Dynamics: Newton's Laws of Motion

Kinematics: how the objects move?

Dynamics: why do they move? What makes an object at rest begin to move? what changes the object velocity?

a force is required

Force has magnitude and direction **– is a VECTOR**

Aristotle (384-322 B.C)   vs.   Galileo (1564 – 1642)

Natural for an object to be at rest

As natural of an object to be in motion with constant velocity as it is for it to be at rest

Galileo: imagine a world with no friction – if no force is applied to a moving object, it will continue to move with constant speed in a straight line

Pushing force cancels the force of friction - constant velocity
(*net* force is zero)

Newton's First Law of Motion

On top of Galileo's work, Newton built his theory of motion

In the ***Principia***, Newton's analysis of motion is summarized in his "three laws of motion"   http://books.google.com/books?q=principia

First Law of Motion (also called **Law of Inertia**)

Every object continues in its state of rest, or uniform velocity in a straight line, as long as no net force acts on it

The tendency of an object to maintain its state of rest or uniform motion in a straight line is called **inertia**

net force → $\Sigma \vec{F} = 0$

Inertial reference frame: any reference frame where Newton's first law holds.

Mass

Mass: is the quantity of matter
is the **inertia** of an object
how much it resists any change in motion

Truck has more inertia than a soccer ball
It is more to difficult to speed up or change direction of motion of a truck

Mass is a **SCALAR**
In SI units the unit of mass is kilogram (kg)

Mass is different from weight
property of   force
an object   VECTOR
SCALAR

Newton's Second Law of Motion

The acceleration of an object is directly proportional to the net force acting on it, and is inversely proportional to its mass. The direction of the acceleration is in the direction of the net force acting on the object.

net force $\rightarrow$ $$\Sigma\vec{F} = m\vec{a}$$

Force is an action capable of accelerating an object, is a VECTOR, its direction is the same as the acceleration

For the motion along a line (one dimension):

$$\Sigma F = ma$$

$$\Sigma F_x = ma_x$$
$$\Sigma F_y = ma_y$$
$$\Sigma F_z = ma_z$$

Unit of force:

In SI units: **newton** (N)
1 N = 1 kg m/s^2

In cgs units: dyne
1dyne= 1 g cm/s^2

What average net force is required to bring a 1500-kg car to rest from 28m/s within a distance of 55 m?

$$v^2 = v_0^2 + 2a(x - x_0)$$

$$a = \frac{v^2 - v_0^2}{2(x - x_0)} = -7.1 m/s^2$$

$$\sum F = ma = (1500 kg)(-7.1 m/s^2) = -1.1 \times 10^4 N$$
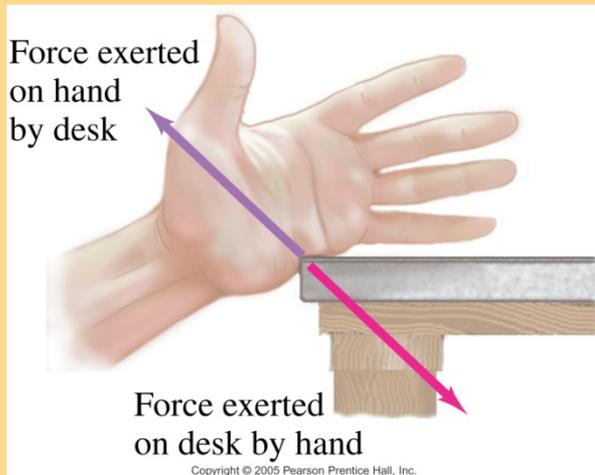
Newton's Third Law of Motion

Force is the interaction between objects.

Whenever on object exerts a force on a second object, the second exerts an equal force in the opposite direction on the first.
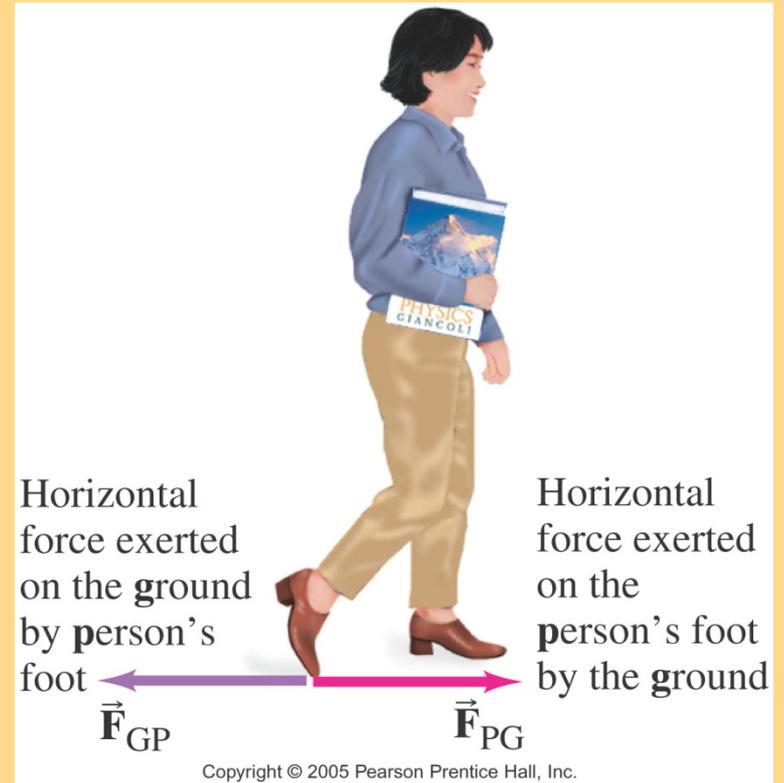
"to every action there is an equal and opposite reaction"

