

Innovating Education to Educate Innovators



@eric_mazur

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New York, NY, 1 March 2016







What are the following...
1. Personal...
2. The...
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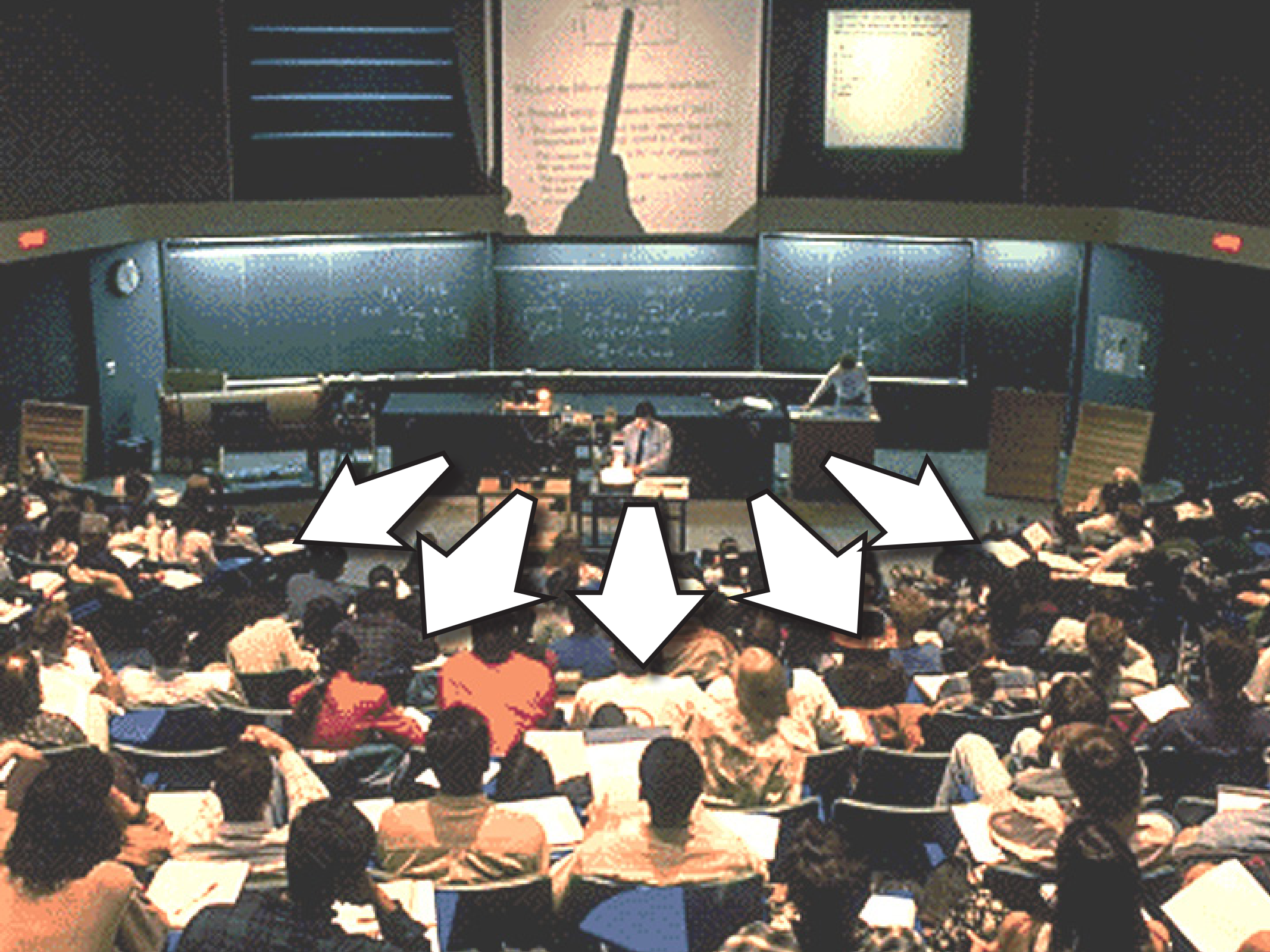
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What are the following...
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annū regni sedechie. Mēse autē quarto nona die mensis obtinuit famulo civitatem: et non erat alimenta ipso tere. Et dirupta ē civitas. et omnes viri belatores eius fugerūt: egredietur de civitate nocte per viam porte que est inter duos muros et ducit ad ortū regis: caldeis obsidentibus urbem in giro: et abierūt per viā que ducit in hecenu. Persecutus est autē caldeoꝝ exercitus regni: et apprehenderūt sedechiā in deserto quō est iuxta ihericho: et omnes comitatus eius diffugerūt ab eo. Lūq; comprehenderūt regem adduxerunt eum ad regem babilonis in reblatha que est in terra emath: et locutus est ad eū iudicia. Et ingulavit regē babilonis filios sedechie in oculis eius: sed et omnes principes iuda occidit in reblatha. Et oculos sedechie tenuit: et vinxit eum in compedibus. Et adduxit eū regē babilonis in babilonem: et posuit eū in domo carceris usq; ad diē mortis eius. In mense autē quinto decima mēsis ipse est annus decimus nonus nabuchodonosor regis babilonis: venit nabuzardan princeps milite qui stabat coram rege babilonis in iherusalem: et incendit domū domini et domū regis et omnes domū iherusalem: et omne domū magnā igne combussit: et totum murū iherusalem per circuitū destruxit cunctos exercitus caldeoꝝ qui erant cum magistro milite. De pauperibus autē ipse et de reliquo vulgo quod remanserat in civitate et de presugis quę transfugerant ad regem babilonis et ceteros de multitudine. transtulit nabuzardan princeps milite: de pauperibus vero tere reliquit nabuzardan princeps milite vinicos et agricolas. Columnas quoq; teras que erant in

domo domini et bases et mare intum quod erat in domo domini confecerunt caldei: et tulerūt omne eis in babilonē. Et tulerūt et creagrās et psalteria et kalas et mortariola et oia vasa tera quę in ministerio fuerāt tulerūt: et ydrias et thinniamarcia et urceos et plures et cādabra et mortaria et cratos. Quorū quę aurea aurea: et quę argēta argēta. Tulit magister milite columnas duas et mare unū et vitulos duodecim teras quę erāt sub basibus: quę fecerat rex salomō in domo dñi. Quę erāt pōd⁹ teras oim vasoy ipse. De columnis autē: decē et octo cubiti altitudinis erāt et columna una: et funicul⁹ duodecim cubitoꝝ circumbar eā. Porro prostranda erāt quę digitoꝝ: et intinētes: tava erāt: et capitella super utraq; tera. Altitudo capitelli un⁹ quinq; cubitoꝝ: et retiacia et malagranata supra coronā in circuitū: omnia emea. Et fuerūt malagranata nonagitate dependētia: et omnia malagranata circum retiacis circumdabant. Et tulit magister milite saraiam sacerdotem primū: et sophoniam sacerdotē secundū: et ceteros custodes vestibuli. Et de civitate tulit eunuchū unū quę erāt iposus super viros bellatores: et septē viros de hys quę videbāt faciem regis quę inveniūt in civitate: et scribā principē militū quę pbatat tyrones: et septē viros de ipso tere qui inveniūt in medio civitatis. Tulit autē eos nabuzardan magister milite: et duxit eos ad regē babilonis in reblatha. Et percussit eos rex babilonis: et interfecit eos in reblatha in terra emath. Et trāllat⁹ ē iuda de terra sua. Ipse ē ipse quę trāstulit nabuchodonosor i anno septimo: iudos tria milia et viginti tres. In anno octavo decimo nabuchodonosor trāstulit de iherusalem aīas odigēta triginta duas.

In anno vice simo teras nabuchodonosor trāstulit nabuzardan magister milite animas iudicoꝝ septingentas quadraginta quinq;. Vires ergo anime: quatuor milia septem. Et factum est in vice simo primo anno trāmigrationis ioachim regis iuda duodecimo mense vice sima quinta mēsis elevarūt eunuchos rex babilonis ipso anno regni sui caput ioachim regis iude. et duxit eum de domo carceris: et locutus est cum eo bona. Et posuit thronū eius super thronos regum qui erant post se in babilonē: et morabatur panem coram eo semp cunctis diebus vite sue. Et cibaria eius cibaria perpetua dabatur ei a rege babilonis statuta per singulos dies: usq; ad diē mortis sue cunctis diebus vite eius.

