Physics 8 — Monday, October 7, 2019

- On Wednesday I'll hand out HW6, due on Friday 10/18.
- This week, you're reading Ch11 (motion in a circle): the first half for today, and the second half for Wednesday.
- Ponder this with your neighbor while we get started:
  Why do modern cars have anti-lock brakes?

(A) because the pumping action of the anti-lock brake mechanism keeps the brake pads from getting too hot.

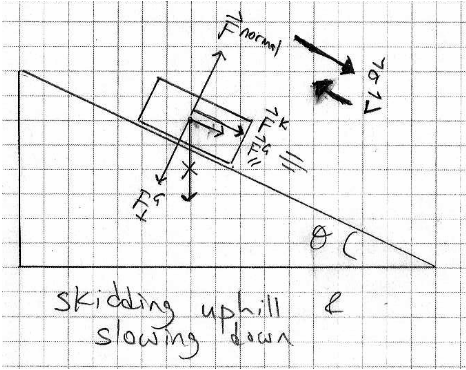
(B) because pulsing the brakes on and off induces kinetic friction, which is preferable to static friction.

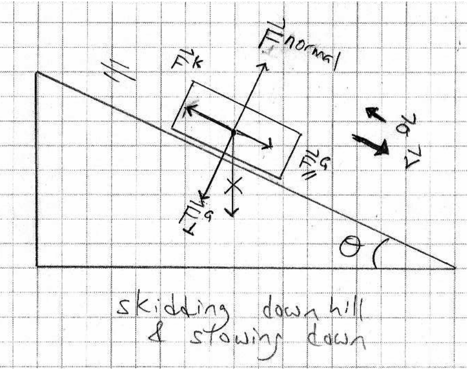
(C) because the cofficient of static friction is larger than the coefficient of kinetic friction, so you stop faster if your wheels roll on the ground than you would if your wheels were skidding on the ground.

(D) because the weird pulsating sensation you feel when the anti-lock brakes engage is fun and surprising!

Another Chapter 10 reading question:

You've slammed on the brakes, and your car is skidding to a stop on a steep and slippery winter road. Other things being equal, will the car come to rest more quickly if it is traveling uphill or if it is traveling downhill? Why? (Consider FBD for each case.)





(We stopped on this page. Let's look again at FBDs then go on.)

If I gently step on my car's accelerator pedal, and the car starts to move faster (without any screeching sounds), the frictional force between the road and the rubber tire surface that causes my car to accelerate is

(A) static friction.

(B) kinetic friction.

(C) normal force.

(D) gravitational force.

(E) there is no frictional force between road and tire.

If I **slam down** on my car's accelerator pedal, and the car **screeches** forward noisily like a drag-race car, the frictional force between the road and the rubber tire surface that causes my car to accelerate is

(A) static friction.

(B) kinetic friction.

(C) normal force.

(D) gravitational force.

(E) there is no frictional force between road and tire.

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Anti-Lock Brakes

(photo credit: Bill Berner)

Static friction and kinetic (sometimes confusingly called "sliding") friction:

$$F^{\text{Static}} \;\le\; \mu_S \; F^{\text{Normal}}$$

$$F^{\text{Kinetic}} \;=\; \mu_K \; F^{\text{Normal}}$$

"normal" & "tangential" components are $\perp$ to and $\parallel$ to surface

Static friction is an example of what physicists call a "force of constraint" and engineers call a "reaction force." In most cases, you don't know its magnitude until you solve for the other forces in the problem and impose the condition that $\vec{a} = \vec{0}$. (An exception is if we're told that static friction "just barely holds on / just barely lets go," i.e. has its maximum possible value.)

TABLE 10.1
Coefficients of friction

Material1	Material 2	μ_s	μ_k
aluminum	aluminum	1.1–1.4	1.4
aluminum	steel	0.6	0.5
glass	glass	0.9–1.0	0.4
glass	nickel	0.8	0.6
ice	ice	0.1	0.03
oak	oak	0.6	0.5
rubber	concrete	1.0–4.0	0.8
steel	steel	0.8	0.4
steel	brass	0.5	0.4
steel	copper	0.5	0.4
steel	lead	0.95	0.95
wood	wood	0.25–0.5	0.2

The values given are for clean, dry, smooth surfaces.

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rubber	concrete	1.0–4.0	0.8
steel	steel	0.8	0.4
steel	brass	0.5	0.4
steel	copper	0.5	0.4
steel	lead	0.95	0.95
wood	wood	0.25–0.5	0.2

The values given are for clean, dry, smooth surfaces.

- Steel on steel μ_K is about half that of rubber on concrete, and much less than that of μ_S for rubber on concrete.
- So a train can take a while to skid to a stop!
- Even more so if the tracks are wet: $\mu_K \approx 0.1$
- At $\mu = 0.1$ on level ground: 360 m to stop from 60 mph.
- At $\mu = 0.1$ on 6° slope: not possible to stop.

