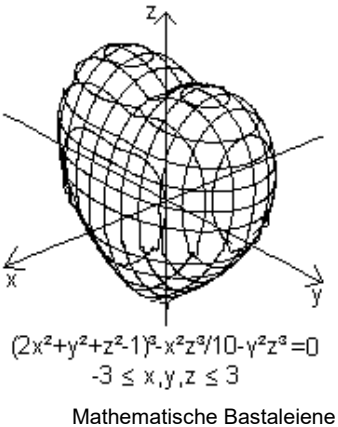
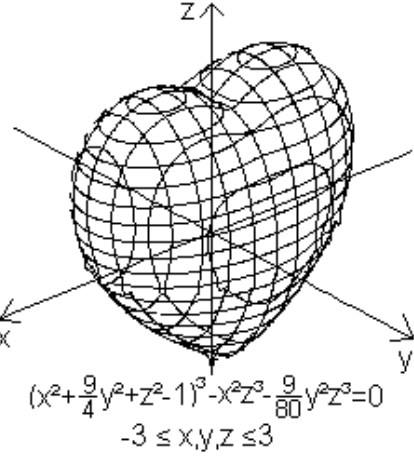


# Tuesday February 14

Topics for this Lecture:  
*Torque, center-of-mass, equilibrium.*

- Torque:
  - Referred to with Greek letter tau:  $\tau$
  - Force about an axis.
  - Clockwise: negative torque
  - Counter clockwise: positive torque
  - Directed perpendicular to Force & rotation



- Assignment 6 due Friday ...like almost every Friday
- Pre-class due 15min before class ...like every class
- Help Room: Here, 6-9pm Wed/Thurs
- SI: Morton 326, M&W 7:15-8:45pm
- Office Hours: 204 EAL, 10-11am Wed or by appointment (meisel@ohio.edu)

- Torque:  $\tau = r \times F = |F||r| \sin(\theta)$
- Two ways to think about this:
  - (1) Perpendicular distance:
  - (2) Perpendicular force:

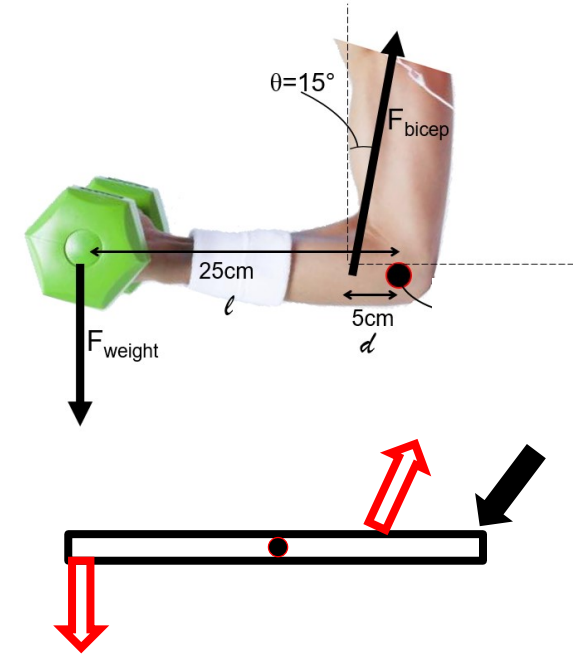
$\tau = F \cdot r_{\perp} = F \cdot [d \cdot \cos(\theta)]$

$\tau = F_{\perp} d = [F \cdot \cos(\theta)] \cdot d$

# Tips for solving static equilibrium problems

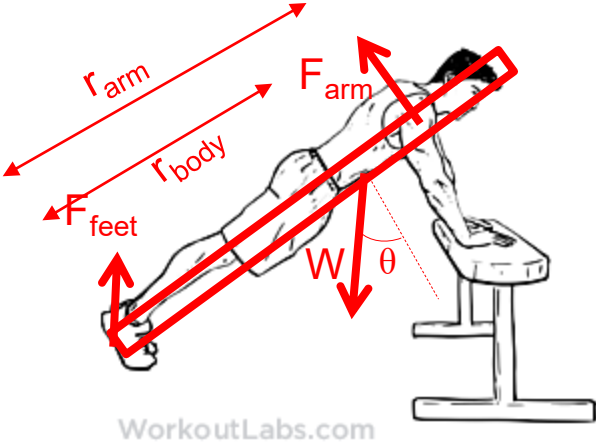
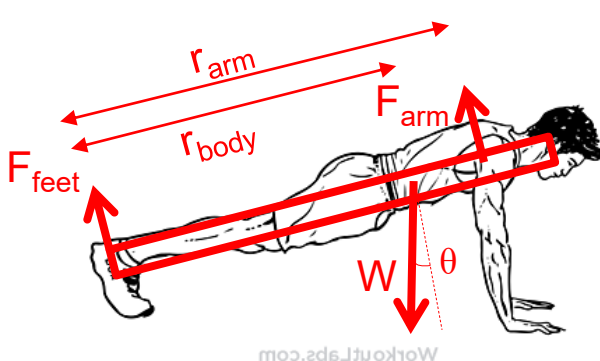
*no translational or rotational motion*