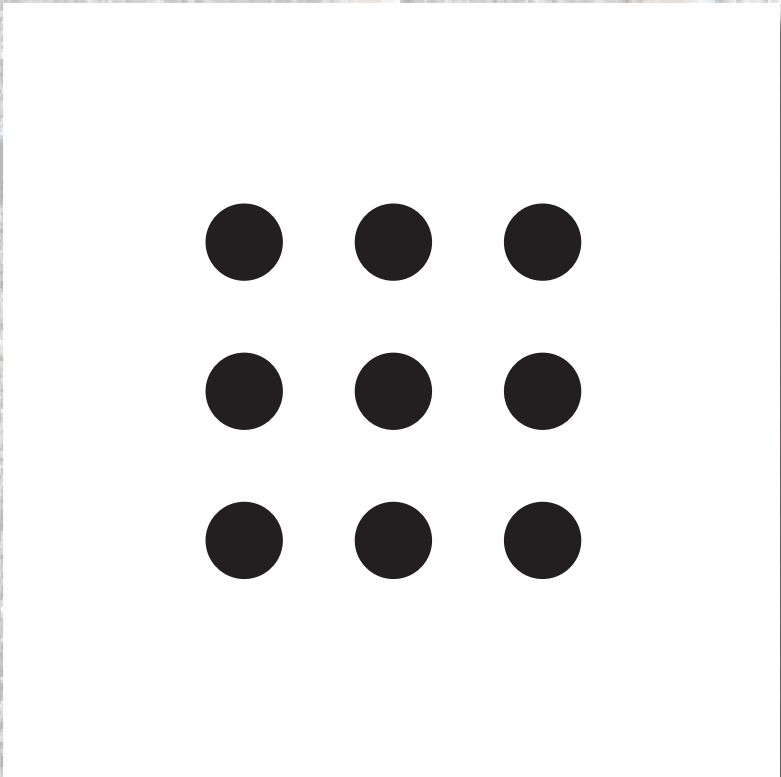
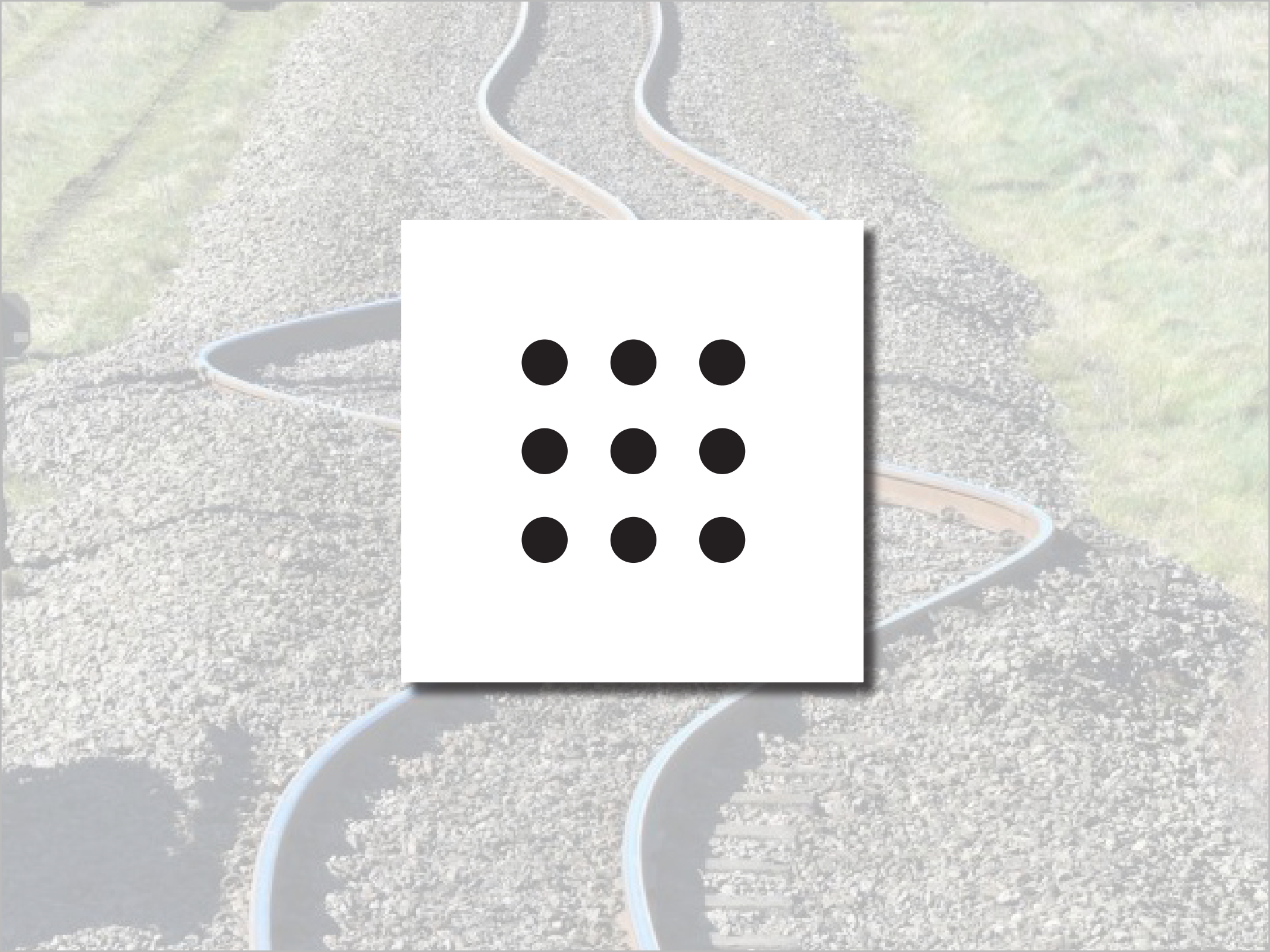
Et mēta cōs iheric

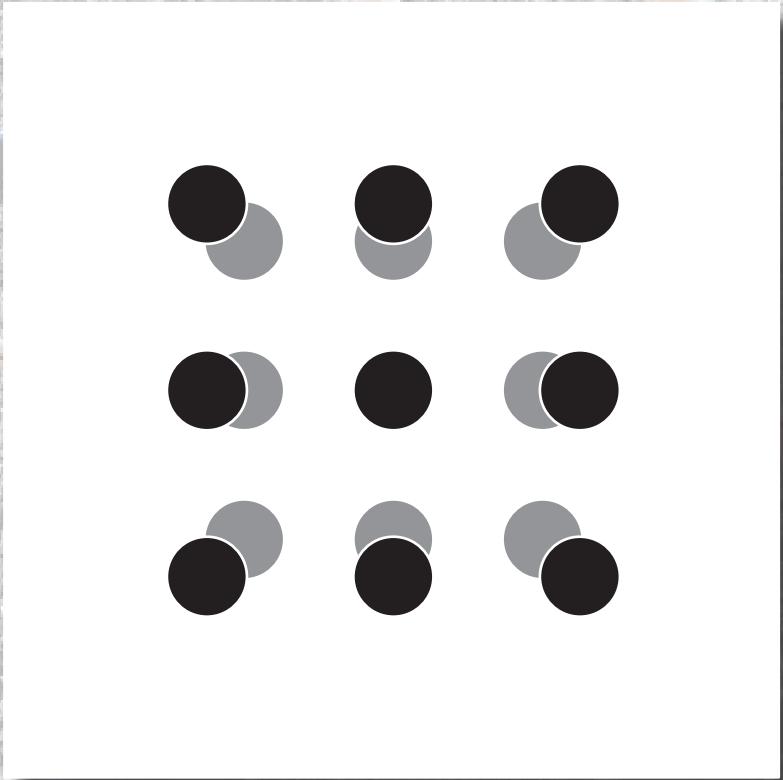
Q factum ē postq; in captivitate redactus est israhel et iherusalem deserta est: sedit iheremias propheta fletus et plāxit lamento hęc in iherusalem: et amaro animo suspiras et eulās dixit. **Aleph** Quomodo sedet sola civitas plena ipso. facta est sicut vidua domina gentū: princeps punitas facta est sub tributo. **Beth** Plorans ploravit in nocte: et lacrimę eius in maxillis eius. Non est qui consolatur eam: et omnibus caris eius. Omnes amici eius spererūt eā: et facti sunt ei inimici. **Gmel** Migravit iudas propter afflictionē et multitudinē servitutis. Habitavit inter gentes: nec invenit requiē. Omnes persecutores eius apprehenderūt

