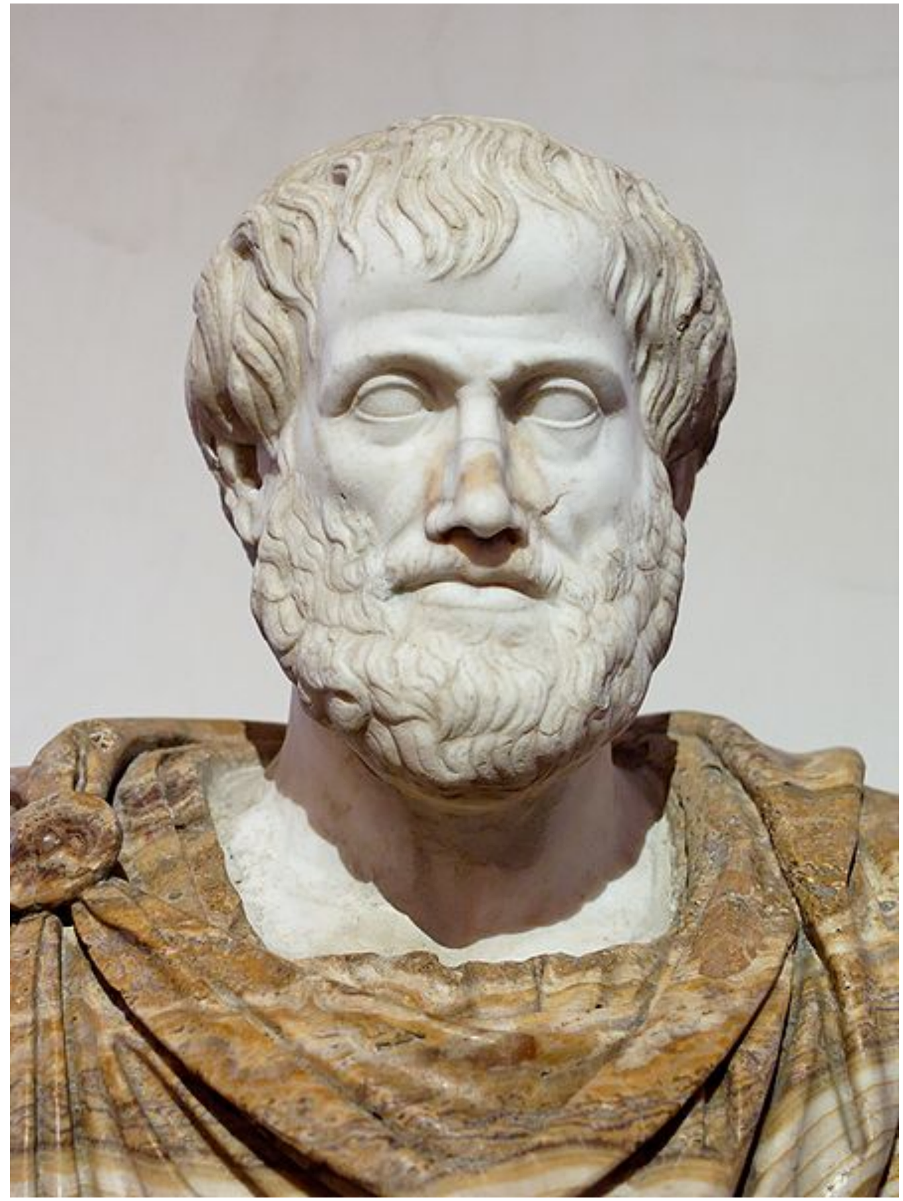
Ch 5 – Newton’s Laws

Aristotle

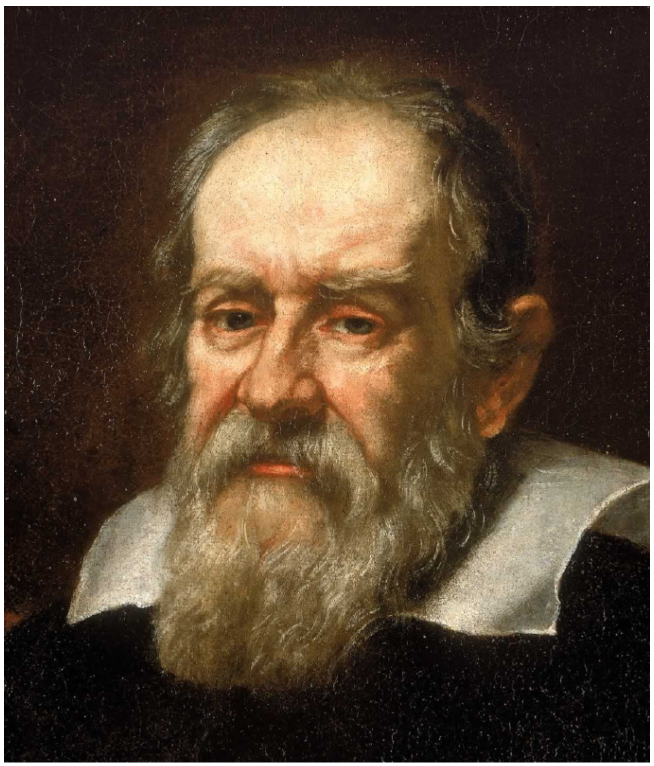
The Greek philosopher & metaphysicist Aristotle (384-322 B.C.) based his analysis of falling bodies on pure logic: "Heavier objects fall faster in proportion to their weight." This belief was *so* logical that it persisted for almost 2000 years.

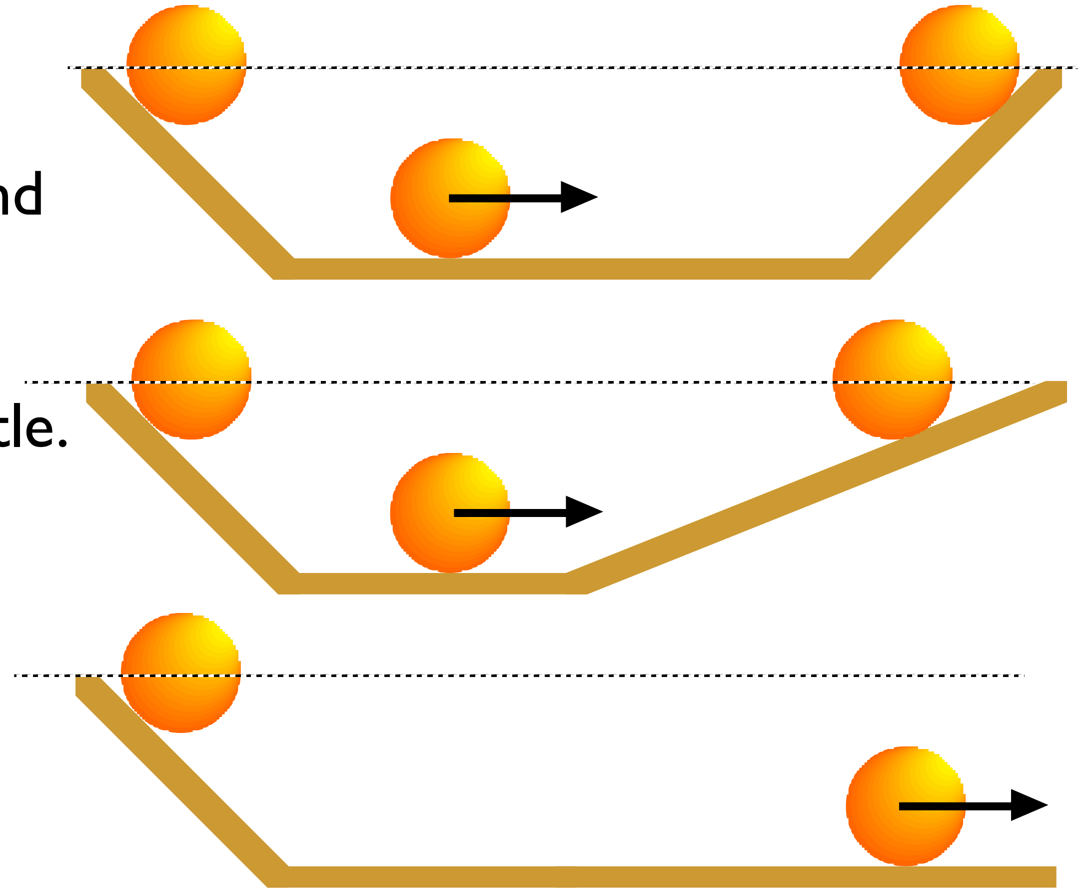
Aristotle also surmised that motion could be described as *violent* (a ball getting kicked, say) and *natural* (the ball rolling to a stop). The natural state of of a body, of course, is "at rest."



Galileo

Galileo (1564-1642) rebelled against blind acceptance of Aristotle's "logical" thinking, and encouraged repeatable experiments, earning him the "Father of Modern Science" title.