1. Draw a simplified version of your situation, including the forces in a free-body diagram
2. Select your axis of rotation
  - For static equilibrium, there is no rotation, so the rotation axis can be anywhere.
  - Choose your rotation axis so that a force you do not know provides zero torque.
3. Write expressions for the balanced forces & torques
  1.  $\sum F_x = 0$
  2.  $\sum F_y = 0$
  3.  $\sum \tau = 0$
4. Work through the algebra & arithmetic



# Static Equilibrium example: Push-ups

• Why are incline push-ups easier than push-ups on the ground?



*How did we choose  $r_{body}$ ?  
Center-of-gravity*

1. Draw free-body diagrams for both situations
2. Choose the feet as the axis of rotation because we don't care about the force of the feet on the ground

3. Write expressions for sum of forces & torques:

- $\sum F_x = 0$ ;  $\sum F_y = 0$ ;  $\sum \tau = 0$
- Here just need to consider torques:
  - $\sum \tau = \tau_{arm} - \tau_{weight}$  .... So:  $\tau_{arm} = \tau_{weight}$  ... i.e.  $F_{arm} r_{arm} = W \cos(\theta) r_{body}$
  - $F_{arm} = W \cos(\theta) r_{body} / r_{arm}$  (note:  $\cos(\theta) \rightarrow 0$  as  $90^\circ$ .)

*Because arm is perpendicular to body*

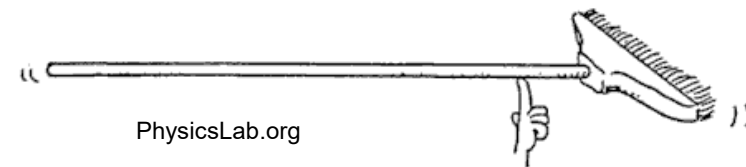
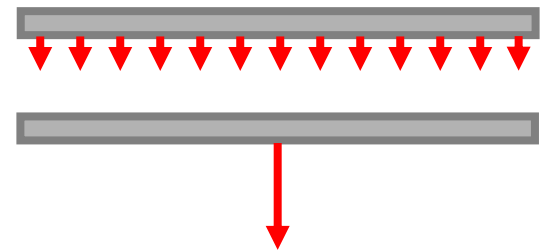
4. For both cases, arm is perpendicular to body. But,  $\theta$  is larger for incline push-ups.

# Center of Gravity (a.k.a. Center of Mass)

- For extended objects, it is preferable to draw gravity acting on that object at a single location
  - In reality, gravity acts on several parts of an object.
  - However, the average interaction is as if all of the object's mass was concentrated at center of the object's mass distribution
- This location is known as the “center of gravity” (or “center of mass”)
- For a symmetric object, actual center
- For irregular object, will be offset
- Think about where you would have to hang an object from for it to hang balanced & not tilted



Youtube: @CrazyRussianHacker

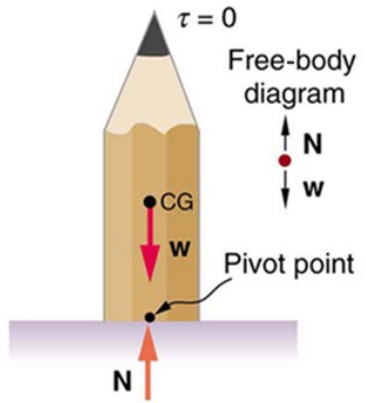
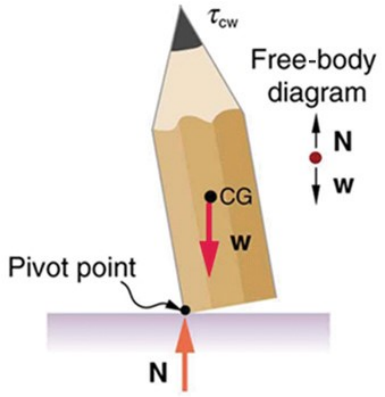


PhysicsLab.org

# Stability & Equilibrium

If center of gravity (CG) over or under point(s) of support, then stable.

