

# Getting every student prepared for every class



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Webinar  
3 December 2015

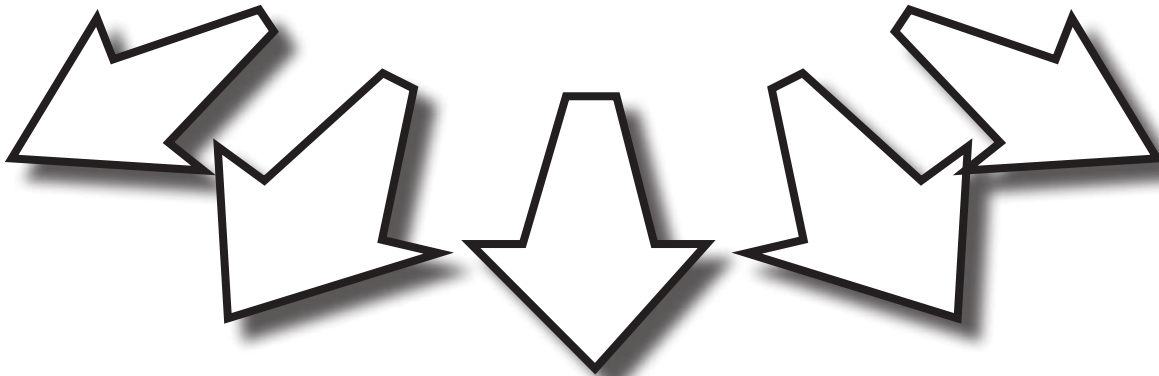
# Getting every student prepared for every class



@eric\_mazur

Webinar  
12 April 2016







**CLASS**

**1st exposure**



**ROOM**

**deeper understanding**



1st exposure



deeper understanding



1st exposure



deeper understanding



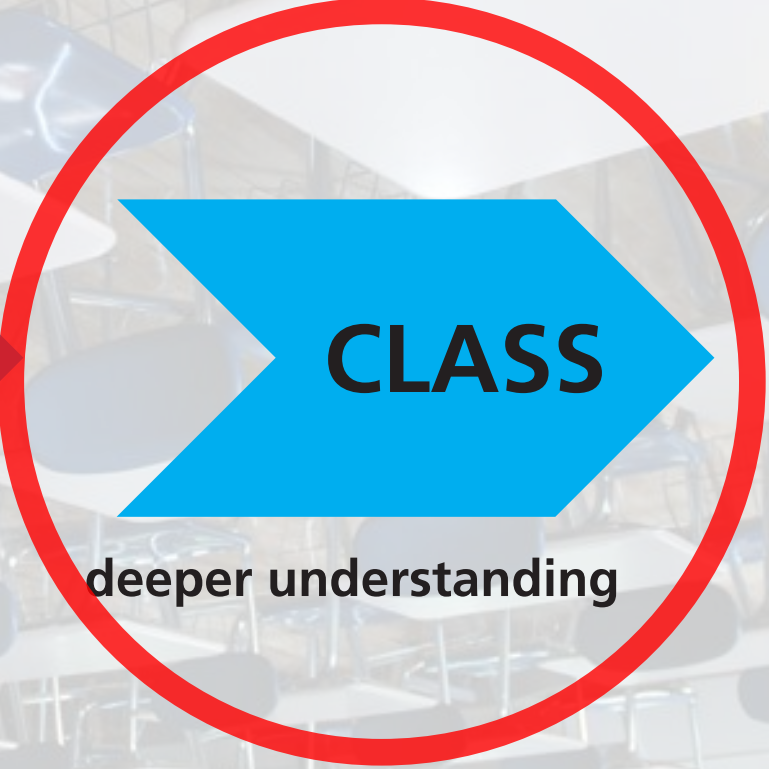
1st exposure



deeper understanding



1st exposure



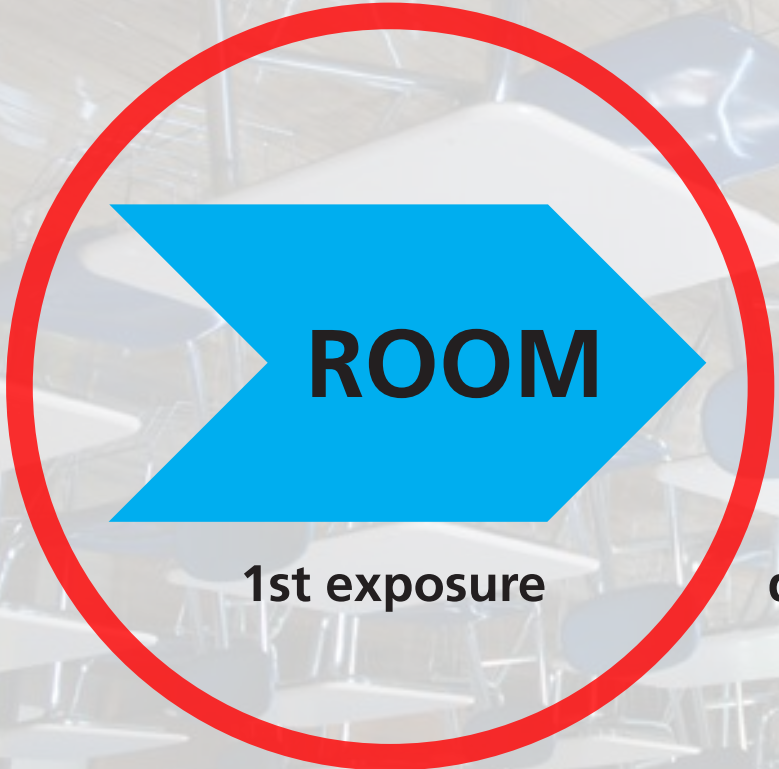
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1st exposure



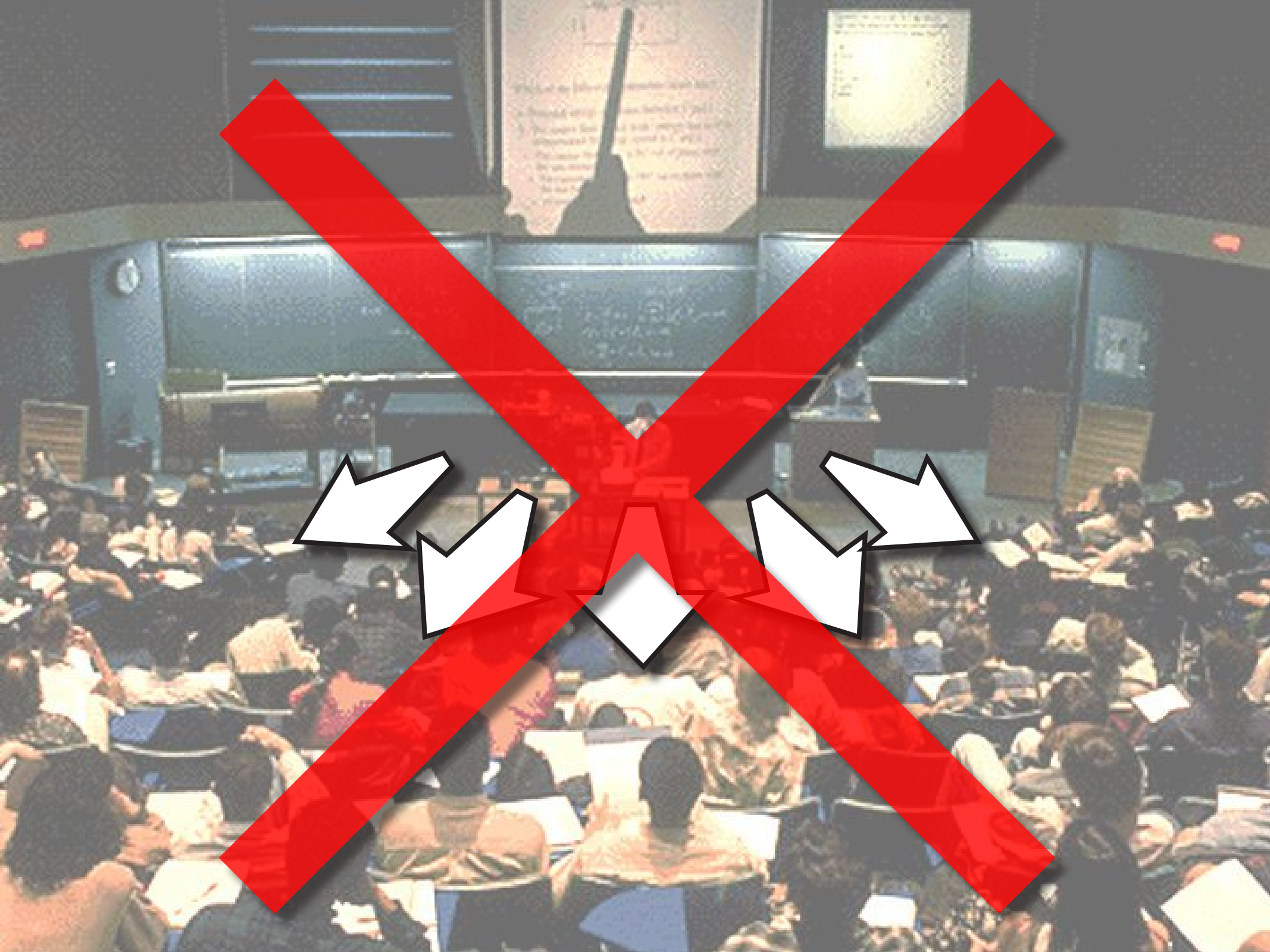
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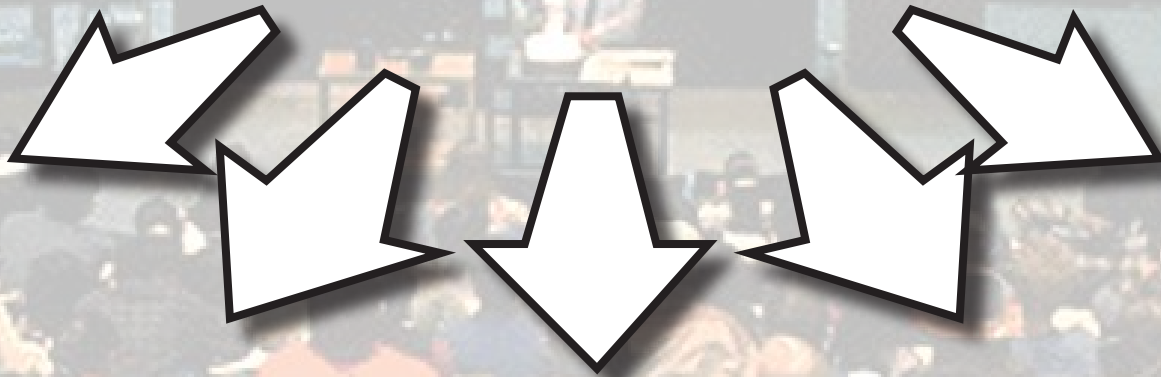


deeper understanding





**how to effectively transfer information outside classroom?**





**but...**




- **transfer pace set by video**
- **viewer passive**
- **viewing/attention tanks as time passes**
- **isolated/individual experience**





**we're simply moving this outside classroom!**




- 
- **transfer pace set by reader**
  - **viewer active**

**but...**







**isolated/individual experience &  
no real accountability**



**want:**

***every student prepared for every class***



**want:**  
***every student prepared for every class***  
**(without additional instructor effort)**



**Solution**

**turn out-of-class component  
also into a social interaction!**

# Perusall

every student prepared for every class



## 76 CHAPTER 4 MOMENTUM

In the preceding two chapters, we developed a mathematical framework for describing motion along a straight line. In this chapter, we continue our study of motion by investigating inertia, a property of objects that affects their motion. The experiments we carry out in studying inertia lead us to discover one of the most fundamental laws in physics—conservation of momentum.

## 4.1 Friction

Picture a block of wood sitting motionless on a smooth wooden surface. If you give the block a shove, it slides some distance but eventually comes to rest. Depending on the smoothness of the block and the smoothness of the wooden surface, this stopping may happen sooner or it may happen later. If the two surfaces in contact are very smooth and slippery, the block slides for a long time. In fact, if the surfaces are perfectly smooth, you can observe the following day experience: A hockey puck slides easily on ice but not on a rough road.

Figure 4.1 shows how the velocity of a wooden block decreases on three different surfaces. The slowing down is due to *friction*—the resistance to motion that one surface or object encounters when moving over another. Notice that, during the interval covered by the velocity-versus-time graph, the velocity decrease as the block slides over ice is hardly observable. The block slides easily over ice because there is very little friction between the two surfaces. The effect of friction is to bring two objects to rest with respect to each other—in this case the wooden block and the surface it is sliding on. The less friction there is, the longer it takes for the block to come to rest.

Figure 4.1 Velocity-versus-time graph for a wooden block sliding on three different surfaces. The rougher the surface, the more quickly the velocity decreases.



Figure 4.2 Low-friction track and carts used in the experiments described in this chapter.



You may wonder whether it is possible to make surfaces that have no friction at all, such that an object, once given a shove, continues to glide forever. There is no totally frictionless surface over which objects slide forever, but there are ways to minimize friction. You can, for instance, float an object on a cushion of air. This is most easily accomplished with an air hockey table. The air serves as a cushion on which a conveniently shaped object can float, with friction between the object and the track all but eliminated. Alternatively, one can use wheeled carts with low-friction bearings on an ordinary track. Figure 4.2 shows low-friction carts you may have encountered in your lab or class. Although there is still some friction both for low-friction tracks and for the track shown in Figure 4.2, this friction is so small that it can be ignored during an experiment. For example, if the track in Figure 4.2 is horizontal, carts move along its length without slowing down appreciably. In other words:

**In the absence of friction, objects moving along a horizontal track keep moving without slowing down.**

Another advantage of using such carts is that the track constrains the motion to being along a straight line. We can then use a high-speed camera to record the cart's position at various instants, and from that information determine its speed and acceleration.



4.1 (a) Are the accelerations of the motions shown in Figure 4.1 constant? (b) For which surface is the acceleration largest in magnitude?

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Figure 4.1 shows how the velocity of a wooden block decreases on three different surfaces. The slowing down is due to friction—the resistance to motion that one surface or object encounters when moving over another. Notice that the velocity decreases as the block slides. The block slides easily over ice. Friction between the two surfaces is so small that it can be neglected. For example, if the track in Figure 4.2 is perfectly smooth, the carts will move along its length without stopping. In other words, in the absence of friction, objects on a horizontal track keep moving without stopping.

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log in through social network



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Picture a block of wood sitting motionless on a smooth wooden surface. If you give the block a shove, it slides some distance but eventually comes to rest. Depending on the smoothness of the block and the smoothness of the wood, this distance varies. The smoother the surfaces, the more slippery, the block slides for a longer time interval than if the surfaces are rough or sticky. This you know from everyday experience: A hockey puck slides easily on ice but not on a rough road.

Figure 4.1 shows how the velocity of a wooden block decreases on three different surfaces. The slowing down is due to *friction*—the resistance to motion that one surface or object encounters when moving over another. Notice that, during the interval covered by the velocity-versus-time graph, the velocity decreases as the block slides over ice; it hardly decreases as the block slides over a smooth surface; and it decreases rapidly as the block slides over a rough surface. The effect of friction is to bring two objects to rest with respect to each other—in this case the wooden block and the surface it is sliding on. The less friction there is, the longer it takes for the block to come to rest.

