physics

FOR SCIENTISTS AND ENGINEERS

a strategic approach

THIRD EDITION

randall d. knight

Chapter 5 Force and Motion

Chapter Goal: To establish a connection between force and motion.

Ch 5: Forces

In the first four chapters, we have concentrated on answering the question:

How do things move? Answer: Kinematics

$$\vec{v} = \frac{d\vec{r}}{dt}$$

$$\vec{a} = \frac{d\vec{v}}{dt}$$

Now, we want to begin to address the question:

Why do things move? Answer: Dynamics
(What causes an acceleration?)

Kinematics + Dynamics = Mechanics

First, in this chapter, we'll develop some basic concepts, then in Chapter 6, we'll take up the details in 1D, and then finally in 2D (Chapter 8).

OBJECTIVE FOR TODAY: MAKE FREE-BODY DIAGRAMS!

What is a Force? Force is what causes acceleration!

Sec 5.1

Force

The fundamental concept of dynamics is that of *force*.

- A force is a push or a pull.
- A force acts on an object.
- A force is a vector.
- A force can be a contact force or a long-range force.

Some important forces that we'll study in this chapter are

Gravity

Tension

Friction

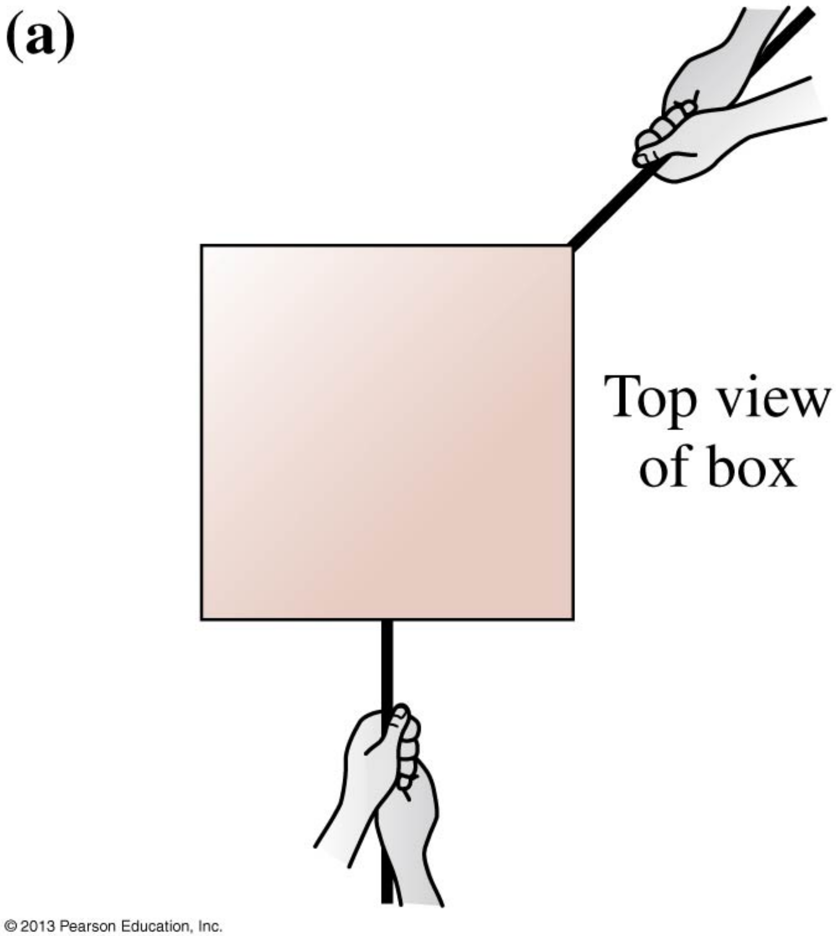
Drag

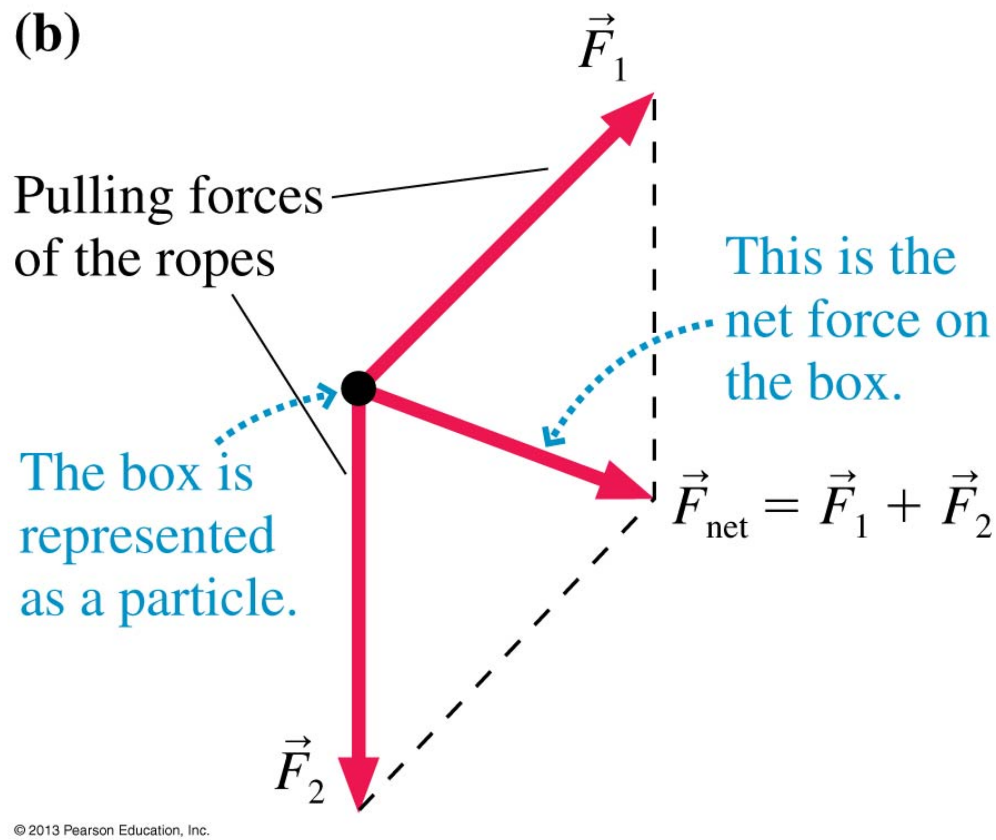
Contact Force vs. Long-Range Force (Sec 5.1)

- **Contact forces** are forces that act on an object by touching it at a point of contact. For example, the bat must touch the ball to hit it.

- **Long-range forces** are forces that act on an object without physical contact. For example, a coffee cup released from your hand is pulled to the earth by the long-range force of gravity.

Represent forces on a body by a **free-body diagram (Sec 5.7)**

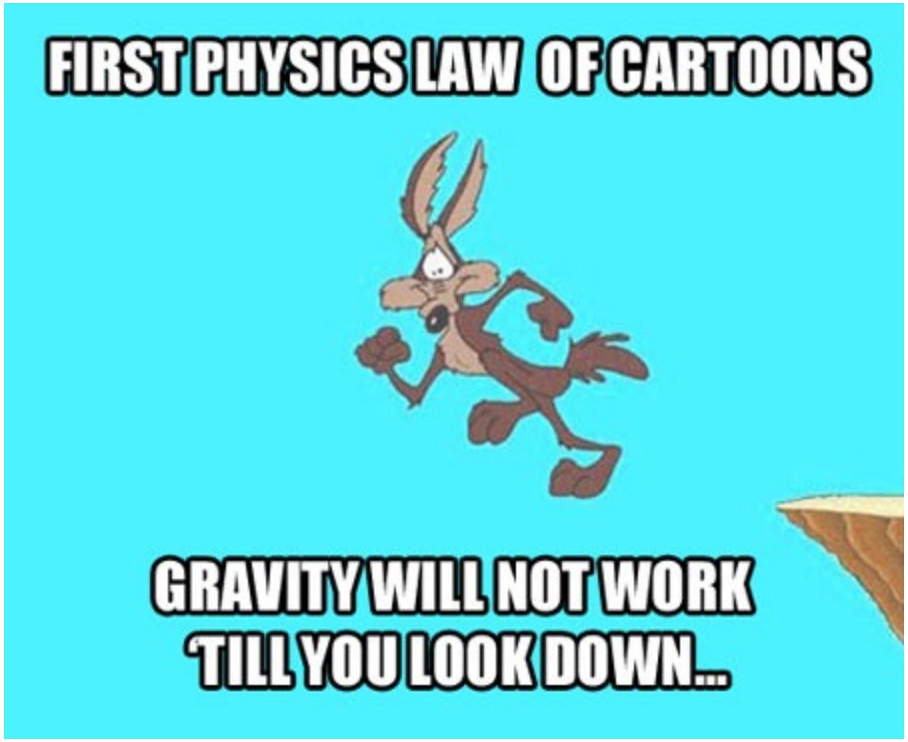




Forces are vectors, hence add just like ordinary vectors!