A car of mass 1000 kg travels at constant speed 20 m/s on dry, level pavement. The friction coeffs are $\mu_k = 0.8$ and $\mu_s = 1.2$. What is the **normal force** exerted by the road on the car?

(A) 1000 N downward

(B) 1000 N upward

(C) 1000 N forward

(D) 1000 N backward

(E) 9800 N downward

(F) 9800 N upward

(G) 11800 N downward

(H) 11800 N upward

A car of mass 1000 kg is traveling (in a straight line) at a constant speed of 20 m/s on dry, level pavement, with the cruise control engaged to maintain this speed. The friction coefficients are $\mu_k = 0.8$ and $\mu_s = 1.2$. The tires roll on the pavement without slipping. What is the frictional force exerted by the road on the car? (Let's use $g \approx 10\ \mathrm{m/s^2}$ for simplicity here.)

(A) 8000 N backward

(B) 8000 N forward

(C) 8000 N upward

(D) 10000 N backward

(E) 10000 N forward

(F) 12000 N backward

(G) 12000 N forward

(H) It points forward, must have magnitude $\leq 12000\ \mathrm{N}$, and has whatever value is needed to counteract air resistance.

A car of mass 1000 kg is initially traveling (in a straight line) at 20 m/s on dry, level pavement, when suddenly the driver jams on the (**non**-anti-lock) brakes, and the car skids to a stop with its wheels locked. The friction coefficients are $\mu_k = 0.8$ and $\mu_s = 1.2$. What is the frictional force exerted by the road on the car? (Let's use $g \approx 10\ \mathrm{m/s^2}$ for simplicity here.)

(A) 8000 N backward

(B) 8000 N forward

(C) 8000 N upward

(D) 10000 N backward

(E) 10000 N forward

(F) 12000 N backward

(G) 12000 N forward

(H) It points forward, must have magnitude $\leq 12000\ \mathrm{N}$, and has whatever value is needed to counteract air resistance.

Suppose that for rubber on dry concrete, $\mu_k = 0.8$ and $\mu_s = 1.2$. If a car of mass m traveling at initial speed v_i on a level road jams on its brakes and skids to a stop with its wheels locked, how do I solve for the length L of the skid marks? (Let's use $g \approx 10\ \mathrm{m/s^2}$ for simplicity here.)

(A) use $v_f^2 = v_i^2 + 2aL$ with $v_f = 0$ and $a = -2.0\ \mathrm{m/s^2}$
(B) use $v_f^2 = v_i^2 + 2aL$ with $v_f = 0$ and $a = -4.0\ \mathrm{m/s^2}$
(C) use $v_f^2 = v_i^2 + 2aL$ with $v_f = 0$ and $a = -6.0\ \mathrm{m/s^2}$
(D) use $v_f^2 = v_i^2 + 2aL$ with $v_f = 0$ and $a = -8.0\ \mathrm{m/s^2}$
(E) use $v_f^2 = v_i^2 + 2aL$ with $v_f = 0$ and $a = -10.0\ \mathrm{m/s^2}$
(F) use $v_f^2 = v_i^2 + 2aL$ with $v_f = 0$ and $a = -12.0\ \mathrm{m/s^2}$
(G) use $v_f^2 = v_i^2 + 2aL$ with $v_f = 0$ and $a = -14.0\ \mathrm{m/s^2}$

Suppose that for rubber tires on dry, level pavement, the friction coefficients are $\mu_k = 0.8$ and $\mu_s = 1.2$. If you assume that the forces between the ground and the tires are the same for all four tires (4-wheel drive, etc.), what is a car's maximum possible acceleration for this combination of tires and pavement? (Let's use $g \approx 10\ \mathrm{m/s^2}$ for simplicity here.)

(A) $1.0\ \mathrm{m/s^2}$

(B) $5.0\ \mathrm{m/s^2}$

(C) $8.0\ \mathrm{m/s^2}$

(D) $10.0\ \mathrm{m/s^2}$

(E) $12.0\ \mathrm{m/s^2}$

An object "O" of mass m slides down an inclined surface "S" at constant velocity. What is the magnitude of the **normal force** F^n_{so} exerted by the surface on the object? Repeat from here next time.