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Figure 4.1 shows how the velocity of a wooden block decreases on three different surfaces. The slowing down is due to *friction*—the force that opposes the motion of an object encountered during the interaction. In a velocity-versus-time graph, the velocity decreases as the block slides over ice, which is hardly observable. The block slides easily over ice because there is very little friction between the two surfaces. The effect of friction is to bring two objects to rest with respect to each other—in this case the wooden block and the surface it is sliding on. The less friction there is, the longer it takes for the block to come to rest.

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Figure 4.1 shows how the velocity of a wooden block decreases on three different surfaces. The rougher the surface, the more quickly the velocity decreases due to *friction*—the resistance to motion that one surface of an object encounters when moving over another. Notice that, during the interval covered by the velocity-versus-time graph, the velocity decrease as the block slides on ice is hardly observable. The block slides easily over ice because there is very little friction between the two surfaces. The effect of friction is to bring two objects to rest with respect to each other—in this case the wooden block and the surface it is sliding on. The less friction there is, the longer it takes for the block to come to rest.

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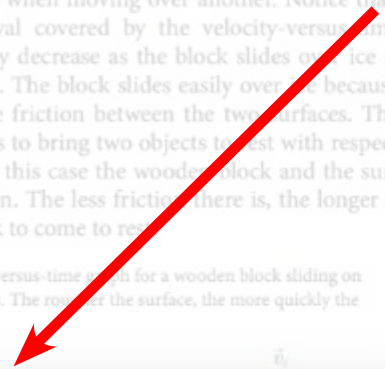
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No friction at all seems impossible. Isn't there always some friction in any real case?

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Figure 4.1 shows how the velocity of a wooden block decreases on three different surfaces. The slowing down is due to *friction*—the resistance to motion that one surface or object encounters when moving over another. Notice that, during the interval covered by the velocity-versus-time graph, the velocity decrease as the block slides over ice is hardly observable. The block slides easily over ice because there is very little friction between the two surfaces. The effect of friction is to bring two objects to rest with respect to each other—in this case the wooden block and the surface it is sliding on. The less friction there is, the longer it takes for the block to come to rest.

Figure 4.2 Low-friction track and carts used in the experiments described in this chapter.



You may wonder whether it is possible to make surfaces that have no friction at all, such that an object, once given a shove, continues to glide forever. There is no totally frictionless surface over which objects slide forever, but there are ways to minimize friction. You can, for instance, float an object on a cushion of air. This is most easily accomplished with a low-friction track—a track whose surface is dotted with little holes through which pressurized air blows. The air serves as a cushion on which a conveniently shaped object can float, with friction between the object and the track all but eliminated. Alternatively, one can use wheeled carts with low-friction bearings on an ordinary track. Figure 4.2 shows low-friction carts you may have encountered in your lab or class. Although there is still some friction both for low-friction tracks and for the track shown in Figure 4.2, this friction is so small that it can be ignored during an experiment. For example, if the track in Figure 4.2 is horizontal, carts move along its length without slowing down appreciably. In other words:

**In the absence of friction, objects moving along a horizontal track keep moving without slowing down.**

Another advantage of using such carts is that the track constrains the motion to being along a straight line. We can then use a high-speed camera to record the cart's position at various instants, and from that information determine its speed and acceleration.



**4.1** (a) Are the accelerations of the motions shown in Figure 4.1 constant? (b) For which surface is the acceleration largest in magnitude?

? No friction at all seems impossible. Isn't there always some friction in any real case.

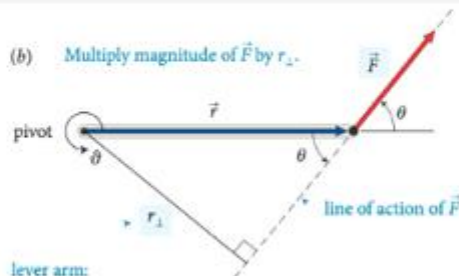
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(b) Multiply magnitude of  $\vec{F}$  by  $r_{\perp}$ .



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action of the force and the axis of rotation. So, the torque caused by a force exerted on an object is the product of the magnitude of the force and its lever arm distance. It can be written equivalently as  $rF_1$  and as  $r_{\perp}F$ .

Like other rotational quantities, torque carries a sign that depends on the choice of direction for increasing  $\vartheta$ . In Figure 12.4, for example, the torque caused by  $\vec{F}_1$  about the pivot tends to rotate the rod in the direction of increasing  $\vartheta$  and so is positive; the torque caused by  $\vec{F}_2$  is negative. The sum of the two torques about the pivot is then  $r_1F_1 + (-r_2F_2)$ . As we've seen, the two torques are equal in magnitude when the rod is balanced, and so the sum of the torques is zero. When the sum of the torques is not zero, the rod's rotational acceleration is nonzero, and so its rotational velocity and angular momentum change.

In the situations depicted in Figures 12.4 and 12.5 we used the pivot to calculate the lever arm distances. This is a natural choice because that is the point about which the object under consideration is free to rotate. However, torques also play a role for stationary objects that are suspended or supported at several different points and that are not free to rotate—for example, a plank or bridge supported at either end. To determine what reference point to use in such cases, complete the following exercise.

#### Exercise 12.1 Reference point

Consider again the rod in Figure 12.4. Calculate the sum of the torques about the left end of the rod.

**SOLUTION** I begin by making a sketch of the rod and the three forces exerted on it, showing their points of application on the rod (Figure 12.6).

reference point



The lever arm distances must now be determined relative to the left end of the rod. The lever arm distance of force  $\vec{F}_1$  to this point is zero, and so the torque caused by that force about the left end of the rod is zero. If I choose counterclockwise as the positive direction of rotation,  $\vec{F}_2$  causes a negative torque about the left end of the rod; the force  $\vec{F}_{pr}^c$  exerted by the pivot causes a positive torque about the left end of the rod. The lever arm distance of  $\vec{F}_2$  about the left end of the rod is  $r_1 + r_2$ ; that of  $\vec{F}_{pr}^c$  is  $r_1$ . Because the rod is at rest, the magnitude of the force exerted by the pivot is equal to the sum of the forces  $\vec{F}_1$  and  $\vec{F}_2$ . Taking into account the signs of the torques, we find that the sum of the torques about the left end of the rod is  $r_1(F_1 + F_2) - (r_1 + r_2)F_2 = r_1F_1 - r_2F_2$ . This is the same result we obtained for the torques about the pivot, and so the sum of the torques about the left end is zero. ✓

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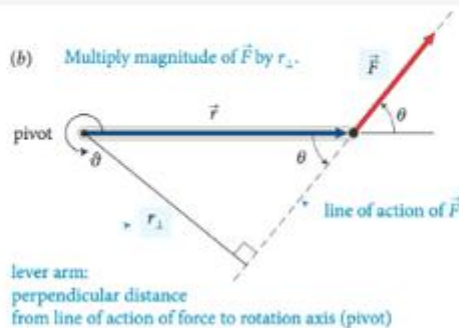
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#### Example 12.2 Torques on lever

Three forces are exerted on the lever of Figure 12.7. Forces  $\vec{F}_1$  and  $\vec{F}_3$  are equal in magnitude, and the magnitude of  $\vec{F}_2$  is half as great. Force  $\vec{F}_1$  is horizontal,  $\vec{F}_2$  and  $\vec{F}_3$  are vertical, and the lever makes an angle of  $45^\circ$  with the horizontal. Do these forces cause the lever to rotate about the pivot? If so, in which direction?



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I think you may be able to think about the direction separately. So, after multiplying this magnitude and distance, you can attach a sign to the torque based on the defined parameters of the system. In the following paragraph, they start to explain how to choose this direction. Oct 20 12:38 am

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**question flag**




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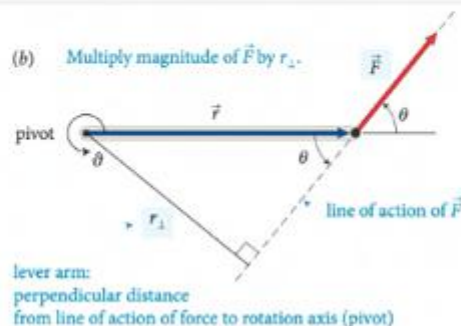
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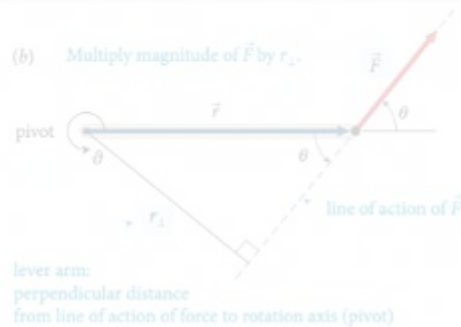
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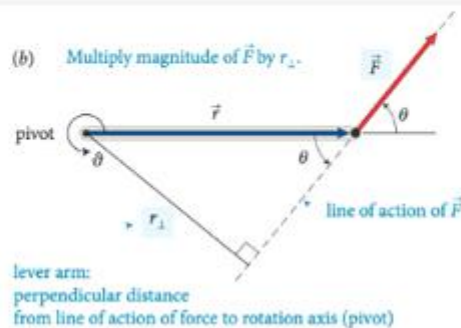
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How small is small? As ... 3

I think it would be slightly ...

While I believe I underst... 3

(a) The change in rotationa...

As we saw earlier in the chap...

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Generally, for rotating bod... 2

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## email notifications

Brian Lukoff responded to a question in Mazur Chapter 4 Sample that you wanted to know the answer to

21 minutes ago, you asked this question on Perusall:

No friction at all seems impossible. Isn't there always some friction in any real case?

Brian Lukoff just responded to the question by saying:

Right - I think there will always be some friction due to the second law of thermodynamics.

If this helps your understanding, click the button below. If you want to respond, simply reply to this email to post to Perusall.

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## option 1: reply

If this helps your understanding, click the button below. If you want to respond, simply reply to this email to post to Perusall.

View conversation

This comment helps my understanding

I don't understand factors tells you lever arm distance know some sort of

I think you mean direction separation distance, you can parameters of the explain how to choose

This is a great question can think of this in torque is  $\tau = r \times F$ , force. We know this in regards to "r" it means is that this to the point where general convention direction which has axis and to the force

Enter your comment

On the very left, we see th...

It's interesting that the white ...

force frame l... 2

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option 2: view chat

View conversation

This comment helps my understanding

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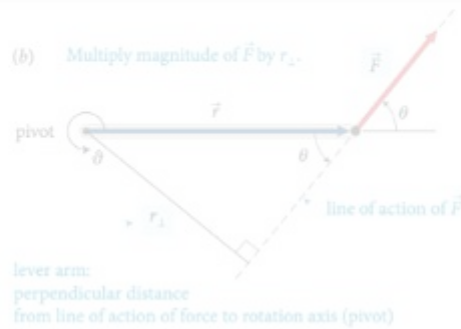
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View conversation

This comment helps my understanding

option 3: mark as answered



action of the force and the axis of rotation. So, the torque caused by a force exerted on an object is the product of the magnitude of the force and its lever arm distance. It can be

The lever arm distances must now be determined relative to the left end of the rod. The lever arm distance of force  $\vec{F}_1$  to this point is zero, and so the torque caused by that force about the left end of the rod is zero. If I choose counterclockwise as the positive direction of rotation,  $\vec{F}_2$  causes a negative torque about the left end of the rod; the force  $\vec{F}_{pr}$  exerted by the pivot causes a positive torque about the left end of the rod. The lever arm distance of  $\vec{F}_2$  about the left end of the rod is  $r_1 + r_2$ ; that of  $\vec{F}_{pr}$  is  $r_1$ . Because the rod is at rest, the magnitude of the force exerted by the pivot is equal to the sum of the forces  $\vec{F}_1$  and  $\vec{F}_2$ . Taking into account the signs of the torques, we find that the sum of the torques about the left end of the rod is  $r_1(F_1 + F_2) - (r_1 + r_2)F_2 = r_1F_1 - r_2F_2$ . This is the same result we obtained for the torques about the pivot, and so the sum of the torques about the left end is zero. ✓

Exercise 12.1 shows that the sum of the torques about the left end of the rod is zero, just like the sum of the torques about the pivot. You can repeat the calculation for the right end of the rod. The result is the same. The sum of the torques about any point is zero. The reason is that the rod is not rotating about any point, and so the sum of the torques must be zero about any point. In general we can say:

For a stationary object, the sum of the torques is zero.

For a stationary object we can choose any reference point we like to calculate torques. It pays to choose a reference point that simplifies the calculation. As you have seen, we do not need to consider any force that is exerted at the reference point. So, by putting the reference point at the point of application of a force, we can eliminate that force from the calculation.

**12.2** In the situation depicted in Figure 12.2a, you must continue to exert a force on the seesaw to keep the child off the ground. The force you exert causes a torque on the seesaw, and yet the seesaw's rotational acceleration is zero. How can this be if torques cause objects to accelerate rotationally?

#### Example 12.2 Torques on lever

Three forces are exerted on the lever of Figure 12.7. Forces  $\vec{F}_1$  and  $\vec{F}_2$  are equal in magnitude, and the magnitude of  $\vec{F}_3$  is half as great. Force  $\vec{F}_1$  is horizontal,  $\vec{F}_2$  and  $\vec{F}_3$  are vertical, and the lever makes an angle of  $45^\circ$  with the horizontal. Do these forces cause the lever to rotate about the pivot? If so, in which direction?

# how to get students to participate?

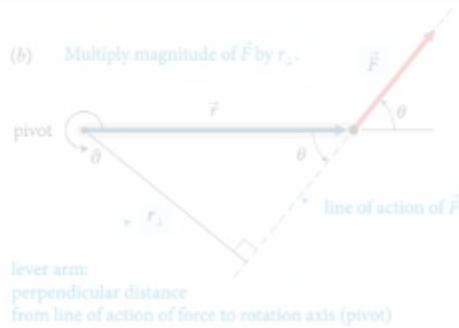
I don't understand how this combination of factors tells you about the direction of the lever arm distance. I would like to see how you know some sort of direction to calculate torque.

I think you may be able to think about the direction separately. So, after multiplying this magnitude and distance, you can attach a sign to the torque based on the defined parameters of the system. In the following paragraph, they start to explain how to choose this direction.

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Enter your comment or question and press Enter

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reference point.

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# use combination of

# intrinsic and extrinsic motivation drivers

I don't understand how this combination of factors tells you anything about direction? Aren't magnitude and lever arm distance both scalar quantities? It seems like we would need to know some sort of direction to calculate torque.

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For a stationary object, the sum of the torques is zero.

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**12.2** In the situation depicted in Figure 12.2a, you must continue to exert a force on the seesaw to keep the child off the ground. The force you exert causes a torque on the seesaw, and yet the seesaw's rotational acceleration is zero. How can this be if torques cause objects to accelerate rotationally?

**Example 12.2 Torques on lever**

Three forces are exerted on the lever of Figure 12.7. Forces  $\vec{F}_1$  and  $\vec{F}_2$  are equal in magnitude, and the magnitude of  $\vec{F}_3$  is half as great. Force  $\vec{F}_1$  is horizontal,  $\vec{F}_2$  and  $\vec{F}_3$  are vertical, and the lever makes an angle of  $45^\circ$  with the horizontal. Do these forces cause the lever to rotate about the pivot? If so, in which direction?

