 100 N, to the left
B. 10 N, to the left
C. 5 N, to the left
D. 10 N, to the right
E. 5 N, to the right

Example



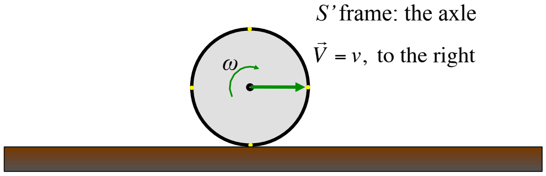
- A sled of mass 5.0 kg is pulled at a constant velocity by a rope which makes an angle of 20.0° above the horizontal. The coefficient of kinetic friction between the sled and the snow is 0.030. What is the tension in the rope? (F_{pull} in the diagram)

Rolling without slipping

S frame: the ground

S' frame: the axle

$\vec{V} = v$, to the right



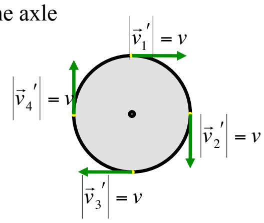
The wheel rotates with angular speed ω.

The tangential speed of a point on the rim is $v = \omega r$, relative to the axle.

In "rolling without slipping", the axle moves at speed v. This is the S' frame.

Rolling without slipping

S' frame: the axle



$v = \omega r$ is the tangential speed of any point on the rim.

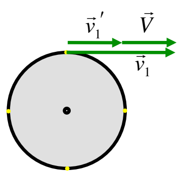
$\vec{V} = v$, to the right

$V = \omega r$ is the speed of the *S'* frame relative to the ground.

Rolling without slipping

Point 1: Top of the wheel

$$\vec{v} = \vec{v}' + \vec{V}$$



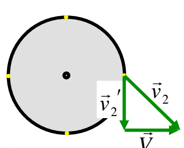
$$|\vec{v}_1| = |\vec{v}_1{}' + \vec{V}| = v + v = 2v = 2\omega r$$

In *S* frame (the ground), the top point moves at speed $2v = 2\omega r$

Rolling without slipping

Point 2: right-side of the wheel

$$\vec{v} = \vec{v}' + \vec{V}$$



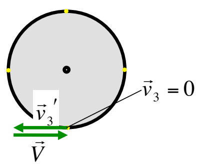
$$|\vec{v}_2| = |\vec{v}_2{}' + \vec{V}| = \sqrt{v^2 + v^2} = \sqrt{2}v = \sqrt{2}\omega r$$

In *S* frame (the ground), the right side of the wheel is moving on a diagonal down and to the right.

Rolling without slipping

Point 3: Bottom of the wheel

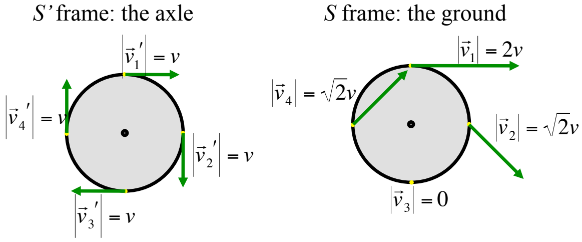
$\vec{v} = \vec{v}' + \vec{V}$



$$|\vec{v}_3| = |\vec{v}_3' + \vec{V}| = v - v = 0$$

In *S* frame (the ground), the bottom point is at rest.

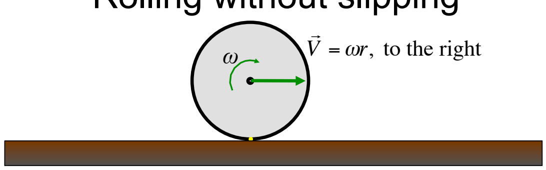
Rolling without slipping



$\vec{V} = v$, to the right

$$\vec{v} = \vec{v}' + \vec{V}$$

Rolling without slipping



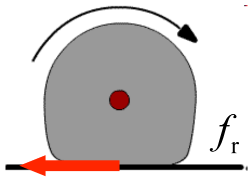
The wheel rotates with angular speed ω.

The axle moves with linear speed $v = \omega r$., where r is the radius of the wheel.

Since the bottom point is always at rest, it is *static friction* which acts between the ground and the wheel.

Rolling Friction (a type of kinetic friction)

- Due to the fact that the wheel is soft, and so is the surface upon which it is rolling. Plowing effect produces a force which slows down the rolling.
- Transportation engineers call μ_r the *tractive resistance*.
- Typical values of μ_r are 0.002 for steel wheels on steel rails, and 0.02 for rubber tires on concrete.



$$f_r = \mu_r n$$

TABLE 6.1 Coefficients of friction

Materials	Static μ_s	Kinetic μ_k	Rolling μ_r
Rubber on concrete	1.00	0.80	0.02
Steel on steel (dry)	0.80	0.60	0.002
Steel on steel (lubricated)	0.10	0.05	
Wood on wood	0.50	0.20	
Wood on snow	0.12	0.06	
Ice on ice	0.10	0.03	

- Problem 6.23: A 50,000 kg locomotive is traveling at 10 m/s when its engine and brakes both fail. How far will the locomotive roll before it comes to a stop?