Forces you'll encounter…**Gravity (Sec 5.2)**

Weight – acts on us keeping us on the earth. Caused by the "*mass*" of an object.



http://www.manvsbrain.com/2014/03/work-cartoons-kids-coyotes-how-both-your-minds-see-data/

Spring Force - This is interesting as many objects in our universe can be approximated as a mass on a spring (e.g. a diatomic molecule).

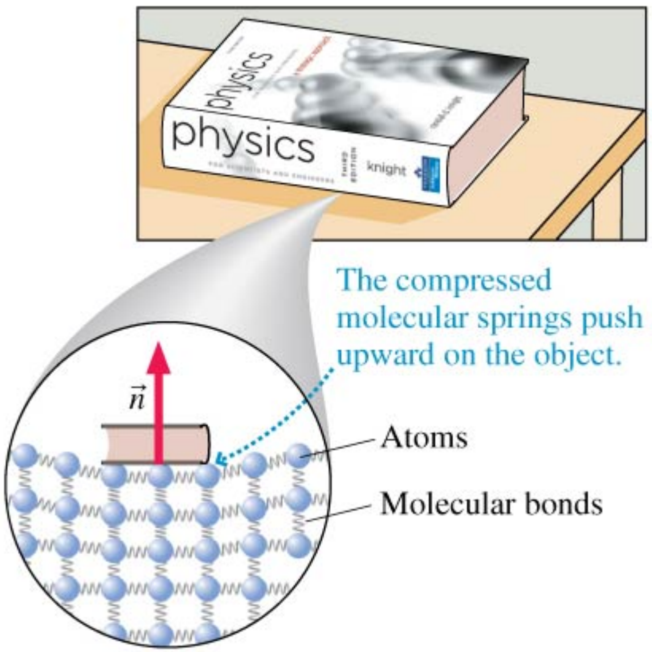
Tension – When a rope pulls on an object.

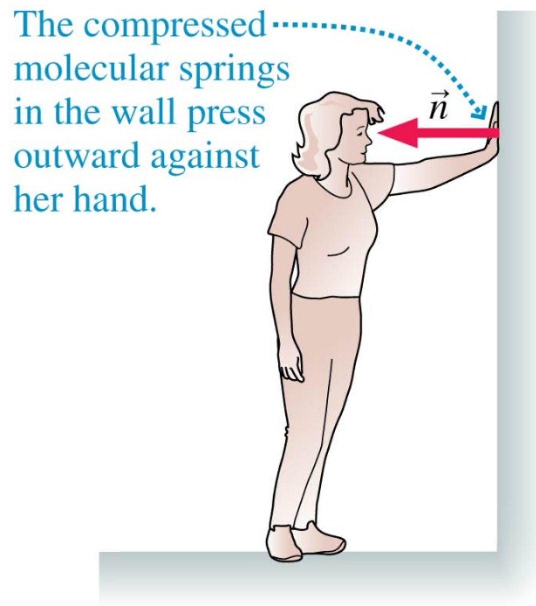
Forces you'll encounter…**Normal Force (Sec 5.2)**

Normal Force – The contact force between two objects pushing against each other which is perpendicular to the interface between the two objects.

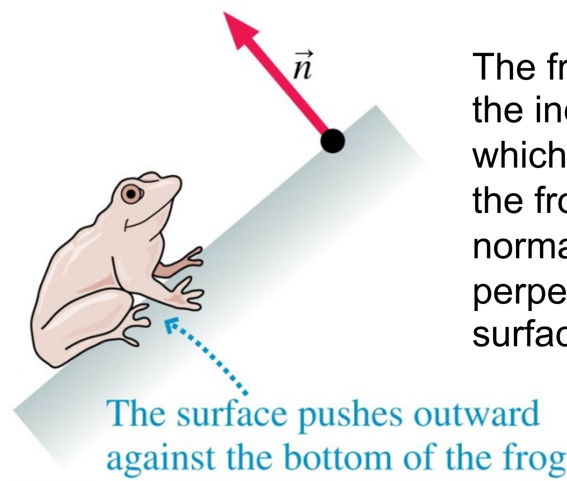
Note! Normal force is not always equal and opposite to the weight!

The book pushes down on the table with its weight, but the table 'pushes' back, thus keeping the book stationary while sitting on the table.
This "pushing back" is the normal force *by* the table *on* the book.





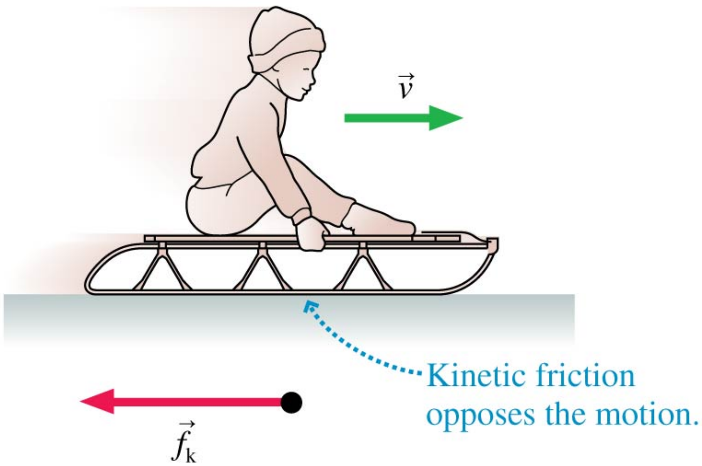
You push against the wall. The wall exerts a horizontal normal force back on your hand.



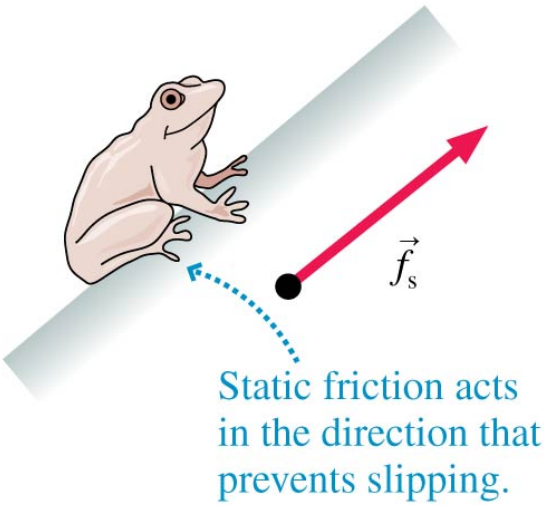
The frog pushes against the inclined surface, which pushes back on the frog. Note that the normal force is perpendicular to the surface.

Forces you'll encounter…**Friction (Sec 5.2)**

Kinetic Friction (a.k.a Sliding Friction) - The contact force between two objects sliding against each other which is parallel to the interface between the two objects, and opposes the relative motion.



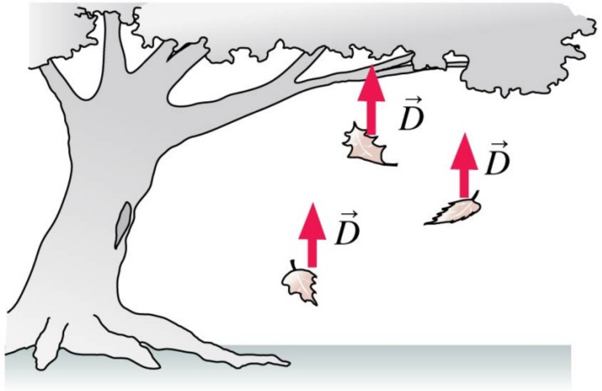
Static Friction - The contact force between two objects pushed against each other which is parallel to the interface between the two objects, <u>and prevents relative motion</u> thereby keeping the two objects "stuck" to each other. Static friction points opposite the direction in which the object *would* move if there were no static friction.



Forces you'll encounter… **Drag** and **Thrust (Sec 5.2)**

Drag – A subset of friction, but caused by friction of a fluid.

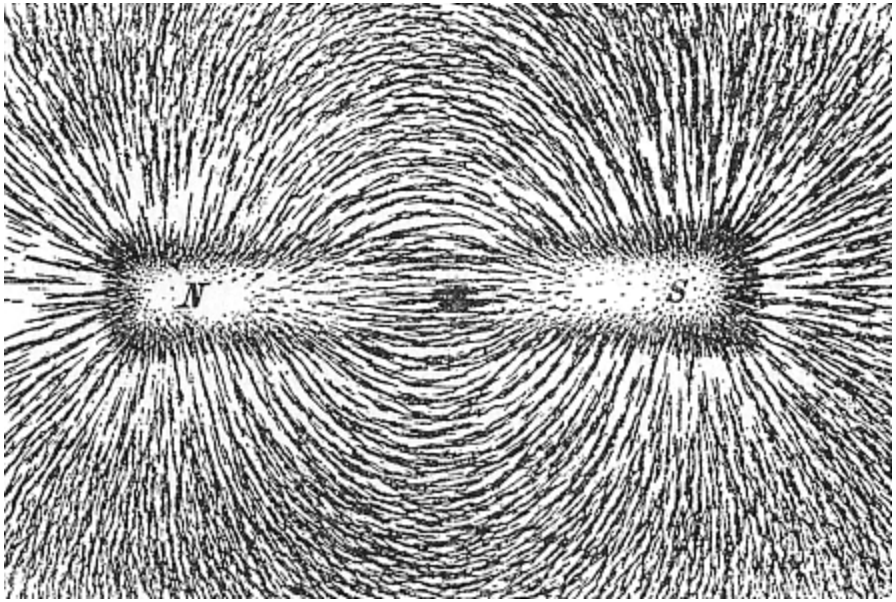
Air resistance is a significant force on falling leaves. It points opposite the direction of motion.