(A) $F^n_{so} = mg$

(B) $F^n_{so} = mg\sin\theta$

(C) $F^n_{so} = mg\cos\theta$

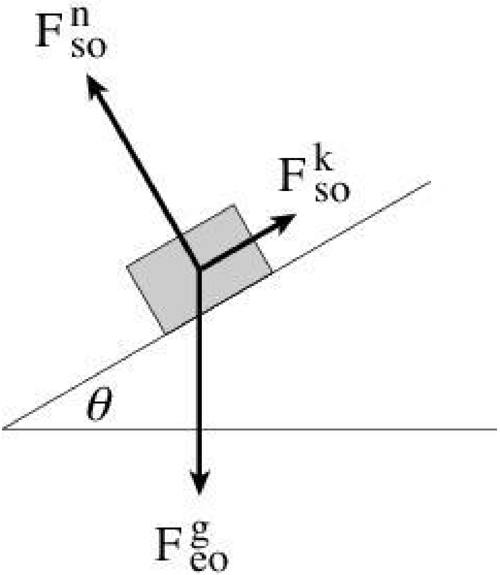
(D) $F^n_{so} = mg\tan\theta$

(E) $F^n_{so} = \mu_k mg$

(F) $F^n_{so} = \mu_k mg\sin\theta$

(G) $F^n_{so} = \mu_k mg\cos\theta$

(H) $F^n_{so} = \mu_k mg\tan\theta$



An object "O" of mass m slides down an inclined surface "S" at constant velocity. What is the magnitude of the (kinetic) **frictional force** F_{so}^{k} exerted by the surface on the object?

(A) $F_{so}^{k} = mg$

(B) $F_{so}^{k} = mg \sin\theta$

(C) $F_{so}^{k} = mg \cos\theta$

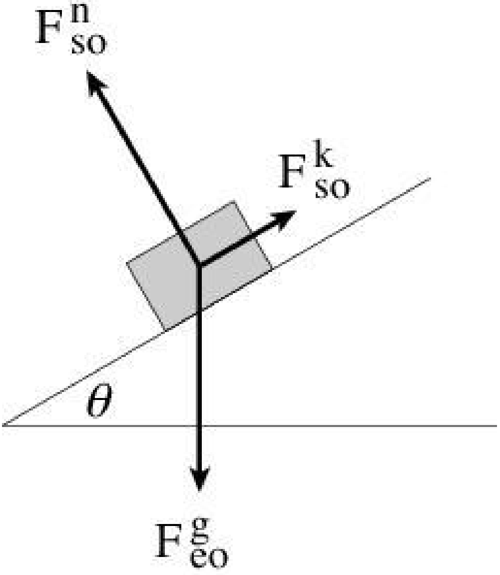
(D) $F_{so}^{k} = mg \tan\theta$

(E) $F_{so}^{k} = \mu_k mg$

(F) $F_{so}^{k} = \mu_k mg \sin\theta$

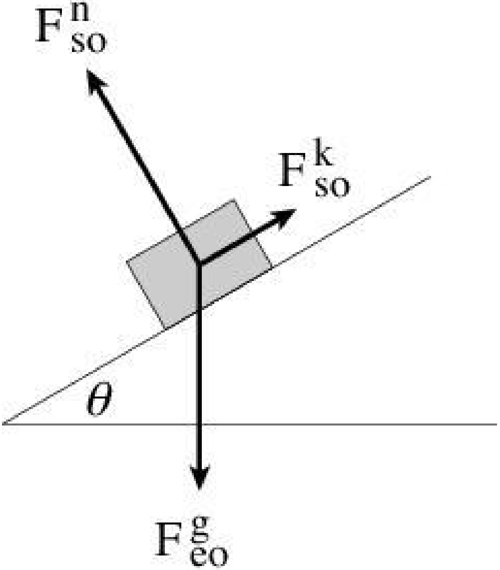
(G) $F_{so}^{k} = \mu_k mg \cos\theta$

(H) $F_{so}^{k} = \mu_k mg \tan\theta$



An object "O" of mass m slides down an inclined surface "S" at constant velocity. What is the magnitude of the **gravitational force** F_{eo}^{g} exerted by Earth on the object?

(A) $F_{eo}^{g} = mg$
(B) $F_{eo}^{g} = mg \sin\theta$
(C) $F_{eo}^{g} = mg \cos\theta$
(D) $F_{eo}^{g} = mg \tan\theta$
(E) $F_{eo}^{g} = \mu_k mg$
(F) $F_{eo}^{g} = \mu_k mg \sin\theta$
(G) $F_{eo}^{g} = \mu_k mg \cos\theta$
(H) $F_{eo}^{g} = \mu_k mg \tan\theta$



An object "O" of mass m slides down an inclined surface "S" at constant velocity. Let the x-axis point downhill. What is the magnitude of the **downhill (tangential) component** $F^g_{eo,x}$ of the gravitational force exerted by Earth on the object?