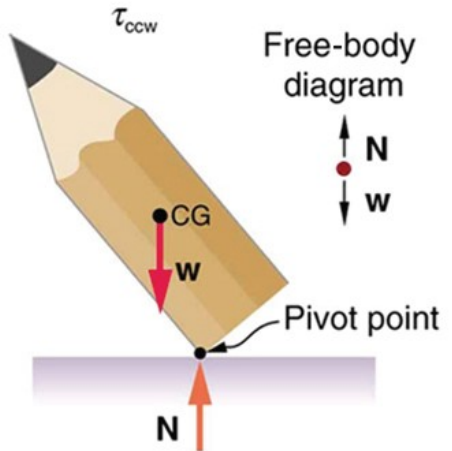
## Stable Equilibrium:



displace from equilibrium and it returns

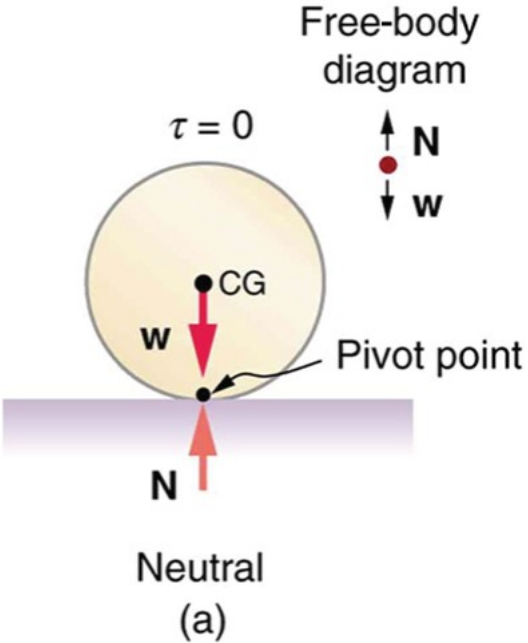
## Unstable equilibrium:

displaced but does not return to equilibrium



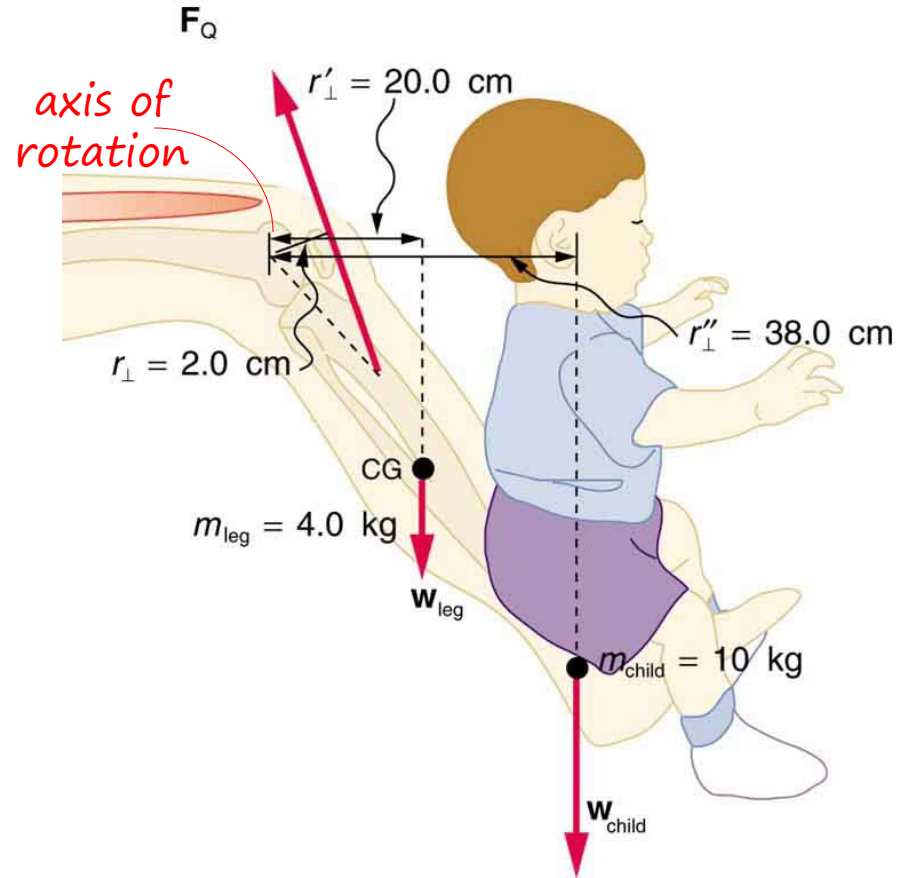
# **Neutral** Equilibrium: The most boring kind of equilibrium

Neutral equilibrium: displace & object winds up in a new stable state  
(e.g. rolling around a sphere)



A child is sitting on an adult's leg. Given the measurements shown, what is the torque due to the child if we use the knee-cap as the axis of rotation?