Thrust – Occurs when an engine expels gas at high speed in a certain direction, causing thrust back on the engine in the opposite direction.

Forces you'll encounter in PHY192: **Electric**, **Magnetic** Forces (Sec 5.2)

Electric and magnetic – Similar to gravity ('force at a distance'). Caused by electric charge or magnetic particle. These will be important in PHY192.



Symbols for Forces (Sec 5.3)

Force	Notation
General force	$\vec{F}$
Gravitational force	$\vec{F}_{\mathrm{G}}$
Spring force	$\vec{F}_{\mathrm{sp}}$
Tension	$\vec{T}$
Normal force	$\vec{n}$
Static friction	$\vec{f}_{\mathrm{s}}$
Kinetic friction	$\vec{f}_{\mathrm{k}}$
Drag	$\vec{D}$
Thrust	$\vec{F}_{\mathrm{thrust}}$

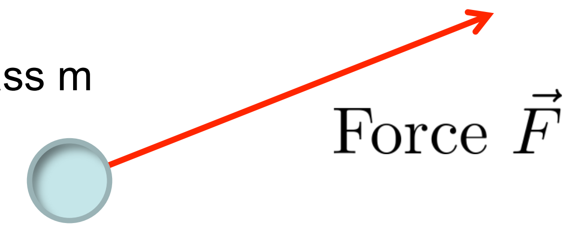
Approximate Magnitude of Some Typical Forces

TABLE 5.1 Approximate magnitude of some typical forces

Force	Approximate magnitude (newtons)
Weight of a U.S. quarter	0.05
Weight of a 1 pound object	5
Weight of a 110 pound person	500
Propulsion force of a car	5,000
Thrust force of a rocket motor	5,000,000

Forces tend to cause an acceleration! (Sec 5.4 & 5.5)

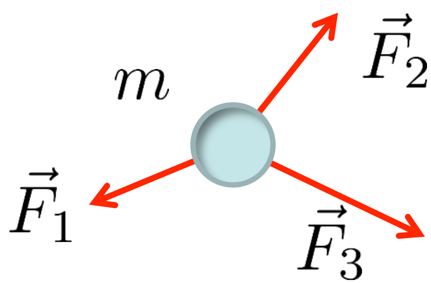
Object of mass m



The force causes the mass to move, but how?

In section 5.4, your author describes a simple set of experiments that would lead you to the conclusion that “force produces an acceleration in the same direction as the force and with magnitude inversely proportional to the mass”. We call this:

<u>Newton’s Second Law:</u>



$$\vec{F}_{\rm net} = \vec{F}_1 + \vec{F}_2 + \vec{F}_3$$

The <u>acceleration</u> of the body is: $\vec{a} = \frac{\vec{F}_{\rm net}}{m}$

Once we know the acceleration, kinematics tells us how the object moves.

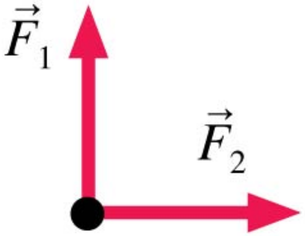
NOTE! You must **only** consider forces acting **ON** the object, not forces exerted **BY** the object on other things!!

$\vec{F} = m\vec{a}$ also gives us the units of force:

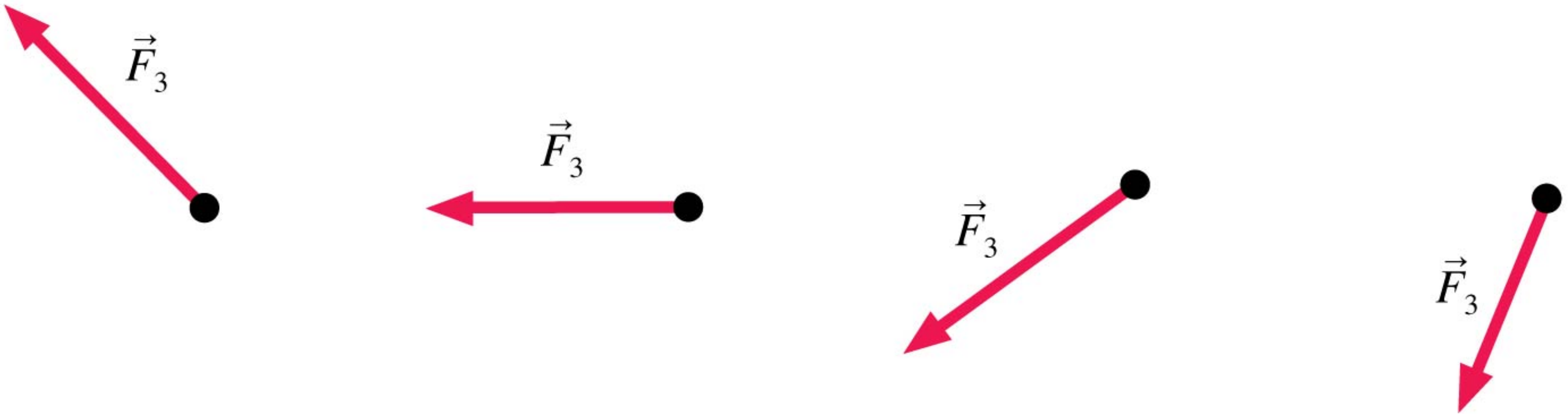
$[\text{units of } \vec{F}] = kg \ \frac{m}{s^2} \equiv \text{Newton (N)}$

QuickCheck

The net force on an object points to the left. Two of three forces are shown. Which is the missing third force?



Two of the three forces exerted on an object



A. B. C. D.

Newton's 1st Law: Concept of **Inertia**

Sec. 5.6

Newton's 1st Law of Motion:

"Things keep on doing what they were doing unless you make them do something else."

or

"A body, at rest or in motion, remains at rest or in motion with a constant velocity, unless acted upon by a net external force"

a.k.a. Newton's Law of Inertia

ASIDE:

Quantitative measure of "Inertia"?

MASS (SI unit: kg)

NOTE! a) NOT same as WEIGHT*!!

b) 2 identical masses may have completely different weights!

Ex: Weigh 1 kg mass on the Moon.

* Then, what is WEIGHT? **(Sec 6.3)**

What is Force?

Sec. 5.1

CONCEPT OF "FORCE"

Q1: What causes "motion"? ← i.e. "velocity"

Q2: What causes "changes in motion"? ← "acceleration"

A1: Newton's 1st Law of Motion

Vital corollary: DON'T SHAKE THE BABY!

A2: Newton's 2nd Law of Motion
.... introduce the concept of "FORCE"

Sec. 5.5

Newton's 2nd law of Motion:

" If you hit something it will scoot, but the more massive it is, the slower it scoots ..."

or

"The net external force acting on a body equals the product of its mass and acceleration.

$$\vec{F}_{ext} = m\vec{a}$$

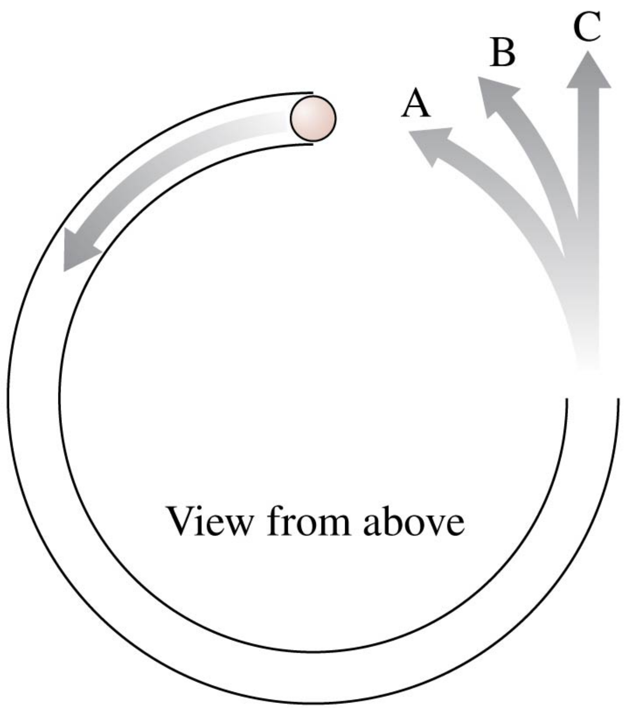
- $\vec{F}_{ext}$ → net external force on mass 'm'
- m → mass of body
- $\vec{a}$ → accn.