$$\vec{F}_{12} = -\vec{F}_{21}$$
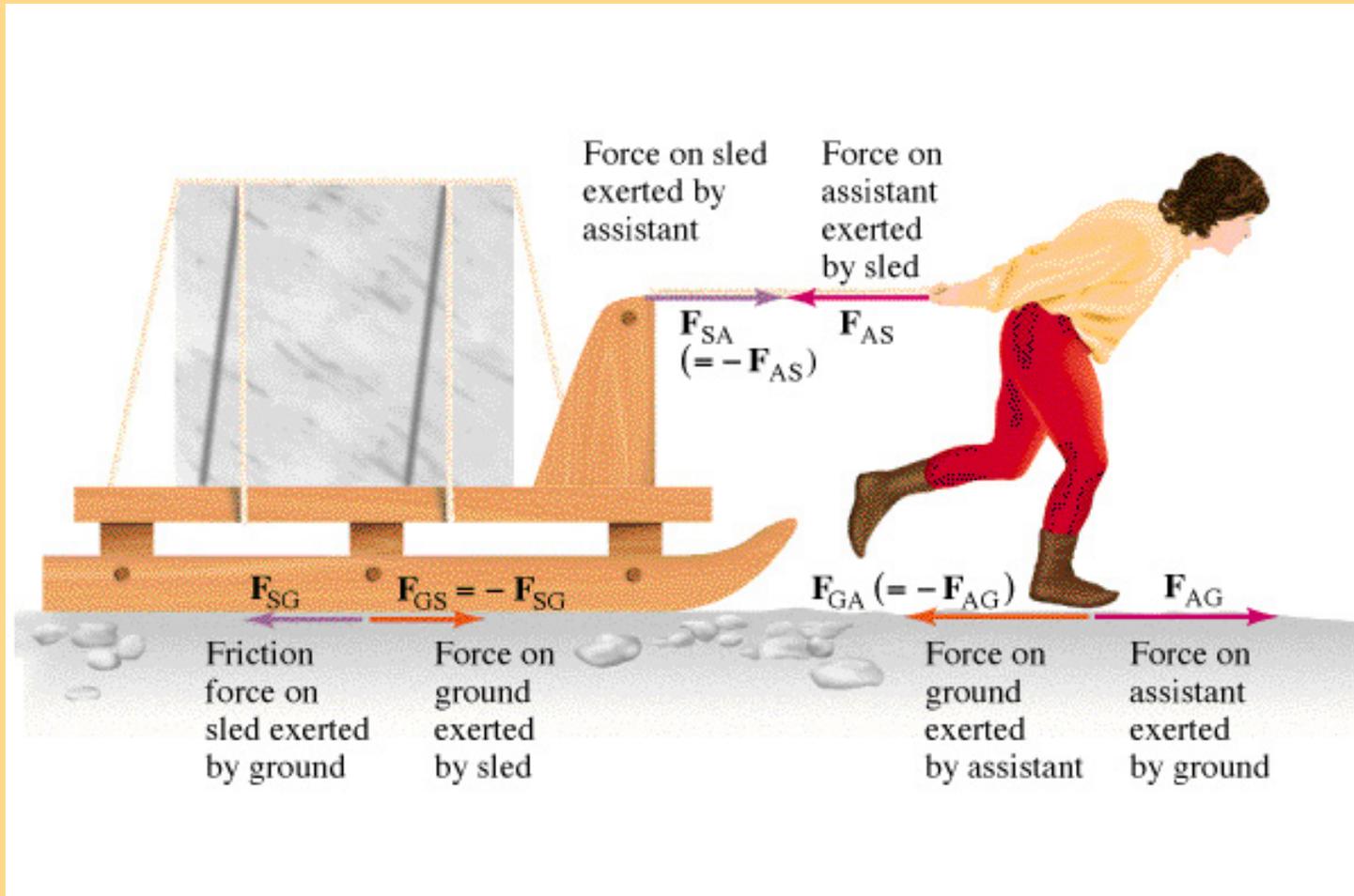
3rd Law's forces act on **different** objects!

Force exerted on hand by desk

Force exerted on desk by hand

Copyright © 2005 Pearson Prentice Hall, Inc.

Newton's Third Law of Motion

Force on skater — Force on wall

Copyright © 2005 Pearson Prentice Hall, Inc.