- (A) +0.388 Nm                      (B) - 0.388 Nm  
 (C) + 3.80 Nm                      (D) - 3.80 Nm  
 (E) + 3.72 Nm                      (F) - 3.72 Nm  
 (G) + 37.2 Nm                      (H) - 37.2 Nm

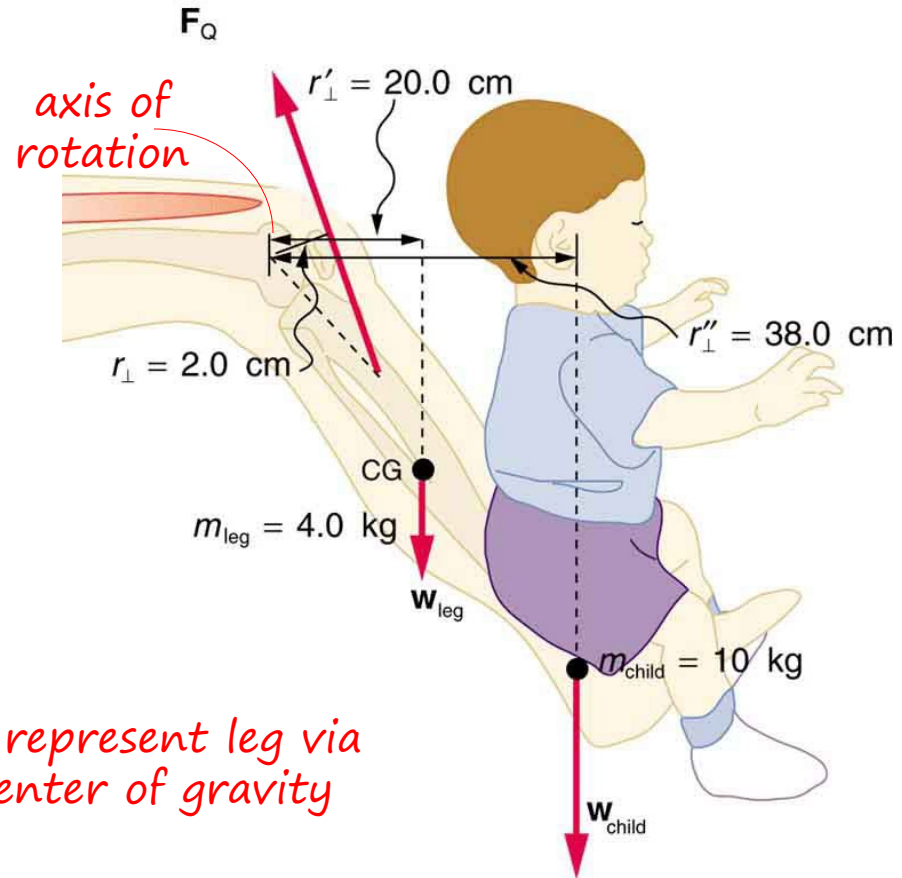


$$\begin{aligned}\tau &= F \cdot r_\perp \\ &= -m_{\text{child}} g \cdot r''_\perp \\ &= -(10 \text{ kg})(9.8 \text{ m/s}^2)(0.38 \text{ m}) \\ &= -37.2 \text{ N} \cdot \text{m}\end{aligned}$$

A child is sitting on an adult's leg. Given the measurements shown, what is the torque due to the leg if we use the knee-cap as the axis of rotation?

- (1) +0.8 Nm                      (2) - 0.8 Nm  
 (3) + 3.20 Nm                  (4) - 3.20 Nm  
 (5) + 7.84 Nm                  **(6) - 7.84 Nm**  
 (7) + 15.8 Nm                  (8) - 15.8 Nm