Units: $1\ kgms^{-2} \equiv 1\ N$

- net external force?
- weight?

Newton’s First Law of Inertia (Sec 5.6)

The figure below shows a hollow tube forming three-quarters of a circle. A ball is shot through the tube at high speed. As the ball emerges from the other end, does it follow path A, path B, or path C?



Newton’s Laws of Motion (Chapters 5, 6, 7, 8)

- Concept of FORCE and INERTIA (Chapter 5)

  Newton's 1st Law of Motion (another nice "simplification") (Sec 5.6)

  Vital corollary: Don't shake the baby!

  What are the units for Inertia? (Sec 5.4)

- Measuring FORCE (Chapters 5 and 6)

  Newton's 2nd Law of Motion (Sec 5.4, 5.5, 6.2)

  What are the units for WEIGHT…kg? NOT! (Sec 5.2, 5.4, 6.3)

  Measuring Weight…what do bathroom scales actually measure? (Sec 5.2, 6.3)

- Concept of ACTION and REACTION (Chapter 7, and sections of 5 & 6)

  Newton's 3rd Law of Motion (Sec 7.3)

  The NORMAL FORCE (or CONTACT FORCE) (Sec 5.2, 6.3, 7.1 – 7.3)

  The concepts of TENSION, FRICTION (Sec 5.2, 6.4, 7.1 – 7.3)

  Simple applications of Newton's Laws

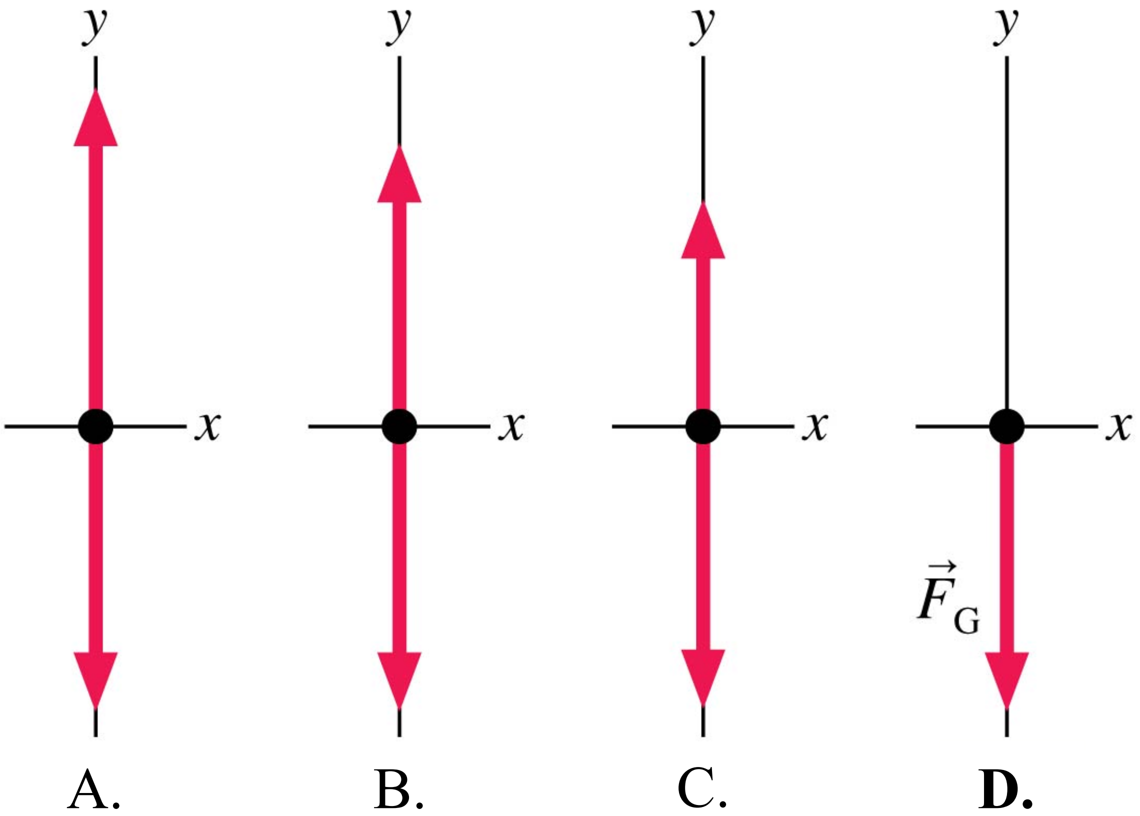
  What’s the “system”? What’s the “environment”? (Sec 7.1)

  Why do your knees buckle when the elevator starts up? Why do pulleys make it easier to haul stuff up? (Sec 7.1 – 7.3)

  How to draw Free-Body Diagrams! Solve sample exam problems (Sec 5.7)

QuickCheck (Sec 5.7)

A ball has been tossed straight up. Which is the correct free-body diagram just after the ball has left the hand? Ignore air resistance.



Free-body Diagrams (System? Environment?)

- The object of interest is the "SYSTEM".
- Everything else is the "ENVIRONMENT".
- Only draw forces acting **ON** THE SYSTEM!

(Sec 7.1 – 7.3)

TACTICS BOX 5.2 **Identifying forces**

1. **Identify the object of interest.** This is the object whose motion you wish to study.
2. **Draw a picture of the situation.** Show the object of interest and all other objects—such as ropes, springs, or surfaces—that touch it.
3. **Draw a closed curve around the object.** Only the object of interest is inside the curve; everything else is outside.

Exercises 3–8

TACTICS BOX 5.3 **Drawing a free-body diagram**

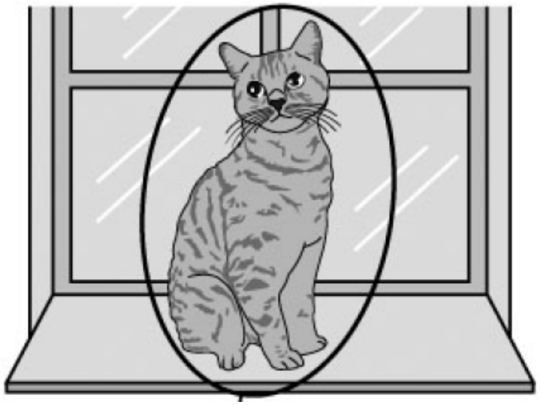
1. **Identify all forces acting on the object.** This step was described in Tactics Box 5.2. Choose and draw (there is no incorrect choice, but there are inconvenient ones)
2. **Draw a coordinate system.** Use the axes defined in your pictorial representation.
3. **Represent the object as a dot at the origin of the coordinate axes.** This is the particle model. The tail of the force vectors go on the body
4. **Draw vectors representing each of the identified forces.** This was described in Tactics Box 5.1. Be sure to label each force vector.
5. **Draw and label the *net force* vector $\vec{F}_{net}$.** Draw this vector beside the diagram, not on the particle. Or, if appropriate, write $\vec{F}_{net} = \vec{0}$. Then check that $\vec{F}_{net}$ points in the same direction as the acceleration vector $\vec{a}$ on your motion diagram.

***In any dynamics problem, if the free body diagram is incorrect, then everything done after that is incorrect as well!**