Horizontal force exerted on the **ground** by **p**erson's foot

$\vec{F}_{GP}$

Horizontal force exerted on the **p**erson's foot by the **ground**

$\vec{F}_{PG}$

Copyright © 2005 Pearson Prentice Hall, Inc.

Read Ex. 4.5

Force on sled exerted by assistant

Force on assistant exerted by sled

$\mathbf{F}_{SA}$ $(= -\mathbf{F}_{AS})$

$\mathbf{F}_{AS}$

$\mathbf{F}_{SG}$ $\mathbf{F}_{GS} = -\mathbf{F}_{SG}$

$\mathbf{F}_{GA}$ $(= -\mathbf{F}_{AG})$ $\mathbf{F}_{AG}$

Friction force on sled exerted by ground

Force on ground exerted by sled

Force on ground exerted by assistant

Force on assistant exerted by ground

Ex. A

A massive truck collides head-on with a small car. (a) Which vehicle experiences the greater force of impact? (b) Which experiences the greater acceleration? (c) Which of Newton's laws is useful to obtain the correct answer for each item?

(a) The same; (b) the car; (c) third law for (a) and second law for (b)

Weight = the Force of Gravity
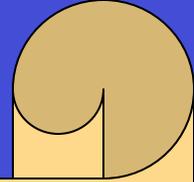
All objects dropped on Earth fall with constant acceleration.
The force causing this acceleration is the *force of gravity* or *gravitational force.*
EARTH exerts the gravitational force on an object.

Newton's second law:

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

Direction is down toward the center of Earth
Magnitude is called WEIGHT

Weight on Earth vs. weight on the Moon

The Normal Force

Force of gravity acts on an object when it is falling.
It ALSO acts on an object when it is at rest on Earth,
but the the object does not move because of the **contact force**

Contact force perpendicular to the surface = **normal force**

(a) (b)

Copyright © 2005 Pearson Prentice Hall, Inc.
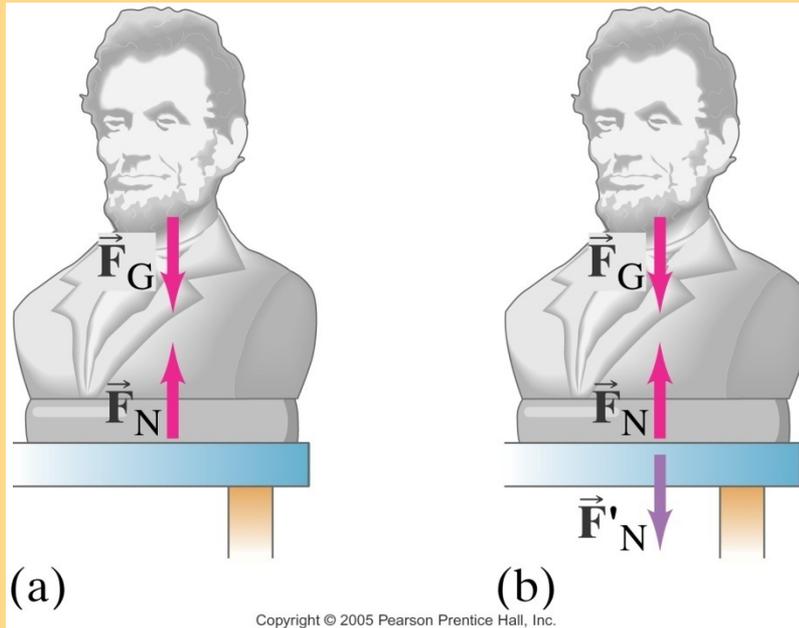
At rest:

$$\Sigma \vec{F} = \vec{F}_G + \vec{F}_N = 0$$

$$|\vec{F}_G| = -|\vec{F}_N|$$

Weight is the gravitational force on the object.

Normal force is the force exerted by the support on the object.

Problems

Ex.4-6 A box of mass 10.0 kg rests on a smooth (frictionless) horizontal surface of a table. (a) What is its weight and normal force exerted by the table? (b) If you push it down with force 40.0 N, what is the normal force exerted by the table? (c) If you pull it upward with force 40.0 N, what is normal force exerted by the table?

$$\Sigma F_y = ma_y$$

(a) F_G=98.0N downward   , F_N=98.0N upward

(b) 138 N   (c) 58.0 N

Ex. 4-7 If you pull it upward with force 100.0 N, what is the acceleration upwards?