eum inter angustias. **Delech** Vir syon lugens: eo quod non sunt qui veniant ad solamnitatem. Omnes porte eius destruxit: sacerdos eius genuerunt. Virgines eius squalide: et ipsa oppressa a maceritudine. **He** facti sunt hostes eius in capite: et inimici eius locupletati sunt: quia dñs locutus est super eā propter multitudinē iniquitatum eius. Parvuli eius ducti sunt in captivitatem: ante faciem tribulantis. **Vau** Et regressus ē a filia syon omnis decor eius. facti sunt principes eius velut arietes non invenientes pasua: et abierunt absq; comitum ante faciem subsequētis. **Sai** Recordata est iherusalem diē afflictionis sue: et purgationis omnium desiderabilium suorum: que habuerat a diebus antiquis: cum caderet ipse eius in manu hostili: et non esset auxiliator. **Viderūt** eā hostes: et destruxerūt sabbara eius. **Heth** Peccatū peccavit iherusalem: propterea instabilis facta est. Omnes qui glorificabāt eam spererūt illā: quia viderunt ignominiam eius. Ipsa autē genuerunt: et cōversa retrorsum. **Teth** Bordes eius in pedibus eius: nec recordata est finis sui. Deposita est vehementer: non habens consolatorē. **Vide** domine afflictionē meā: quoniam cecidit inimicus. **Ioth** Manū suā misit ipse ad omnia desiderabilia eius: quia vidit gentes ingressas sanctuarium suū: de quibus precepit ne intrarent in ecclesiam tuā. **Laph** Omnis ipse eius genens: et quercus panem. **Dederunt** preciosa queq; pro cibo: ad resollādā animā. **Vide** domine et cōsidera: quā facta sum vilis. **Lamech** Vos omnes qui transitis per viam advertite et videte: si est dolor sicut dolor meus. Quoniam vindicavit me ut locutus est dñs:

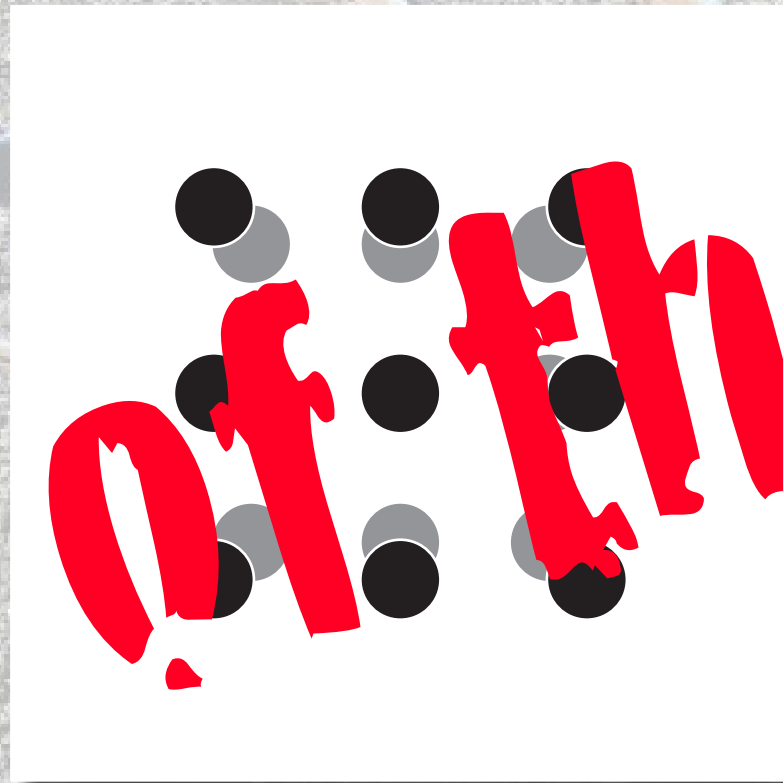
A photograph of a railway track with a wavy, undulating track bed, illustrating thermal expansion. The track is composed of gravel and wooden sleepers. The text "thermal expansion" is overlaid on the image.

thermal expansion

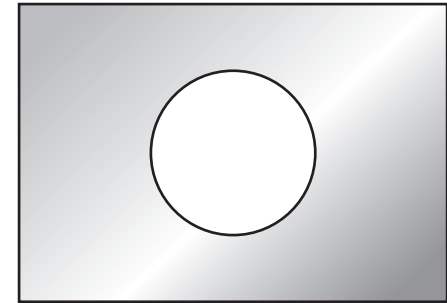




all of them!

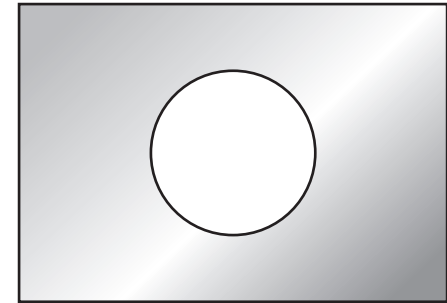


**Consider a rectangular metal plate
with a circular hole in it.**



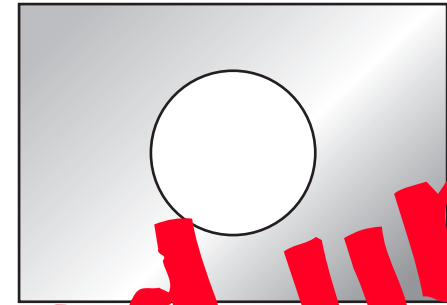
Consider a rectangular metal plate with a circular hole in it.

When the plate is uniformly heated, the diameter of the hole



- 1. increases.**
- 2. stays the same.**
- 3. decreases.**

Consider a rectangular metal plate with a circular hole in it.



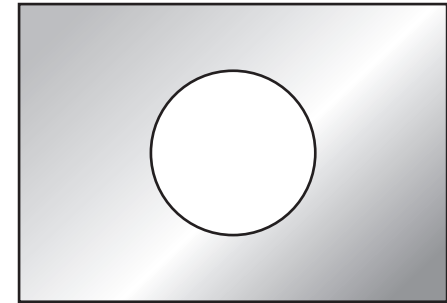
When the plate is uniformly heated, the diameter of the hole

1. increases.
2. stays the same.
3. decreases.

you got all fired up!

Consider a rectangular metal plate with a circular hole in it.

When the plate is uniformly heated, the diameter of the hole



- 1. increases.**
- 2. stays the same.**
- 3. decreases.**

Before I tell you the answer, let's analyze what happened.

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You...

Before I tell you the answer, let's analyze what happened.

You...

1. made a commitment

Before I tell you the answer, let's analyze what happened.

You...

- 1. made a commitment**
- 2. externalized your answer**

Before I tell you the answer, let's analyze what happened.

You...

- 1. made a commitment**
- 2. externalized your answer**
- 3. moved from the answer/fact to reasoning**

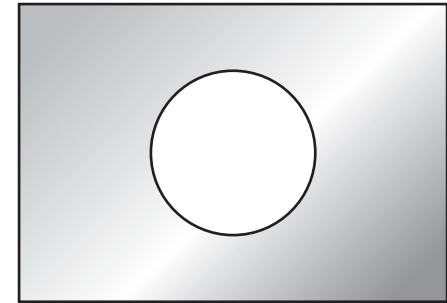
Before I tell you the answer, let's analyze what happened.

You...

- 1. made a commitment**
- 2. externalized your answer**
- 3. moved from the answer/fact to reasoning**
- 4. became emotionally invested in the learning process**

Consider a rectangular metal plate with a circular hole in it.