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# rubric-based assessment

(b) Multiply magnitude of  $\vec{F}$  by  $r_{\perp}$ .



lever arm:  
perpendicular distance  
from line of action of force to rotation axis (pivot)

- quality (thoughtful reading & interpretation)

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Enter your comment or question and press Enter

- On the very left, we see th...
- It's interesting that the white ...
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# rubric-based assessment

(b) Multiply magnitude of  $\vec{F}$  by  $r_{\perp}$ .



lever arm:  
perpendicular distance  
from line of action of force to rotation axis (pivot)

- quality (thoughtful reading & interpretation)

- quantity (minimum 10)

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# rubric-based assessment

(b) Multiply magnitude of  $\vec{F}$  by  $r_{\perp}$ .



lever arm:  
perpendicular distance  
from line of action of force to rotation axis (pivot)

- quality (thoughtful reading & interpretation)

- quantity (minimum 10)

- timeliness (before class)

I don't understand how direction tells you anything about direction? Aren't magnitude and lever arm distance both scalar quantities? It seems like we would need to know some sort of direction to calculate torque.

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# rubric-based assessment

(b) Multiply magnitude of  $\vec{F}$  by  $r_{\perp}$ .



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perpendicular distance  
from line of action of force to rotation axis (pivot)

- quality (thoughtful reading & interpretation)

- quantity (minimum 10)

- timeliness (before class)

- distribution (not clustered)

I don't understand how direction tells you anything about direction? Aren't magnitude and lever arm distance both scalar quantities? It seems like we would need to know some sort of direction to calculate torque.

I think you may be able to think about direction separately. So, for the lever arm distance, you can attach a sign to the torque based on the defined parameters of the system. In the following paragraph, they start to explain how to choose this direction.

This is a great question. To find the direction of the torque, you can think of this in terms of the cross product. The magnitude of the torque is  $\tau = r \times F$ , with  $r$  being the level arm distance and  $F$  being force. We know that force is a vector vector from previous chapters, and in regards to " $r$ " it can also be thought of as the radial vector. What this means is that this distance from the pivot points from the axis of rotation to the point where the force acts. In as previously mentioned, there is a general convention (the right-hand rule) that is used to determine the direction which happens to be perpendicular to both the radius from the axis and to the force.

Enter your comment or question and press Enter

The lever arm distances must now be determined relative to the left end of the rod. The lever arm distance of force  $\vec{F}_1$  to this point is zero, and so the torque caused by that force about the left end of the rod is zero. If I choose counterclockwise as the positive direction of rotation,  $\vec{F}_2$  causes a negative torque about the left end of the rod; the force  $\vec{F}_{pr}$  exerted by the pivot causes a positive torque about the left end of the rod. The lever arm distance of  $\vec{F}_2$  about the left end of the rod is  $r_1 + r_2$ ; that of  $\vec{F}_{pr}$  is  $r_1$ . Because the rod is at rest, the magnitude of the force exerted by the pivot is equal to the sum of the forces  $\vec{F}_1$  and  $\vec{F}_2$ . Taking into account the sign of the torques on the rod,  $r_1(\vec{F}_1 + \vec{F}_2) - (r_1 + r_2)\vec{F}_2 = r_1\vec{F}_1 - r_2\vec{F}_2$ . This is the same result we obtained for the torques about the pivot, and so the sum of the torques about the left end is zero. ✓

Exercise 12.1 shows that the sum of the torques about the left end of the rod is zero, just like the sum of the torques about the pivot. You can repeat the calculation for the torques about the right end of the rod or any other point, and each time you will find that the sum of the torques is zero. The reason is that the rod is not rotating about any point, and so the sum of the torques must be zero about any point. In general we can say:

For any stationary object, the sum of the torques is zero.

For a stationary object we can choose any reference point we like to calculate torques. It pays to choose a reference point that simplifies the calculation. As you have seen, we do not need to consider any force that is exerted at the reference point. So, by putting the reference point at the point where a force is applied, we can eliminate that force from the calculation.

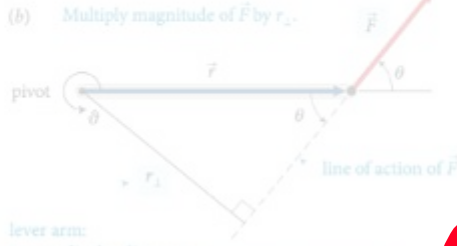
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### Example 12.2 Torques on lever

Three forces are exerted on the lever of Figure 12.7. Forces  $\vec{F}_1$  and  $\vec{F}_2$  are equal in magnitude, and the magnitude of  $\vec{F}_3$  is half as great. Force  $\vec{F}_1$  is horizontal,  $\vec{F}_2$  and  $\vec{F}_3$  are vertical, and the lever makes an angle of  $45^\circ$  with the horizontal. Do these forces cause the lever to rotate about the pivot? If so, in which direction?

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# rubric-based assessment



- quality (thoughtfulness & insight)

**over 20,000 annotations!**

- timeliness (before class)

- distribution (not clustered)

The lever arm distances must now be determined relative to the pivot point. The lever arm distance of force  $\vec{F}_1$  about the left end of the rod is zero. If I choose the left end of the rod as the pivot, the force  $\vec{F}_1$  causes a positive torque about the left end of the rod; the force  $\vec{F}_2$  causes a negative torque about the left end of the rod. The lever arm distance of  $\vec{F}_2$  about the left end of the rod is  $r_2$ . The lever arm distance of  $\vec{F}_3$  about the left end of the rod is  $r_3$ . The lever arm distance of  $\vec{F}_3$  about the left end of the rod is  $r_3$ . The lever arm distance of  $\vec{F}_3$  about the left end of the rod is  $r_3$ .

For the rod to be in equilibrium, the sum of the torques about the pivot must be zero. You can repeat the calculation for the torques about the right end of the rod for any other point, and each time you will find that the sum of the torques is zero. The reason is that the rod is not rotating about any point, and so the sum of the torques about any point must be zero. In general we can choose any point as the pivot. For a rotating object, we choose the pivot point that makes the calculation easiest. As we have seen, we do not need to know the mass of the object to calculate the torque.

**Example 12.2 Torques on lever**

Three forces are exerted on the lever of Figure 12.7. Forces  $\vec{F}_1$  and  $\vec{F}_2$  are equal in magnitude, and the magnitude of  $\vec{F}_3$  is half as great. Force  $\vec{F}_1$  is horizontal,  $\vec{F}_2$  and  $\vec{F}_3$  are vertical, and the lever makes an angle of  $45^\circ$  with the horizontal. Do these forces cause the lever to rotate about the pivot? If so, in which direction?

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# rubric-based assessment

(b) Multiply magnitude of  $\vec{F}$  by  $r_{\perp}$ .



lever arm:  
perpendicular distance  
from line of action of force to rotation axis (pivot)

- quality (thoughtful reading & interpretation)

action of the force and the axis of rotation. So, the torque caused by a force exerted on an object is the product of the magnitude of the force and its lever arm distance. It can be

The lever arm distances must now be determined relative to the left end of the rod. The lever arm distance of force  $\vec{F}_1$  to this point is zero, and so the torque caused by that force about the left end of the rod is zero. If I choose counterclockwise as the positive direction of rotation,  $\vec{F}_2$  causes a negative torque about the left end of the rod; the force  $\vec{F}_3$  exerted by the pivot causes a positive torque about the left end of the rod. The lever arm distance of  $\vec{F}_2$  about the left end of the rod is  $r_1 + r_2$ ; that of  $\vec{F}_3$  is  $r_1$ . Because the rod is at rest, the magnitude of the force exerted by the pivot is equal to the sum of the forces  $\vec{F}_1$  and  $\vec{F}_2$ . Taking into account the sign of the torques, we find  $r_1(\vec{F}_1 + \vec{F}_2) - (r_1 + r_2)\vec{F}_2 = r_1\vec{F}_1 - r_2\vec{F}_2$ . This is the same result we obtained for the torques about the pivot, and so the sum of the torques about the left end is zero. ✓

Exercise 12.1 shows that the sum of the torques about the left end of the rod is zero, just like the sum of the torques about the pivot. This result is not surprising. If the rod is at rest, the sum of the torques about any point must be zero. The reason is that the rod is not rotating about any point, and so the sum of the torques must be zero about any point. In general we can say:

For a stationary object, the sum of the torques is zero.

For a stationary object we can choose any reference point we like to calculate torques. It pays to choose a reference point that simplifies the calculation. As you have seen, we do not need to consider any force that is exerted at the reference point. So, by putting the reference point at the point where a force is exerted, we can eliminate that force from the calculation.

**12.2** In the situation depicted in Figure 12.2a, you must continue to exert a force on the seesaw to keep the child off the ground. The force you exert causes a torque on the seesaw, and yet the seesaw's rotational acceleration is zero. How can this be if torques cause objects to accelerate rotationally?

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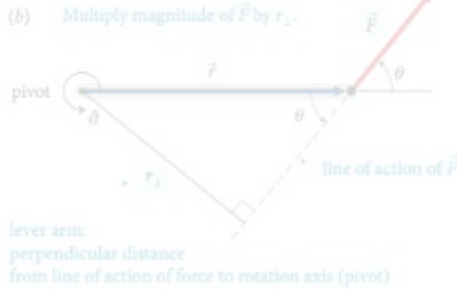
# how do you process all of that??

- quantity (minimum 10)
- timeliness (before class)

- distribution (not clustered)

- On the very left, we see th...
- It's interesting that the white ...
- Is the reference frame i... 2
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# rubric-based assessment



- quality (though future research on interpretation)

**fully automated**

**you process all of that??**

**assessment**

- timeliness (before class)

- distribution (not clustered)

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Exercise 12.1 shows that the sum of the torques about the left end of the rod is zero, just like the sum of the torques about the pivot. This is a useful result that can be used to check your calculations. For a static equilibrium problem, you can choose a reference point to calculate the torques. It is often convenient to choose a reference point where one of the forces acts. As you have seen, we do not need to consider any force that is exerted at the reference point. So, by putting the reference point at the point where one of the forces acts, we can eliminate that force from the calculation.

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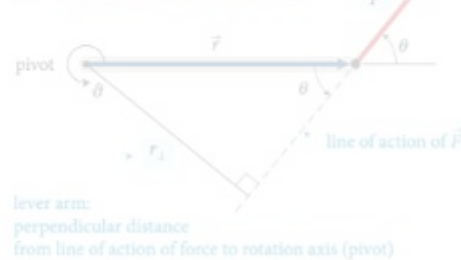
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Enter your comment or question and press Enter

# fully automated assessment

(b) Multiply magnitude of  $\vec{F}$  by  $r_{\perp}$ .



- specialized machine learning algorithm

- assesses intellectual content

- exceeds intercoder reliability

I don't understand how this combination of factors tells you anything about direction? Aren't magnitude and lever arm distance both scalar quantities that seem like they should be known some sort of direction?

I think you may be able to think about the direction separately. So, after multiplying this magnitude and distance, you can attach a sign to the torque based on the defined parameters of the system. I can't explain how to choose the sign.

This is a great question. To further elaborate on this, we can think of this in terms of the Torque equation. The equation for torque is  $\tau = r \times F$ , with  $r$  being the level arm distance and  $F$  being force. We know that force is a vector vector from previous chapters, and in regards to " $r$ " it can also be thought of as the radial vector. What this means is that this distance from the pivot points from the axis of rotation to the point where the force acts. In as previously mentioned, there is a general convention (the right-hand rule) that is used to determine the direction which happens to be perpendicular to both the radius from the axis and to the force.

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For a stationary object, the sum of the torques is zero.

For a stationary object we can choose any reference point to calculate the torques. We can choose a reference point that is not on the object. As you have seen, we do not need to consider any force that is exerted at the reference point. So, by putting the reference point at the point of application of a force, we can eliminate that force from the calculation.

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Total number of annotations **16**

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Total number of annotations submitted on time **11**

Average quality of top 10 annotations submitted on time **1.80**

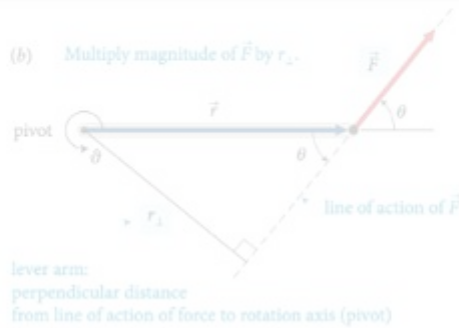
2 = demonstrates thorough and thoughtful reading and insightful interpretation of the reading, 1 = demonstrates reading, but no (or only superficial) interpretation of the reading, 0 = does not demonstrate any thoughtful reading or interpretation

Distribution of annotations **3.8**

0 = clustered, 5 = evenly distributed throughout assignment

Assignment score **1**

scores range from 0 to 3



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 $\vec{F}_1$   
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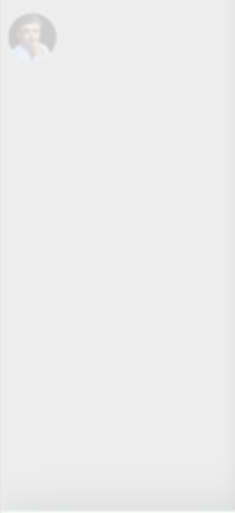
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# connect pre-class and in-class activities



- I don't understand why torque is calculated as  $\tau = r \times F$  instead of  $\tau = r F \sin(\theta)$ . I think you may be able to think about the direction separately. So, after multiplying this magnitude and distance, you can attach a sign to the torque based on the defined parameters of the system. In the following paragraph, they start to explain how to choose this direction.
- This is a great question. To further elaborate on this, we can think of this in terms of the Torque equation. The equation for torque is  $\tau = r \times F$ , with  $r$  being the level arm distance and  $F$  being force. We know that force is a vector vector from previous chapters, and in regards to "r" it can also be thought of as the radial vector. What this means is that this distance from the pivot points from the axis of rotation to the point where the force acts. In as previously mentioned, there is a general convention (the right-hand rule) that is used to determine the direction which happens to be perpendicular to both the radius from the axis and to the force.
- Enter your comment or question and press Enter

# confusion report

## Confusion report for Chapter 24

### right hand rule (11 questions)

- JB Can someone in simpler terms explain the right- hand rule? +1
- WJ Is there another way, besides the right hand rule, to find the direction of the magnetic field with a current? 1
- SB Using the right hand rule, I believe the answer is D. Is that correct? 1  
Show more...

### direction magnetic field (8 questions)

- CP Why is it that the magnet field points away from the north pole and towards the south pole? When on the previous page it stated that the direction of the magnetic field is the direction that the north pole of a compass needle points. +2
- AB How can you determine which direction the magnetic field will point towards? +1
- KH So whichever way the north pole faces is the direction of the magnetic field but that doesn't always mean its pointing true north? +1  
Show more...

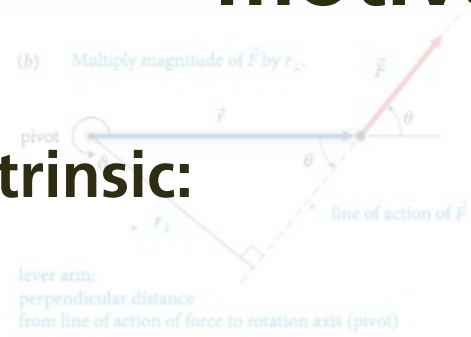
### earth magnetic field (6 questions)

- CP Does that mean that the compass will be distracted from the Earth's magnetic field and use the magnetic field that the current of the wire gives off? 1
- AK Can someone explain why this type of bacteria knows what direction the earth's magnetic fields are facing? 1
- J Does the circular loop of current have any similarities with the look of the earths magnetic field? They kind of look similar to me. 1  
Show more...