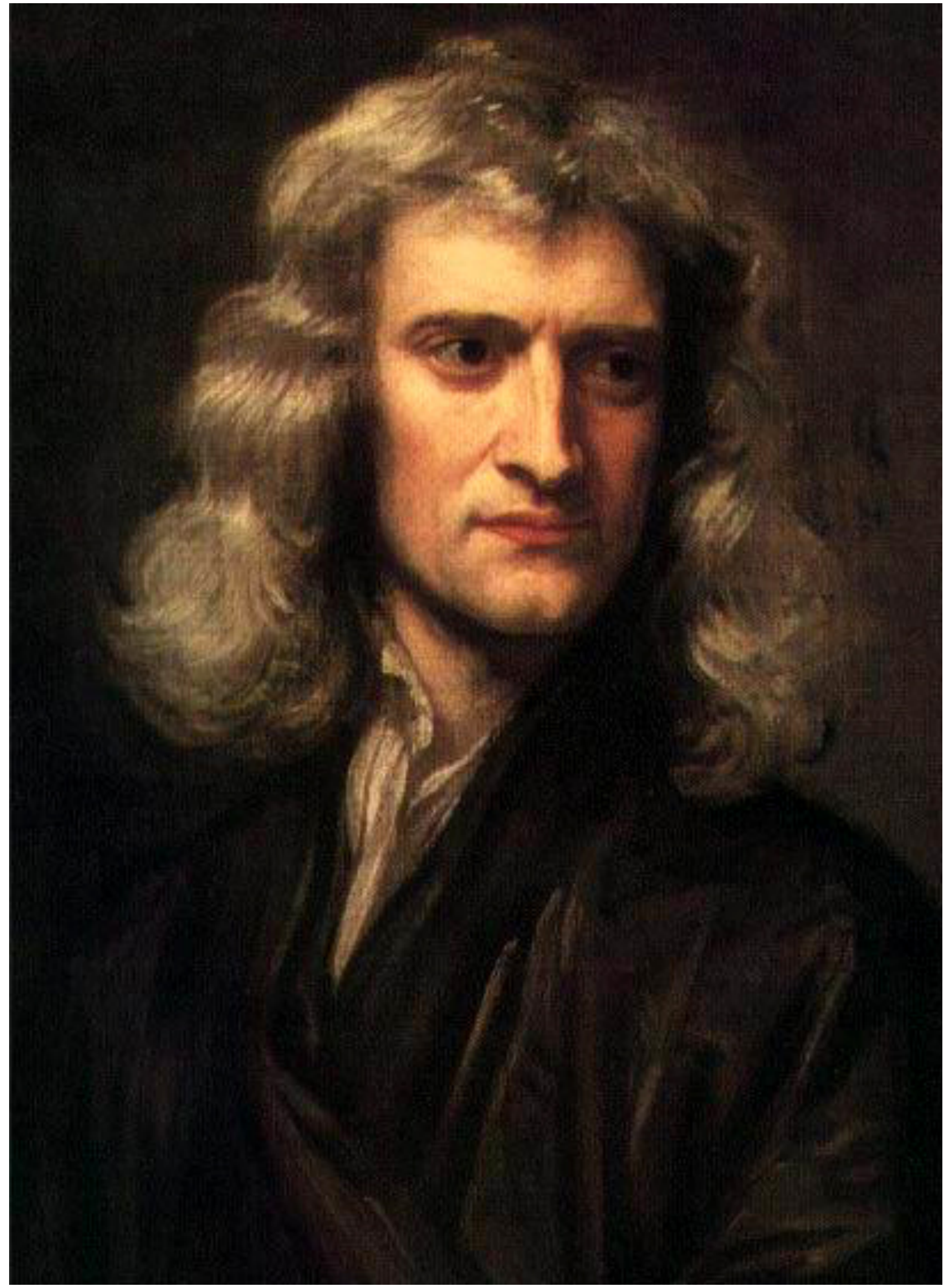


He also demonstrated, with a little logical thinking of his own, that Aristotle's ideas regarding "natural states of rest" were wrong.

Newton

Newton (1643-1727) continued Galileo's studies of motion. Newton wasn't known for publicizing his work, but in 1687, he published the *Philosophiae Naturalis Principia Mathematica*, which summarized his studies. This book was written in Latin, the language of scholars, and is considered by many to be the single greatest scientific book ever published.

Among other things, it included his analysis of motion, summarized in three laws.



Newton's First Law of Motion

"Every body continues its state of rest or uniform speed *in a straight line*, unless it is compelled to change that state by a *net force* acting on it."

This tendency to maintain one's state of motion (whether actually moving or at rest) is called **inertia**; for this reason, the Newton's First Law of Motion is commonly called "The Law of Inertia."

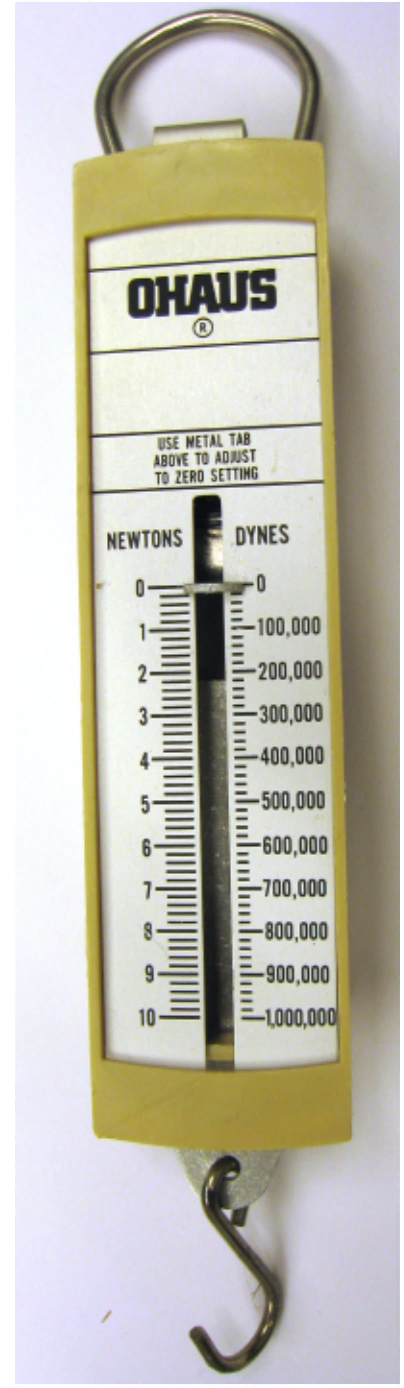
Force

Force = “a push or pull on an object”. Doesn’t always cause motion, but does cause deformation (change in shape).

Forces have a *magnitude* and a *direction*: they are vector quantities.

One of the most common ways of measuring force magnitude is with a *spring scale*.

The units of force are **kg•m/s²**, otherwise known as the **Newton**.



Mass

Mass is one of the single most misunderstood concepts in chemistry and physics. It is *not* the same as "weight," although the two measurements are related.

Mass is a measure of the amount of *inertia* that a body has—it's a measure of how hard it is to change an object' s motion. The more mass you have, the more inertia you have, and the more inertia you have, the harder it is to get you moving (if you're motionless), or to stop your motion (if you're moving).

Example 1

A spring scale is used to measure forces. Can you measure mass with a spring scale?

Well... sort of. Sometimes.

We can use a spring scale to measure the mass of an object on earth, because a given mass has a given weight on the earth. This won't work if we're out in space, though—earth's gravity won't pull the object down on the spring scale. Clearly, the "stuff" in an object doesn't just disappear when we go into space, so an object can still have mass, but be weightless. (In space, where a spring scale is useless, we have other ways of measuring an object's mass.)

Weight

Weight is a measure of how strongly earth's gravity pulls on a mass. It is a measure of Force, and written as $\mathbf{F_g}$, or sometimes as *W*, and as with all forces, its SI units are the kg•m/s^2 (Newton).

The weight of an object at the surface of the earth may be calculated as follows:

$$\mathbf{F_g} = m\mathbf{g} \ (= W)$$

Example 2

"I weigh 79.0 kilograms." Is this an acceptable statement? If true, is it true out in space as well?

No; *mass* $\neq$ *weight*, although in common usage, one may hear this. *Mass* is the same everywhere.