Whiteboard Problem 5.1: Free-body Diagrams

Draw the free-body diagram for **(Sec 5.7)**

A cat sitting on a window sill



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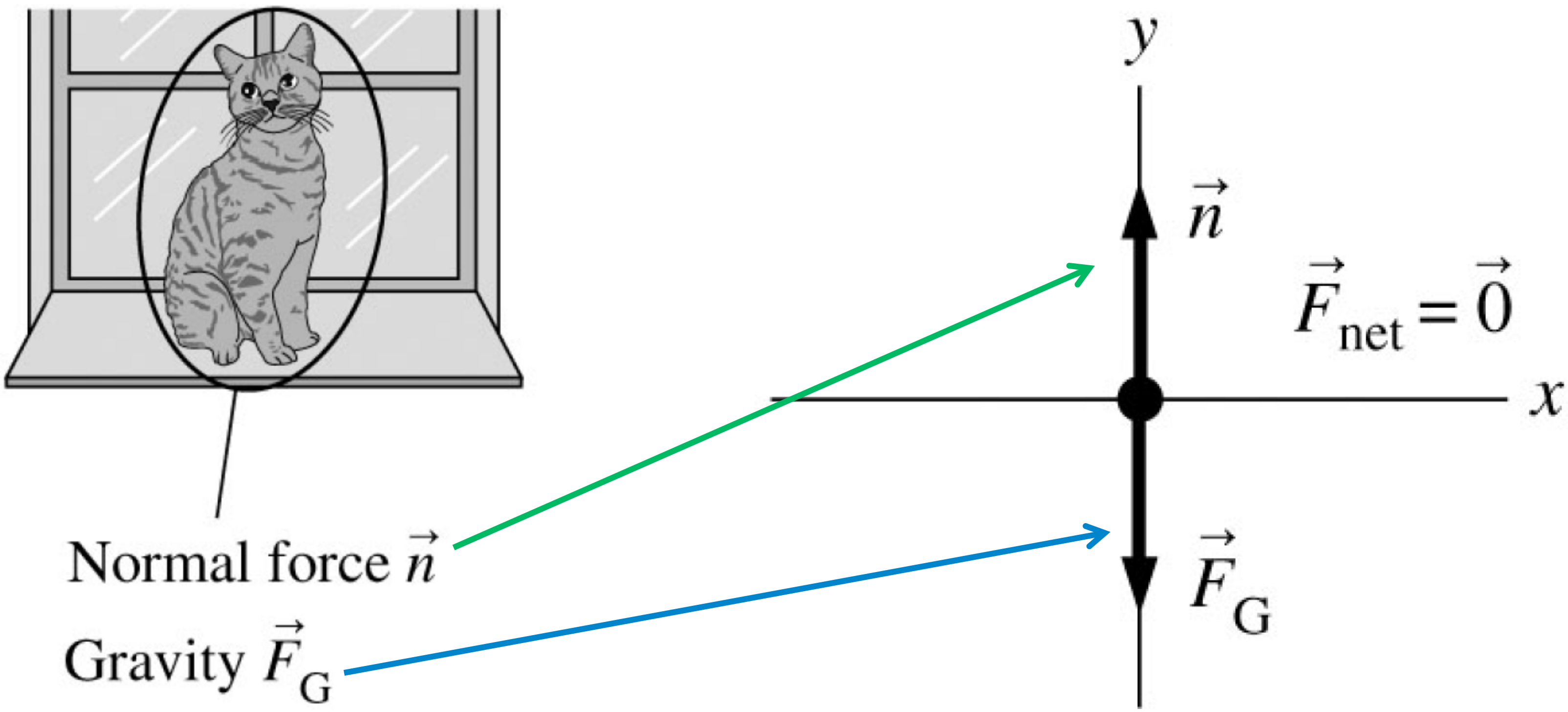
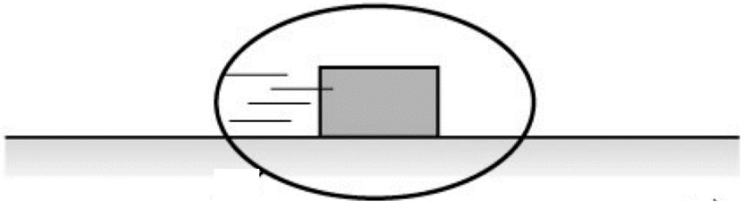


Whiteboard Problem 5.2: Free-body Diagrams

Draw the free-body diagram for **(Sec 5.7)**

An ice hockey puck gliding across frictionless ice



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(Sec 5.7)

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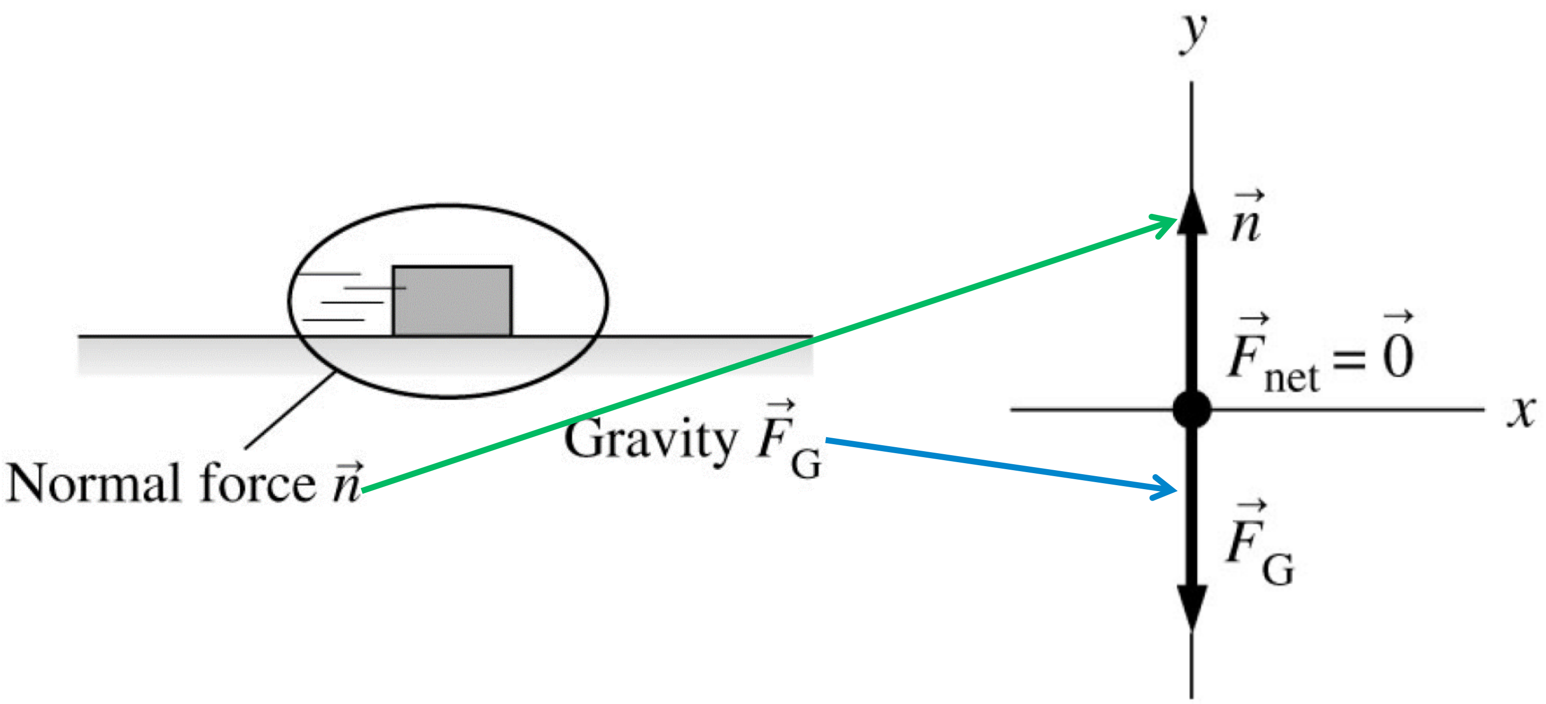
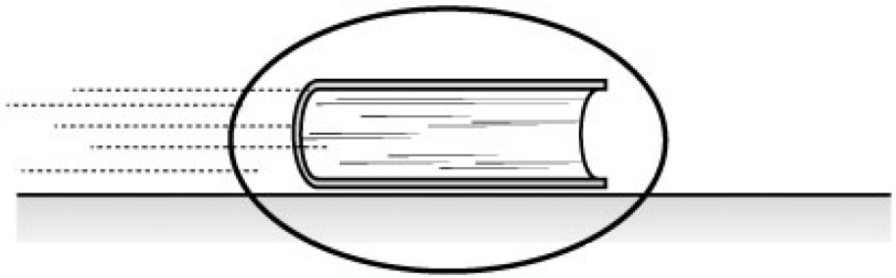