Net force= 2.00 N upward,   a=2.00/10.0kg=0.20m/s^2

Weight and Scale

At rest:

$$\vec{a} = 0 \implies \Sigma\vec{F} = 0$$

$$\vec{F}_N + \vec{F}_g = 0 \qquad F_N - mg = 0 \implies \boxed{F_N = mg}$$

Scale marked in weight or mass units
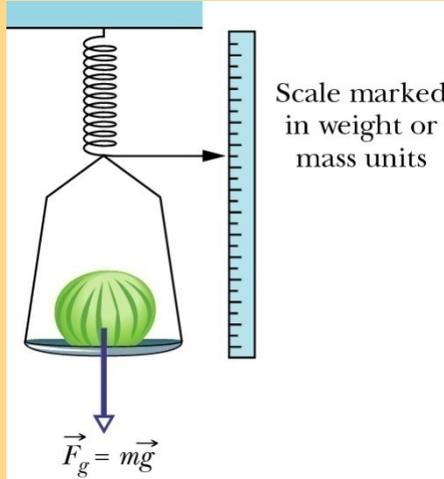
$$\vec{F}_g = m\vec{g}$$

At motion with **uniform acceleration:**

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

$$\vec{F}_N + \vec{F}_g = m\vec{a}$$

$$F_N - mg = ma \implies \boxed{F_N = m(g + a)}$$

If a=0, scale gives a reading of mg
If a>0, the reading is larger
If a<0, the reading is smaller

y

$\vec{N}$

$\vec{a}$

Passenger

$\vec{F}_g$

(a) (b)
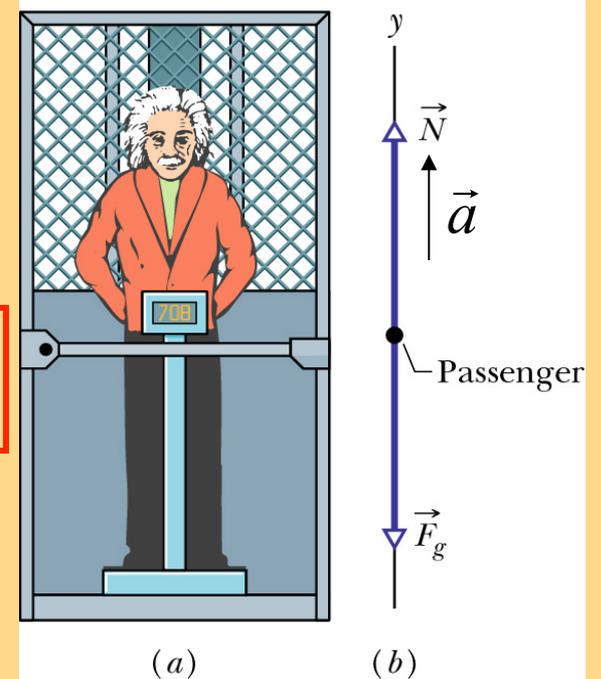
Problems

Ex.4.9 Calculate the magnitude of the resultant force exerted on the boat by workers A and B.
(no friction)

Fx=52.3N, Fy=10.2N

F_R=53.3N   tan(theta)=0.195
             theta=11.0degrees
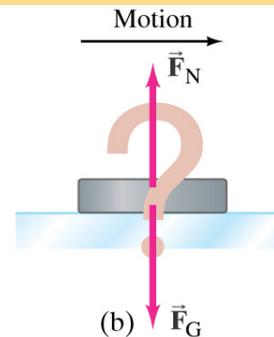

$F_A = 40.0$ N

$45.0°$

$37.0°$

y

x

$F_B = 30.0$ N

A

B
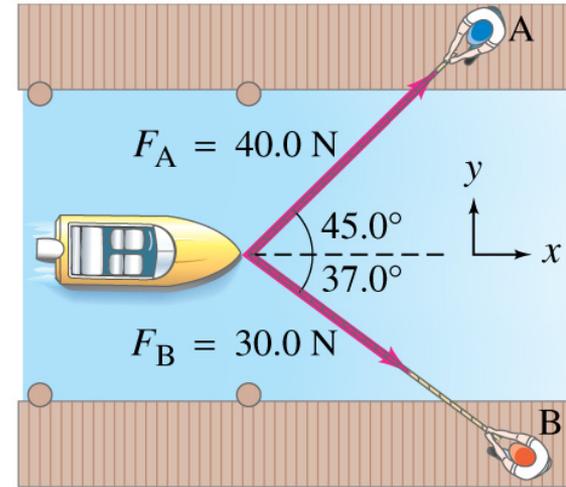
(a)

Ex.4.10 Frictionless surface. The object moves with constant velocity. Which figure correctly describes the motion?