(A) $F^g_{eo,x} = mg$

(B) $F^g_{eo,x} = mg\sin\theta$

(C) $F^g_{eo,x} = mg\cos\theta$

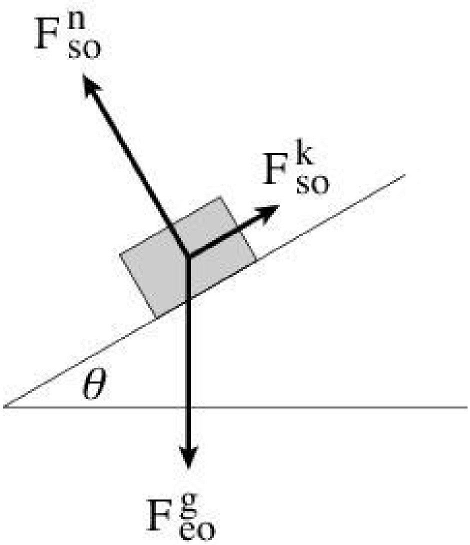
(D) $F^g_{eo,x} = mg\tan\theta$

(E) $F^g_{eo,x} = \mu_k mg$

(F) $F^g_{eo,x} = \mu_k mg\sin\theta$

(G) $F^g_{eo,x} = \mu_k mg\cos\theta$

(H) $F^g_{eo,x} = \mu_k mg\tan\theta$



Since object "O" slides down surface "S" at constant velocity, the forces on O must sum vectorially to zero. How do I express this fact for the forces acting along the downhill (tangential) axis?

(A) $\mu_k mg = mg\cos\theta$

(B) $\mu_k mg = mg\sin\theta$

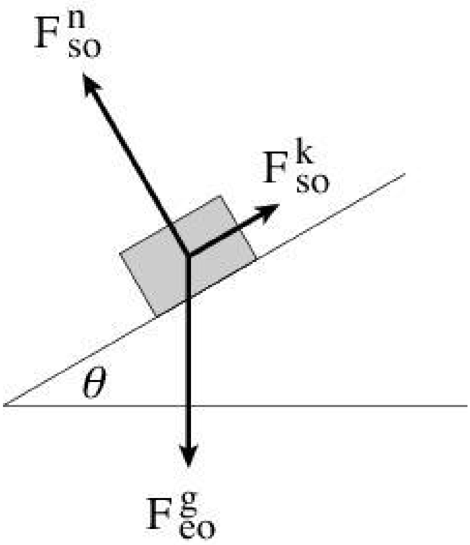
(C) $\mu_k mg\cos\theta = mg$

(D) $\mu_k mg\sin\theta = mg$

(E) $\mu_k mg\cos\theta = mg\sin\theta$

(F) $\mu_k mg\sin\theta = mg\cos\theta$

(G) $mg\sin\theta = mg\cos\theta$



Suppose friction holds object "O" at rest on surface "S." Which statement is true?

(A) $mg\sin\theta = F_{so}^{s} = \mu_k mg\cos\theta$

(B) $mg\sin\theta = F_{so}^{s} = \mu_s mg\cos\theta$

(C) $mg\sin\theta = F_{so}^{s} \le \mu_k mg\cos\theta$

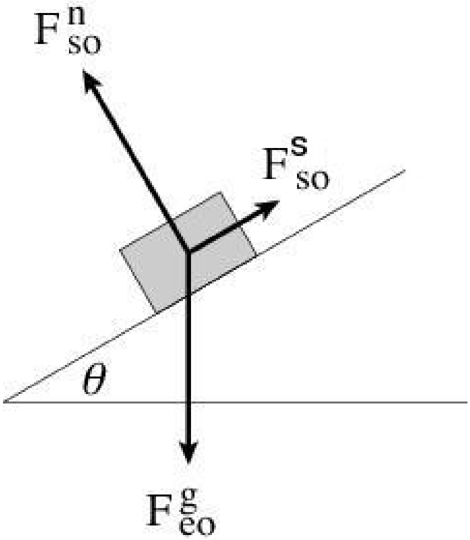
(D) $mg\sin\theta = F_{so}^{s} \le \mu_s mg\cos\theta$

(E) $mg\cos\theta = F_{so}^{s} = \mu_k mg\sin\theta$

(F) $mg\cos\theta = F_{so}^{s} = \mu_s mg\sin\theta$

(G) $mg\cos\theta = F_{so}^{s} \le \mu_k mg\sin\theta$

(H) $mg\cos\theta = F_{so}^{s} \le \mu_s mg\sin\theta$



Suppose friction holds object "O" at rest on surface "S." Then I gradually increase θ until the block just begins to slip. Which statement is true at the instant when the block starts slipping?