Whiteboard Problem 5.3: Free-body Diagrams

Draw the free-body diagram for **(Sec 5.7)**

Your physics textbook sliding across the table



Whiteboard Problem 5.3: Free-body Diagrams

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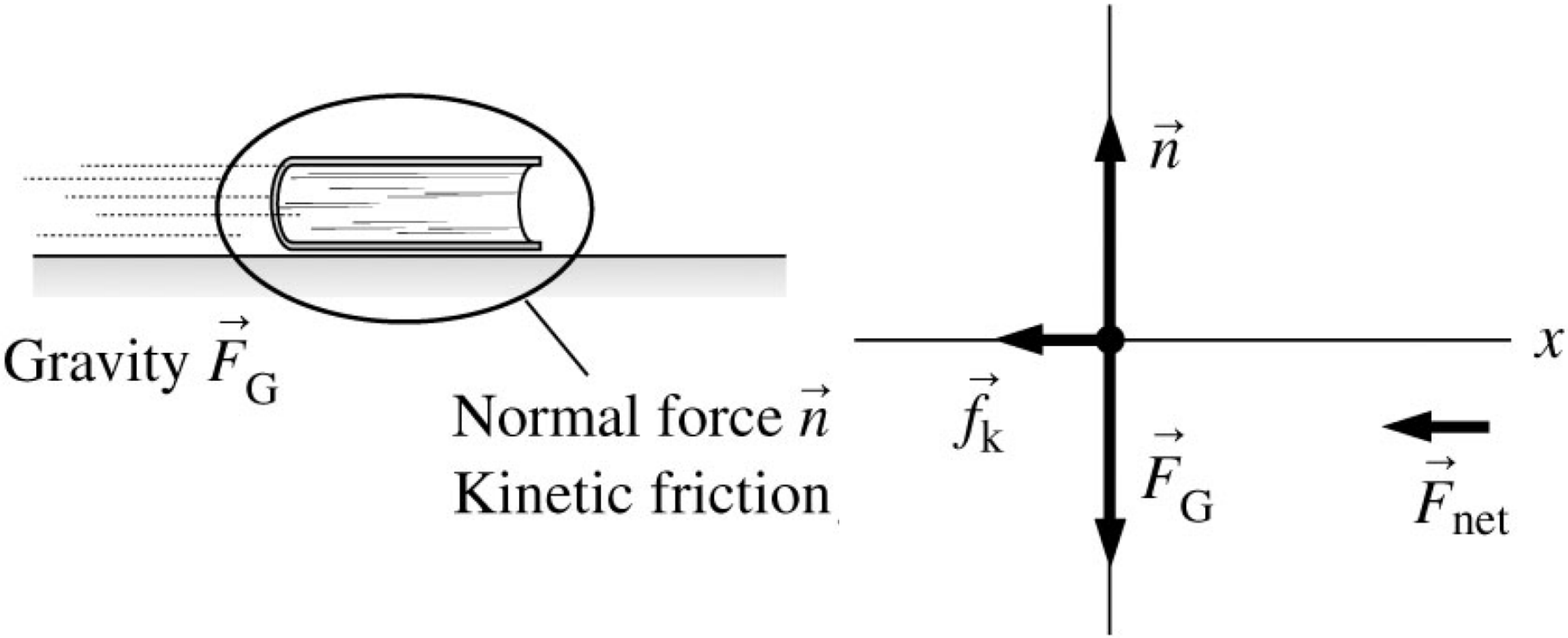
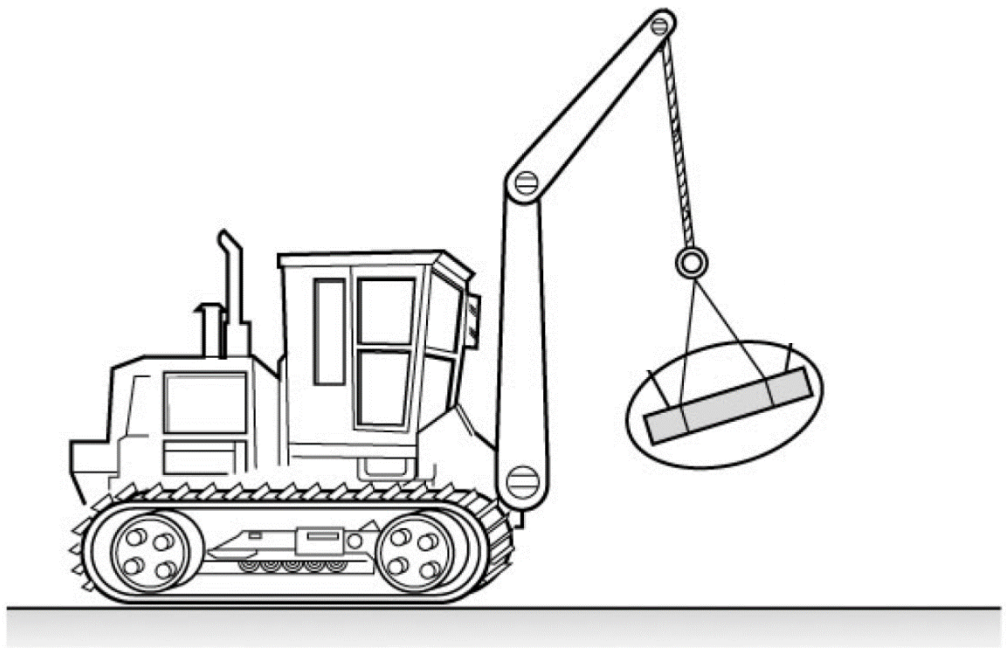


Whiteboard Problem 5.4: Identify and draw the Forces

A steel beam hangs from a cable as a crane lowers the beam at a steady speed. What forces act on the beam? **(Sec 5.7)**

Draw a **free-body diagram** for the beam, labeling the forces acting on the beam.



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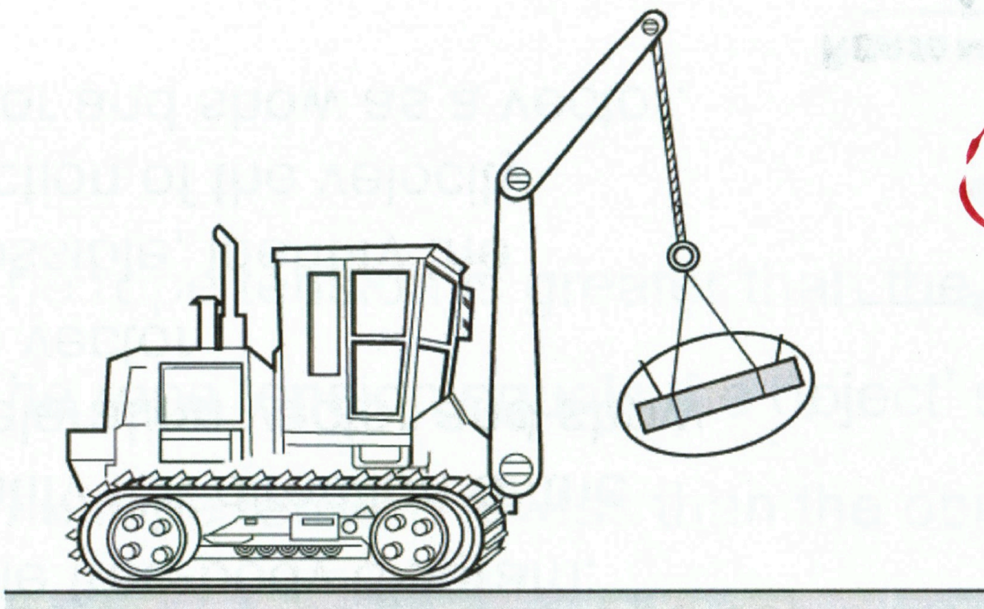
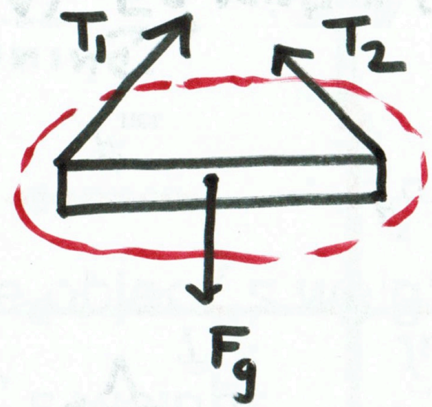




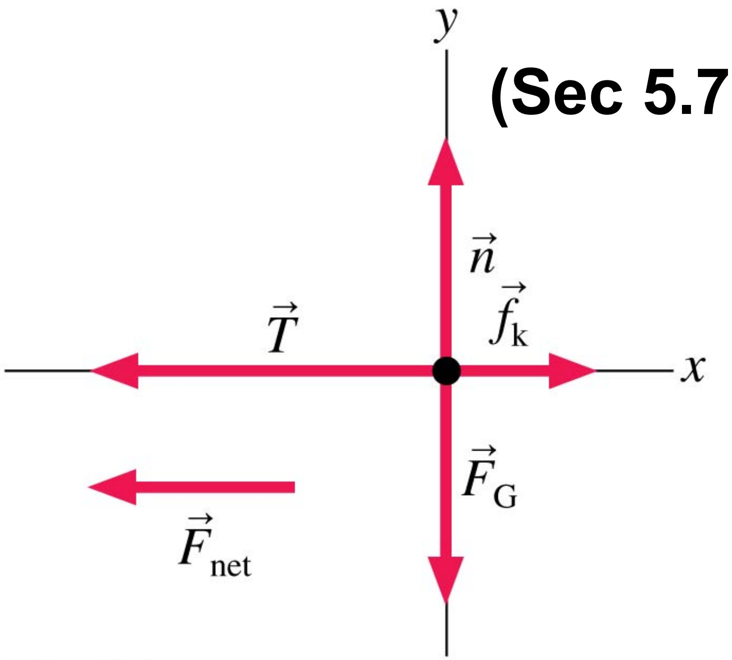
Whiteboard Problem 5.5

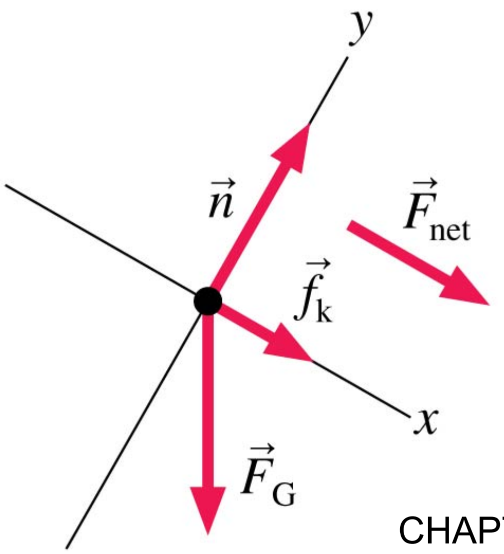
(Sec 5.7)

Given the free-body diagram:

(A) Identify the direction of the acceleration vector and show as a vector.