Motion

$\vec{F}_N$

$\vec{F}$

(a) $\vec{F}_G$

Motion

$\vec{F}_N$

(b) $\vec{F}_G$
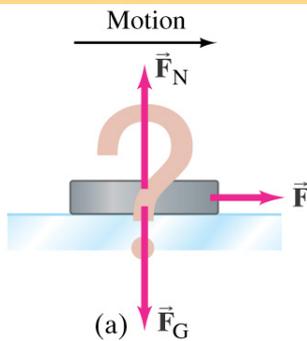
Problem Solving

1. Draw a **free-body diagram** for each object.
   (show ALL forces ON the object alone)

2. Apply **Newton's second law** to the x and y **components** separately.
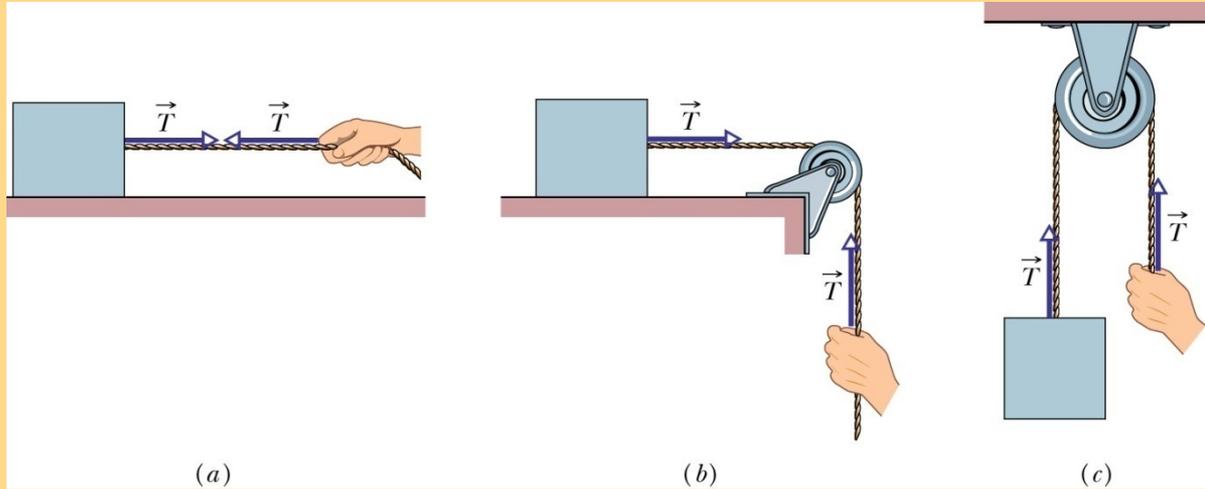
3. Solve the equations for the unknowns

Ex. 4.11 The mass is 10.0 kg.
The surface is frictionless. Find
(a) the acceleration of the box
and (b) the magnitude of the normal force.

(a) a_x=3.46 m/s^2

(b) F_N=78.0N

$F_P = 40.0$ N

$30.0°$

(a)

(a)   (b)   (c)
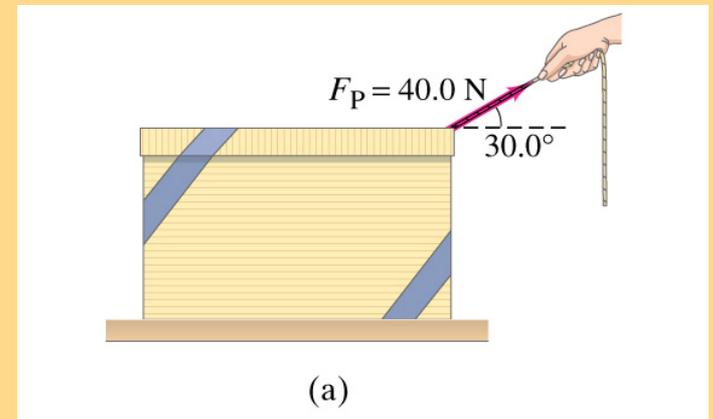
Cord pulling an object is said to be under **tension**

Ex.4-12.
Find (a) the acceleration of each box and (b) the tension in the cord connecting the boxes.

y

x

$m_B =$ 12.0 kg

$m_A =$ 10.0 kg

$\vec{F}_P$

40.0 N

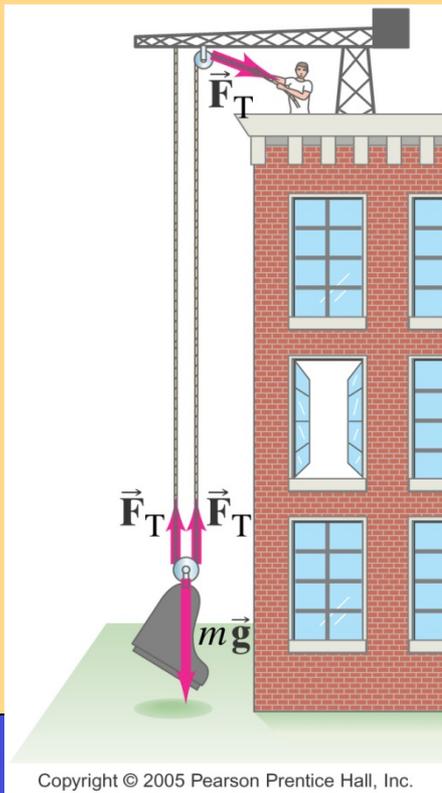Box B   Box A

(a)