(A) $mg\sin\theta = F^s_{so} = \mu_k mg\cos\theta$

(B) $mg\sin\theta = F^s_{so} = \mu_s mg\cos\theta$

(C) $mg\sin\theta = F^s_{so} \le \mu_k mg\cos\theta$

(D) $mg\sin\theta = F^s_{so} \le \mu_s mg\cos\theta$

(E) $mg\cos\theta = F^s_{so} = \mu_k mg\sin\theta$

(F) $mg\cos\theta = F^s_{so} = \mu_s mg\sin\theta$

(G) $mg\cos\theta = F^s_{so} \le \mu_k mg\sin\theta$

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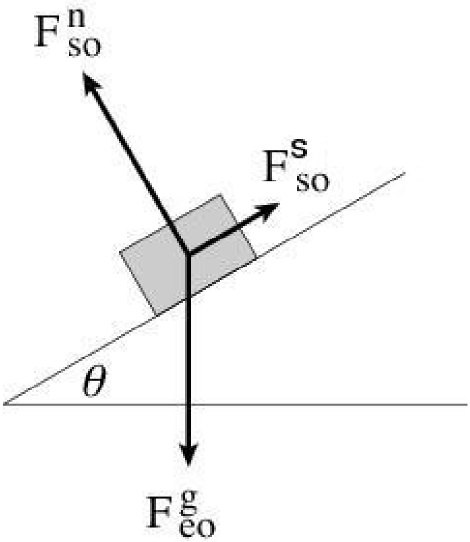
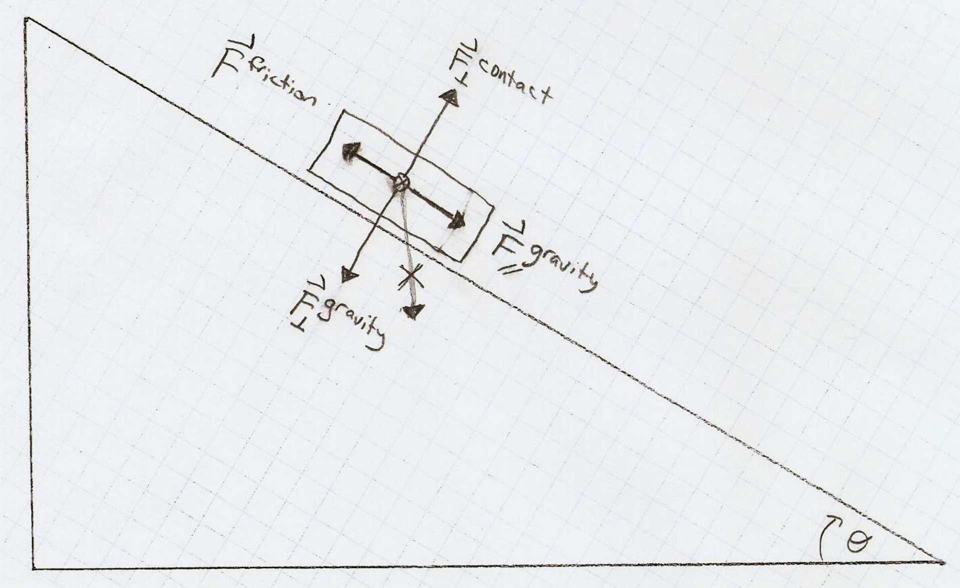
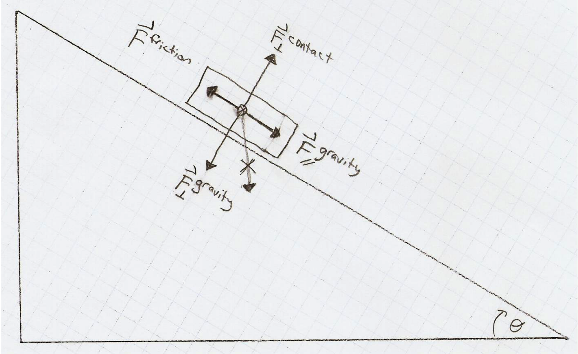


Friction on inclined plane



Why do I "cross off" the downward gravity arrow?



Take x-axis to be downhill, y-axis to be upward $\perp$ from surface.

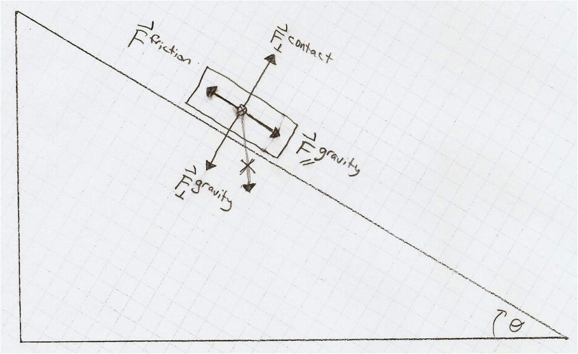
$$\vec{F}^G_\perp = -mg\cos\theta\ \hat{j}, \qquad \vec{F}^N = +mg\cos\theta\ \hat{j}$$

$$\vec{F}^G_\parallel = +mg\sin\theta\ \hat{i}$$

If block is not sliding then friction balances downhill gravity:

$$\vec{F}^S = -mg\sin\theta\ \hat{i}$$

(I'll skip this slide, but it's here for reference.)