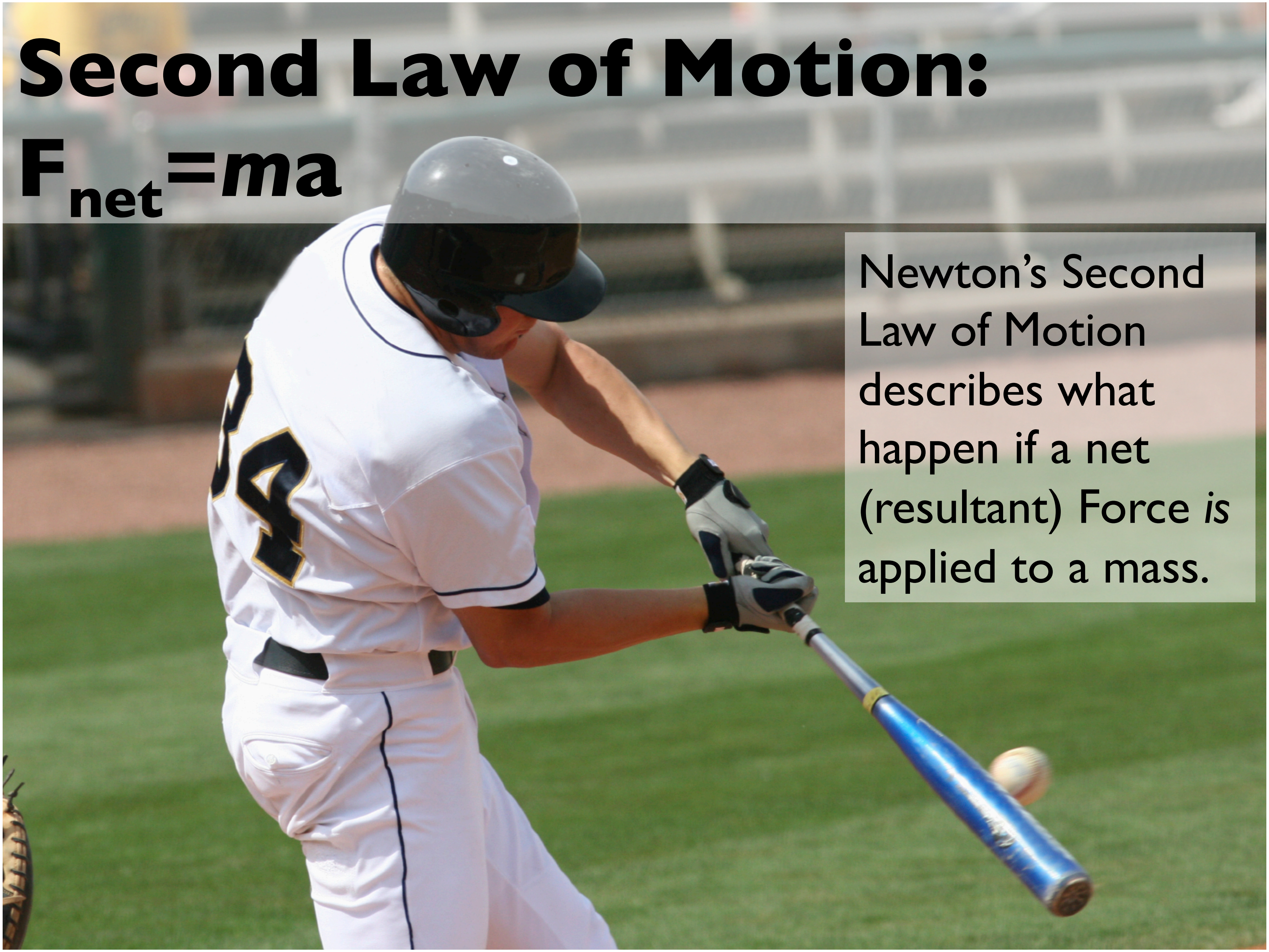
"I weigh 174 pounds." Is this an acceptable statement? Is this true out in space as well?
What's the relationship between a pound and a kilogram?

No; weight = force of earth's gravity, which varies with distance from Earth. 1.00kg at Earth's surface = 2.21pounds.

"I weigh 774 Newtons." Is this an acceptable statement? If true, is it true out in space as well? What is the relationship between a Newton and a kilogram?

Yes, this is acceptable, but weight varies with distance from Earth. 1.00 kg = 9.8 N (according to F_g=mg).

Second Law of Motion: $F_{net}=ma$



Newton's Second Law of Motion describes what happen if a net (resultant) Force *is* applied to a mass.

Example 3

How much force is required to accelerate a 70.0-kg human from 0.00 m/s to 3.00 m/s in 5.00 s?

Solution:

Known: v_o=0 m/s, v_f=3 m/s,
t=5 s, m=70.0kg

Unknown: a=?, F=?

Formulae: $$a = \frac{v_f - v_i}{t}, \; F = ma$$

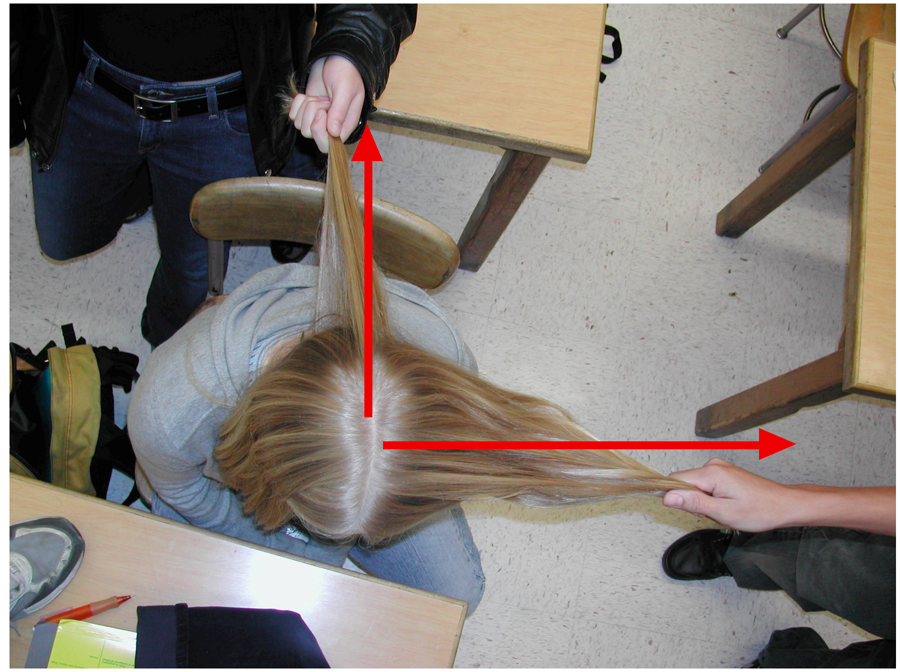
Solution:

$$a = \frac{3\text{m/s} - 0\text{m/s}}{5\text{s}} = 0.600\text{m/s}^2$$

$$F = ma = (70\text{kg})(0.600\text{m/s}^2) = \boxed{42\text{kg} \bullet \text{m/s}^2}$$

Example 4

A force of 30.0 N is applied to a student's head at 90°, while a force of 40.0 N is applied at 0°. What is the net acceleration of the student's 10.0kg head?



$$\sum F = ?$$

$$F_x = +40N$$

$$F_y = +30N$$

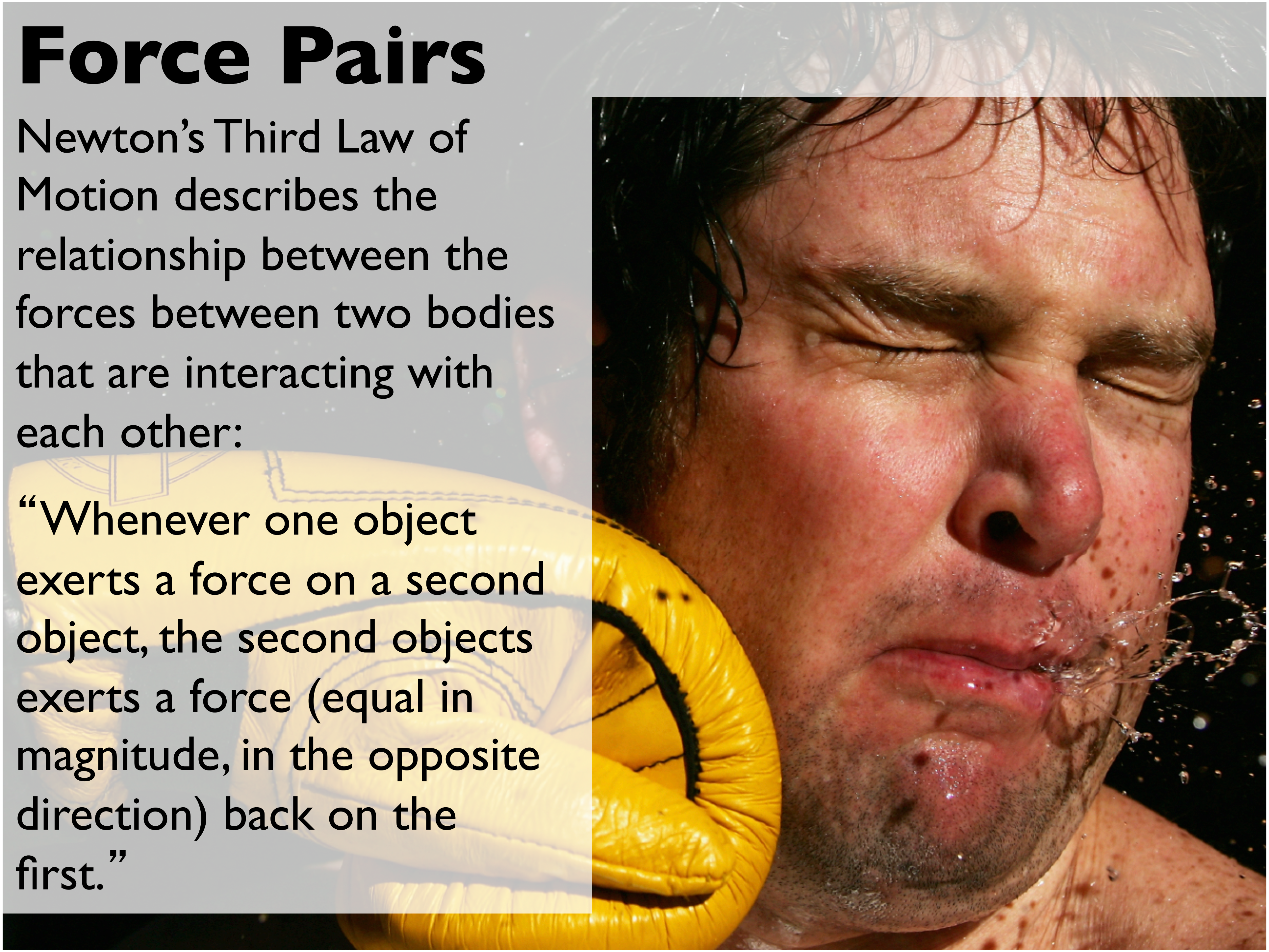
$$F_{net}^2 = F_x^2 + F_y^2, \text{so } F_{net} = \sqrt{F_x^2 + F_y^2}$$