(a) a=1.82 m/s^2
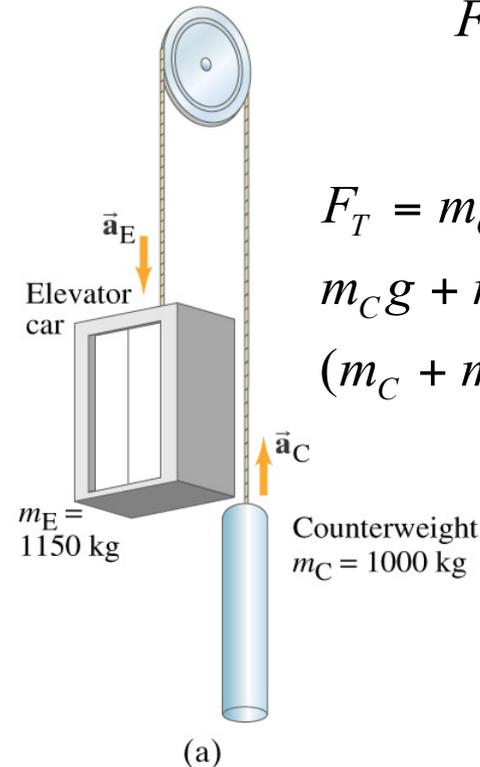
(b) F$_T$=21.8.0N
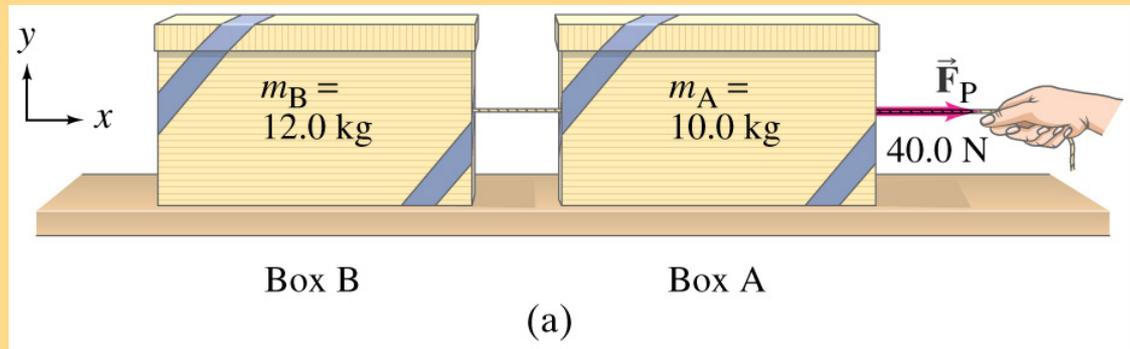
Read Ex. 4-13 and Ex. 4-14

Atwood's machine and pulley

Ex. 4-14 What force must be exerted on the rope to lift the piano with constant velocity?

Ex. 4-13 Find (a) the acceleration of the elevator and (b) the tension in the cable
(choose upward positive)

Advantage of a pulley

Copyright © 2005 Pearson Prentice Hall, Inc.

Atwood's machine

$$F_T - m_E g = -m_E a_E$$

$$F_T - m_C g = +m_C a_C$$

$$a_E = a_C$$

$$F_T = m_C g + m_C a$$

$$m_C g + m_C a - m_E g = -m_E a$$

$$(m_C + m_E)a = (m_E - m_C)g$$

$\vec{a}_E$

Elevator car

$\vec{a}_C$

$m_E = 1150$ kg

Counterweight $m_C = 1000$ kg

(a)

Revision

What are the three Newton's law?

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

First law
*Every object continues in its state of rest,
or uniform velocity in a straight line*

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

Second law
What is the difference between mass and weight?
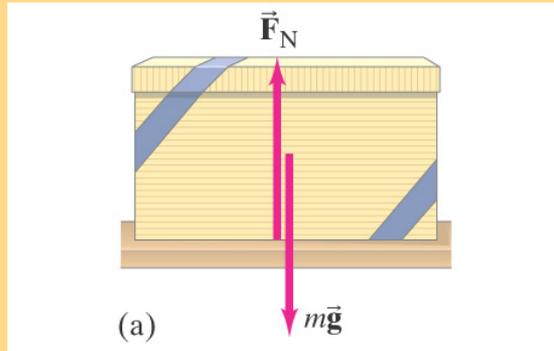
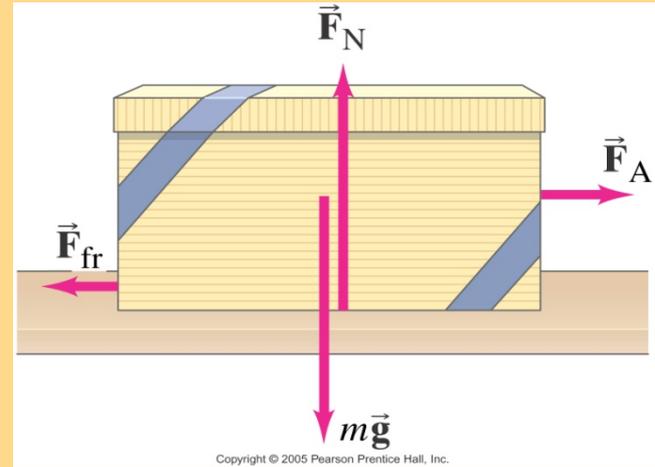$$\vec{F}_{12} = -\vec{F}_{21}$$

Third law
Examples?