(B) If possible, identify the direction of the velocity vector and show as a vector.





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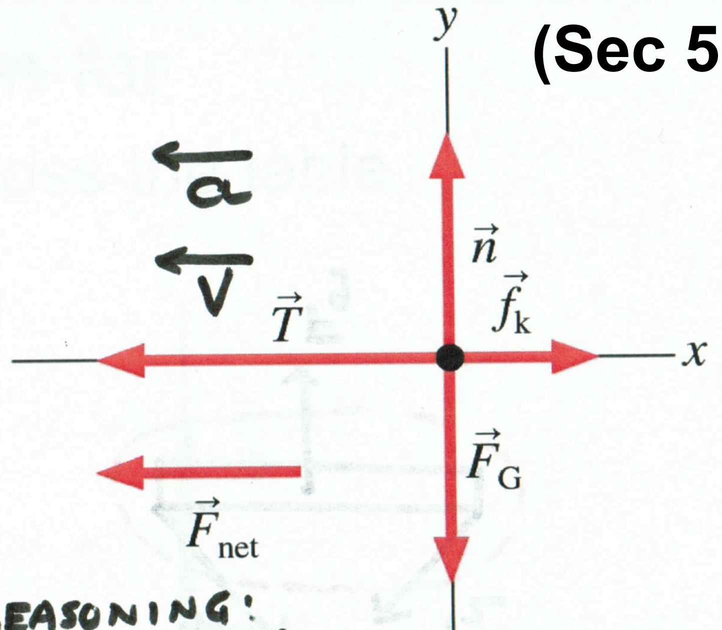
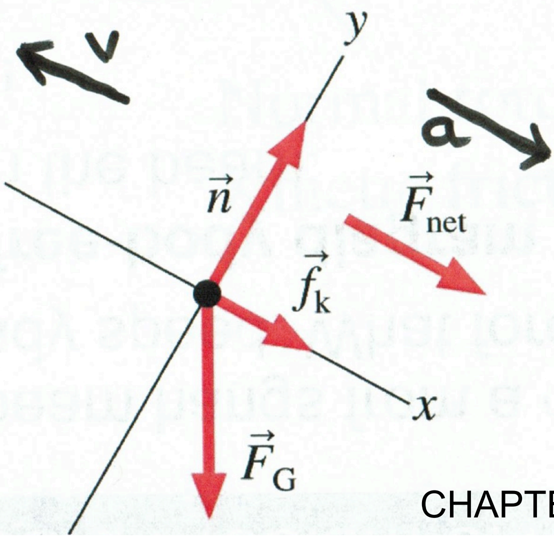


REASONING:

A) $\vec{a}$ points in same direction as $\vec{F}_{net}$. Why? B/c $\vec{F}_{net} = m\vec{a}$!

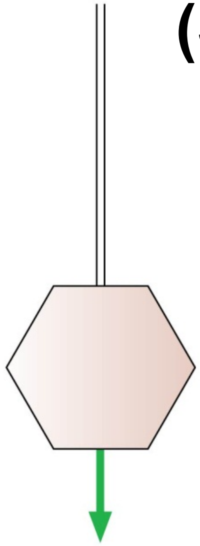
B) $\vec{v}$ points in opposite direction to force of kinetic friction $\vec{f}_k$!



QuickCheck

(Sec 5.7)

An object on a rope is lowered at a steadily decreasing speed. Which is true?



A. The rope tension is greater than the object's weight.

B. The rope tension equals the object's weight.

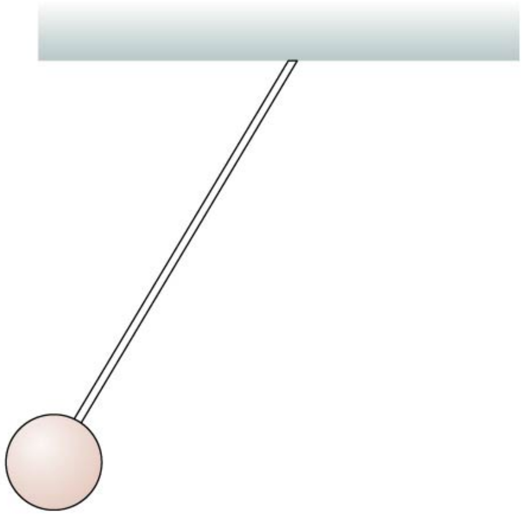
C. The rope tension is less than the object's weight.

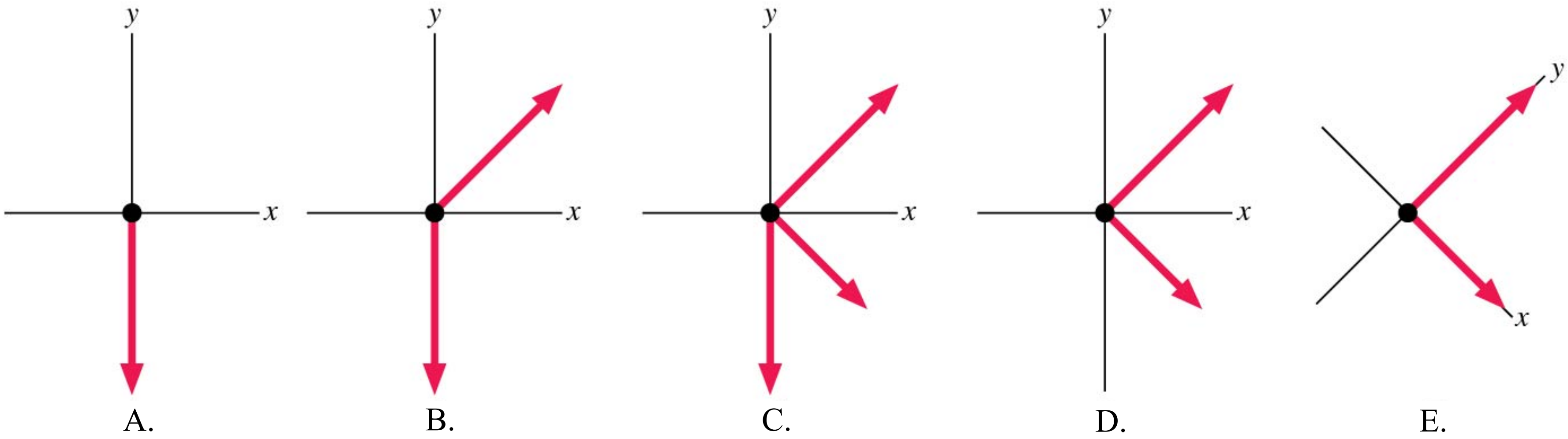
D. The rope tension can't be compared to the object's weight.

QuickCheck

(Sec 5.7)

A ball, hanging from the ceiling by a string, is pulled back and released. Which is the correct free-body diagram just after its release?





System and Environment: An example

Sections 5.5, 5.2 and 6.3

Net external force = net force on body exerted by 'environment'

Example: I step off the table....

accn 'a' = g ↓

mass 'm'

Then, net external force = mg

'External environment' = EARTH

My Weight = Force by Earth on me

$= \vec{F}_W = m\vec{g}$

NOTE: Force by Earth on me = mg ONLY near Earth's surface.

'g' is NOT constant! Decreases w/ ht!!

Q: Where does 'g' come from? What is the origin of 9.8 m/s²?