$$F_{net} = \sqrt{40^2 + 30^2} = 50N, \ \theta = \tan^{-1}(30/40) = 36.9°$$

Force Pairs

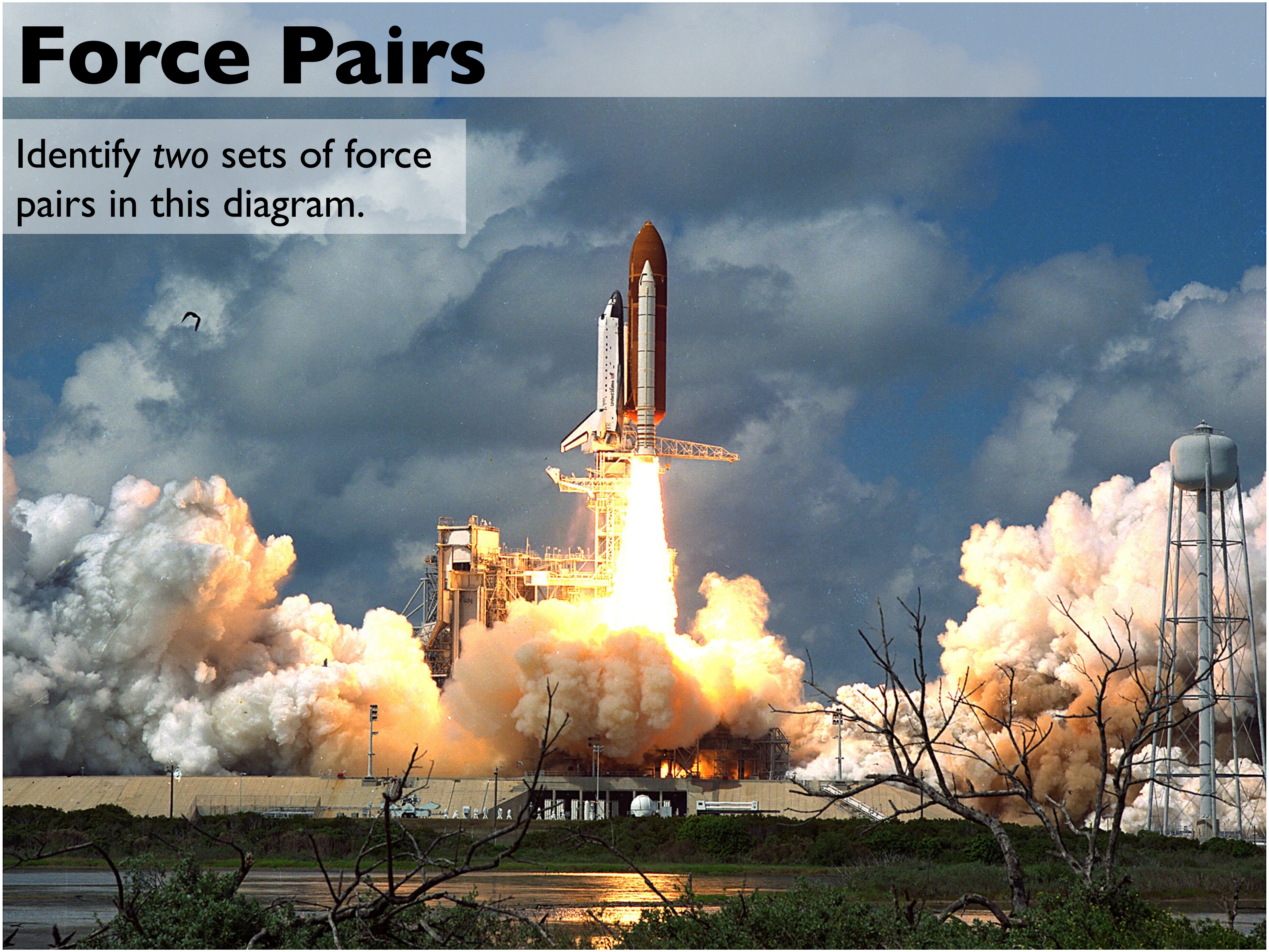
Newton's Third Law of Motion describes the relationship between the forces between two bodies that are interacting with each other:

"Whenever one object exerts a force on a second object, the second objects exerts a force (equal in magnitude, in the opposite direction) back on the first."

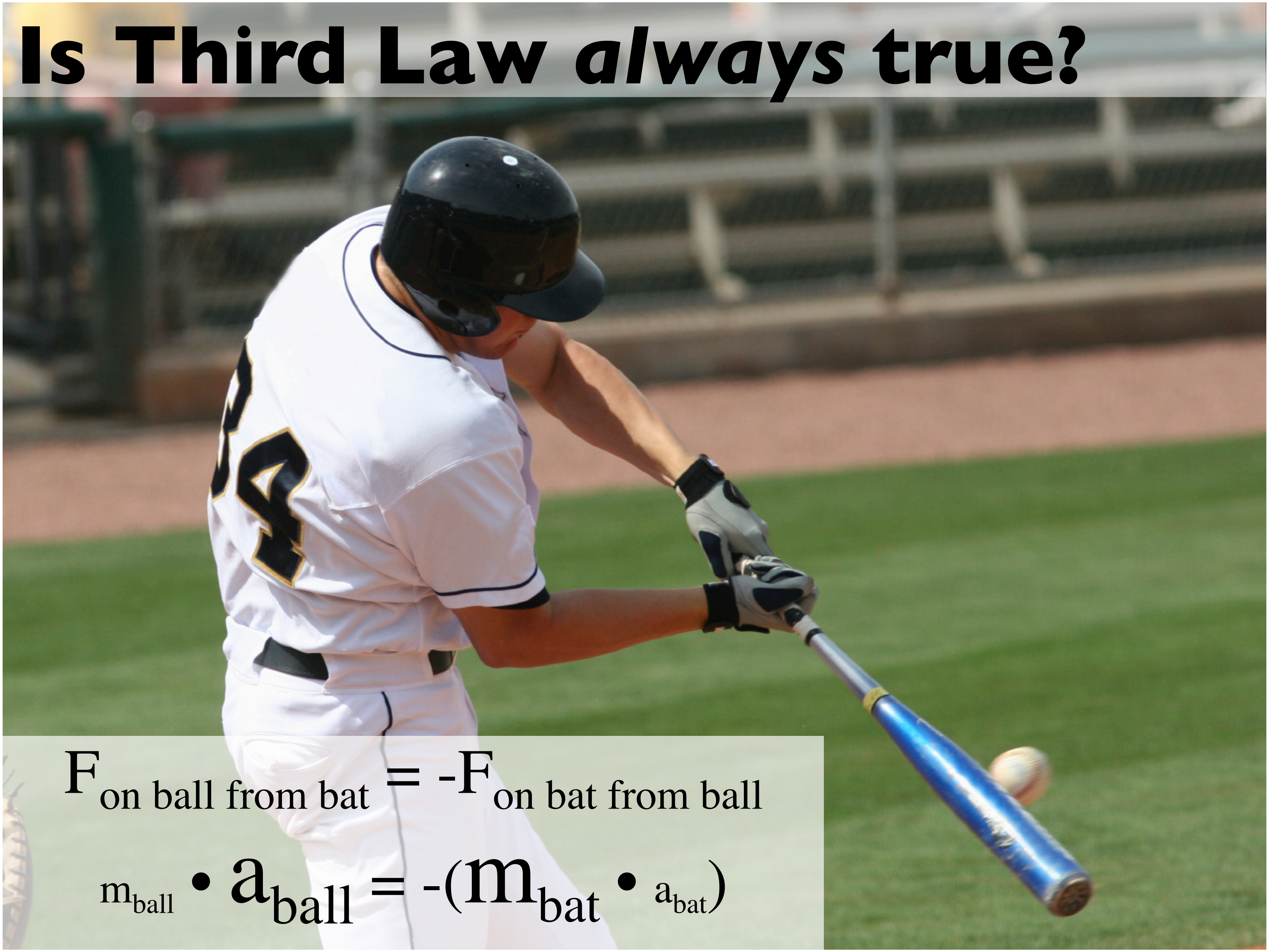


Force Pairs

Identify *two* sets of force pairs in this diagram.