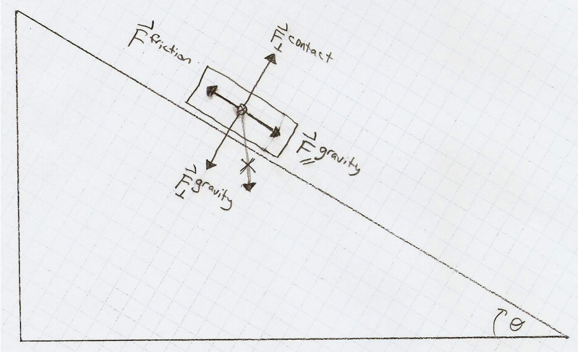
Magnitude of "normal" force ("normal" is a synonym for "perpendicular") between surfaces is

$$F^N = mg\cos\theta$$

Magnitude of static friction must be less than maximum:

$$F^S \;\leq\; \mu_S F^N = \mu_S \; mg\cos\theta$$

Block begins sliding when downhill component of gravity equals maximum magnitude of static friction . . .



Block begins sliding when downhill component of gravity equals maximum magnitude of static friction:

$$\mu_S \; mg \cos\theta = mg \sin\theta$$

$$\mu_S = \frac{mg \sin\theta}{mg \cos\theta}$$

$$\mu_S = \tan\theta$$

A Ch10 problem that may not fit into HW6

The coefficient of static friction of tires on ice is about 0.10. (a) What is the steepest driveway on which you could park under those circumstances? (b) Draw a free-body diagram for the car when it is parked (successfully) on an icy driveway that is just a tiny bit less steep than this maximum steepness. [We might want to do (b) before we do (a).]

Answering part (a) starts by expressing (in math) which statement:

(A) (total gravitational force on car) equals (kinetic friction)

(B) (total gravitational force on car) equals (largest possible value of static friction)

(C) (downhill component of gravity) equals (kinetic friction)

(D) (downhill component of gravity) equals (largest possible value of static friction)

A Ch10 problem that may not fit into HW6

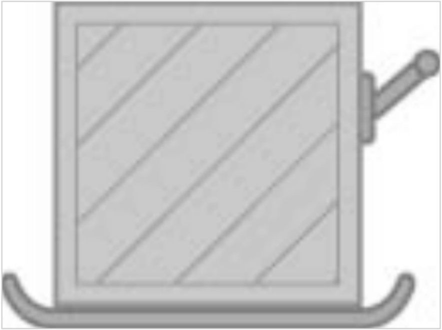
A fried egg of inertia m slides (at constant speed) down a Teflon frying pan tipped at an angle θ above the horizontal. [This only works if the angle θ is just right.] (a) Draw the free-body diagram for the egg. Be sure to include friction. (b) What is the "net force" (i.e. the vector sum of forces) acting on the egg? (c) How do these answers change if the egg is instead speeding up as it slides?

A heavy crate has plastic skid plates beneath it and a tilted handle attached to one side. Which requires a smaller force (directed along the diagonal rod of the handle) to move the box? Why?

(A) Pushing the crate is easier than pulling.

(B) Pulling the crate is easier than pushing.

(C) There is no difference.



Example (tricky!) problem

A woman applies a constant force to pull a 50 kg box across a floor **at constant speed**. She applies this force by pulling on a rope that makes an angle of 37° above the horizontal. The friction coefficient between the box and the floor is $\mu_k = 0.10$.

(a) Find the tension in the rope.

(b) How much work does the woman do in moving the box 10 m?

free-body diagram for box

What are all of the forces acting on the box? Try drawing your own FBD for the box. It's tricky!

free-body diagram for box

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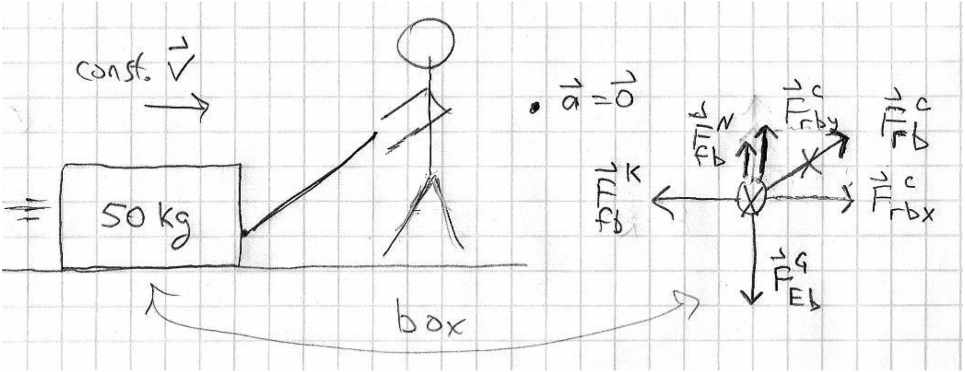


(I should redraw the RHS of this diagram on the board.)

find tension in rope

Step one: If T is the tension in the rope, then what is the normal force (by floor on box)?