Drag force in a fluid, such as air

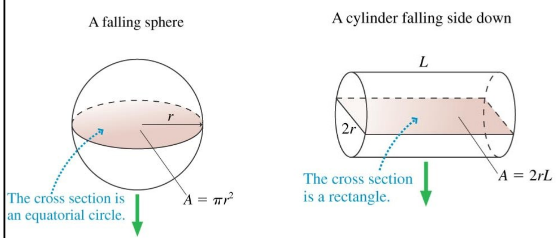
- Air resistance, or drag, is complex and involves fluid dynamics.
- For objects on Earth, with speeds between 1 and 100 m/s and size between 1 cm and 2 m, there is an approximate equation which predicts the magnitude of air resistance

$$D = (0.25\ \text{kg/m}^3)Av^2$$

where A is the cross-sectional area of the object, and v is the speed.

- The direction of air resistance, or Drag Force, is opposite to the direction of motion.
- It depends on size and shape, but not mass.

Cross Sectional Area depends on size, shape, and direction of motion.



…Consider the forces on a falling piece of paper, crumpled and not crumpled.

Ch.6 force summary

Specific information about three important forces:

Gravity $\vec{F}_G = (mg, \text{downward})$

Friction $\vec{f}_s = (0 \text{ to } \mu_s n, \text{direction as necessary to prevent motion})$

$\vec{f}_k = (\mu_k n, \text{direction opposite the motion})$

$\vec{f}_r = (\mu_r n, \text{direction opposite the motion})$

Drag $\vec{D} \approx (\frac{1}{4}Av^2, \text{direction opposite the motion})$

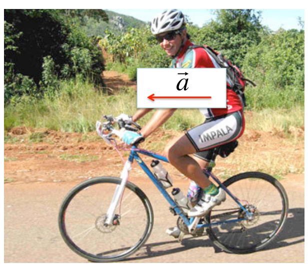
Analyzing problems in segments

- The equations of chapters 1-6 help us solve problems in which the acceleration is constant.
- Sometimes the acceleration changes abruptly.
- In this case, divide the motion into segments: 1, 2, 3, …
- The final position and velocity of segment 1 become the initial position and velocity of segment 2, etc…
- Solve using the equations of constant acceleration for each segment.

4 quizzes in a set. [1 / 4]

- A cyclist is pushing on his pedals, and therefore accelerating to the left.
- What is the direction of the force of static friction of the ground on the back wheel?

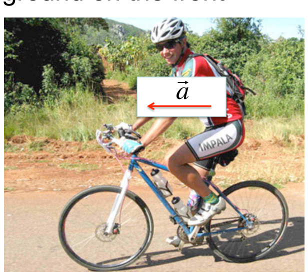
A. Left
B. Right
C. Up
D. Down
E. zero



4 quizzes in a set. [2 / 4]

- A cyclist is pushing on his pedals, and therefore accelerating to the left.
- What is the direction of the force of static friction of the ground on the front wheel?

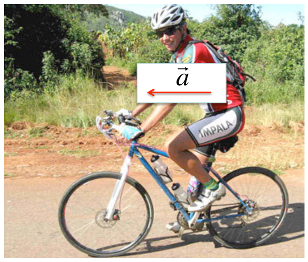
A. Left
B. Right
C. Up
D. Down
E. zero



4 quizzes in a set. [3 / 4]

- A cyclist is pushing on his pedals, and therefore accelerating to the left.
- What is the direction of the force of rolling friction of the ground on the back wheel?

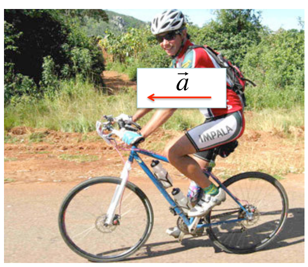
A. Left
B. Right
C. Up
D. Down
E. zero



4 quizzes in a set. [4 / 4]

- A cyclist is pushing on his pedals, and therefore accelerating to the left.
- What is the direction of the force of rolling friction of the ground on the front wheel?

A. Left
B. Right
C. Up
D. Down
E. zero



Test on Thursday evening

- Test will be Thursday, June 2 from 6:10pm to 8:00pm in EX100.
- There are no practicals that day, nor is there a class in BA1160.
- Test will cover Chs.1-6, the Error Analysis Document and Practicals Sessions 1-4 Material.
- Please bring a non-communicating calculator and a single 2-sided 8.5"x11" **aid sheet** which **you** have prepared yourself with helpful equations, etc.
- I will provide any numerical constants you may need on the test.