Is Third Law *always* true?



$$F_{\text{on ball from bat}} = -F_{\text{on bat from ball}}$$

$$m_{\text{ball}} \cdot a_{\text{ball}} = -(m_{\text{bat}} \cdot a_{\text{bat}})$$

Free Body Diagram

A *free-body diagram* identifies all of the vector forces (magnitude and direction) acting on a single object of interest, with the intention of analyzing what effect those forces have on the object.

What forces are acting on the bowling ball sitting on a table here?

Solving Problems Using 3 Laws

By judiciously applying our understanding of Newton's Laws (especially the Second Law, $\mathbf{F}_{\mathbf{net}} = m\mathbf{a}$), we can analyze a lot of different situations.

In all of these situations, we'll use the same problem-solving procedure:

a. Identify *x*- and *y*-axes on our diagram.

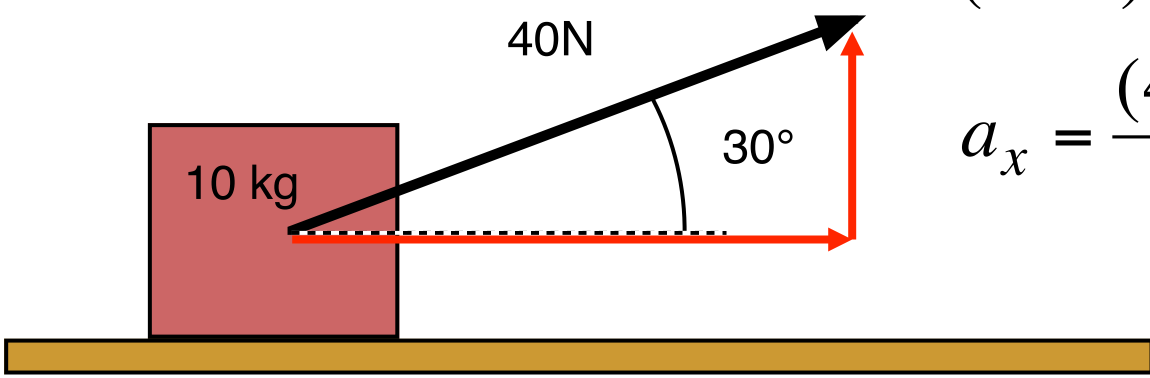
b. Identify & label forces acting on objects.

c. Apply Newton's 2nd Law to *x*- and *y*- axes separately.

d. Resolve *x*- and *y*- results into a single vector result.

Example 5

Determine the acceleration of this box, resting on a frictionless table.



$$\sum F = ma$$

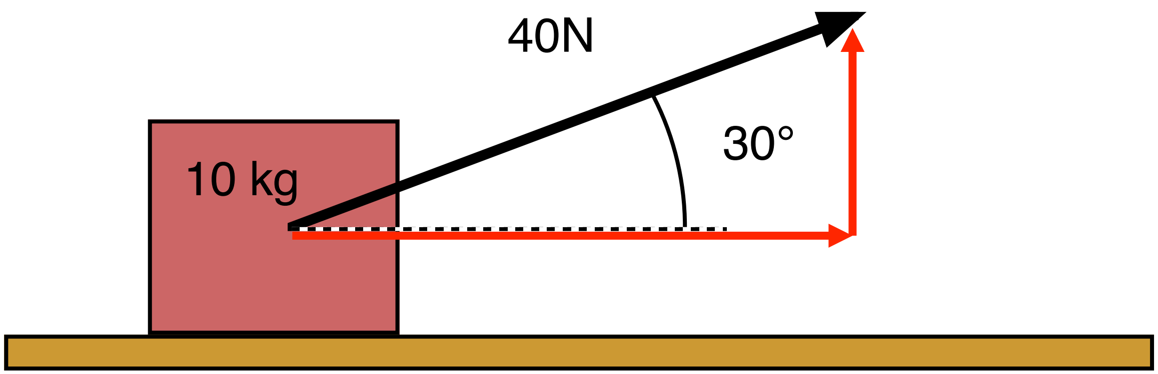
$$\sum F_x = ma_x$$

$$(40N)\cos 30° = (10kg)a_x$$

$$a_x = \frac{(40N)\cos 30°}{10kg} = 3.46m/s^2$$

Example 5b

Determine the force of the table pushing up on the box.



$$\sum F = ma$$

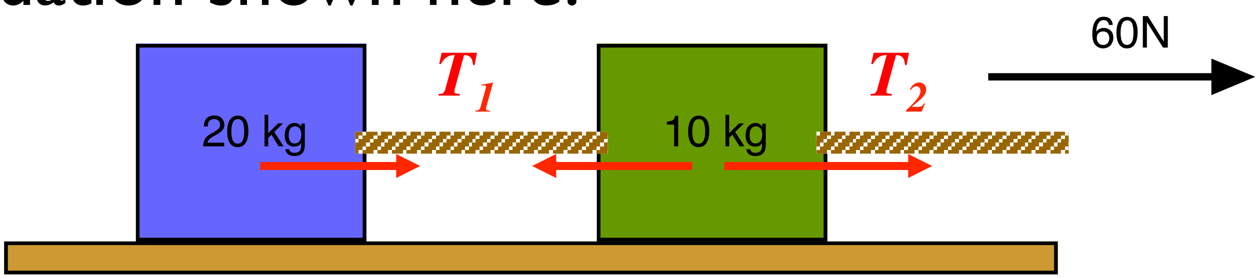
$$\sum F_y = ma_y$$

$$F_N + F_y - F_g = 0$$

$$F_N = -F_y + F_g = -20N + 98N = 78N$$

Example 6

Find the acceleration of each mass, and the tension in each cord, for the frictionless situation shown here.



$$\sum F_{x-blue} = m_{blue} a_{x-blue}$$

$$F_{tension1} = (20kg) a_{x-blue}$$

$$\sum F_{x-green} = m_{green} a_{x-green}$$

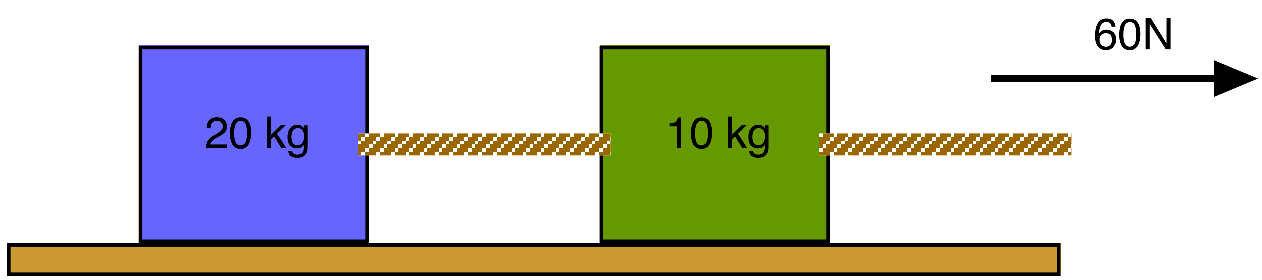
$$F_{tension2} - F_{tension1} = m_{green} a_{x-green}$$

$$60N - F_{tension1} = (10kg) a_{x-green}$$

Using the fact that the $a_{x\text{-}blue}$ and $a_{x\text{-}green}$ are the same, we can substitute and solve to get a and $F_{tension\ 1}$.