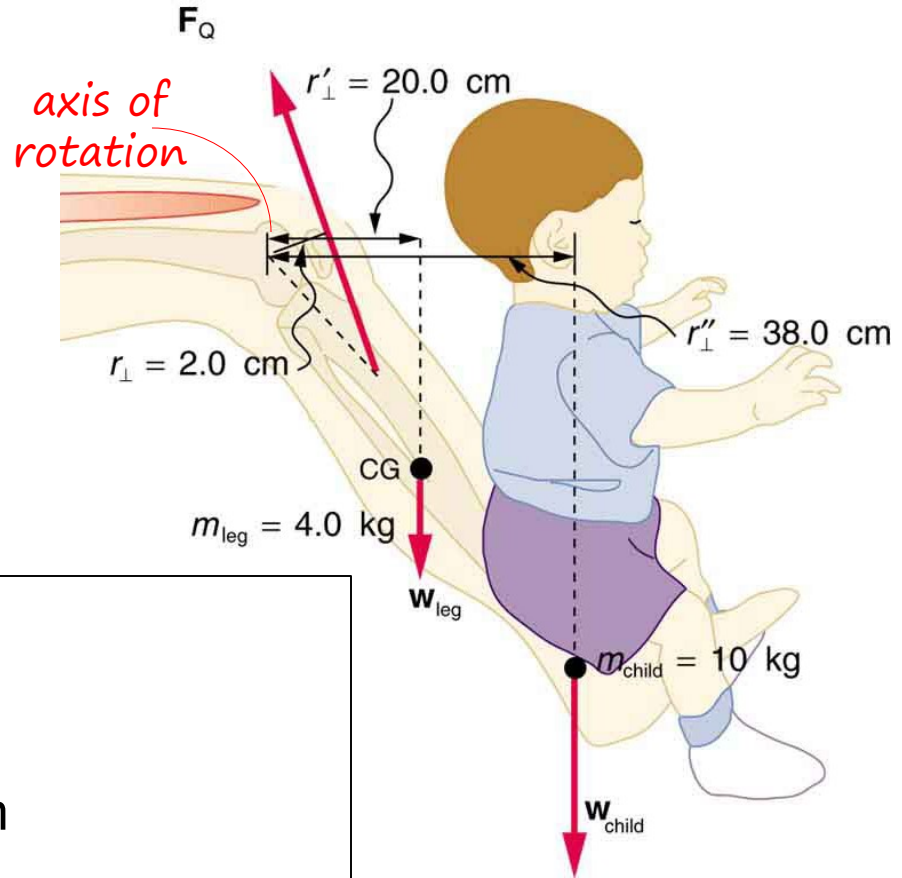
$$\begin{aligned}
 \tau &= F \cdot r_{\perp} \\
 &= -m_{\text{leg}} g \cdot r_{\perp}' \\
 &= -(4\text{kg})(9.8\text{m/s}^2)(0.2\text{m}) \\
 &= -7.84 \text{ N}\cdot\text{m}
 \end{aligned}$$



*Can represent leg via its center of gravity*



A child is sitting on an adult's leg, as shown. What is the tension in the upper leg muscle (pink arrow pointing to the upper-left)?



(1) 0.0 N

(3) 2252 N

(5) 0.9 N

(2) 225 N

(4) 45 N

(6) 5600 N

Balance torques:

$$1. \sum \tau = \tau_{\text{muscle}} - \tau_{\text{leg}} - \tau_{\text{child}} = 0$$

$$2. \tau_{\text{muscle}} = m_{\text{leg}}g * r_{\perp}' + m_{\text{child}}g * r_{\perp}''$$

$$3. \quad = 7.84\text{Nm} + 37.2\text{Nm} = 45.04\text{Nm}$$

$$4. \tau_{\text{muscle}} = F_{\text{muscle}} * r_{\perp}$$

$$5. F_{\text{muscle}} = \tau_{\text{muscle}} / r_{\perp} = (45.04\text{Nm}) / 0.02\text{m} = 2252\text{N}$$

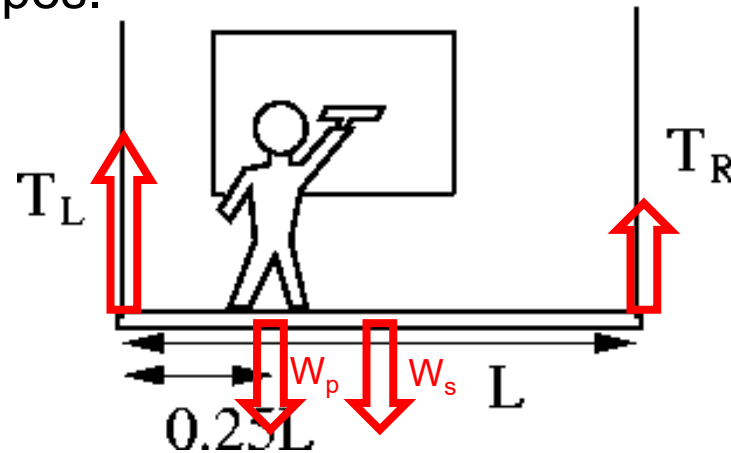
A 800N painter stands on a 400N scaffold (a uniform rectangular board) with one rope supporting each end.

The painter stands one-quarter of the length of the scaffold from the left side. Compare the tension in the two ropes.