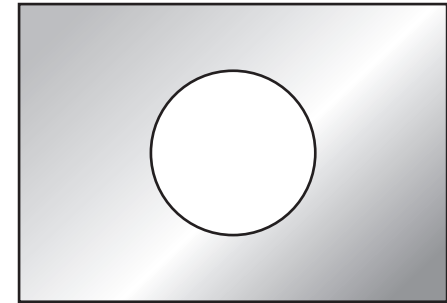
When the plate is uniformly heated, the diameter of the hole



- 1. increases.**
- 2. stays the same.**
- 3. decreases.**

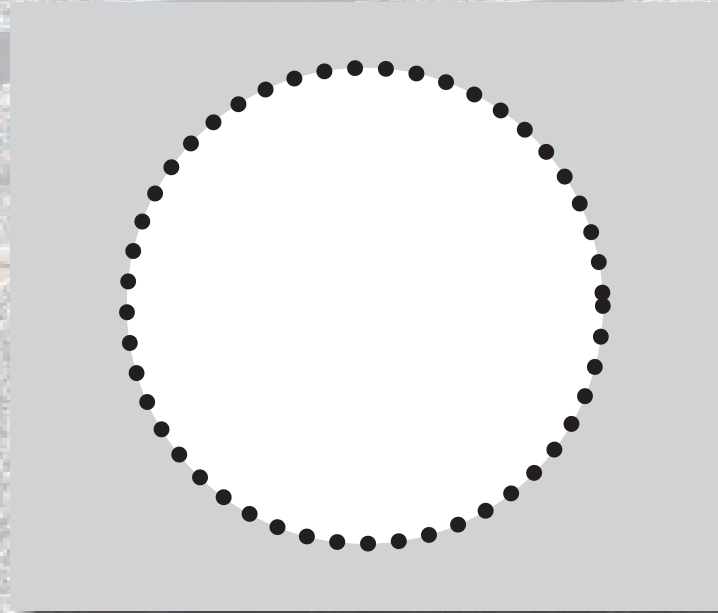
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When the plate is uniformly heated, the diameter of the hole

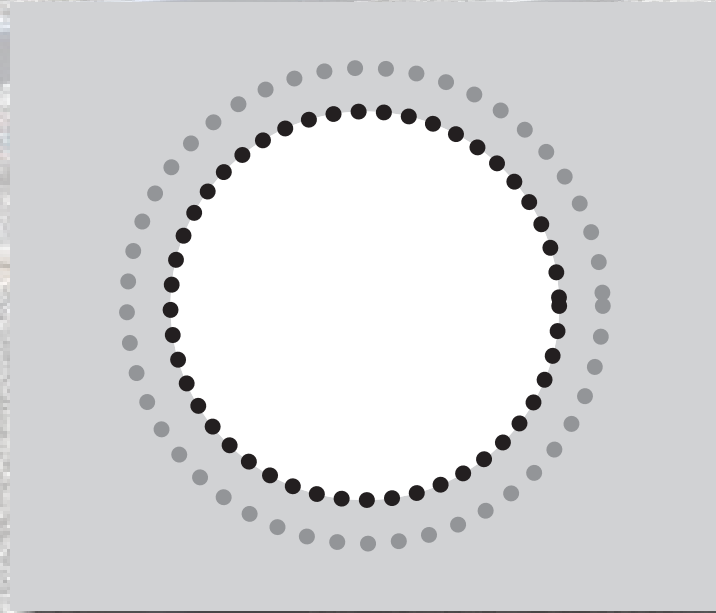


- 1. increases. ✓**
2. stays the same.
3. decreases.