# motivating factors

Intrinsic:

- social interaction



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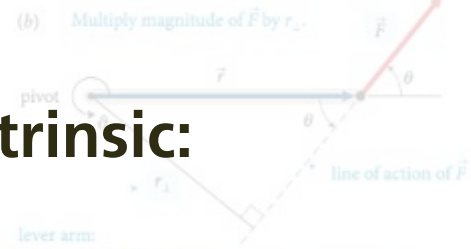
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- Enter your comment or question and press Enter

# motivating factors

Intrinsic:

- social interaction
- tie-in to in-class activity



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Enter your comment or question and press Enter

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Intrinsic:

• social interaction

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Extrinsic:

• assessment (fully automated)



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Profile picture

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Oct 20 12:38 am

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Oct 22 8:46 am

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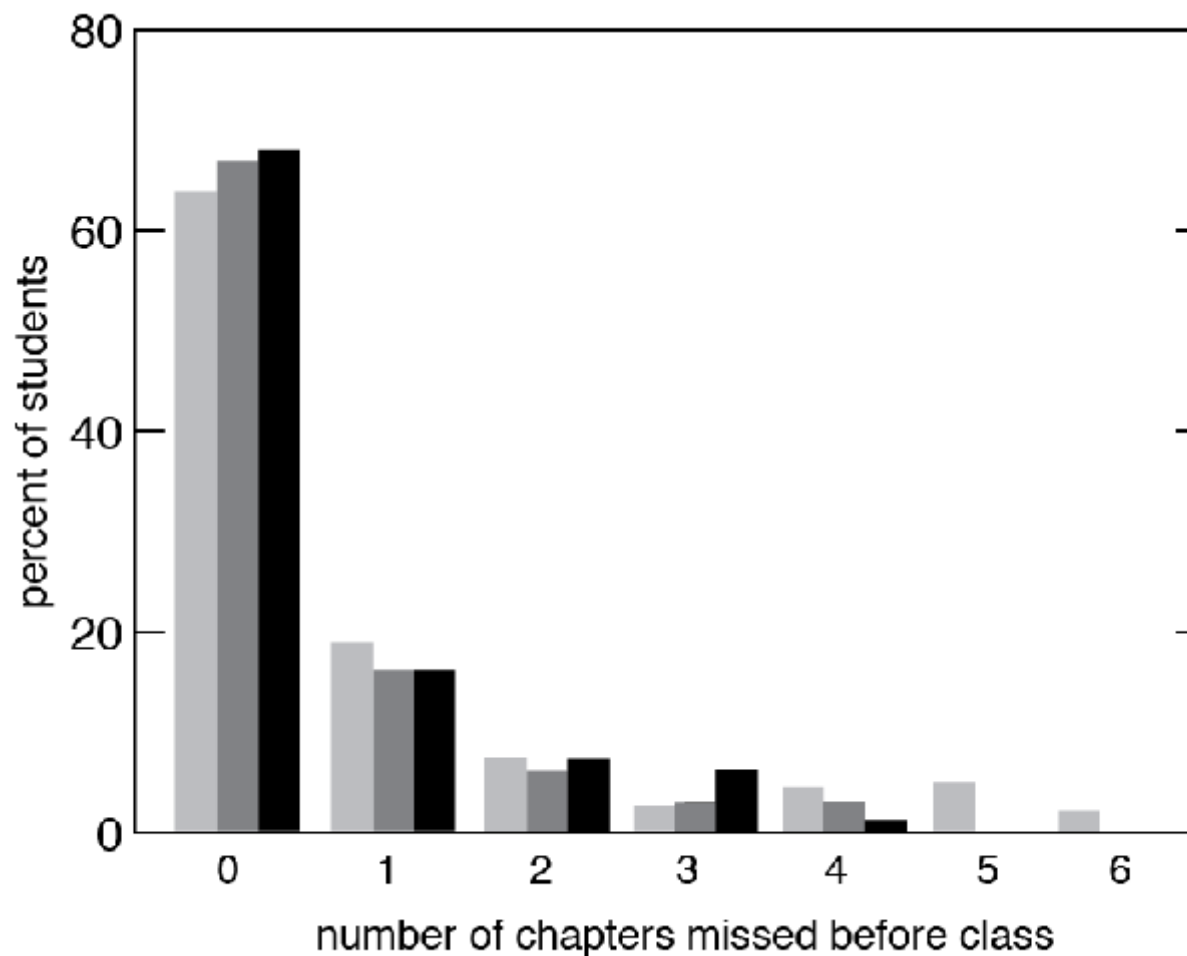
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(b) Multiply magnitude of  $\vec{F}$  by  $r_{\perp}$ .



$\vec{F}_3$

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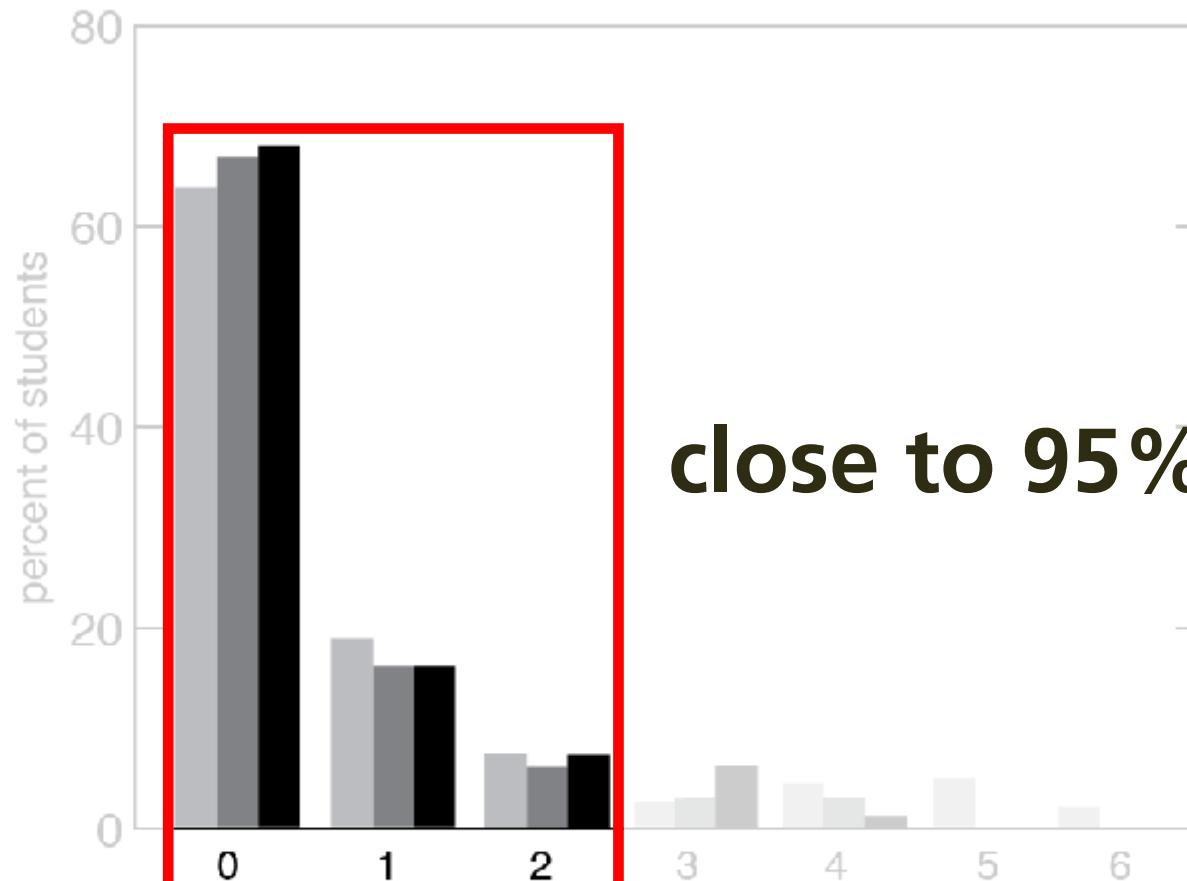
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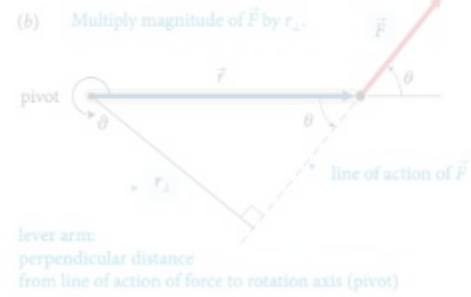
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# research data



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# every student prepared for every class

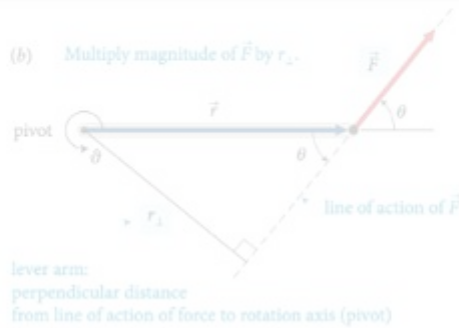
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**12.2** In the situation depicted in Figure 12.2a, you must continue to exert a force on the seesaw to keep the child off the ground. The force you exert causes a torque on the seesaw, and yet the seesaw's rotational acceleration is zero. How can this be if torques cause objects to accelerate rotationally?

**Example 12.2 Torques on lever**

Three forces are exerted on the lever of Figure 12.7. Forces  $\vec{F}_1$  and  $\vec{F}_2$  are equal in magnitude, and the magnitude of  $\vec{F}_3$  is half as great. Force  $\vec{F}_1$  is horizontal,  $\vec{F}_2$  and  $\vec{F}_3$  are vertical, and the lever makes an angle of  $45^\circ$  with the horizontal. Do these forces cause the lever to rotate about the pivot? If so, in which direction?

- On the very left, we see th...
- It's interesting that the white ...
- Is the refernece frame i...
- How does force affect ...
- I was curious about this, t...
- I understand partially w...
- In this class, we always emp...
- The part before this wa...
- The extended free-body d...
- This just means the net...
- I understand why ...
- To note that...
- This reminds me of when we ...
- Torque is the ability of a forc...
- The type of diagram to use d...
- It sounds like it is sayin...
- So then do we have a p...
- Since torque is the cross pro...
- The right-hand rule can al...
- I don't understand how ...
- Orientation-based descriptio...
- I don't really understand...
- How small is small? As ...
- I think it would be slightly ...
- While I believe I underst...
- (a) The change in rotationa...
- As we saw earlier in the chap...
- Objects executing motion ar...
- Generally, for rotating bod...
- Does torque have the s...

## 76 CHAPTER 4 MOMENTUM

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#### 4.1 Friction

Picture a block of wood sitting motionless on a smooth wooden surface. If you give the block a shove, it slides some distance but eventually comes to rest. Depending on the smoothness of the block and the smoothness of the wooden surface, this stopping may happen sooner or it may happen later. If you give the same shove to a block on a very slippery surface, the block slides for a longer time interval than if the surfaces are rough or sticky. This you know from everyday experience: A hockey puck slides easily on ice but not on a rough road.

Figure 4.1 shows how the velocity of a wooden block decreases on three different surfaces. The slowing down is most noticeable on the roughest surface. During the interval covered by the velocity-versus-time graph, the velocity decrease as the block slides over ice is hardly observable. The block slides easily over ice because there is very little friction between the two surfaces. The effect of friction is to bring two objects to rest with respect to each other; in this case the wooden block and the surface it is sliding on. The rougher the surface, the more quickly the block comes to rest.

Figure 4.1 Velocity-versus-time graph for a wooden block sliding on three different surfaces. The rougher the surface, the more quickly the velocity decreases.



Figure 4.2 Low-friction track and carts used in the experiments described in this chapter.



You may wonder whether it is possible to make surfaces that have no friction at all, such that an object, once given a shove, continues to glide forever. There is no totally frictionless surface over which objects slide forever, but there are ways to make surfaces that are nearly frictionless. One way is to use a low-friction track—a track whose surface is dotted with little holes through which pressurized air blows. The air serves as a cushion on which a conveniently shaped object can float, with friction between the object and the track all but eliminated. Alternatively, one can use wheeled carts with low-friction bearings on an ordinary track. Figure 4.2 shows low-friction carts you may have encountered in your lab or class. Although there is still some friction both for low-friction tracks and for the track shown in Figure 4.2, this friction is so small that it can be ignored during an experiment. For example, if the track in Figure 4.2 is horizontal, carts move along its length without slowing down appreciably. In other words:

of friction, objects moving along a low-friction track keep moving without slowing down.

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4.1 (a) Are the accelerations of the motions shown in Figure 4.1 constant? (b) For which surface is the acceleration largest in magnitude?

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- click on "Chapter 4"
- scroll to second page

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Brian Lukoff

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? No friction at all seems impossible. Isn't there always some friction in any real case.

Nov 1 4:41 pm



Enter your comment or question and press Enter



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Click to request an answer

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## 88 CHAPTER 4 MOMENTUM

## Example 4.5 Bullet and bowling ball

Compare the magnitude of the momenta of a 0.010-kg bullet fired from a rifle at 1300 m/s and a 6.5-kg bowling ball lumbering across the floor at 4.0 m/s.

**1 GETTING STARTED** Momentum is the product of inertia and velocity. I have to calculate this quantity for both the bullet and the bowling ball and then compare the resulting values.

**2 DEVISE PLAN** Equation 4.6 gives the momentum of an object. To determine the magnitude of the momentum of an object, I must take the product of the inertia  $m$  and the speed  $v$ :  $p = mv$ .

**3 EXECUTE PLAN** Substituting the values given in the problem statement, I get

$$p_{\text{bullet}} = (0.010 \text{ kg})(1300 \text{ m/s}) = 13 \text{ kg} \cdot \text{m/s} \checkmark$$

$$p_{\text{bowling}} = (6.5 \text{ kg})(4.0 \text{ m/s}) = 26 \text{ kg} \cdot \text{m/s} \checkmark$$

**4 EVALUATE RESULT** Surprisingly, the magnitudes of the momenta are very close! I have no way of evaluating momenta because I don't have much experience yet with this quantity. However, the bullet has less inertia and a high speed and the bowling ball has greater inertia and a low speed, so it is not unreasonable that the product of these quantities is similar.

Momentum is a quantitative measure of “matter in motion” and depends on both the amount of matter in motion and how fast that matter is moving. Momentum is very different from inertia. A truck, for example, has greater inertia than a fly (it has a higher resistance to a change in its velocity), but if the truck is at rest and the fly is in motion, then the magnitude of the fly's momentum is larger than that of the truck, which is zero. In Example 4.5, the inertias of the bullet and the bowling ball are very different, yet their momenta are similar. Conceptually you can think of an object's momentum as its capacity to affect the motion of other objects in a collision.

With the definition of momentum, we can rewrite Eq. 4.5 in the form

$$p_{uxf} - p_{uxi} + p_{sxf} - p_{sxi} = 0. \quad (4.8)$$

If we write  $\Delta p_{ux} = p_{uxf} - p_{uxi}$  and  $\Delta p_{sx} = p_{sxf} - p_{sxi}$ , Eq. 4.8 takes on the beautifully simple form

$$\Delta p_{ux} + \Delta p_{sx} = 0. \quad (4.9)$$

This equation means that, whenever an object of unknown inertia collides with the inertial standard, the changes in the  $x$  components of the momenta of the two objects add up to zero. In other words, the change in the  $x$  component of the momentum for one object is always the negative of the change for the other.