(A) $F^N = mg$
(B) $F^N = mg + T\cos\theta$
(C) $F^N = mg + T\sin\theta$
(D) $F^N = mg - T\cos\theta$
(E) $F^N = mg - T\sin\theta$

find tension in rope

Step two: what is the frictional force exerted by the floor on the box (which is sliding across the floor at constant speed)?

(A) $F^K = \mu_K(mg - T\sin\theta)$
(B) $F^K = \mu_K(mg - T\cos\theta)$
(C) $F^K = \mu_S(mg - T\sin\theta)$
(D) $F^K = \mu_S(mg - T\cos\theta)$
(E) $F^K = (mg - T\sin\theta)$
(F) $F^K = (mg - T\cos\theta)$

find tension in rope

Step three: how do I use the fact that the box is moving at constant velocity (and hence is not accelerating)?

(A) $T = F^K = \mu_K(mg - T\sin\theta)$

(B) $T\cos\theta = F^K = \mu_K(mg - T\sin\theta)$

(C) $T\sin\theta = F^K = \mu_K(mg - T\sin\theta)$

solution (part a): find tension in rope

Force by rope on box has upward vertical component $T \sin\theta$. So the normal force (by floor on box) is $\boxed{F^N = mg - T\sin\theta}$.

Force of friction is $\boxed{F^K = \mu_K (mg - T\sin\theta)}$. To keep box sliding at constant velocity, horizontal force by rope on box must balance F^K.

$$\boxed{T\cos\theta = F^K = \mu_K(mg - T\sin\theta)} \quad \Rightarrow \quad T = \frac{\mu_K mg}{\cos\theta + \mu_K \sin\theta}$$

This reduces to familiar $T = \mu_K mg$ if $\theta = 0^\circ$ (pulling horizontally) and even reduces to a sensible $T = mg$ if $\theta = 90^\circ$ (pulling vertically).

Plugging in $\theta = 37^\circ$, so $\cos\theta = 4/5 = 0.80$, $\sin\theta = 3/5 = 0.60$,

$$T = \frac{(0.10)(50\ \mathrm{kg})(9.8\ \mathrm{m/s^2})}{(0.80) + (0.10)(0.60)} = 57\ \mathrm{N}$$

solution (part b): work done by pulling for 10 meters

In part (a) we found tension in rope is $T = 57\ \mathrm{N}$ and is oriented at an angle $\theta = 36.9^\circ$ above the horizontal.

In 2D, work is displacement times **component of force along direction of displacement** (which is horizontal in this case). So the work done by the rope on the box is

$$W = \vec{F}_{rb} \cdot \Delta\vec{r}_b$$

This is the dot product (or "scalar product") of the force $\vec{F}_{rb}$ (by rope on box) with the displacement $\Delta\vec{r}_b$ of the point of application of the force.

In part (a) we found tension in rope is $T = 57\ \mathrm{N}$ and is oriented at an angle $\theta = 36.9^\circ$ above the horizontal.

What is the work done by the rope on the box by pulling the box across the floor for 10 meters? (Assume my arithmetic is correct.)

(In two dimensions, work is the dot product of the force $\vec{F}_{rb}$ with the displacement $\Delta\vec{r}_b$ of the point of application of the force.)

(A) $W = (10\ \mathrm{m})(T) = (10\ \mathrm{m})(57\ \mathrm{N}) = 570\ \mathrm{J}$

(B) $W = (10\ \mathrm{m})(T\cos\theta) = (10\ \mathrm{m})(57\ \mathrm{N})(0.80) = 456\ \mathrm{J}$

(C) $W = (10\ \mathrm{m})(T\sin\theta) = (10\ \mathrm{m})(57\ \mathrm{N})(0.60) = 342\ \mathrm{J}$

(D) $W = (8.0\ \mathrm{m})(T\cos\theta) = (8.0\ \mathrm{m})(57\ \mathrm{N})(0.80) = 365\ \mathrm{J}$

(E) $W = (8.0\ \mathrm{m})(T\sin\theta) = (8.0\ \mathrm{m})(57\ \mathrm{N})(0.60) = 274\ \mathrm{J}$

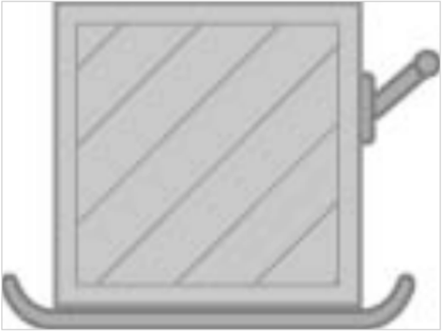
Repeat, now that we've analyzed this quantitatively

A heavy crate has plastic skid plates beneath it and a tilted handle attached to one side. Which requires a smaller force (directed along the diagonal rod of the handle) to move the box? Why?