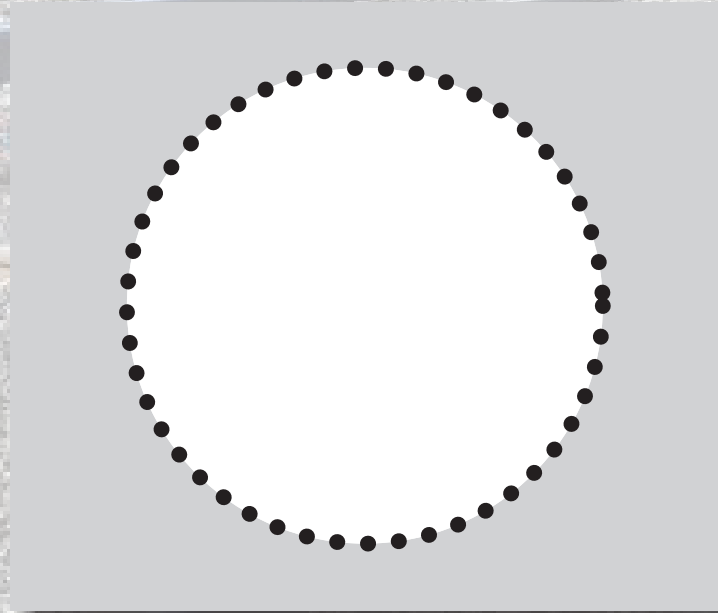
consider atoms at rim of hole



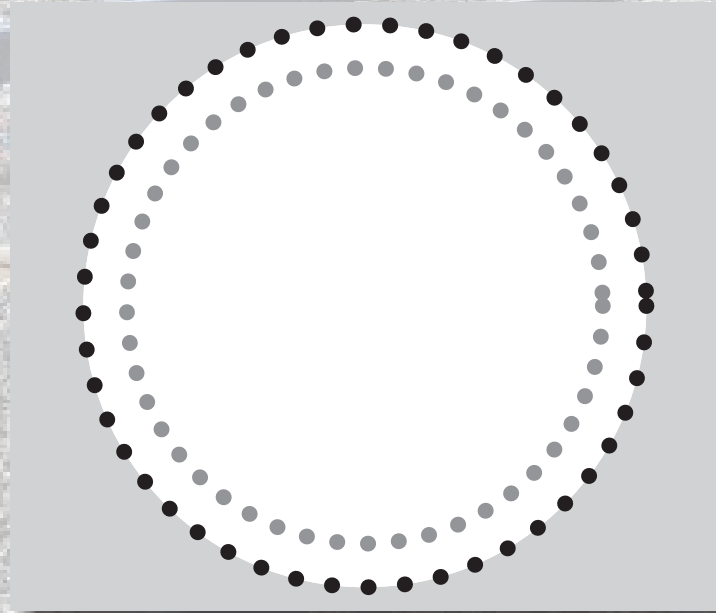
consider atoms at rim of hole



consider atoms at rim of hole



consider atoms at rim of hole



consider atoms at rim of hole

you won't forget this



Peer

back to pi

INSTRUCTION

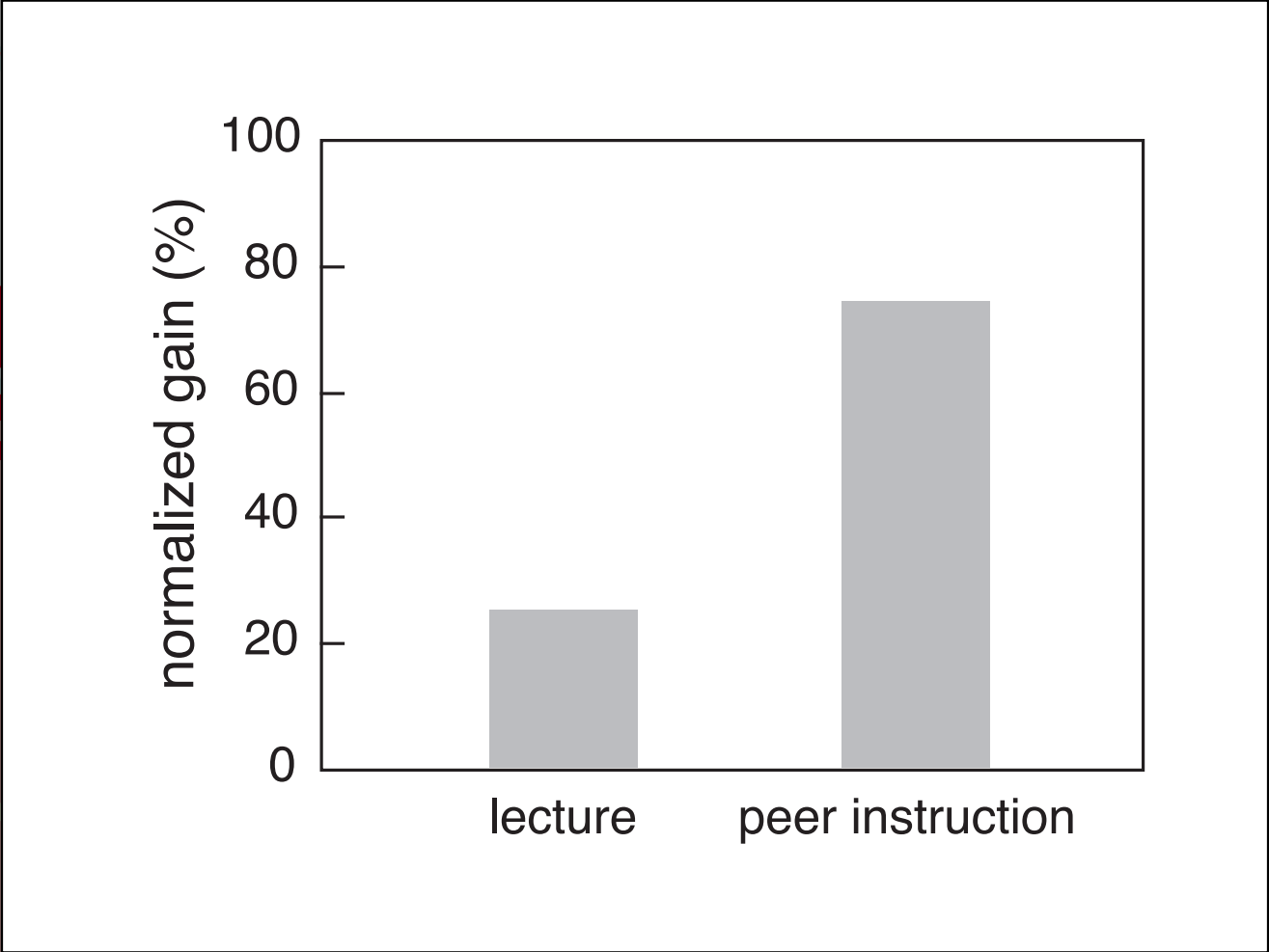
Peer

eer

INSTRUCTION

Higher learning & gains

INSTRUCTION



Higher learning gains

Better retention

INSTRUCTION



CLASS

1st exposure



ROOM

deeper understanding



CLASS

1st exposure



ROOM

deeper understanding



ROOM

1st exposure



CLASS

deeper understanding



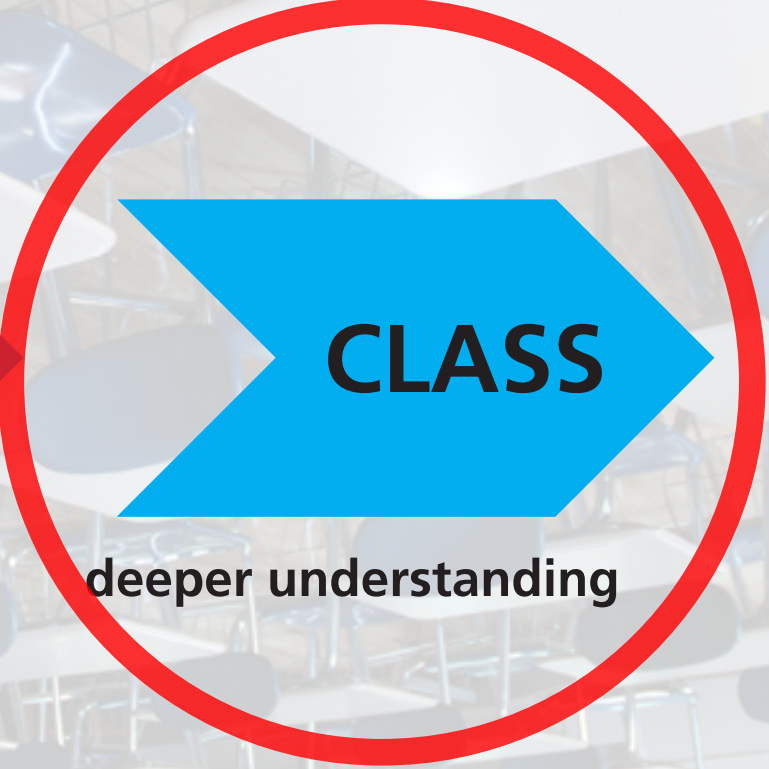
1st exposure



deeper understanding



1st exposure



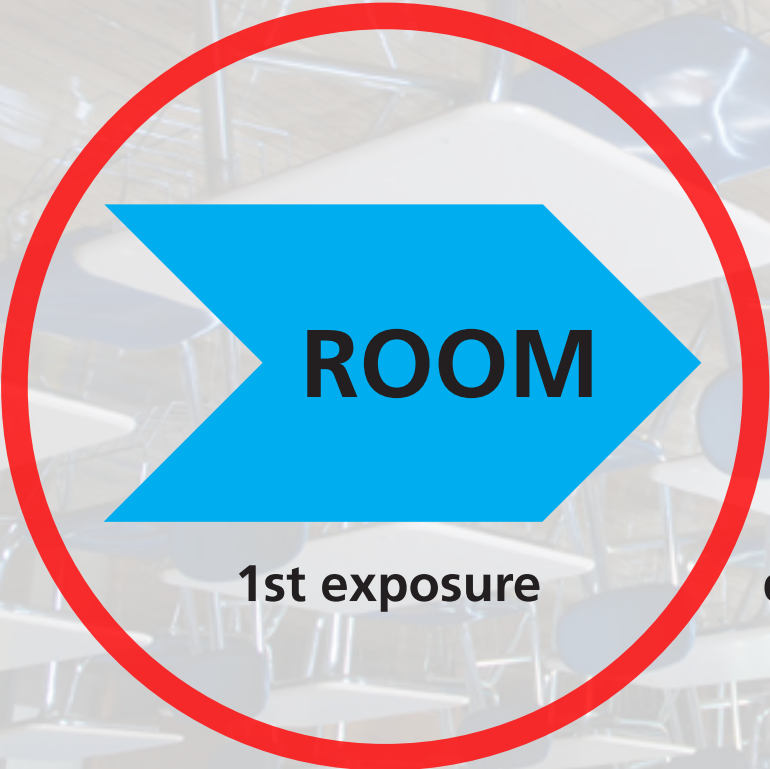
deeper understanding



1st exposure



deeper understanding

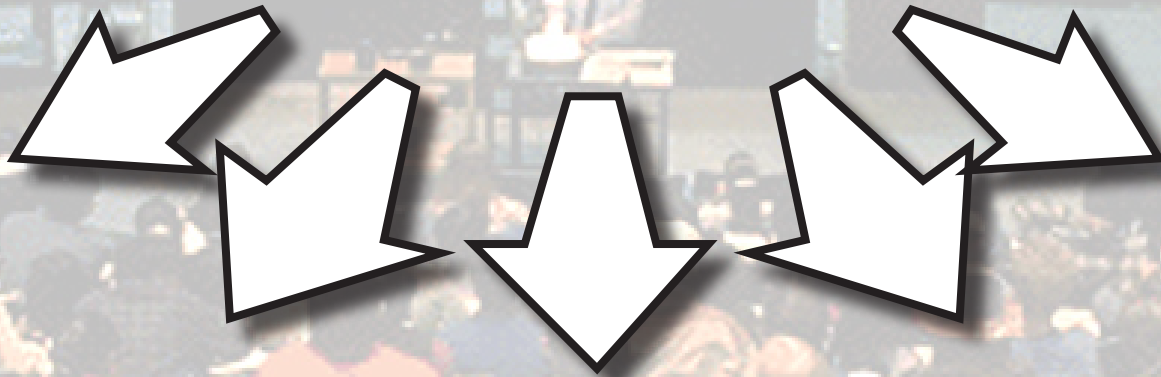


1st exposure



deeper understanding

how to effectively transfer information outside classroom?





but...