Example 6 - Shortcut

Substituting and solving for two or more bodies in a problem can get tedious. In some cases, consider the following shortcut:

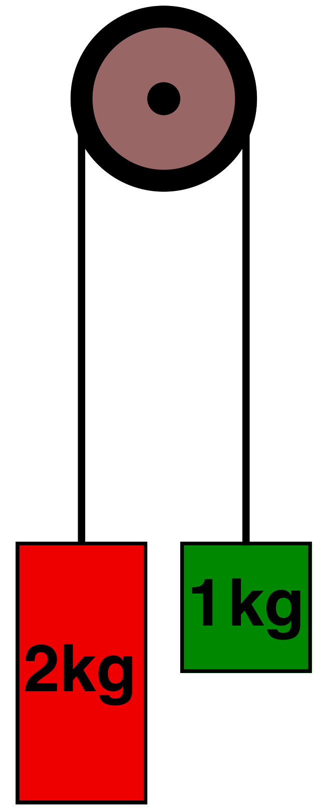


1. Solve for net *external* force, total mass, and common acceleration.

2. Apply analysis to individual bodies based on individual free-body diagram.

Example 7

Find the acceleration of the larger mass in this Atwood's machine, and determine the tension in the rope attached to the masses.



$$F_{net} = ma$$

$$-F_{g2} + F_T = m_2 a \qquad\qquad -F_{g1} + F_T = -(m_1 a)$$

(We've chosen direction of a to be clockwise positive.)

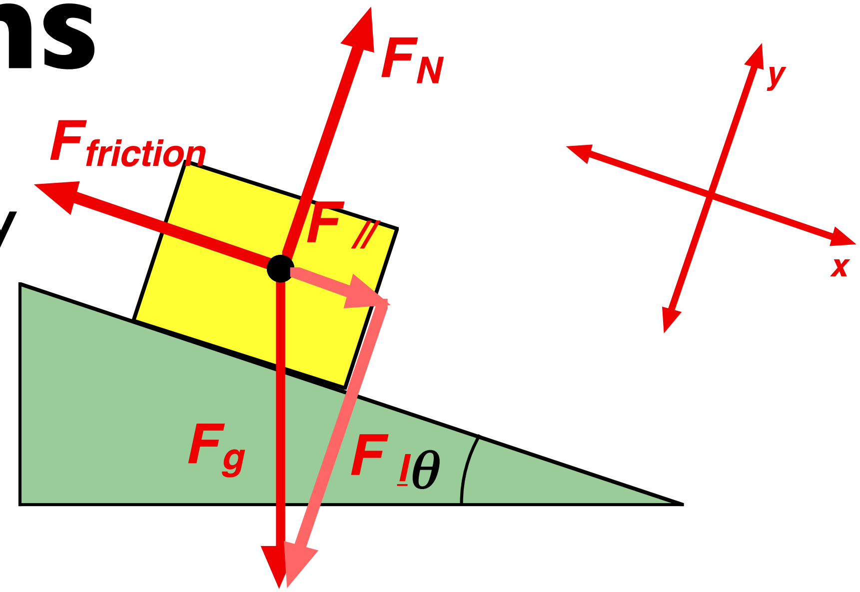
$$F_T = m_2 a + m_2 g \qquad -> \qquad -m_1 g + (m_2 a + m_2 g) = -m_1 a$$

$$a(m_1 + m_2) = g(m_1 - m_2)$$

$$a = \frac{m_1 - m_2}{m_1 + m_2} g$$

Incline Problems

Because the incline "tilts" the motion, we usually "tilt" our way of looking at the problem. As a result of these new axes, we' ll need to split F_g up into *x* and *y* components. The F_{gx} , which acts parallel to the plane, is usually called $F_{//}$. The F_{gy} , which acts perpendicular to the plane, is called $F_{\perp}$.



$$F_{//} = mg\sin\theta$$

$$F_{perp} = mg\cos\theta$$

How can we calculate the components of F_g ? Note that the small angle between F_g and F is θ, due to the mutually perpendicular segments.

Example 8

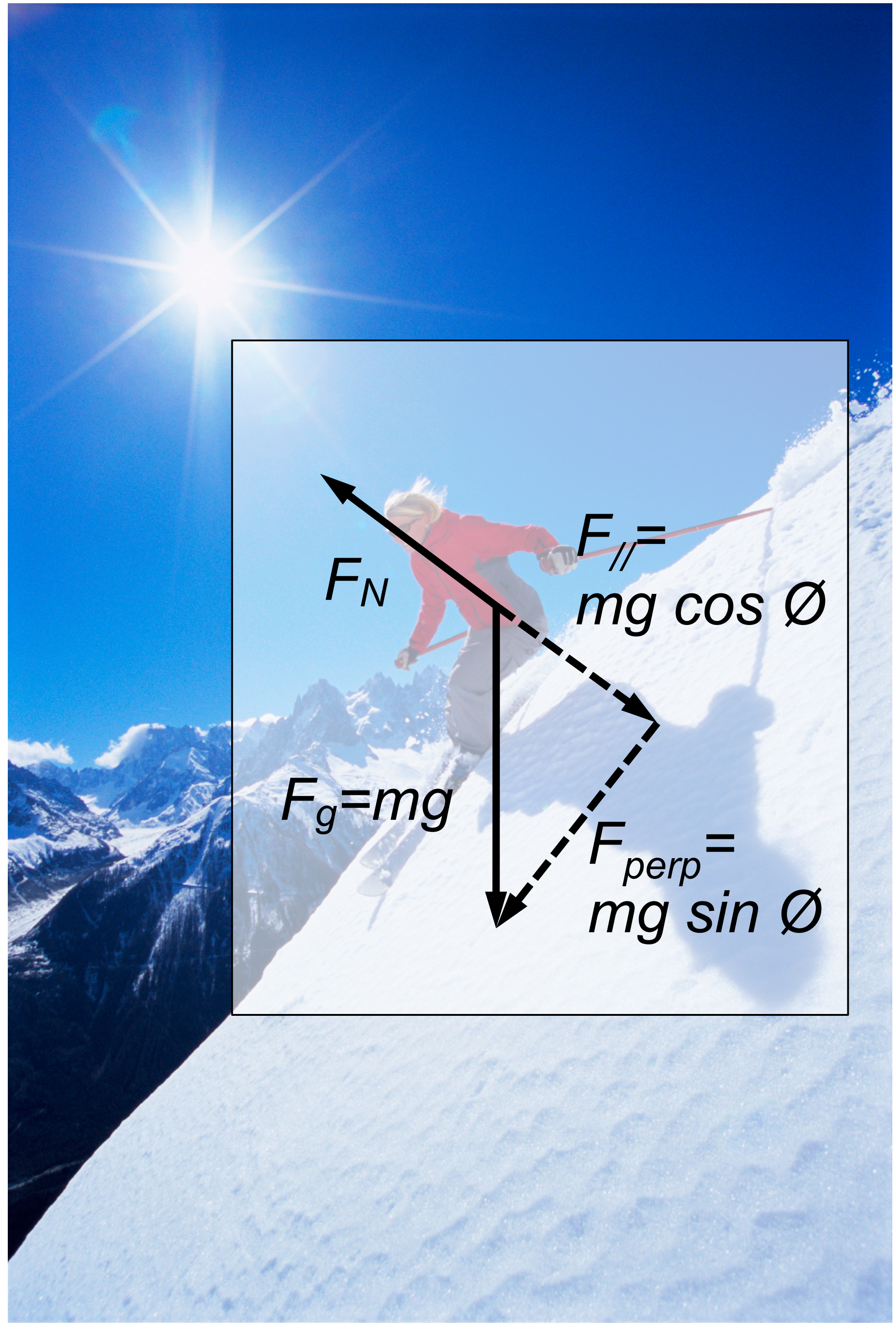
A skier, beginning from rest, descends a 60° essentially frictionless slope. What is her acceleration? What is her speed after 6.0 s have passed?

$$\sum F_x = ma_x$$

$$mg\sin\phi = ma_x$$

$$a = g\sin\phi = (9.8)\sin(60) = 8.49m/s^2$$

$$v_f = v_i + at = 0 + 8.49(6) = 50.9m/s$$



Lab

- Derivation of *a* as a function of Ø, m_{cart}, and $m_{hanging}$ (Ø<<20°)

- Instructor demonstrates set-up

- Collect data (what do you need to record?)

  Ø, $m_{hanging}$*,* m_{cart}*, printout of velocity-time graph w/ linear regression*

- How will you evaluate results?

  Compare theoretical **a***, predicted from derivation, with measure* **a** *from lab.*

Example 9

At the instant a race began, a 55-kg sprinter exerted a force of 800 N on the starting block at a 25° angle with respect to the ground.

a. What was the horizontal acceleration of the sprinter?

b. If the force was exerted for 0.38 s, with what horizontal speed did the sprinter leave the starting block?

$$\sum F_x = ma_x$$

$$800N\cos 25 = (55kg)a_x$$

$$a = 13.2m/s^2$$

$$v_f = v_i + at$$

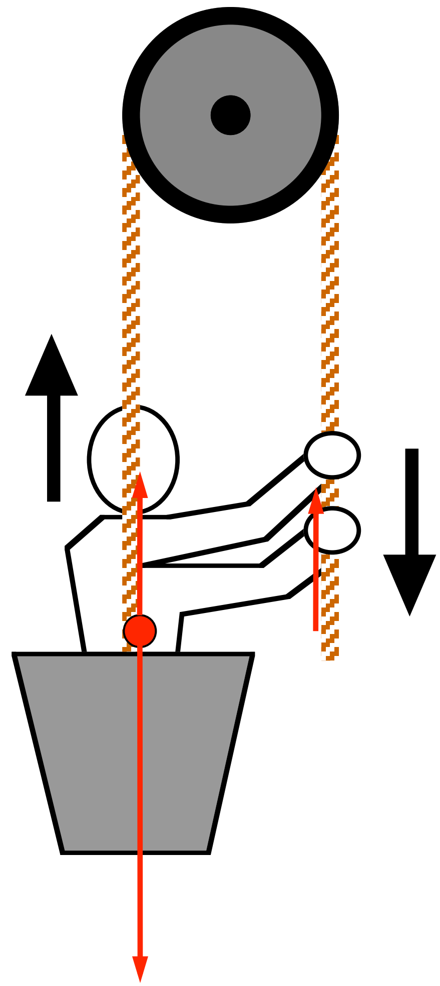
$$v_f = 0 + (13.2m/s^2)(0.38) = 5.01m/s$$

Example 10

A window washer pulls herself upward using a bucket-pulley apparatus.

a. How hard must she pull to raise herself slowly at constant speed? (Total mass of woman & bucket = 75 kg.)

b. If she increases this force by 10%, what is her acceleration?