(A)  $T_L > T_R$

(B)  $T_L < T_R$

(C)  $T_L = T_R$



• Consider torque axes where ropes connect

• Left rope:  $\sum \tau = \tau_{\text{rope},r} - \tau_{\text{painter},1} - \tau_{\text{scaffold}} = T_R * L - W_p(0.25 * L) - W_{\text{scaffold}}(0.5 * L) = 0$

• Right rope:  $\sum \tau = -\tau_{\text{rope},l} + \tau_{\text{painter},2} + \tau_{\text{scaffold}} = (-T_L * L) + W_p(0.75 * L) + W_{\text{scaffold}}(0.5 * L) = 0$

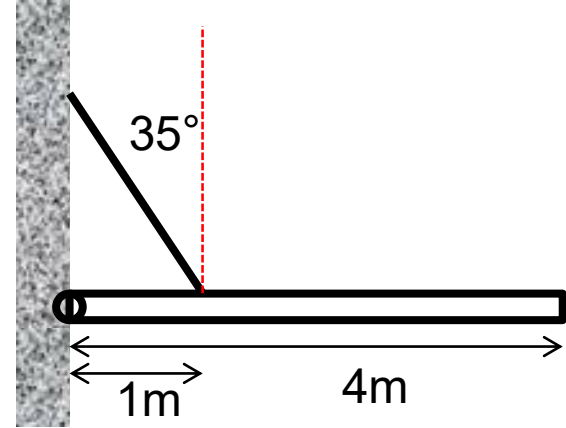
• From the left rope:

•  $T_R = (W_p * 0.25) + (W_s * 0.5)$

• From the right rope:

•  $T_L = (W_p * 0.75) + (W_s * 0.5)$

A 1500N beam is attached to a wall by a hinge. The beam is 4.0m long, and the mass of the beam is distributed evenly along the beam. The beam is supported by a cable that is attached 1.0m to the beam from the wall and makes an angle of  $35^\circ$  from the vertical. We want to find the tension in the cable.



At what point does it make the most sense to place the axis of rotation?

(A) Hinge

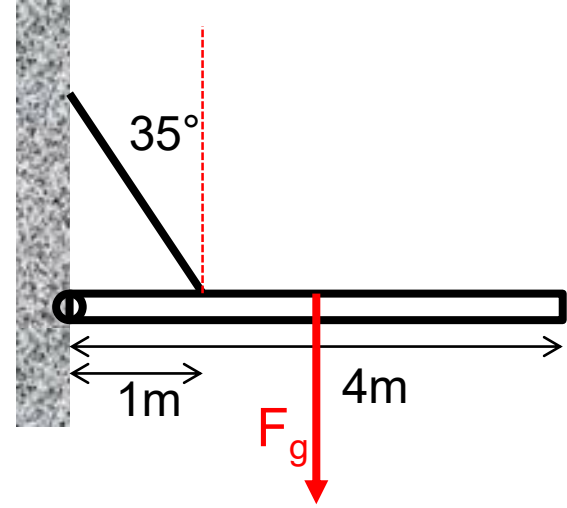
(B) Point Cable attaches

(C) Center of beam

(D) Right End

- The forces involved are: force of hinge on the board, the tension of the cable pulling on the board, and gravity pulling the board down.
- If we place the axis of rotation at the hinge, we can ignore the force of the wall on the board.
- Then, by equating our torques, the torque from the weight of the board can be related to the torque of the cable on the board.

A 1500N beam is attached to a wall by a hinge. The beam is 4.0m long, and the mass of the beam is distributed evenly along the beam. The beam is supported by a cable that is attached 1.0m to the beam from the wall and makes an angle of  $35^\circ$  from the vertical. We want to find the tension in the cable.



What is the lever-arm for the force due to gravity, where the hinge is the axis?

(A) 1m

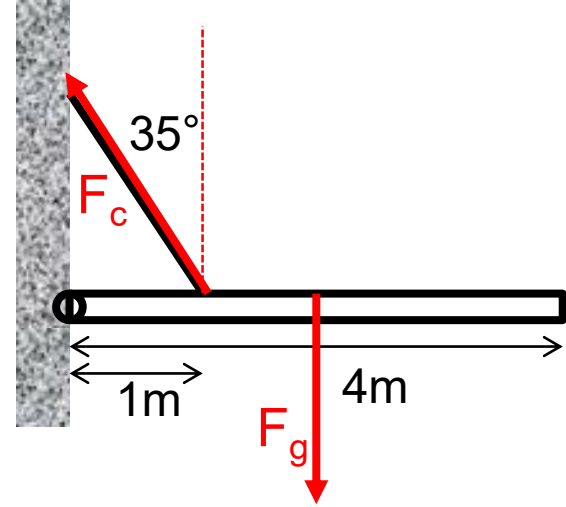
(B) 2m

(C) 3m

(D) 4m

- The force of gravity will act as if it is pulling on the center-of mass of the board.
- The board is a uniform object, so the center-of-mass will be at the physical center.

A 1500N beam is attached to a wall by a hinge. The beam is 4.0m long, and the mass of the beam is distributed evenly along the beam. The beam is supported by a cable that is attached 1.0m to the beam from the wall and makes an angle of  $35^\circ$  from the vertical.



What is the tension in the cable?