We'll answer this later, not now…

To complete the story…. Newton's 3rd Law: Chapter 7

Newton's 3rd Law of Motion:

"To every action there is an equal and opposite reaction"

"Action" & "Reaction" } are FORCES

or

"Forces always occur in pairs. A single, isolated force cannot exist"

or

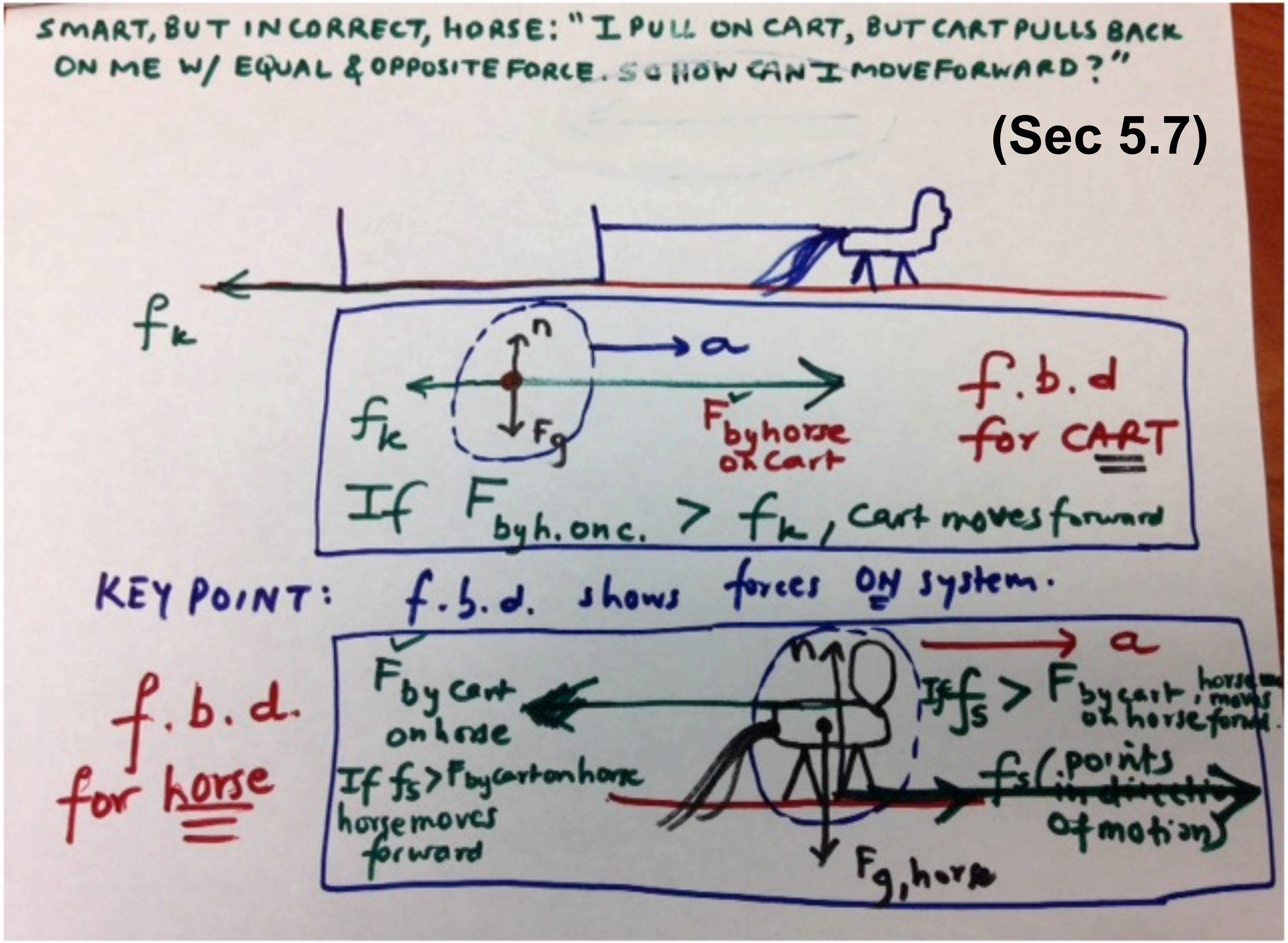
"If you kick a lead football, it will break your foot".

CHECK: Newton's law of Gravitation

CHECK: Book on table

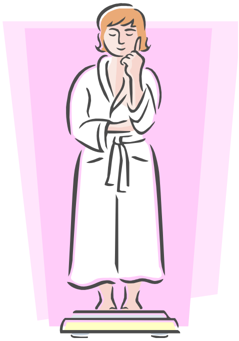
Note 1! "Action" on one body, "Reaction" on ANOTHER!!!

Note 2! Important concept "NORMAL FORCE"...


SMART, BUT INCORRECT, HORSE: "I PULL ON CART, BUT CART PULLS BACK ON ME W/ EQUAL & OPPOSITE FORCE. SO HOW CAN I MOVE FORWARD?"
(Sec 5.7)
f_k
n
a
f_k
F_g
$F_{by horse on cart}$
f.b.d for CART
If $F_{by h. on c.} > f_k$, cart moves forward
KEY POINT: f.b.d. shows forces ON system.
f.b.d. for horse
$F_{by cart on horse}$
If $f_s > F_{by cart on horse}$ horse moves forward
n
a
If $f_s > F_{by cart on horse}$, horse moves forward.
f_s (points in direction of motion)
$F_{g, horse}$

THE NORMAL FORCE

Sec. 5.2



We measure Weight using bathroom scales.
Or do we?

Q: What do bathroom scales actually measure??

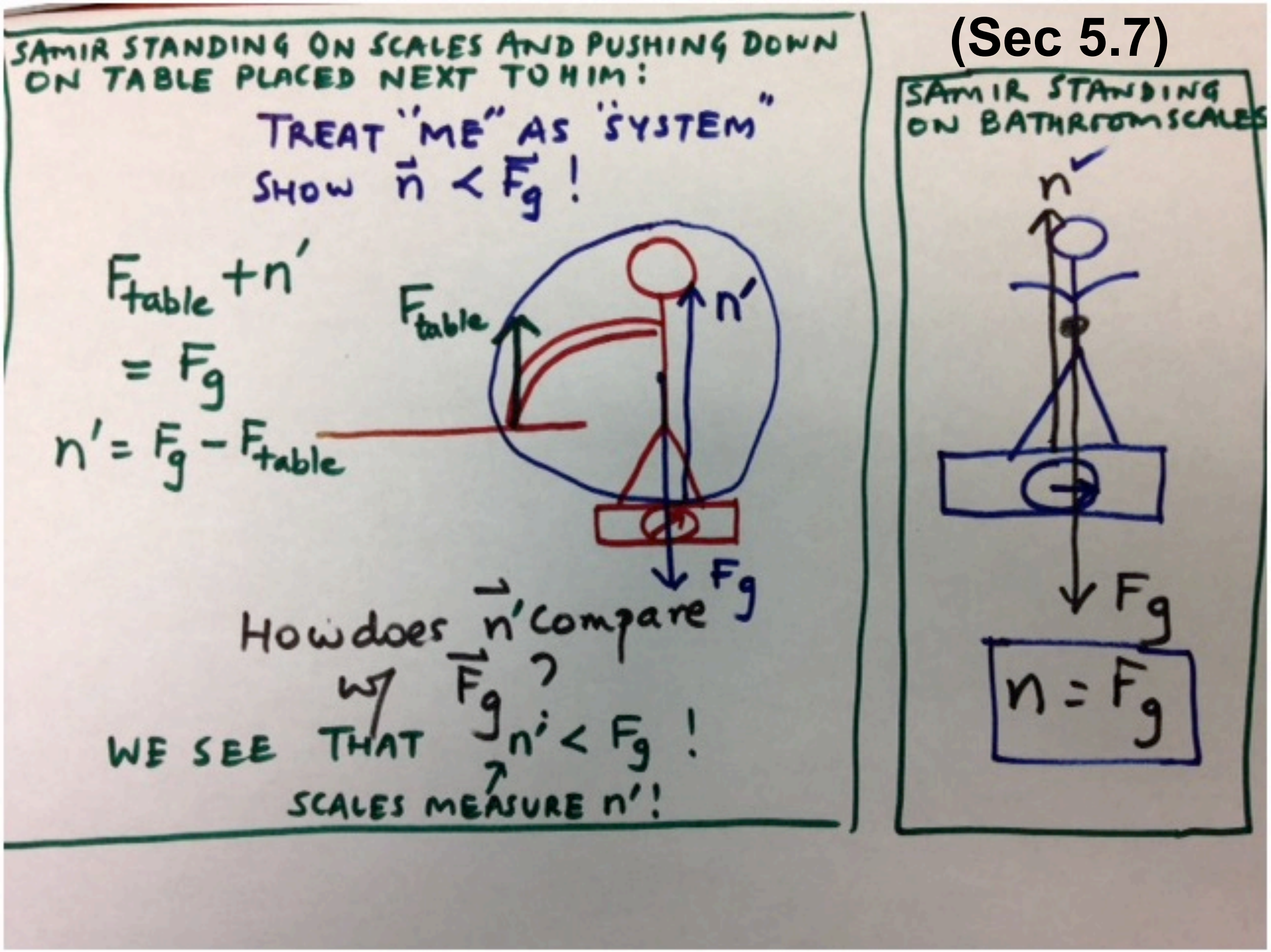
A: The bathroom scales actually measure the , which is the CONTACT force between the surfaces, and is perpendicular to the interface.

Interesting applications of the concept of Normal Force:

- Why do your knees buckle when the elevator starts upward?

- The instant weight reduction program! Draw a free-body diagram.

(Sec 5.7)



SAMIR STANDING ON SCALES AND PUSHING DOWN ON TABLE PLACED NEXT TO HIM:
TREAT "ME" AS "SYSTEM"
SHOW n < Fg !
Ftable + n′ = Fg
n′ = Fg − Ftable
Ftable
n′
Fg
How does n′ compare w/ Fg ?
WE SEE THAT n′ < Fg !
SCALES MEASURE n′!
SAMIR STANDING ON BATHROOM SCALES
n
Fg
n = Fg