1. Draw a **free-body diagram** for each object.
   (show ALL forces ON the object alone)

2. Apply **Newton's second law** to the x and y **components** separately.

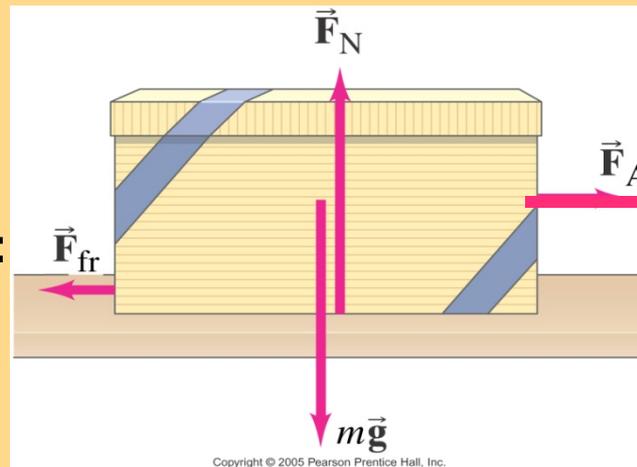3. Solve the equations for the unknowns

Friction

Object at rest:

$$F_{fr} = 0$$

$$F_A - F_{fr} = 0$$

Object at motion:

$$F_A - F_{fr} = ma_x$$

Friction

Experiments show that the *magnitude* of the
friction force is proportional to the **normal force**

$$F_{fr} = \mu F_N$$

Friction force is parallel to the surface
while
Normal force is perpendicular to the surface

Coefficient of Static/Kinetic Friction

TABLE 4–2 Coefficients of Friction[†]

Surfaces	Coefficient of Static Friction, μ_s	Coefficient of Kinetic Friction, μ_k
Wood on wood	0.4	0.2
Ice on ice	0.1	0.03
Metal on metal (lubricated)	0.15	0.07
Steel on steel (unlubricated)	0.7	0.6
Rubber on dry concrete	1.0	0.8
Rubber on wet concrete	0.7	0.5
Rubber on other solid surfaces	1–4	1
Teflon® on Teflon in air	0.04	0.04
Teflon on steel in air	0.04	0.04
Lubricated ball bearings	<0.01	<0.01
Synovial joints (in human limbs)	0.01	0.01

[†] Values are approximate and intended only as a guide.

Friction

Experiments show that the *magnitude* of the
friction force is proportional to the **normal force**

$$F_{fr} = \mu F_N$$

Friction force is parallel to the surface
while
Normal force is perpendicular to the surface

μ_S μ_K

Generally

when at rest: when at motion:

$$\mu_S > \mu_K$$

Coefficient of   Coefficient of
static friction   *kinetic* friction

Why?

Surface on a microscopic scale: bumps

Atoms of different surfaces - bonds

Friction at Rest vs. at Motion

Object at rest:

$$0 \leq F_{fr} \leq \mu_S F_N$$

Object at motion:

$$F_{fr} = \mu_K F_N$$

Ex. 4-16 A box of mass m=10.0 kg rests on a horizontal floor. The coefficient of static friction is 0.40 and the coefficient of kinetic friction is 0.30. In a graph, show the values of the friction force when there is a horizontal external force of magnitude 0, 10N, 20N, 38N, 40N, 50N, 60N
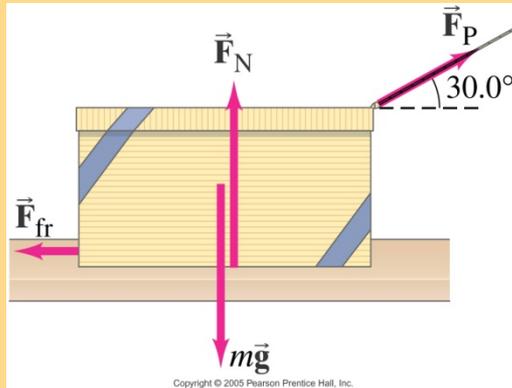
$$F_N = 98 N$$

$$F_{fr}^{\max(static)} = \mu_S F_N = 39 N$$

$$F_{fr}^{(kinetic)} = \mu_K F_N = 29 N$$

Copyright © 2005 Pearson Prentice Hall, Inc.
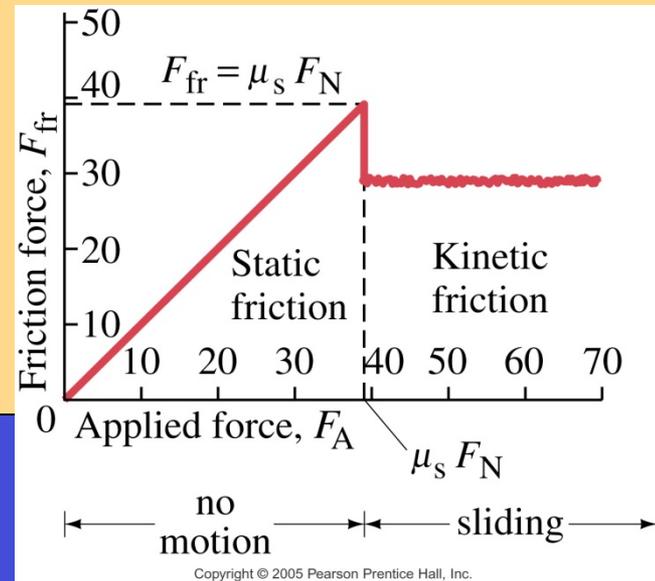
Exercises