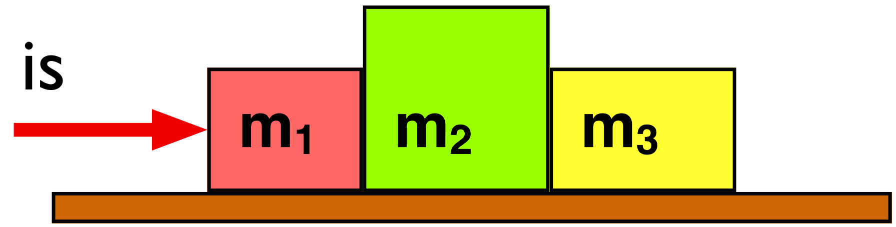
$$\sum F_x = ma_x$$

$$-F_g + 2F_{rope} = m(0)$$

$$F_{rope} = mg/2 = (75kg)(9.8m/s^2)/2 = 368N$$

Example 11

Three blocks on a frictionless horizontal surface are in contact with each other as shown. A force **F** is applied to mass m_1.



a. Draw a free-body diagram for each block.

b. Determine the acceleration of the system (in terms of m_1, m_2, and m_3).

c. Determine the net force on each block.

d. Determine the contact force that each block exerts on its neighbor.

Example 11

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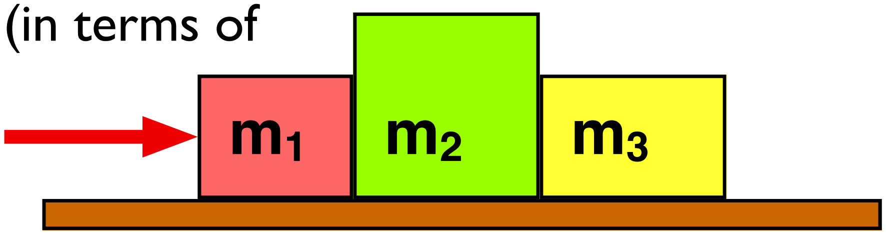

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Friction

Friction = a force that opposes the motion of a body

There are different types of friction, including rolling friction, fluid friction (liquid or gas), sliding friction.

Sliding Friction
- → **Static Friction**
- → **Kinetic Friction**

Friction

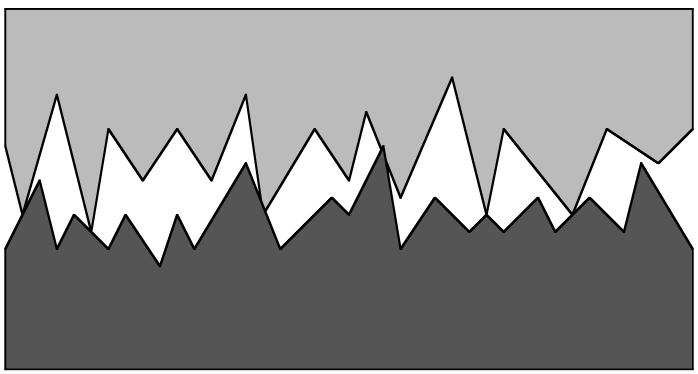
The magnitude of the force of friction depends on two things:

1. the nature of the two surfaces in contact with each other, as indicated by the "coefficient of friction" μ (the Greek letter "mu")

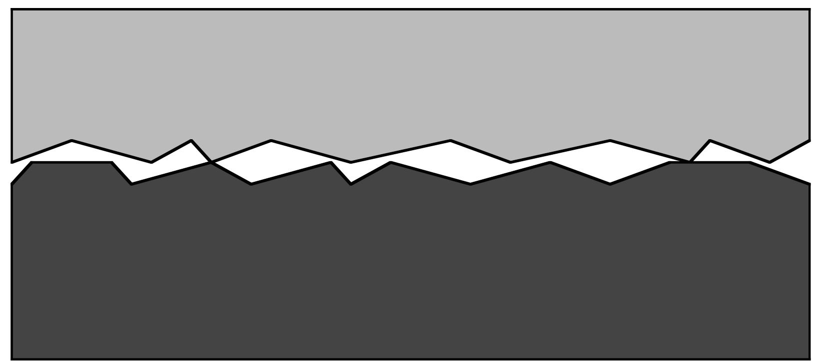
2. how hard the two surfaces are being pushed together, as indicated by the normal force F_N

Coefficient of Friction

The coefficient of friction μ is a number, experimentally determined, that describes how "sticky" two surfaces are when placed next to each other: the higher the μ, the more sticky the two surfaces are, and thus, the more friction force there will be when they try to slide against each other.



Close-up of high μ



Close-up of low μ

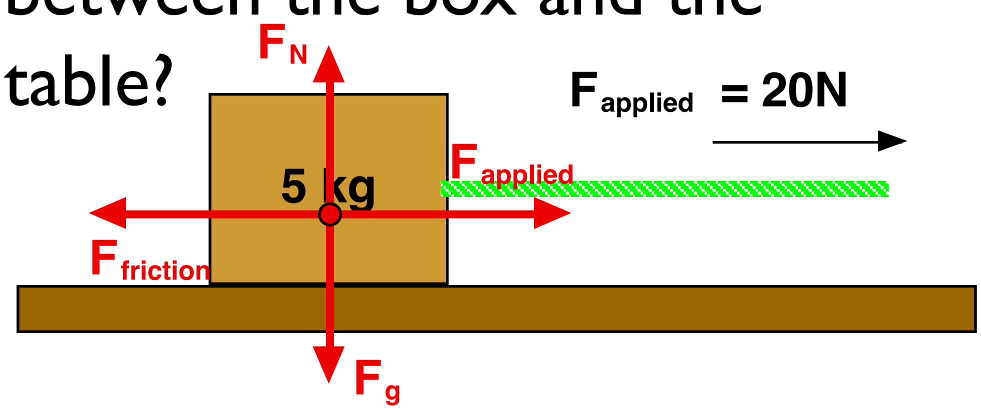
Coefficient of Friction

μ is defined as a ratio between $F_{friction}$ and F_{Normal} :

$$\mu = \frac{F_{friction}}{F_{Normal}}$$

Example 12

A wooden box rests on a wooden table. A cord is attached, and pulled with a gradually increasing force; the box finally begins to move when the Force applied to the cord is 20 N. What is the static coefficient of friction μ_s between the box and the table?