(A) Pushing the crate is easier than pulling.

(B) Pulling the crate is easier than pushing.

(C) There is no difference.



Easier example

How hard do you have to push a 1000 kg car (with brakes on, all wheels, on level ground) to get it to start to slide? Let's take $\mu_S \approx 1.2$ for rubber on dry pavement.

Easier example

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$$F^{\text{Normal}} = mg = 9800 \text{ N}$$

$$F^{\text{Static}} \leq \mu_S F^N = (1.2)(9800 \text{ N}) \approx 12000 \text{ N}$$

So the static friction gives out (hence car starts to slide) when your push exceeds 12000 N.

How hard do you then have to push to keep the car sliding at constant speed? Let's take $\mu_K \approx 0.8$ for rubber on dry pavement.

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$$F^{\mathrm{Kinetic}} = \mu_K F^N = (0.8)(9800 \mathrm{~N}) \approx 8000 \mathrm{~N}$$

How far does your car slide on dry, level pavement if you jam on the brakes, from 60 mph (27 m/s)?

$$F^N = mg, \quad F^K = \mu_K mg$$

$$a = ? \qquad \Delta x = ?$$

(The math is worked out on the next slides, but we won't go through them in detail. It's there for you to look at later.)

How far does your car slide on dry, level pavement if you jam on the brakes, from 60 mph (27 m/s)?

$$F^N = mg, \quad F^K = \mu_K mg$$

$$a = -F^K/m = -\mu_K g = -(0.8)(9.8\ \mathrm{m/s^2}) \approx -8\ \mathrm{m/s^2}$$

Constant force $\rightarrow$ constant acceleration from 27 m/s down to zero:

$$v_f^2 = v_i^2 + 2ax$$

$$x = \frac{v_i^2}{-2a} = \frac{(27\ \mathrm{m/s})^2}{2 \times (8\ \mathrm{m/s^2})} \approx 45\ \mathrm{m}$$

How much time elapses before you stop?

$$v_f = v_i + at \quad \Rightarrow \quad t = \frac{27\ \mathrm{m/s}}{8\ \mathrm{m/s^2}} = 3.4\ \mathrm{s}$$

How does this change if you have anti-lock brakes (or good reflexes) so that the tires never skid?

How does this change if you have anti-lock brakes (or good reflexes) so that the tires never skid? Remember $\mu_S > \mu_K$. For rubber on dry pavement, $\mu_S \approx 1.2$ (though there's a wide range) and $\mu_K \approx 0.8$. The best you can do is *maximum* static friction:

$$F^S \le \mu_S mg$$

$$a = -F^S/m = -\mu_S g = -(1.2)(9.8\ \mathrm{m/s^2}) \approx -12\ \mathrm{m/s^2}$$

Constant force $\rightarrow$ constant acceleration from 27 m/s down to zero:

$$v_f^2 = v_i^2 + 2ax$$

$$x = \frac{v_i^2}{-2a} = \frac{(27\ \mathrm{m/s})^2}{2 \times (12\ \mathrm{m/s^2})} \approx 30\ \mathrm{m}$$

How much time elapses before you stop?

$$v_f = v_i + at \quad \Rightarrow \quad t = \frac{27\ \mathrm{m/s}}{15\ \mathrm{m/s^2}} = 2.2\ \mathrm{s}$$

So you can stop in about 2/3 the time (and 2/3 the distance) if you don't let your tires skid. Or whatever μ_K/μ_S ratio is.

A Ch10 problem that may not fit into HW6

Calculate $\vec{C} \cdot (\vec{B} - \vec{A})$ if $\vec{A} = 3.0\hat{\imath} + 2.0\hat{\jmath}$, $\vec{B} = 1.0\hat{\imath} - 1.0\hat{\jmath}$, and $\vec{C} = 2.0\hat{\imath} + 2.0\hat{\jmath}$. Remember that there are two ways to compute a dot product—choose the easier method in a given situation: one way is $\vec{P} \cdot \vec{Q} = |\vec{P}||\vec{Q}| \cos\varphi$, where φ is the angle between vectors $\vec{P}$ and $\vec{Q}$, and the other way is $\vec{P} \cdot \vec{Q} = P_x Q_x + P_y Q_y$.

A Ch10 problem that may not fit into HW6

A child rides her bike 1.0 block east and then $\sqrt{3} \approx 1.73$ blocks north to visit a friend. It takes her 10 minutes, and each block is 60 m long. What are (a) the magnitude of her displacement, (b) her average velocity (magnitude and direction), and (c) her average speed?

Physics 8 — Monday, October 7, 2019

- On Wednesday I'll hand out HW6, due on Friday 10/18.
- This week, you're reading Ch11 (motion in a circle): the first half for today, and the second half for Wednesday.