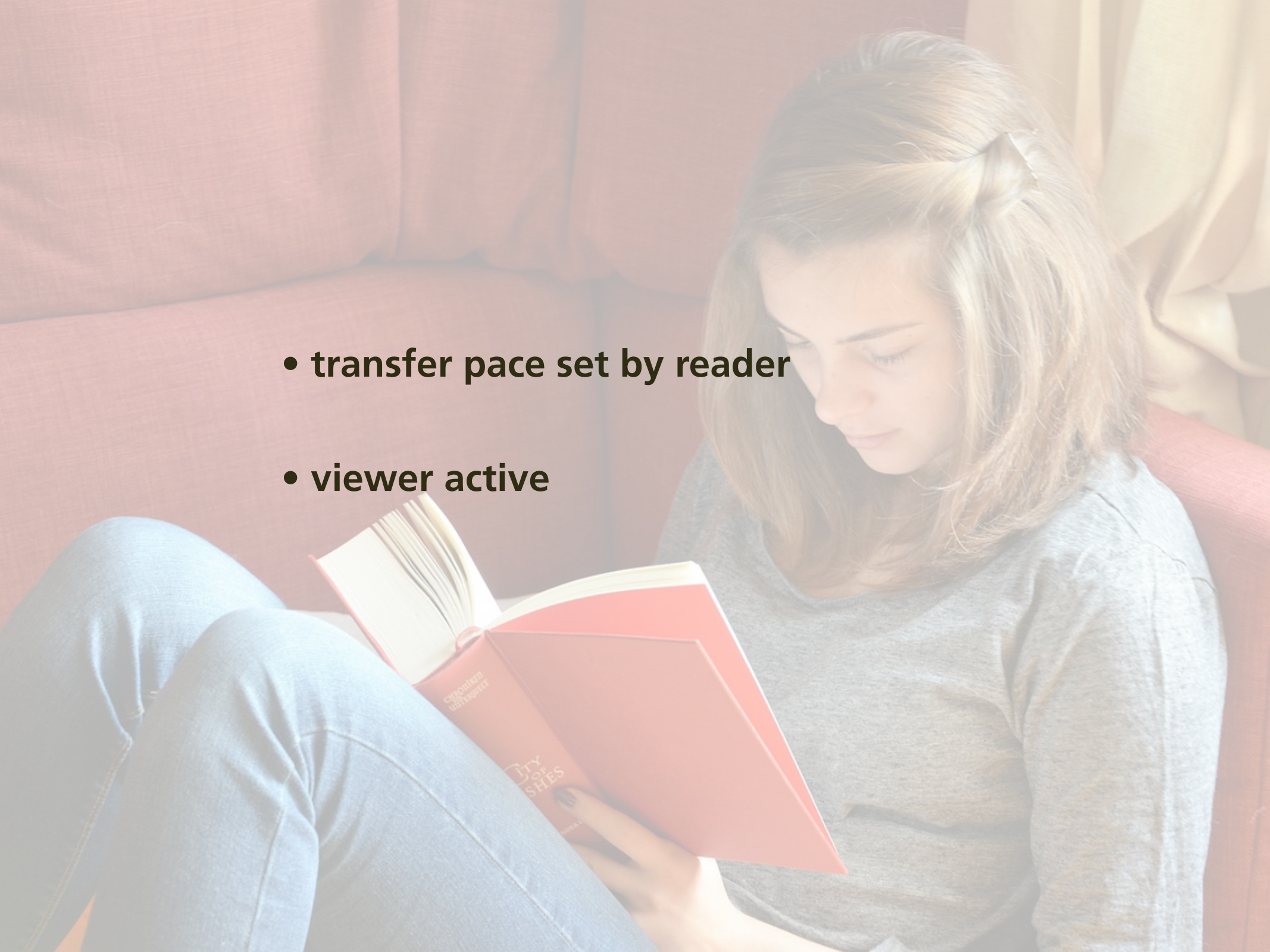
- **transfer pace set by video**
- **viewer passive**
- **viewing/attention tanks as time passes**
- **isolated/individual experience**






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)

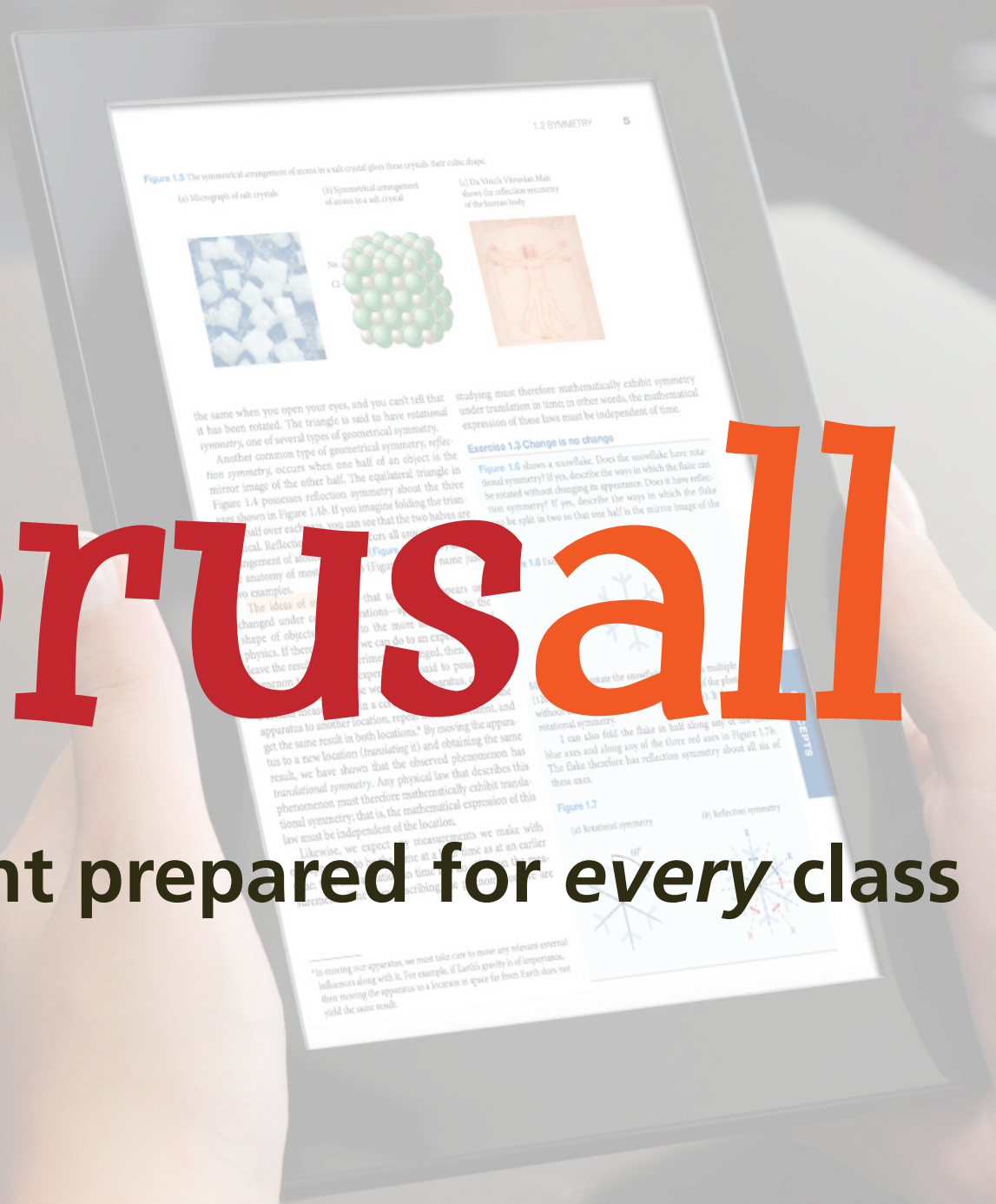


Solution

**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 longer time interval than if the surfaces are rough. This is a familiar 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 on the smooth wooden surface; and it decreases rapidly on the rough wooden 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.