- (A) 1500N    (B) 2460N    (C) 3000 N    **(D) 3660 N**    (E) 5230 N    (F) 6000N

1. Choose the hinge as the axis of rotation, so that we can ignore its force, and then balance the torques about there.

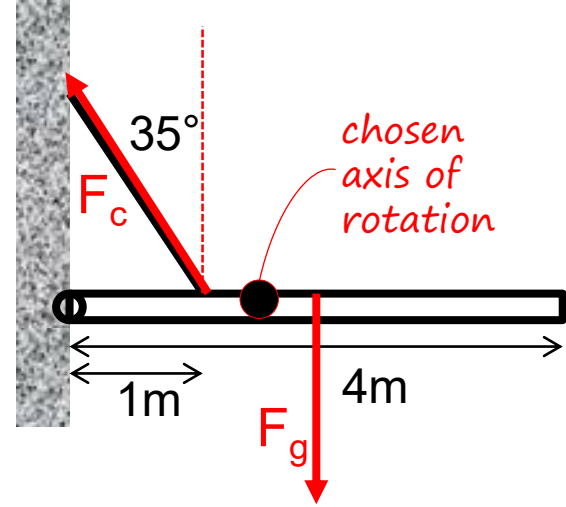
$$2. \quad \sum \tau = \tau_{\text{cable}} - \tau_{\text{gravity}} = 0$$

$$3. \quad \tau_{\text{cable}} = \tau_{\text{gravity}} = m_{\text{board}} g (L_{\text{board}}/2) = (1500\text{N})(2\text{m}) = 3000\text{Nm}$$

$$4. \quad \tau_{\text{cable}} = F_{\text{cable}, \perp} r_{\text{cable}} = F_{\text{cable}} \cos(\theta) r_{\text{cable}}$$

$$5. \quad F_{\text{cable}} = \tau_{\text{cable}} / [r_{\text{cable}} \cos(\theta)] = (3000\text{Nm}) / (1\text{m} * \cos(35^\circ)) \approx 3660\text{N}$$

A 1500N beam is attached to a wall by a hinge. The beam is 4.0m long, and the mass of the beam is distributed evenly along the beam. The beam is supported by a cable that is attached 1.0m to the beam from the wall and makes an angle of  $35^\circ$  from the vertical.

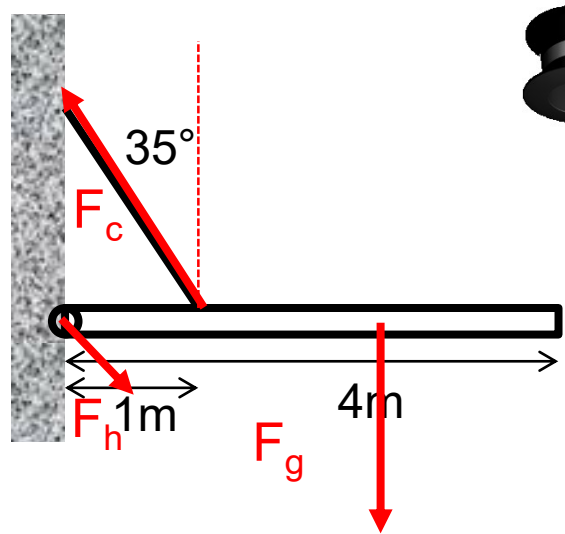


What direction is the force of the hinge on the board?

- (A) Up & Right    (B) Directly Right    **(C) Down & Right**

- Want to choose a different axis of rotation, so we can consider what torque the hinge exerts on the board.  
We can do this because the board is in static equilibrium, i.e. not rotating about any point.
- We can choose the point in between where the cable connects and the board's center of mass.
  - (If we chose for instance, the right end of the board, this would be a valid choice, but it wouldn't help us solve for the wall's force).
- Want to balance the torques.
  - Weight & cable provide negative torques.
  - So wall must provide positive torque by pushing down.

A 1500N beam is attached to a wall by a hinge. The beam is 4.0m long, and the mass of the beam is distributed evenly along the beam. The beam is supported by a cable that is attached 1.0m to the beam from the wall and makes an angle of  $35^\circ$  from the vertical.



What is the magnitude of the force of the hinge on the board?

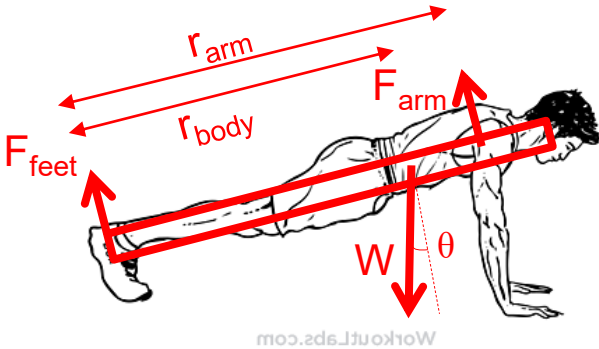
- (A) 1498 N    (B) 3660 N    **(C) 2580 N**    (D) 2100 N