Ex. 4-19 Mass of the box=10.0 kg, the applied force is 40.0N, and the coefficient of kinetic friction is 0.30. Calculate the acceleration.
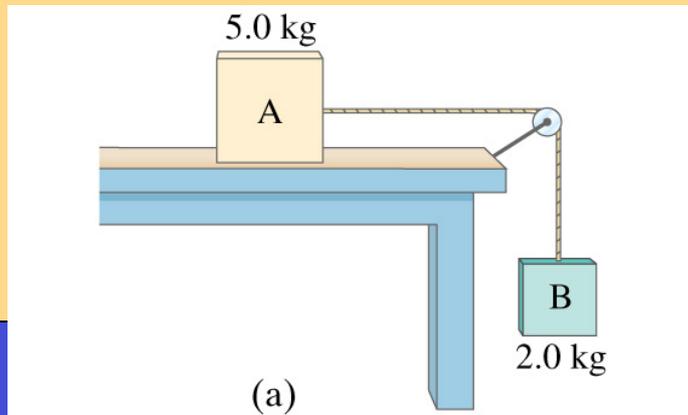

$$F_N = 78.0N$$

$$F_{fr} = \mu_K F_N = 23.4N$$

$$a = 1.1m/s^2$$

Ex. 4-20 The coefficient of kinetic friction is 0.20. As box B moves down, box A moves to the right. Calculate the acceleration.
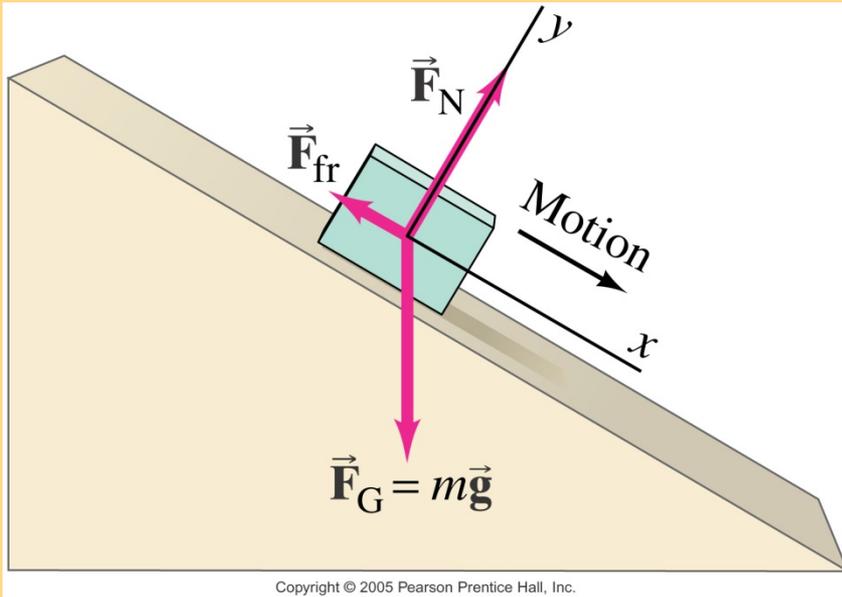
(positive to the right and positive downward)
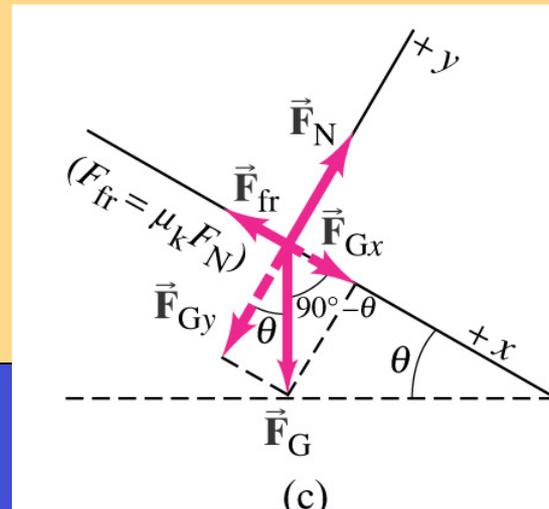

$$F_N = 49.0N$$

$$F_{fr} = \mu_K F_N = 9.8N$$

$$a = 1.4m/s^2$$

Incline

Copyright © 2005 Pearson Prentice Hall, Inc.

Ex. 4.21 Given the slope and the coefficient of kinetic friction, calculate the acceleration

$$a = (\sin\theta - \mu\cos\theta)g$$

(c)

Acceleration does not depend on the mass