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 that flows through the table 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 takes a long time to bring two objects to rest with respect to each other. In this case the wooden block and the ice. 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.



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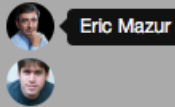
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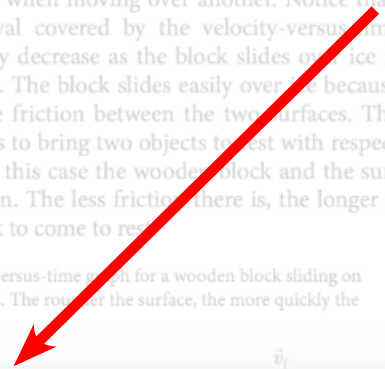
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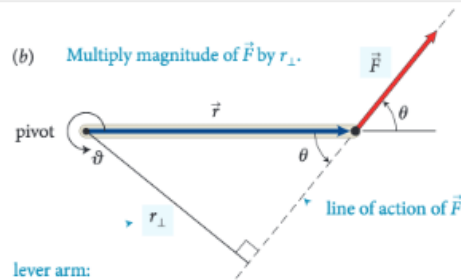
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(b) Multiply magnitude of \vec{F} by r_{\perp} .



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_1 and as $r_{\perp}F$.

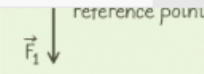
Like other rotational quantities, torque carries a sign that depends on the choice of direction for increasing ϑ . In Figure 12.4, for example, the torque caused by \vec{F}_1 about the pivot tends to rotate the rod in the direction of increasing ϑ and so is positive; the torque caused by \vec{F}_2 is 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}^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. ✓

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.

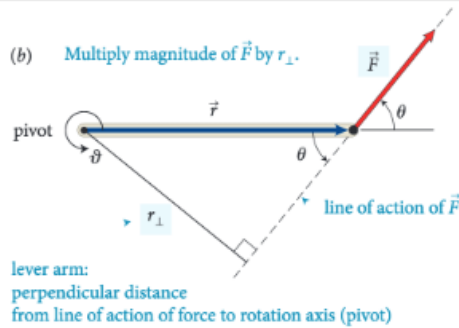
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Enter your comment or question and press Enter

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question flag





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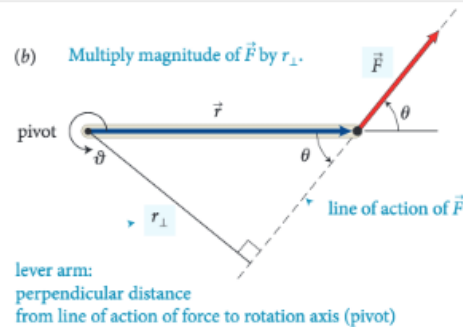
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+1 

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

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21 minutes ago, you asked this question on Perusall:

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\vec{F}

\vec{r}_1

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option 2: view chat

View conversation

This comment helps my understanding

Chat sidebar with user avatars and messages:

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option 3: mark as answered

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

$$p_{u,x,f} - p_{u,x,i} + p_{s,x,f} - p_{s,x,i} = 0. \quad (4.8)$$

If we write $\Delta p_{u,x} \equiv p_{u,x,f} - p_{u,x,i}$ and $\Delta p_{s,x} \equiv p_{s,x,f} - p_{s,x,i}$, Eq. 4.8 takes on the beautifully simple form

$$\Delta p_{u,x} + \Delta p_{s,x} = 0. \quad (4.9)$$

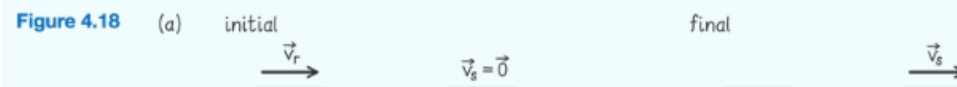
This equation means that, whenever an object of unknown inertia collides with the inertial standard, the changes in the x components of the momenta of the two objects add up to zero. In other words, the change in the x component of the momentum for one object is always the negative of the change for 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 $v_{r,x,f} = +0.032$ m/s and $v_{b,x,f} = -0.039$ 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

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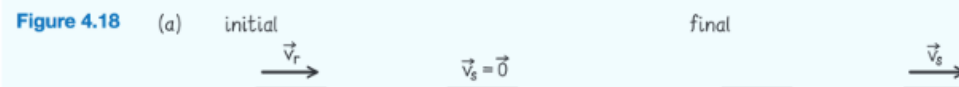
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76 CHAPTER 4 MOMENTUM

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 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 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?

4.2 Inertia

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

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

Nov 1 12:03 pm

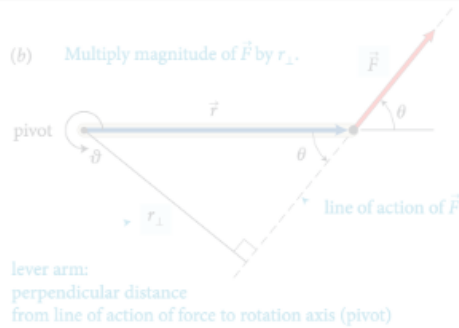


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Nov 1 12:09 pm



Enter your comment or question and press Enter



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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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how to get students to participate?

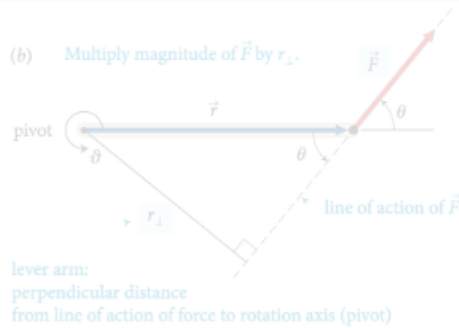
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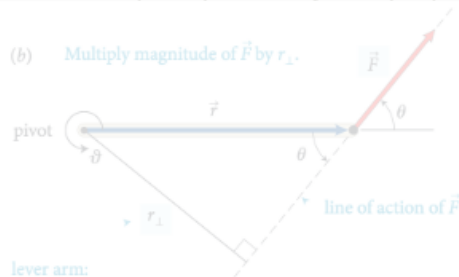
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Enter your comment or question and press Enter

rubric-based assessment

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Enter your comment or question and press Enter

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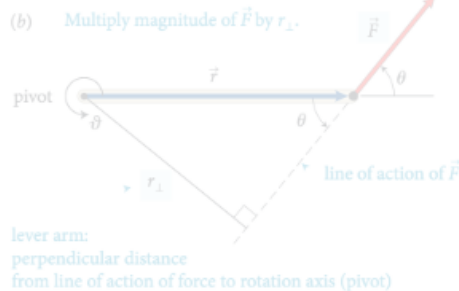
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rubric-based assessment



• quality (thoughtful reading & interpretation)

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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 where a force is applied, 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° 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

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 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 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.

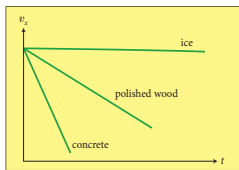
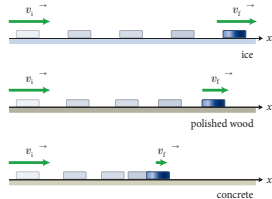


Figure 4.2 Low-friction track and carts used in the experiments described in this chapter.



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

4.2 Inertia

We can discover one of the most fundamental principles of physics by studying how the velocities of two low-friction carts change when the carts collide. Let's first see what happens with two identical carts. We call these standard carts because we'll use them as a standard against which to compare the motion of other carts. First we put one standard cart on the low-friction track and make sure it doesn't move. Next we place the second cart on the track some distance from the first one and give the second cart a shove toward the first. The two carts collide, and the collision alters the velocities of both.

ANNOTATION

Alan: I remember, in high school, being amazed at how quickly carts could travel on these tracks - air would blow up through these tiny holes evenly distributed along the length of the track and the cart would essentially float on the air and consequently - the cart would move very quickly with the slightest push.

Bob: Although there is no way to create frictionless surfaces, I find it interesting that we consider experiments "in the absence of friction." In a way, this relates back to Chapter 1.5 where we talked about the importance of having too little or too much information in our representations. In some cases, the friction is so insignificant that we ignore it (simplifying our representation).