## Example 4.6 Collisions and momentum changes

(a) A red cart with an initial speed of 0.35 m/s collides with a stationary standard cart ( $m_s = 1.0$  kg). After the collision, the standard cart moves away at a speed of 0.38 m/s. What is the momentum change for each cart? (b) The experiment is repeated with a blue cart, and now the final speed of the standard cart is 0.31 m/s. What is the momentum change for each cart in this second

collision? (c) If in the collisions  $v_{rxf} = +0.032$  m/s and  $v_{bxf} = -0.039$  m/s, what are the inertias of the red and the blue carts?

**1 GETTING STARTED** I begin organizing the information given in the problem in a picture by showing the initial and final conditions for each of the two collisions (Figure 4.18).



## 88 CHAPTER 4 MOMENTUM

Right - I think there will always be some friction due to the second law of thermodynamics.

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**Example 4.6 Collisions and momentum changes**

(a) A red cart with an initial speed of 0.35 m/s collides with a stationary standard cart ( $m_s = 1.0$  kg). After the collision, the standard cart moves away at a speed of 0.38 m/s. What is the momentum change for each cart? (b) The experiment is repeated with a blue cart, and now the final speed of the standard cart is 0.31 m/s. What is the momentum change for each cart in this second

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**1 GETTING STARTED** I begin organizing the information given in the problem in a picture by showing the initial and final conditions for each of the two collisions (Figure 4.18).



## 88 CHAPTER 4 MOMENTUM

## Example 4.5 Bullet and bowling ball

Compare the magnitude of the momenta of a 0.010-kg bullet fired from a rifle at 1300 m/s and a 6.5-kg bowling ball lumbering across the floor at 4.0 m/s.

**1 GETTING STARTED** Momentum is the product of inertia and velocity. I have to calculate this quantity for both the bullet and the bowling ball and then compare the resulting values.

**2 DEVISE PLAN** Equation 4.6 gives the momentum of an object. To determine the magnitude of the momentum of an object, I must take the product of the inertia  $m$  and the speed  $v$ :  $p = mv$ .

**3 EXECUTE PLAN** Substituting the values given in the problem statement, I get

$$p_{\text{bullet}} = (0.010 \text{ kg})(1300 \text{ m/s}) = 13 \text{ kg} \cdot \text{m/s} \checkmark$$

$$p_{\text{bowling}} = (6.5 \text{ kg})(4.0 \text{ m/s}) = 26 \text{ kg} \cdot \text{m/s} \checkmark$$

**4 EVALUATE RESULT** Surprisingly, the magnitudes of the momenta are very close! I have no way of evaluating momenta because I don't have much experience yet with this quantity. However, the bullet has less inertia and a high speed and the bowling ball has greater inertia and a low speed, so it is not unreasonable that the product of these quantities is similar.

Momentum is a quantitative measure of “matter in motion” and depends on both the amount of matter in motion and how fast that matter is moving. Momentum is very different from inertia. A truck, for example, has greater inertia than a fly (it has a higher resistance to a change in its velocity), but if the truck is at rest and the fly is in motion, then the magnitude of the fly's momentum is larger than that of the truck, which is zero. In Example 4.5, the inertias of the bullet and the bowling ball are very different, yet their momenta are similar. Conceptually you can think of an object's momentum as its capacity to affect the motion of other objects in a collision.

With the definition of momentum, we can rewrite Eq. 4.5 in the form

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Brian Lukoff responded to your comment: **Right - I think there will always be some friction due to the second law of thermodynamics.**

a few seconds ago

## 76 CHAPTER 4 MOMENTUM

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a few seconds ago

+1 ? No friction at all seems impossible. Isn't there always some friction in any real case.

Nov 1 12:03 pm



? Right - I think there will always be some friction due to the second law of thermodynamics.

Nov 1 12:09 pm



Enter your comment or question and press Enter

## 4.2 Inertia

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Figure 4.1 Velocity-versus-time graph for a wooden block sliding on three different surfaces. The rougher the surface, the more quickly the velocity decreases.

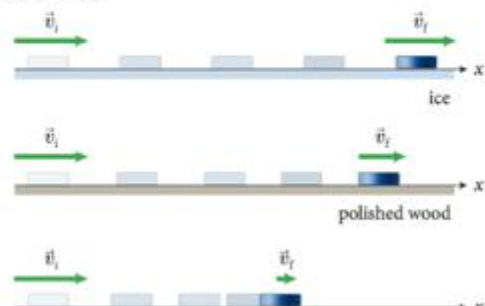


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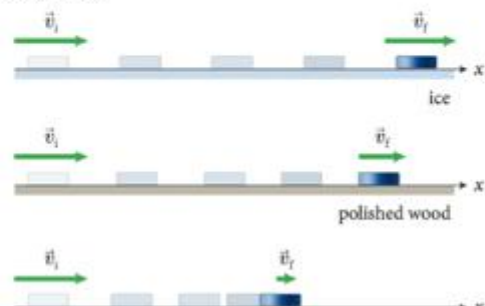


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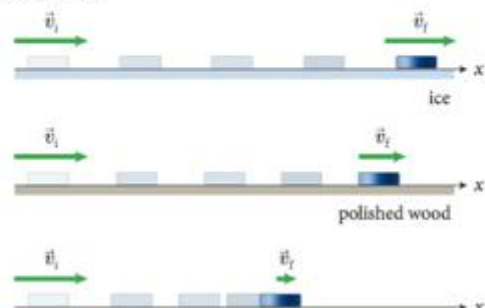


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Annotate a figure

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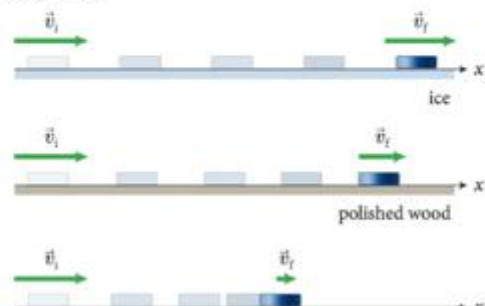


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Try this:

1. post a question
2. answer someone else's question
3. check email and try out email interface

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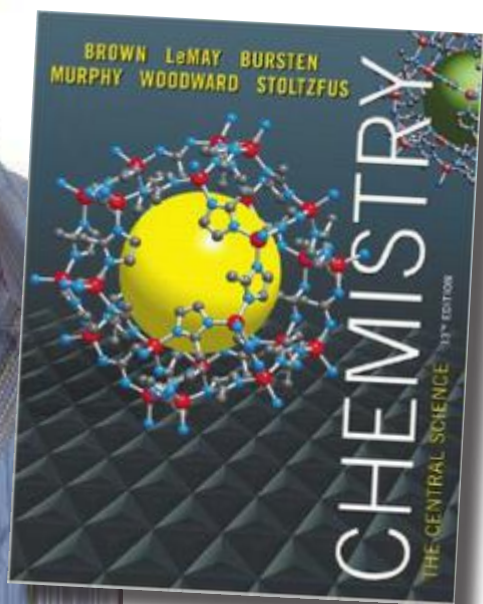
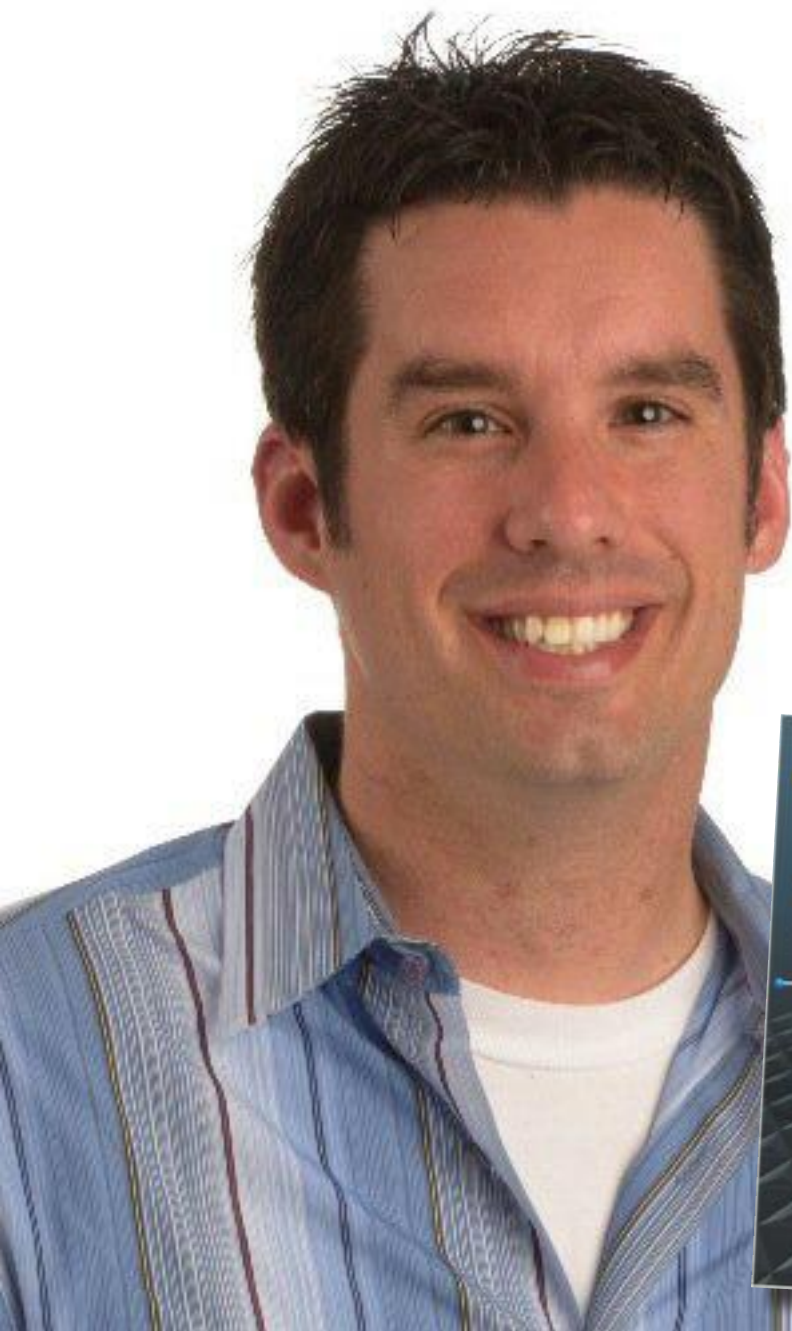
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# CHEM1210: General Chemistry

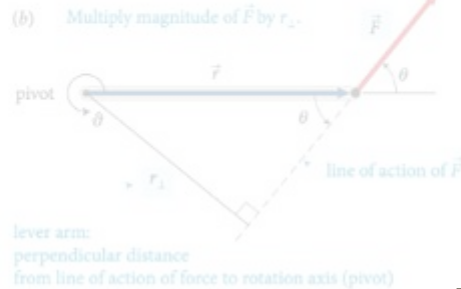
**Matt Stoltzfus**  
**Ohio State University**

**525 students**

**Brown Lemay 13<sup>th</sup> ed (Pearson)**



# additional research data



action of the force and the axis of rotation. So, the torque caused by a force exerted on an object is the product of the magnitude of the force and its lever arm distance. It can be

The lever arm distances must now be determined relative to the left end of the rod. The lever arm distance of force  $\vec{F}_1$  to this point is zero, and so the torque caused by that force about the left end of the rod is zero. If I choose counterclockwise as the positive direction of rotation,  $\vec{F}_2$  causes a negative torque about the left end of the rod; the force  $\vec{F}_2$  exerted by the pivot causes a positive torque about the left end of the rod. The lever arm distance of  $\vec{F}_2$  about the left end of the rod is  $r_1 + r_2$ ; that of  $\vec{F}_{pr}$  is  $r_1$ . Because the rod is at rest, the magnitude of the force exerted by the pivot is equal to the sum of the forces  $\vec{F}_1$  and  $\vec{F}_2$ . The net torque about the left end of the rod is  $r_1(F_1 + F_2) - (r_1 + r_2)F_2 = r_1F_1 - r_2F_2$ . This is the same result we obtained for the torques about the pivot, and so the sum of the torques about the left end is zero. ✓

Exercise 12.1 shows that the sum of the torques about the left end of the rod is zero, just like the sum of the torques about the pivot. You can repeat the calculation for the torques about the right end of the rod or any other point, and each time you will find that the sum of the torques is zero. The reason is that the rod is not rotating about any point, and so the sum of the torques must be zero about any point. In general we can say:

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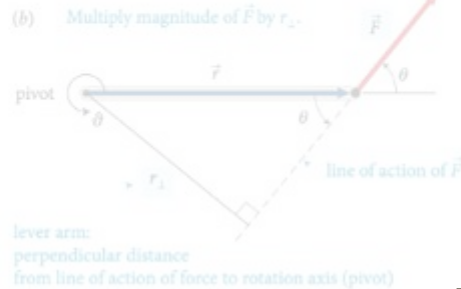
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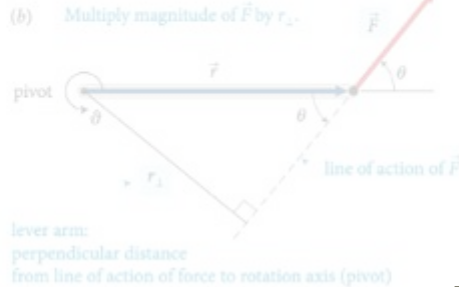
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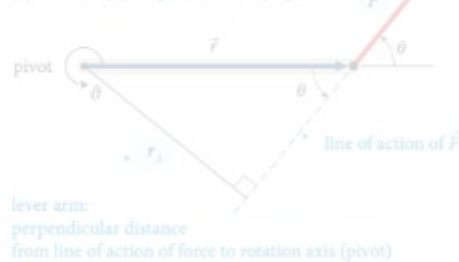
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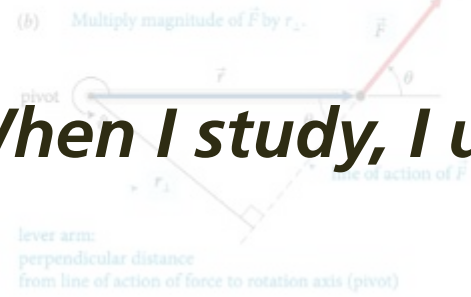
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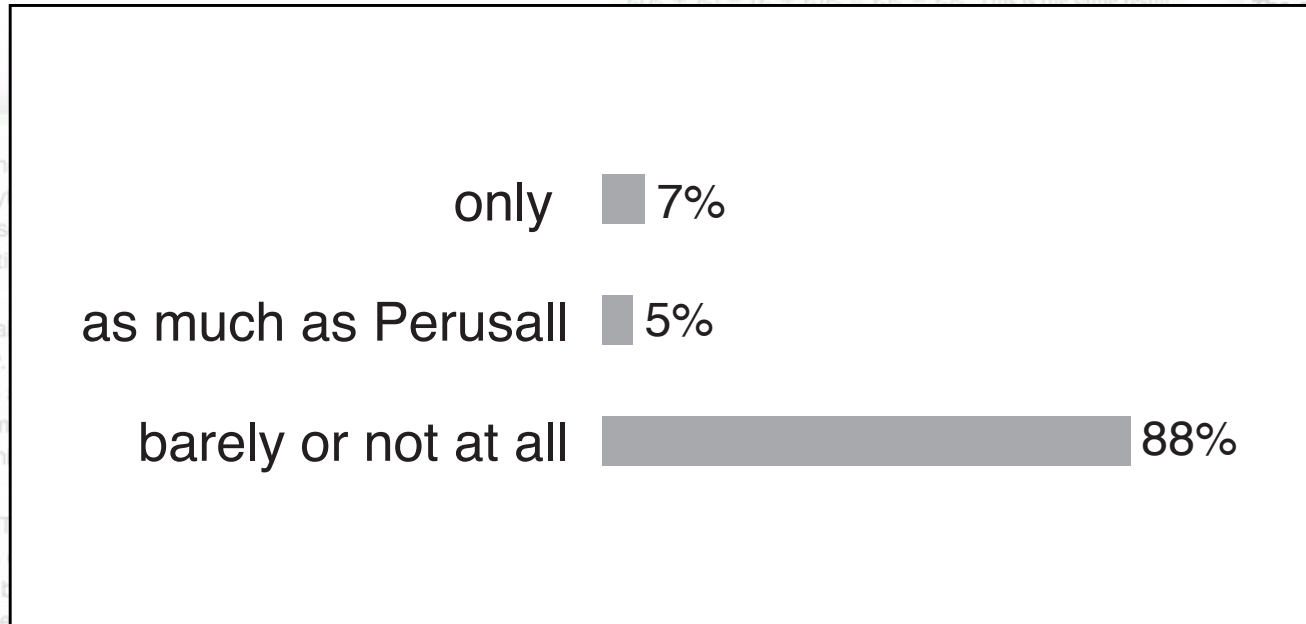
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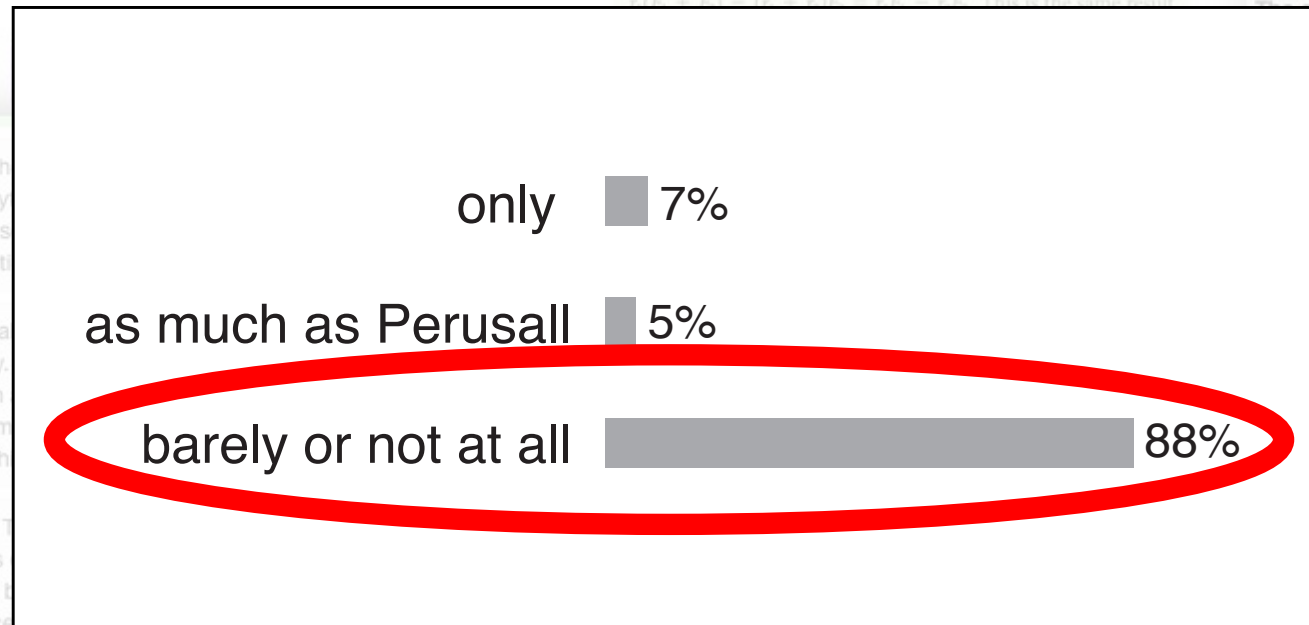
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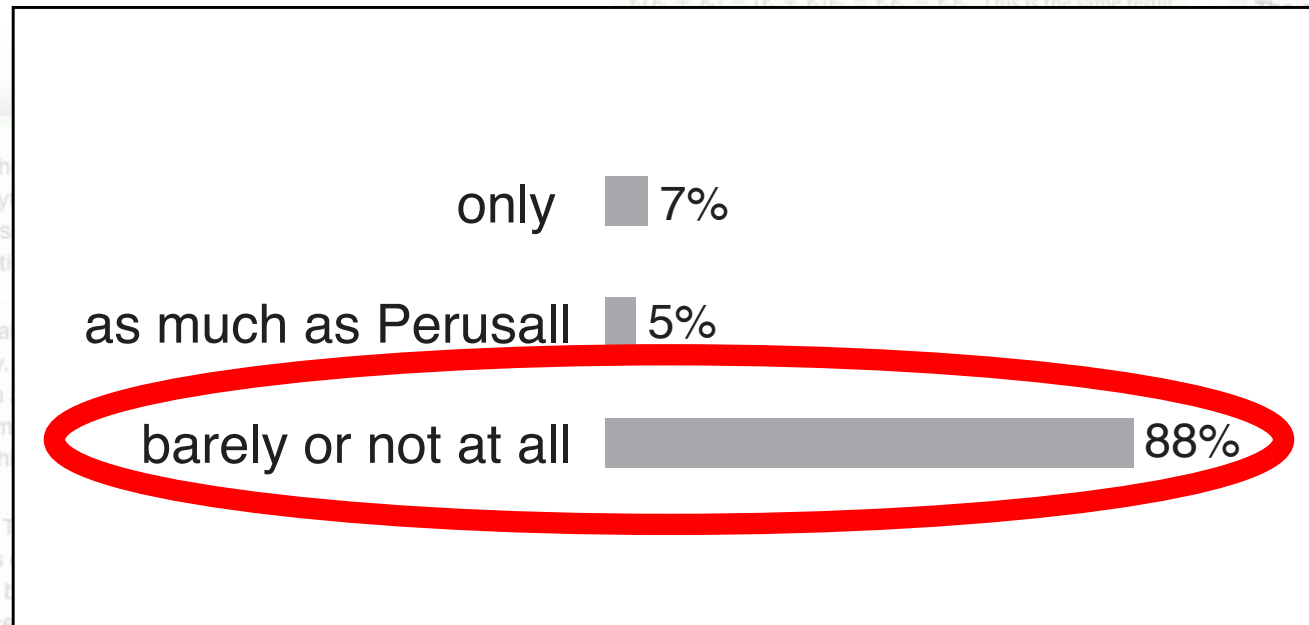
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# current adoption process

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This is a great question. To further elaborate on this, we can think of this in terms of the Torque equation. The equation for torque is  $\tau = r \times F$ , with  $r$  being the level arm distance and  $F$  being force. We know that force is a vector vector from previous chapters, and in regards to "r" it can also be thought of as the radial vector. What this means is that this distance from the pivot points from the axis of rotation to the point where the force acts. In as previously mentioned, there is a general convention (the right-hand rule) that is used to determine the direction which happens to be perpendicular to both the radius from the axis and to the force. Oct 22 8:48 pm +1 🗨️

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(b) Multiply magnitude of  $\vec{F}$  by  $r_{\perp}$ .



lever arm:  
perpendicular distance  
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**12.2** In the situation depicted in Figure 12.2a, you must continue to exert a force on the seesaw to keep the child off the ground. The force you exert causes a torque on the seesaw, and yet the seesaw's rotational acceleration is zero. How can this be if torques cause objects to accelerate rotationally?

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The image shows a screenshot of the Perusall website. At the top, the Perusall logo is visible on the left, and the course information "AP50 Fall 2015" is in the center. The main content area displays a textbook page with a diagram of a lever arm and a force vector. The diagram shows a horizontal rod with a pivot at the left end. A force vector  $\vec{F}$  is applied at a point to the right of the pivot, making an angle  $\theta$  with the horizontal. The lever arm is the perpendicular distance from the pivot to the line of action of the force, labeled  $r_{\perp}$ . The text below the diagram explains that torque is the product of the magnitude of the force and its lever arm distance.

On the right side of the page, there is a list of discussion questions or comments, each with a number in a circle indicating the number of responses. The questions include:

- On the very left, we see th...
- It's interesting that the white ...
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At the bottom of the page, there is a text input field for a comment or question, with the placeholder text "Enter your comment or question and press Enter".

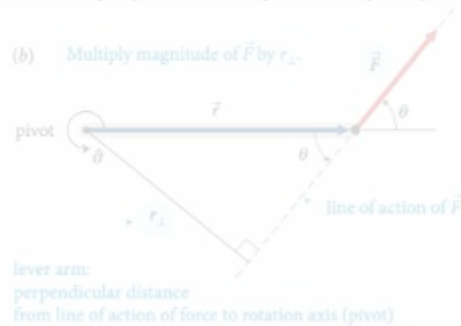


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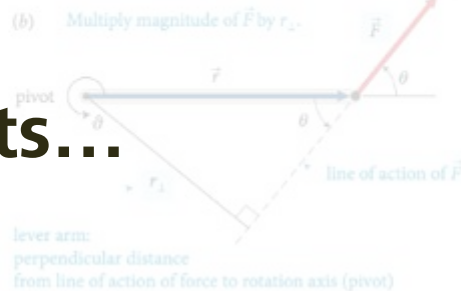
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Students...



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In the situations depicted in Figures 12.4 and 12.5 we used the pivot to calculate the lever arm distances. This is a natural choice because that is the point about which the object under consideration is free to rotate. However, torques also play a role for stationary objects that are suspended or supported at several different points and that are not free to rotate—for example, a plank or bridge supported at either end. To determine what reference point to use in such cases, complete the following exercise.

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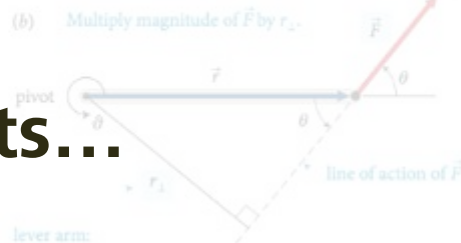
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Students...

- read the textbook



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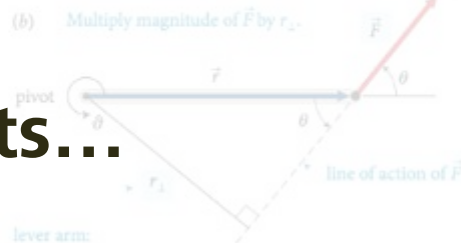
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## Students...

- read the textbook
- learn how to read



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- read the textbook
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**CONCEPT** For a stationary object, the sum of the torques is zero.

For a stationary object we can choose any reference point we like to calculate torques. It pays to choose a reference point that simplifies the calculation. As you have seen, we do not need to consider any force that is exerted at the reference point. So, by putting the reference point at the point of application of a force, we can eliminate that force from the calculation.



**12.2** In the situation depicted in Figure 12.2a, you must continue to exert a force on the seesaw to keep the child off the ground. The force you exert causes a torque on the seesaw, and yet the seesaw's rotational acceleration is zero. How can this be if torques cause objects to accelerate rotationally?

**Example 12.2 Torques on lever**

Three forces are exerted on the lever of Figure 12.7. Forces  $\vec{F}_1$  and  $\vec{F}_2$  are equal in magnitude, and the magnitude of  $\vec{F}_3$  is half as great. Force  $\vec{F}_1$  is horizontal,  $\vec{F}_2$  and  $\vec{F}_3$  are vertical, and the lever makes an angle of  $45^\circ$  with the horizontal. Do these forces cause the lever to rotate about the pivot? If so, in which direction?

## Students...

- read the textbook
- learn how to read
- learn how to read critically
- participate in a collaborative experience

(b) Multiply magnitude of  $\vec{F}$  by  $r_{\perp}$ .



lever arm:  
perpendicular distance  
from line of action of force to rotation axis (pivot)

action of the force and the axis of rotation. So, the torque caused by a force exerted on an object is the product of the magnitude of the force and its lever arm distance. It can be written equivalently as  $rF_{\perp}$  and as  $r_{\perp}F$ .

Lever arm distance also has a sign that depends on the direction of rotation. Increasing  $\theta$ . In Figure 12.4, for example, the torque caused by  $\vec{F}_1$  about the pivot tends to rotate the rod in the direction of increasing  $\theta$  and so is positive; the torque caused by  $\vec{F}_2$  is negative. The sum of the two torques about the pivot is then  $r_1F_1 - r_2F_2$ . As we've seen, the two torques are equal in magnitude when the rod is at rest, so the sum of the torques is zero. When the sum of the torques is not zero, the rod's rotational acceleration is nonzero, and so its rotational velocity and angular momentum change.

In the situations depicted in Figures 12.4 and 12.5 we used the pivot to calculate the lever arm distances. This is a convenient choice because the pivot is the point about which the rod is rotating. It also plays a role for stationary objects that are suspended or supported at several different points and that are not free to rotate—for example, a plank or bridge supported at either end. To determine what reference point to use in such cases, complete the following exercise.

#### Exercise 12.1 Reference point

Consider again the rod in Figure 12.4. Calculate the sum of the torques about the left end of the rod.

**SOLUTION** I begin by making a sketch of the rod and the three forces exerted on it, showing their points of application on the rod (Figure 12.6).

The lever arm distances must now be determined relative to the left end of the rod. The lever arm distance of force  $\vec{F}_1$  to this point is zero, and so the torque caused by that force about the left end of the rod is zero. If I choose counterclockwise as the positive direction of rotation,  $\vec{F}_2$  causes a negative torque about the left end of the rod; the force  $\vec{F}_{pr}$  exerted by the pivot causes a positive torque about the left end of the rod. The lever arm distance of  $\vec{F}_2$  about the left end of the rod is  $r_1 + r_2$ ; that of  $\vec{F}_{pr}$  is  $r_1$ . Because the rod is at rest, the magnitude of the force exerted by the pivot is equal to the sum of the forces  $\vec{F}_1$  and  $\vec{F}_2$ . Taking into account the signs of the torques, we find that the sum of the torques about the left end of the rod is  $r_1(F_1 + F_2) - (r_1 + r_2)F_2 = r_1F_1 - r_2F_2$ . This is the same result we obtained for the torques about the pivot, and so the sum of the torques about the left end is zero. ✓

Exercise 12.1 shows that the sum of the torques about the left end of the rod is zero, just like the sum of the torques about the pivot. You can repeat the calculation for the torques about the right end of the rod or any other point, and each time you will find that the sum of the torques is zero. The reason is that the rod is not rotating about any point, and so the sum of the torques must be zero about any point. In general we can say:

**CONCEPT** For a stationary object, the sum of the torques is zero.

For a stationary object we can choose any reference point we like to calculate torques. It pays to choose a reference point that simplifies the calculation. As you have seen, we do not need to consider any force that is exerted at the reference point. ✓ by putting the reference point at the point of application of a force, we can ignore that force in the calculation.

**12.2** In the situation depicted in Figure 12.2a, you must continue to exert a force on the seesaw to keep the child off the ground. The force you exert causes a torque on the seesaw, and yet the seesaw's rotational acceleration is zero. How can this be if torques cause objects to accelerate rotationally?