$$\sum F_y = ma_y$$

$$F_N - F_g = m(0)$$

$$F_N = F_g = mg$$

$$F_N = (5kg)(9.8m/s^2) = 49N$$

$$\sum F_x = ma_x$$

$$F_{applied} + F_{friction} = m(0)$$

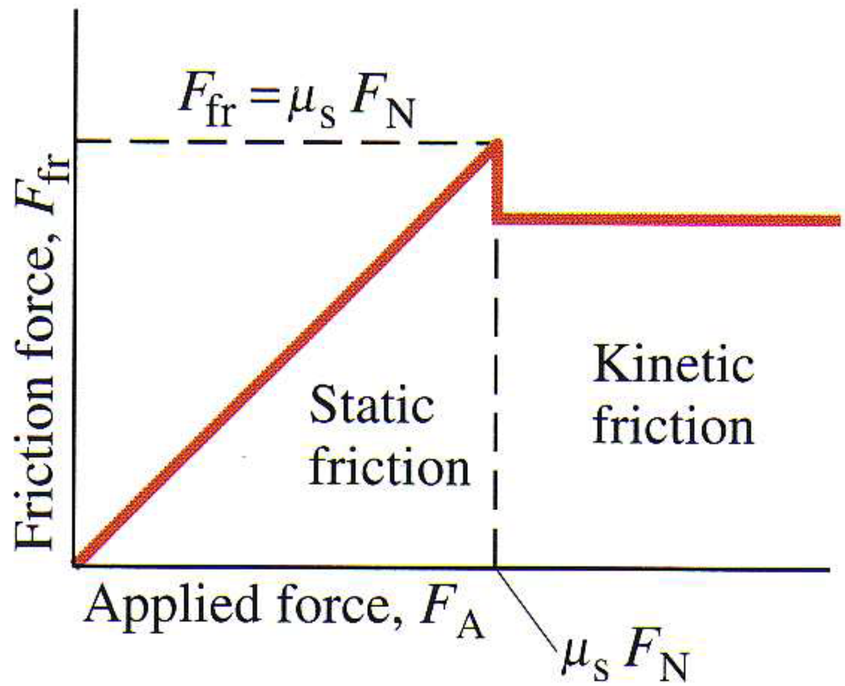
$$F_{friction} = -F_{applied} = -20N$$

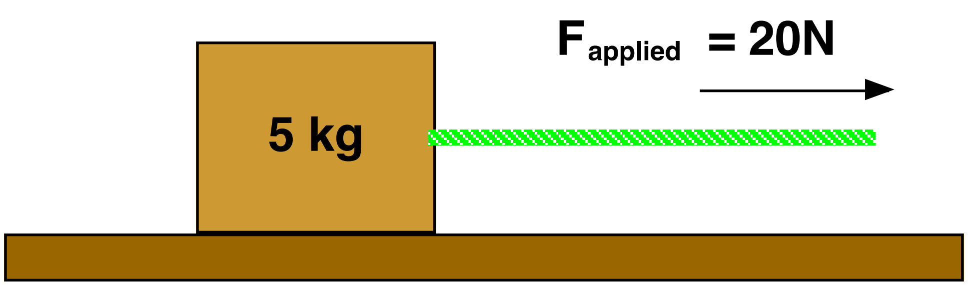
$$\mu = \frac{F_f}{F_N}$$

$$\mu = \frac{20}{49} = 0.41$$

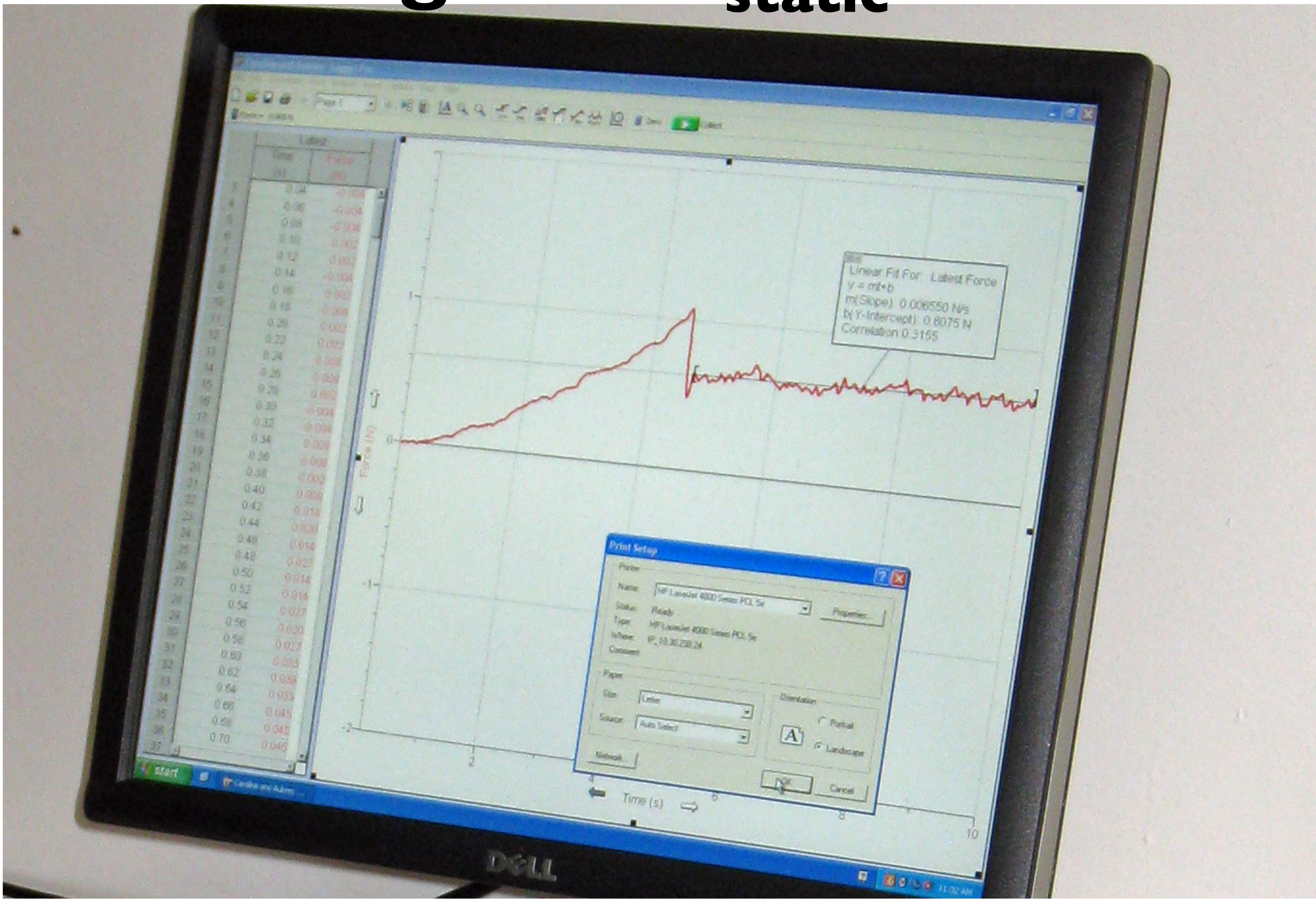
The "Magical" F_{static}

When a force is first applied to the box, and it isn't yet moving, the force of friction that opposes its sliding varies until it reaches a maximum value.





The "Magical" F_{static}



Common Coefficients

Surfaces	Coefficient of Static Friction (μs)	Coefficient of Kinetic Friction (μk)
Rubber on various surfaces	1 to 4	1
Rubber on dry concrete	1	0.8
Rubber on wet concrete	0.7	0.5
Steel on steel (unlubricated)	0.7	0.6
Wood on wood	0.4	0.2
Ice on ice	0.1	0.03
Human joints	0.01	0.01
Lubricated ball bearings	<0.01	<0.01

Note that $\mu_s > \mu_k$; once an object starts sliding, the force of friction opposing that motion decreases a little.

Fine Print: The relationship $F_{friction} = \mu\, F_{Normal}$ is not a law—it's a relationship that's approximate, but useful.

Example 13

Example 13

Kopish (m = 75.0 kg) is skating on ice at 22.4 miles per hour when he falls.

a. How fast is he traveling (in m/s) when he falls?

b. If the μ_k between his body and the ice is 0.1, what is the force of friction acting on his body as he slides across the ice?

c. If he slides 7 meters, how fast is he traveling just before he slams into the wall of the skating rink?

Example 14

If Biaggi is traveling at 10 m/s when he goes down, and slides a distance of 10 meters on the ground, what is the coefficient of friction between him and the ground?

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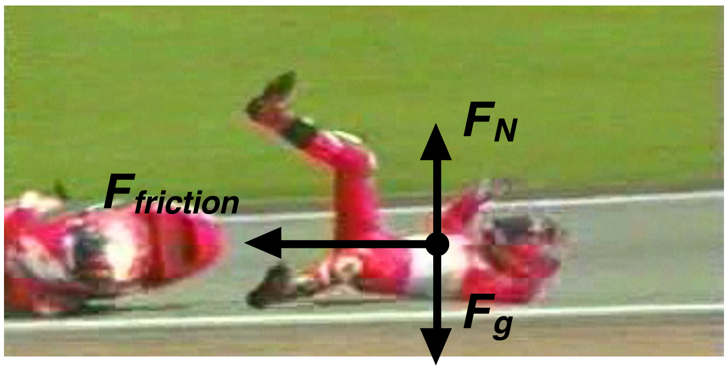

$$\sum F_y = ma_y$$

$$F_{Normal} - F_g = 0$$

$$F_{Normal} = F_g$$

$$F_N = (m)(9.8)$$

$$v_i = 10.0\text{m/s}$$

$$v_f = 0$$

$$\Delta x = 10\text{m}$$

$$a = \frac{v_f^{\ 2} - v_i^{\ 2}}{2\Delta x}$$

$$a = -5.0\text{m/s}^2$$

$$\sum F_x = ma_x$$

$$F_{friction} = ma_x$$

$$\mu F_{Normal} = ma_x$$

$$\mu = \frac{ma_x}{F_{Normal}}$$

$$\mu = \frac{ma_x}{F_{Normal}} = \frac{m(5.0m/s^2)}{m(9.8)} = \boxed{0.51}$$

Example 15

A skier, beginning from rest, descends a 30° slope where the kinetic coefficient of friction is 0.10. What is her acceleration? What is her speed after 6.0 s have passed?