1. Just use  $F=ma$
2.  $\sum F_y = F_{c,y} - F_{g,y} - F_{h,y} = 0$
3.  $F_{h,y} = F_{c,y} - F_{g,y}$
4.  $F_{h,y} = F_c \cos(\theta) - F_g = (3660\text{N}) \cdot \cos(35^\circ) - 1500\text{N} = 1498\text{N}$
5.  $\sum F_x = F_{h,x} - F_{c,x} = 0$
6.  $F_{h,x} = F_c \sin(\theta) = (3660\text{N}) \cdot \sin(35^\circ) = 2100\text{N}$
7.  $F_h = \sqrt{F_{h,x}^2 + F_{h,y}^2} = 2580\text{ N}$

# Static Equilibrium example: Push-ups & Center of Gravity

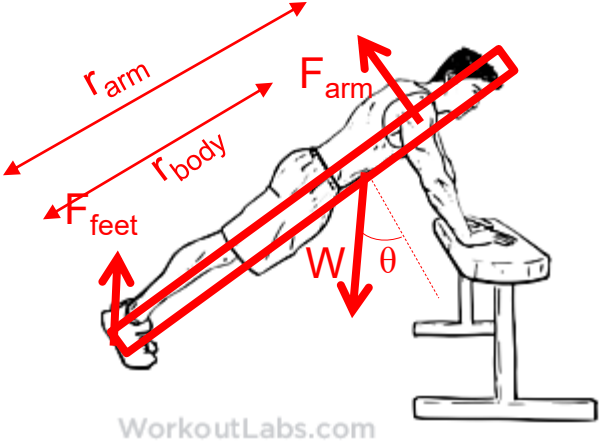
• How else can we make push-ups easier?

## Regular:



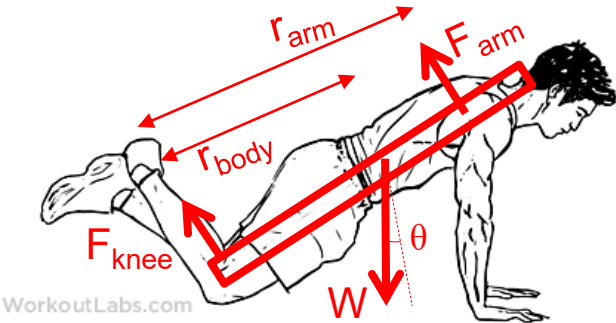
$$F_{arm}r_{arm} = W\cos(\theta)r_{body}$$

## Incline:



- Reduce perpendicular force of gravity
- So need less arm torque to counteract body torque

## “Modified”:

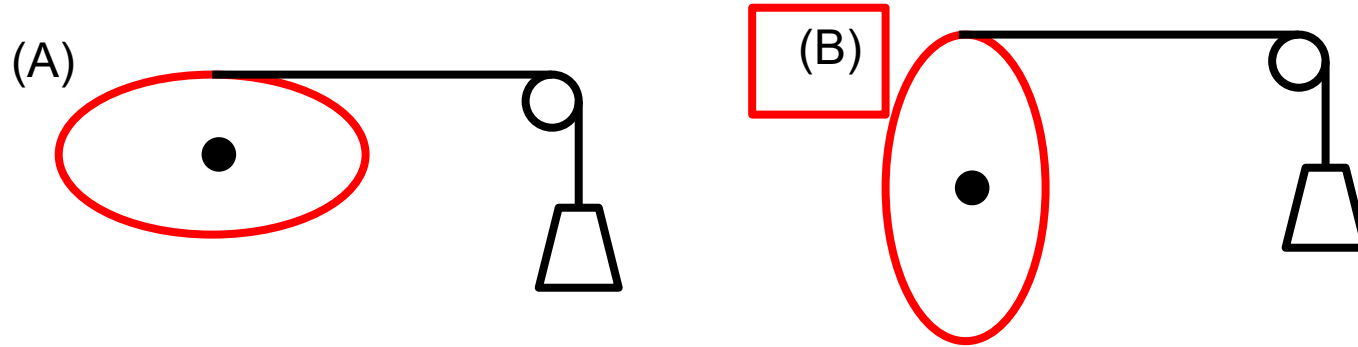


- Reduce weight.
- Reduce perpendicular distance for arms, but reduce perpendicular distance more for weight (because CoG is almost in same spot in body)



A cable is attached to an elliptical rim and attached via a pulley to a weight. The black dot represents the axis.

In which configuration is the torque on the ellipse the greatest?



- Longer lever arm for B, so greater torque.
- Fun fact:
  - Exercise machines take advantage of elliptical gears to adjust the force at different points of motion.
  - Your lever-arm is fixed, but the lever to the connected load varies.