#### Example 12.2 Torques on lever

Three forces are exerted on the lever of Figure 12.7. Forces  $\vec{F}_1$  and  $\vec{F}_2$  are equal in magnitude, and the magnitude of  $\vec{F}_3$  is half as great. Force  $\vec{F}_1$  is horizontal,  $\vec{F}_2$  and  $\vec{F}_3$  are vertical, and the lever makes an angle of  $45^\circ$  with the horizontal. Do these forces cause the lever to rotate about the pivot? If so, in which direction?

## Students...

- read the textbook
- learn how to read
- learn how to read critically
- participate in a collaborative experience
- get more out of their classes

(b) Multiply magnitude of  $\vec{F}$  by  $r_{\perp}$ .

lever arm:  
perpendicular distance  
from line of action of force to rotation axis (pivot)

action of the force and the axis of rotation. So, the torque caused by a force exerted on an object is the product of the magnitude of the force and its lever arm distance. It can be written equivalently as  $rF_{\perp}$  and as  $r_{\perp}F$ .

Lever arm distance also has a sign that depends on the direction of rotation. Increasing  $\theta$ . In Figure 12.4, for example, the torque caused by  $\vec{F}_1$  about the pivot tends to rotate the rod in the direction of increasing  $\theta$  and so is positive; the torque caused by  $\vec{F}_2$  is negative. The sum of the two torques about the pivot is then  $r_1F_1 - r_2F_2$ . As we've seen, the two torques are equal in magnitude when the rod is at rest, so the sum of the torques is zero. When the sum of the torques is not zero, the rod's rotational acceleration is nonzero, and so its rotational velocity and angular momentum change.

In the situations depicted in Figures 12.4 and 12.5 we used the pivot to calculate the lever arm distances. This is a convenient choice because the rod is at rest about the pivot. Lever arm distances also play a role for stationary objects that are suspended or supported at several different points and that are not free to rotate—for example, a plank or bridge supported at either end. To determine what reference point to use in such cases, complete the following exercise.

**Exercise 12.1 Reference point**

Consider again the rod in Figure 12.4. Calculate the sum of the torques about the left end of the rod.

**SOLUTION** I begin by making a sketch of the rod and the three forces exerted on it, showing their points of application on the rod (Figure 12.6).

The lever arm distances must now be determined relative to the left end of the rod. The lever arm distance of force  $\vec{F}_1$  to this point is zero, and so the torque caused by that force about the left end of the rod is zero. If I choose counterclockwise as the positive direction of rotation,  $\vec{F}_2$  causes a negative torque about the left end of the rod; the force  $\vec{F}_{pr}$  exerted by the pivot causes a positive torque about the left end of the rod. The lever arm distance of  $\vec{F}_2$  about the left end of the rod is  $r_1 + r_2$ ; that of  $\vec{F}_{pr}$  is  $r_1$ . Because the rod is at rest, the magnitude of the force exerted by the pivot is equal to the sum of the forces  $\vec{F}_1$  and  $\vec{F}_2$ . Taking into account the signs of the torques, we find that the sum of the torques about the left end of the rod is  $r_1(F_1 + F_2) - (r_1 + r_2)F_2 = r_1F_1 - r_2F_2$ . This is the same result we obtained for the torques about the pivot, and so the sum of the torques about the left end is zero. ✓

Exercise 12.1 shows that the sum of the torques about the left end of the rod is zero, just like the sum of the torques about the pivot. You can repeat the calculation for the torques about the right end of the rod or any other point, and each time you will find that the sum of the torques is zero. The reason is that the rod is not rotating about any point, and so the sum of the torques must be zero about any point. In general we can say:

**For a stationary object, the sum of the torques is zero.**

For a stationary object we can choose any reference point we like to calculate torques. It pays to choose a reference point that simplifies the calculation. As you have seen, we do not need to consider any force that is exerted at the reference point. ✓ by putting the reference point at the point where the force is exerted, we can ignore that force in the calculation.



**12.2** In the situation depicted in Figure 12.2a, you must continue to exert a force on the seesaw to keep the child off the ground. The force you exert causes a torque on the seesaw, and yet the seesaw's rotational acceleration is zero. How can this be? Can the seesaw accelerate rotationally?

**Example 12.2 Torques on lever**

Three forces are exerted on the lever of Figure 12.7. Forces  $\vec{F}_1$  and  $\vec{F}_2$  are equal in magnitude, and the magnitude of  $\vec{F}_3$  is half as great. Force  $\vec{F}_1$  is horizontal,  $\vec{F}_2$  and  $\vec{F}_3$  are vertical, and the lever makes an angle of  $45^\circ$  with the horizontal. Do these forces cause the lever to rotate about the pivot? If so, in which direction?

Students...

- read the textbook
- learn how to read
- learn how to read critically
- learn how to study and work collaboratively
- get more out of their classes

(b) Multiply magnitude of  $\vec{F}$  by  $r_{\perp}$ .



lever arm:  
perpendicular distance  
from line of action of force to rotation axis (pivot)

action of the force and the axis of rotation. The torque caused by a force exerted on an object is the product of the magnitude of the force and the lever arm. It is written as  $\tau = r_{\perp} F$ . The lever arm  $r_{\perp}$  depends on the angle  $\theta$  between the force and the rod. Figure 12.4 shows a rod pivoted at the left end. The torque caused by  $\vec{F}_1$  about the pivot tends to rotate the rod in the direction of increasing  $\theta$ , and so it is positive. The torque caused by  $\vec{F}_2$  is negative, and so the sum of the two torques about the pivot is then  $\tau = r_1 F_1 - r_2 F_2$ . As we've seen, the two torques are equal in magnitude, so the sum of the two torques is zero. When the sum of the torques is not zero, the rod's rotational acceleration is nonzero, and so its rotational velocity and angular momentum change.

In the situations depicted in Figures 12.4 and 12.5 we used the pivot to calculate the lever arm distance. This is a natural choice because it is the point about which the rod rotates. In situations where the rod is supported at several different points and that are free to rotate—for example, a plank or bridge supported at either end. To determine what reference point to use in such cases, complete the following exercise.

#### Exercise 12.1 Reference point

Consider again the rod in Figure 12.4. Calculate the sum of the torques about the left end of the rod.

**SOLUTION** I begin by making a sketch of the rod and the three forces exerted on it, showing their points of application on the rod (Figure 12.6).

The lever arm distances must now be determined relative to the left end of the rod. The lever arm distance of force  $\vec{F}_1$  about this point is zero, and so the torque caused by that force about the left end of the rod is zero. If I choose counterclockwise as the positive direction of rotation,  $\vec{F}_2$  causes a negative torque about the left end of the rod; the force  $\vec{F}_3$  causes a positive torque about the left end of the rod. The lever arm distance of  $\vec{F}_2$  about the left end of the rod is  $r_2$ , and the lever arm distance of  $\vec{F}_3$  about the left end of the rod is  $r_3$ . Because the forces  $\vec{F}_2$  and  $\vec{F}_3$  are perpendicular to the rod, the lever arm distances are  $r_2$  and  $r_3$ , respectively. The torque caused by  $\vec{F}_2$  about the left end of the rod is  $\tau_2 = -r_2 F_2$ , and the torque caused by  $\vec{F}_3$  about the left end of the rod is  $\tau_3 = r_3 F_3$ . The sum of the torques about the left end of the rod is  $\tau = \tau_2 + \tau_3 = -r_2 F_2 + r_3 F_3$ . Because  $r_3 F_3 = r_2 F_2$ , the sum of the torques about the left end of the rod is zero.

Exercise 12.1 shows that the sum of the torques about the left end of the rod is zero, just like the sum of the torques about the pivot. You can repeat the calculation for the torques about the right end of the rod or any other point, and each time you will find that the sum of the torques is zero. The reason is that the rod is not rotating about any point, and so the sum of the torques must be zero about any point. This is a general result that we can state as follows:

**Principle of Torques:** If the sum of the torques about any reference point is zero, then the sum of the torques about any other reference point is also zero. It pays to choose a reference point that makes the calculation easiest. As you have seen, we often choose the pivot as the reference point. In situations where the rod is supported at several different points and that are free to rotate—for example, a plank or bridge supported at either end. To determine what reference point to use in such cases, complete the following exercise.

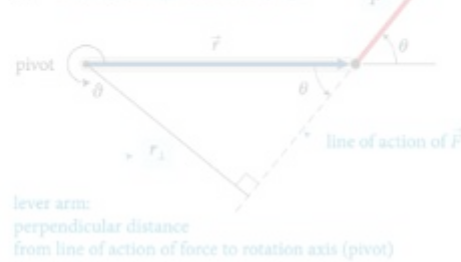
**12.2** In the situation depicted in Figure 12.2a, you must continue to exert a force on the seesaw to keep the child off the ground. The force you exert causes a torque on the seesaw, and yet the seesaw's rotational acceleration is zero. How can this be? How can the seesaw be in equilibrium and yet not accelerate rotationally?

#### Example 12.2 Torques on lever

Three forces are exerted on the lever of Figure 12.7. Forces  $\vec{F}_1$  and  $\vec{F}_2$  are equal in magnitude, and the magnitude of  $\vec{F}_3$  is half as great. Force  $\vec{F}_1$  is horizontal,  $\vec{F}_2$  and  $\vec{F}_3$  are vertical, and the lever makes an angle of  $45^\circ$  with the horizontal. Do these forces cause the lever to rotate about the pivot? If so, in which direction?



(b) Multiply magnitude of  $\vec{F}$  by  $r_{\perp}$ .



action of the force and the axis of rotation. So, the torque caused by a force exerted on an object is the product of the magnitude of the force and its lever arm distance. It can be written equivalently as  $rF_{\perp}$  and as  $r_{\perp}F$ .

Like other rotational quantities, torque carries a sign that depends on the choice of direction for increasing  $\vartheta$ . In Figure 12.4, for example, the torque caused by  $\vec{F}_1$  about the pivot tends to rotate the rod in the direction of increasing  $\vartheta$  and so is positive; the torque caused by  $\vec{F}_2$  is negative. The sum of the two torques about the pivot is then  $r_1F_1 + (-r_2F_2)$ . As we've seen, the two torques are equal in magnitude when the rod is balanced, and so the sum of the torques is zero. When the sum of the torques is not zero, the rod's rotational acceleration is nonzero, and so its rotational velocity and angular momentum change.

In the situations depicted in Figures 12.4 and 12.5 we used the pivot to calculate the lever arm distances. This is a natural choice because that is the point about which the object under consideration is free to rotate. However, torques also play a role for stationary objects that are suspended or supported at several different points and that are not free to rotate—for example, a plank or bridge supported at either end. To determine what reference point to use in such cases, complete the following exercise.

#### Exercise 12.1 Reference point

Consider again the rod in Figure 12.4. Calculate the sum of the torques about the left end of the rod.

**SOLUTION** I begin by making a sketch of the rod and the three forces exerted on it, showing their points of application on the rod (Figure 12.6).

The lever arm distances must now be determined relative to the left end of the rod. The lever arm distance of force  $\vec{F}_1$  to this point is zero, and so the torque caused by that force about the left end of the rod is zero. If I choose counterclockwise as the positive direction of rotation,  $\vec{F}_2$  causes a negative torque about the left end of the rod; the force  $\vec{F}_{\text{pr}}$  exerted by the pivot causes a positive torque about the left end of the rod. The lever arm distance of  $\vec{F}_2$  about the left end of the rod is  $r_1 + r_2$ ; that of  $\vec{F}_{\text{pr}}$  is  $r_1$ . Because the rod is at rest, the magnitude of the force exerted by the pivot is equal to the sum of the forces  $\vec{F}_1$  and  $\vec{F}_2$ . Taking into account the signs of the torques, we find that the sum of the torques about the left end of the rod is  $r_1(F_1 + F_2) - (r_1 + r_2)F_2 = r_1F_1 - r_2F_2$ . This is the same result we obtained for the torques about the pivot, and so the sum of the torques about the left end is zero. ✓

Exercise 12.1 shows that the sum of the torques about the left end of the rod is zero, just like the sum of the torques about the pivot. You can repeat the calculation for the torques about the right end of the rod or any other point, and each time you will find that the sum of the torques is zero. The reason is that the rod is not rotating about any point, and so the sum of the torques must be zero about any point. In general we can say:

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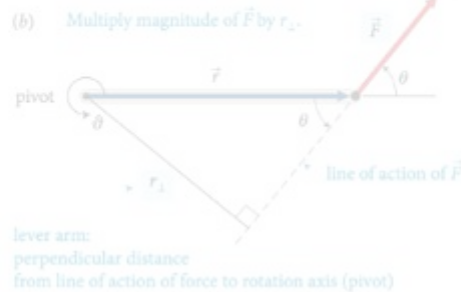
For a stationary object we can choose any reference point we like to calculate torques. It pays to choose a reference point that simplifies the calculation. As you have seen, we do not need to consider any force that is exerted at the reference point. So, by putting the reference point at the point of application of a force, we can eliminate that force from the calculation.



**12.2** In the situation depicted in Figure 12.2a, you must continue to exert a force on the seesaw to keep the child off the ground. The force you exert causes a torque on the seesaw, and yet the seesaw's rotational acceleration is zero. How can this be if torques cause objects to accelerate rotationally?

#### Example 12.2 Torques on lever

Three forces are exerted on the lever of Figure 12.7. Forces  $\vec{F}_1$  and  $\vec{F}_2$  are equal in magnitude, and the magnitude of  $\vec{F}_3$  is half as great. Force  $\vec{F}_1$  is horizontal,  $\vec{F}_2$  and  $\vec{F}_3$  are vertical, and the lever makes an angle of  $45^\circ$  with the horizontal. Do these forces cause the lever to rotate about the pivot? If so, in which direction?



- time recovery

action of the force and the axis of rotation. So, the torque caused by a force exerted on an object is the product of the magnitude of the force and its lever arm distance. It can be written equivalently as  $rF_{\perp}$  and as  $r_{\perp}F$ .

Like other rotational quantities, torque carries a sign that depends on the choice of direction for increasing  $\vartheta$ . In Figure 12.4, for example, the torque caused by  $\vec{F}_1$  about the pivot tends to rotate the rod in the direction of increasing  $\vartheta$  and so is positive; the torque caused by  $\vec{F}_2$  is negative. The sum of the two torques about the pivot is then  $r_1F_1 + (-r_2F_2)$ . As we've seen, the two torques are equal in magnitude when the rod is balanced, and so the sum of the torques is zero. When the sum of the torques is not zero, the rod's rotational acceleration is nonzero, and so its rotational velocity and angular momentum change.

In the situations depicted in Figures 12.4 and 12.5 we used the pivot to calculate the lever arm distances. This is a natural choice because that is the point about which the object under consideration is free to rotate. However, torques also play a role for stationary objects that are suspended or supported at several different points and that are not free to rotate—for example, a plank or bridge supported at either end. To determine what reference point to use in such cases, complete the following exercise.

#### Exercise 12.1 Reference point

Consider again the rod in Figure 12.4. Calculate the sum of the torques about the left end of the rod.

**SOLUTION** I begin by making a sketch of the rod and the three forces exerted on it, showing their points of application on the rod (Figure 12.6).

The lever arm distances must now be determined relative to the left end of the rod. The lever arm distance of force  $\vec{F}_1$  to this point is zero, and so the torque caused by that force about the left end of the rod is zero. If I choose counterclockwise as the positive direction of rotation,  $\vec{F}_2$  causes a negative torque about the left end of the rod; the force  $\vec{F}_{pr}$  exerted by the pivot causes a positive torque about the left end of the rod. The lever arm distance of  $\vec{F}_2$  about the left end of the rod is  $r_1 + r_2$ ; that of  $\vec{F}_{pr}$  is  $r_1$ . Because the rod is at rest, the magnitude of the force exerted by the pivot is equal to the sum of the forces  $\vec{F}_1$  and  $\vec{F}_2$ . Taking into account the signs of the torques, we find that the sum of the torques about the left end of the rod is  $r_1(F_1 + F_2) - (r_1 + r_2)F_2 = r_1F_1 - r_2F_2$ . This is the same result we obtained for the torques about the pivot, and so the sum of the torques about the left end is zero. ✓

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#### Example 12.2 Torques on lever

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(b) Multiply magnitude of  $\vec{F}$  by  $r_{\perp}$ .



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action of the force and the axis of rotation. So, the torque caused by a force exerted on an object is the product of the magnitude of the force and its lever arm distance. It can be written equivalently as  $rF$ , and as  $r_{\perp}F$ .

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#### Exercise 12.1 Reference point

Consider again the rod in Figure 12.4. Calculate the sum of the torques about the left end of the rod.

**SOLUTION** I begin by making a sketch of the rod and the three forces exerted on it, showing their points of application on the rod (Figure 12.6).

$\vec{F}_1$

The lever arm distances must now be determined relative to the left end of the rod. The lever arm distance of force  $\vec{F}_1$  to this point is zero, and so the torque caused by that force about the left end of the rod is zero. If I choose counterclockwise as the positive direction of rotation,  $\vec{F}_2$  causes a negative torque about the left end of the rod; the force  $\vec{F}_{pr}$  exerted by the pivot causes a positive torque about the left end of the rod. The lever arm distance of  $\vec{F}_2$  about the left end of the rod is  $r_1 + r_2$ ; that of  $\vec{F}_{pr}$  is  $r_1$ . Because the rod is at rest, the magnitude of the force exerted by the pivot is equal to the sum of the forces  $\vec{F}_1$  and  $\vec{F}_2$ . Taking into account the signs of the torques, we find that the sum of the torques about the left end of the rod is  $r_1(F_1 + F_2) - (r_1 + r_2)F_2 = r_1F_1 - r_2F_2$ . This is the same result we obtained for the torques about the pivot, and so the sum of the torques about the left end is zero. ✓

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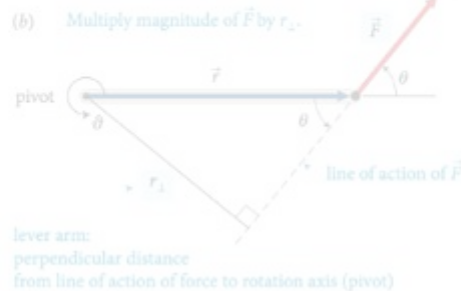


**12.2** In the situation depicted in Figure 12.2a, you must continue to exert a force on the seesaw to keep the child off the ground. The force you exert causes a torque on the seesaw, and yet the seesaw's rotational acceleration is zero. How can this be if torques cause objects to accelerate rotationally?

#### Example 12.2 Torques on lever

Three forces are exerted on the lever of Figure 12.7. Forces  $\vec{F}_1$  and  $\vec{F}_2$  are equal in magnitude, and the magnitude of  $\vec{F}_3$  is half as great. Force  $\vec{F}_1$  is horizontal,  $\vec{F}_2$  and  $\vec{F}_3$  are vertical, and the lever makes an angle of  $45^\circ$  with the horizontal. Do these forces cause the lever to rotate about the pivot? If so, in which direction?

- time recovery
- improved use of class time



- time recovery

- improved use of class time

- enhanced respect and understanding for students

action of the force and the axis of rotation. So, the torque caused by a force exerted on an object is the product of the magnitude of the force and its lever arm distance. It can be written equivalently as  $rF$ , and as  $r_{\perp}F$ . The torque depends on the point of application of the force, the direction of the force, and the direction of rotation. In Figure 12.4, for example, the torque caused by  $\vec{F}_1$  about the pivot tends to rotate the rod in the direction of increasing  $\theta$  and so is positive; the torque caused by  $\vec{F}_2$  is negative. The sum of the two torques about the pivot is then  $r_1F_1 + (-r_2F_2)$ . We've seen that the two torques are equal in magnitude, so the sum of the torques is zero. When the sum of the torques is not zero, the rod's rotational acceleration is nonzero, and so its rotational velocity and angular momentum change.

In the situations depicted in Figures 12.4 and 12.5 we used the pivot to calculate the lever arm distances. This is a natural choice because that is the point about which the object under consideration is free to rotate. However, torques also play a role for stationary objects that are suspended or supported at several different points and that are not free to rotate—for example, a plank or bridge supported at either end. To determine what reference point to use in such cases, complete the following exercise.

#### Exercise 12.1 Reference point

Consider again the rod in Figure 12.4. Calculate the sum of the torques about the left end of the rod.

**SOLUTION** I begin by making a sketch of the rod and the three forces exerted on it, showing their points of application on the rod (Figure 12.6).

The lever arm distances must now be determined relative to the left end of the rod. The lever arm distance of force  $\vec{F}_1$  to this point is zero, and so the torque caused by that force about the left end of the rod is zero. If I choose counterclockwise as the positive direction of rotation,  $\vec{F}_2$  causes a negative torque about the left end of the rod; the force  $\vec{F}_{\text{pr}}$  exerted by the pivot causes a positive torque about the left end of the rod. The lever arm distance of  $\vec{F}_2$  about the left end of the rod is  $r_1 + r_2$ ; that of  $\vec{F}_{\text{pr}}$  is  $r_1$ . Because the rod is at rest, the magnitude of the force exerted by the pivot is equal to the sum of the forces  $\vec{F}_1$  and  $\vec{F}_2$ . Taking into account the signs of the torques, we find that the sum of the torques about the left end of the rod is  $r_1(F_1 + F_2) - (r_1 + r_2)F_2 = r_1F_1 - r_2F_2$ . This is the same result we obtained for the torques about the pivot, and so the sum of the torques about the left end is zero. ✓

Exercise 12.1 shows that the sum of the torques about the left end of the rod is zero, just like the sum of the torques about the pivot. You can repeat the calculation for the torques about the right end of the rod or any other point, and each time you will find that the sum of the torques is zero. The reason is that the rod is not rotating about any point, and so the sum of the torques must be zero about any point. In general, we can say:

For a stationary object we can choose any reference point we like to calculate torques. It pays to choose a reference point that simplifies the calculation. As you have seen, we do not need to consider any force that is exerted at the reference point. So, by putting the reference point at the point of application of a force, we can eliminate that force from the calculation.

**12.2** In the situation depicted in Figure 12.2a, you must continue to exert a force on the seesaw to keep the child off the ground. The force you exert causes a torque on the seesaw, and yet the seesaw's rotational acceleration is zero. How can this be if torques cause objects to accelerate rotationally?

#### Example 12.2 Torques on lever

Three forces are exerted on the lever of Figure 12.7. Forces  $\vec{F}_1$  and  $\vec{F}_2$  are equal in magnitude, and the magnitude of  $\vec{F}_3$  is half as great. Force  $\vec{F}_1$  is horizontal,  $\vec{F}_2$  and  $\vec{F}_3$  are vertical, and the lever makes an angle of  $45^\circ$  with the horizontal. Do these forces cause the lever to rotate about the pivot? If so, in which direction?

(b) Multiply magnitude of  $\vec{F}$  by  $r_{\perp}$ .



lever arm:  
perpendicular distance  
from line of action of force to rotation axis (pivot)

action of the force and the axis of rotation. So, the torque caused by a force exerted on an object is the product of the magnitude of the force and its lever arm distance. It can be written equivalently as  $rF$ , and as  $r_{\perp}F$ . The torque depends on the angle between the force and the rod. In Figure 12.4, for example, the torque caused by  $\vec{F}_1$  about the pivot tends to rotate the rod in the direction of increasing  $\theta$  and so is positive; the torque caused by  $\vec{F}_2$  is negative. The sum of the two torques about the pivot is then  $r_1F_1 + (-r_2F_2)$ . We've seen that the two torques are equal in magnitude, so the sum of the torques is zero. When the sum of the torques is not zero, the rod's rotational acceleration is nonzero, and so its rotational velocity and angular momentum change.

In the situations depicted in Figures 12.4 and 12.5 we used the pivot to calculate the lever arm distances. This is a natural choice because that is the point about which the object under consideration is free to rotate. However, torques also play a role for stationary objects that are suspended or supported at several different points and that are free to rotate about any of them. For example, you can hang a rod from either end. To determine what reference point to use in such cases, complete the following exercise.

#### Exercise 12.1 Reference point

Consider again the rod in Figure 12.4. Calculate the sum of the torques about the left end of the rod.

**SOLUTION** I begin by making a sketch of the rod and the three forces exerted on it, showing their points of application on the rod (Figure 12.6).

$\vec{F}_1$

The lever arm distances must now be determined relative to the left end of the rod. The lever arm distance of force  $\vec{F}_1$  to this point is zero, and so the torque caused by that force about the left end of the rod is zero. If I choose counterclockwise as the positive direction of rotation,  $\vec{F}_2$  causes a negative torque about the left end of the rod; the force  $\vec{F}_{pr}$  exerted by the pivot causes a positive torque about the left end of the rod. The lever arm distance of  $\vec{F}_2$  about the left end of the rod is  $r_1 + r_2$ ; that of  $\vec{F}_{pr}$  is  $r_1$ . Because the rod is at rest, the magnitude of the force exerted by the pivot is equal to the sum of the forces  $\vec{F}_1$  and  $\vec{F}_2$ . Taking into account the signs of the torques, we find that the sum of the torques about the left end of the rod is  $r_1(F_1 + F_2) - (r_1 + r_2)F_2 = r_1F_1 - r_2F_2$ . This is the same result we obtained for the torques about the pivot, and so the sum of the torques about the left end is zero. ✓

Exercise 12.1 shows that the sum of the torques about the left end of the rod is zero, just like the sum of the torques about the pivot. You can repeat the calculation for the torques about the right end of the rod or any other point, and each time you will find that the sum of the torques is zero. The reason is that the rod is not rotating about any point, and so the sum of the torques must be zero about any point. In general, we can say:

For a stationary object we can choose any reference point we like to calculate torques. It pays to choose a reference point that simplifies the calculation. As you have seen, we do not need to consider any force that is exerted at the reference point. So, by putting the reference point at the point of application of a force, we can eliminate that force from the calculation.

**Example 12.2** Torques on lever  
A child sits on a seesaw that is pivoted to the ground. The force you exert causes a torque on the seesaw, and yet the seesaw's rotational acceleration is zero. How can this be if torques cause objects to accelerate rotationally?

#### Example 12.2 Torques on lever

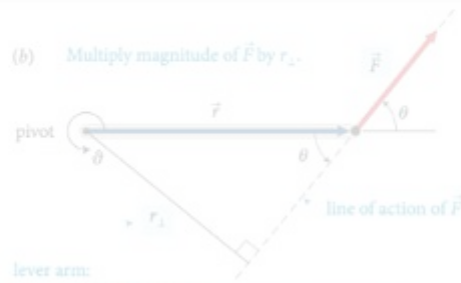
Three forces are exerted on the lever of Figure 12.7. Forces  $\vec{F}_1$  and  $\vec{F}_2$  are equal in magnitude, and the magnitude of  $\vec{F}_3$  is half as great. Force  $\vec{F}_1$  is horizontal,  $\vec{F}_2$  and  $\vec{F}_3$  are vertical, and the lever makes an angle of  $45^\circ$  with the horizontal. Do these forces cause the lever to rotate about the pivot? If so, in which direction?

- time recovery
- improved use of class time
- enhanced respect and understanding for students

CONCEPTS

**all at no cost & no additional effort!**

(b) Multiply magnitude of  $\vec{F}$  by  $r_{\perp}$ .



lever arm:  
perpendicular distance  
from line of action of force to rotation axis (pivot)

action of the force and the axis of rotation. So, the torque caused by a force exerted on an object is the product of the magnitude of the force and its lever arm distance. It can be written equivalently as  $rF_{\perp}$  and as  $r_{\perp}F$ .

Like other rotational quantities, torque carries a sign that depends on the choice of direction for increasing  $\vartheta$ . In Figure 12.4, for example, the torque caused by  $\vec{F}_1$  about the pivot tends to rotate the rod in the direction of increasing  $\vartheta$  and so is positive; the torque caused by  $\vec{F}_2$  is negative. The sum of the two torques about the pivot is then  $r_1F_1 + (-r_2F_2)$ . As we've seen, the two torques are in opposite directions, so the sum is zero. The rod will not rotate, and its rotational velocity and angular momentum change.

In the situations depicted in Figures 12.4 and 12.5 we used the pivot to calculate the lever arm distances. This is a natural choice because that is the point about which the object under consideration is free to rotate. However, torques also play a role for stationary objects that are suspended or supported at several different points and that are not free to rotate—for example, a plank or bridge supported at either end. To determine what reference point to use in such cases, complete the following exercise.

#### Exercise 12.1 Reference point

Consider again the rod in Figure 12.4. Calculate the sum of the torques about the left end of the rod.

**SOLUTION** I begin by making a sketch of the rod and the three forces exerted on it, showing their points of application on the rod (Figure 12.6).

reference point



The lever arm distances must now be determined relative to the left end of the rod. The lever arm distance of force  $\vec{F}_1$  to this point is zero, and so the torque caused by that force about the left end of the rod is zero. If I choose counterclockwise as the positive direction of rotation,  $\vec{F}_2$  causes a negative torque about the left end of the rod; the force  $\vec{F}_{\text{pr}}$  exerted by the pivot causes a positive torque about the left end of the rod. The lever arm distance of  $\vec{F}_2$  about the left end of the rod is  $r_1 + r_2$ ; that of  $\vec{F}_{\text{pr}}$  is  $r_1$ . Because the rod is at rest, the magnitude of the force exerted by the pivot is equal to the sum of the forces  $\vec{F}_1$  and  $\vec{F}_2$ . Taking into account the signs of the torques, we find that the sum of the torques about the left end of the rod is  $F_2(r_1 + r_2) - (F_1 + F_2)r_1$ . We obtained the torques about the pivot, and so the sum of the torques about the left end is zero. ✓

Exercise 12.1 shows that the sum of the torques about the left end of the rod is zero, just like the sum of the torques about the pivot. You can repeat the calculation for the torques about the right end of the rod or any other point, and each time you will find that the sum of the torques is zero. The reason is that the rod is not rotating about any point, and so the sum of the torques must be zero about any point. In general we can say:

The sum of the torques about any point is zero. This is true for any object that is not rotating. We like to calculate torques. It pays to choose a reference point that simplifies the calculation. As you have seen, we do not need to consider any force that is exerted at the reference point. So, by putting the reference point at the point of application of a force, we can eliminate that force from the calculation.



**12.2** In the situation depicted in Figure 12.2a, you must continue to exert a force on the seesaw to keep the child off the ground. The force you exert causes a torque on the seesaw, and yet the seesaw's rotational acceleration is zero. How can this be if torques cause objects to accelerate rotationally?

#### Example 12.2 Torques on lever

Three forces are exerted on the lever of Figure 12.7. Forces  $\vec{F}_1$  and  $\vec{F}_2$  are equal in magnitude, and the magnitude of  $\vec{F}_3$  is half as great. Force  $\vec{F}_1$  is horizontal,  $\vec{F}_2$  and  $\vec{F}_3$  are vertical, and the lever makes an angle of  $45^\circ$  with the horizontal. Do these forces cause the lever to rotate about the pivot? If so, in which direction?

# follow up questions?

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