Claire: Does this only apply to solid surfaces? I feel as if a substance that floats on water either has negligible or very little friction.

Alan: Why is this? I don't get it.

David: believe this applies to almost every surface, although I'm not sure if water would count more as resistance than friction. Anyways, the best example I could think of would be a surf board. If people who were paddling in the same direction as the waves experienced no resistance, they would continually speed up, and eventually reach very high speeds. However, in reality if they were two stop paddling they'd slow down and only the waves would slowly push them to shore.

Alan: Is it possible to have a surface, in real life, that inflicts NO friction at all?

Erica: Doesn't air resistance factor into this at all? It seems that it is not enough for there to be only an absence of friction for something to keep moving without slowing down. What about some other opposing force - like air resistance? Or is air resistance just another example of friction?

Bob: The key word is "appreciably". In the absence of friction, the cart does not slow down appreciably but still would a little due to air resistance

Alan: a) yes b) concrete has the acceleration of greatest magnitude

Erica: I would think that they are not constant because if we think of the formula $F=ma$, the force of friction is different in every case so that would change the acceleration value (where mass would stay the same since it's assumed that the object is the same in each situation).

Claire: As a theoretical question about inertia, if an object in motion will stay in motion, but is being affected by friction, will it slow down perpetually but remain in motion, or will it eventually stop completely due to the friction? Just curious.

Alan: With friction everything slows down to a half at one point or another. It is only if an outside force acts on the object if that object will maintain motion after the effects of inertia.

Claire: Standard carts: identical carts in mass, shape, etc. I like this notion of standard carts, it provides a good baseline to compare other motion and to understand the concepts before building on it.

Alan: Great visual representation of friction! It is interesting how this compares the velocity of things on different surfaces

Bob: The rougher the surface, the more friction between the surface and the wooden block, and thus acceleration will be greater.

EVALUATION

No substance. Does not demonstrate any thoughtful interpretation of the text. **0**

Annotation interprets the text and demonstrates understanding of concepts through analogy and synthesis of multiple concepts. **2**

Possibly insightful question but does not elaborate on thought process, nor demonstrate thoughtful reading of the text. **1**

Question does not explicitly identify point of confusion nor demonstrates thoughtful reading or interpretation of the text. **0**

Response demonstrates a thoughtful explanation with a claim substantiated with a concrete example **2**

Question exhibits superficial reading, but does not exhibit any interpretation of the textbook. **1**

Demonstrates thoughtful interpretation of the text by refuting a statement through a counter example. **2**

Responds to the question by thoughtfully interpreting the text **2**

Annotation not backed up by any reasoning or theoretical assumptions. No evidence of thoughtful reading of text. **0**

Response backed up with reasoning that demonstrates an interpretation of the text and applies understanding of concepts **2**

Profound question that goes beyond the material covered in the textbook. **2**

Demonstrates some thought but does not really address Claire's question **1**

No substance. Does not demonstrate any thoughtful reading. **0**

No substance. Does not demonstrate any thoughtful reading. **0**

Interprets the graph and applies understanding of both the concept of friction, how a v-t graph corresponds to acceleration and the relationship between the force of friction and acceleration **2**

CONCEPTS

and F_3 are equal in magnitude, and the magnitude of F_2 is half as great. Force F_1 is horizontal, F_2 and F_3 are vertical, and the lever makes an angle of 45° with the horizontal. Do these forces cause the lever to rotate about the pivot? If so, in which direction?

As we saw earlier in the chap...

Objects executing motion ar...

Generally, for rotating bod... **2**

Does torque have the s... **3**

ANNOTATION

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Response demonstrates a thoughtful explanation with a claim substantiated with a concrete example

2

Enter your comment or question and press Enter

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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 (thoughtfulness & in-depth)

action of the force and the rotation. So, the torque caused by a force \vec{F} is the product of the force's magnitude and the lever arm distance. It can

- quality (minimum 10)

- timeliness (before class)

- direction (right or left)

over 20,000 annotations!

The lever arm distances must now be determined relative to the pivot point. The lever arm distance of a force \vec{F} is the perpendicular distance from the pivot point to the line of action of the force. If I choose the pivot point to be at the left end of the rod, the lever arm distance of the force \vec{F} is the perpendicular distance from the left end of the rod to the line of action of the force. The lever arm distance is the perpendicular distance from the pivot point to the line of action of the force. The lever arm distance is the perpendicular distance from the pivot point to the line of action of the force.

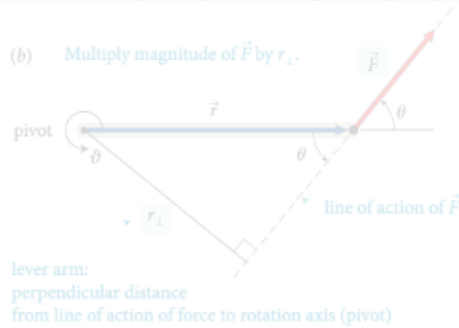
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rubric-based assessment

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- quality (thoughtful reading & interpretation)

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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 result is important to the study of static equilibrium. 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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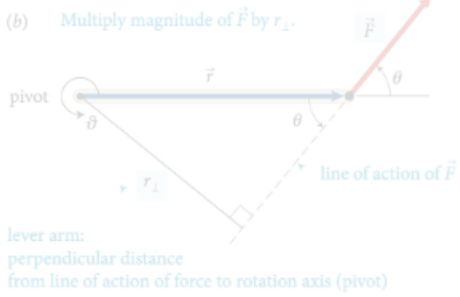
how do you process all of that??

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

- distribution (not clustered)

- On the very left, we see th...
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rubric-based assessment



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fully automated

quality (though future research in interpretation)

you process all of that??

timeliness (before class)

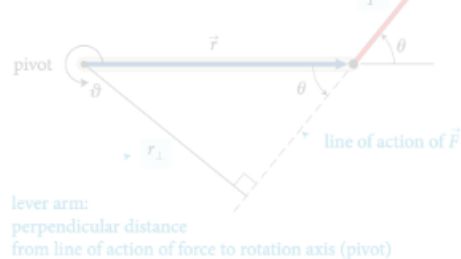
distribution (not clustered)

assessment



fully automated assessment

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



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

- 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? It seems like you would just know some sort of direction from the force vector.

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. For example, in the diagram, you can explain how to choose the sign of the torque.

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

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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 we like. For example, we can choose a reference point at the pivot. In this case, 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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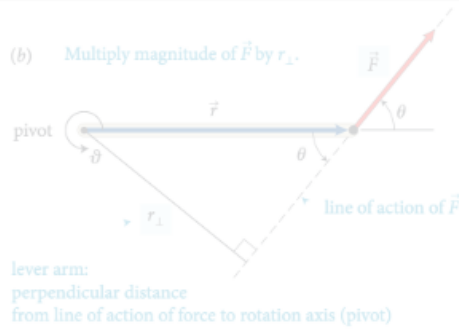
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Total number of annotations	16
Total number of annotations submitted on time	11
Average quality of top 10 annotations submitted on time	1.80
2 = demonstrates thorough and thoughtful reading and insightful interpretation of the reading, 1 = demonstrates 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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connect pre-class and in-class activities

I don't think you can think of torque as a scalar quantity. Torque is a vector quantity. The magnitude of torque is the product of the force and the 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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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? +
- SB Using the right hand rule, I believe the answer is D. Is that correct? +
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? +
- AK Can someone explain why this type of bacteria knows what direction the earth's magnetic fields are facing? +
- 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. +
Show more...

motivating factors

Intrinsic:

- social interaction

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



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

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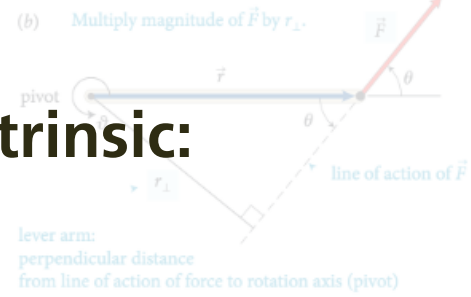
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motivating factors

Intrinsic:

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



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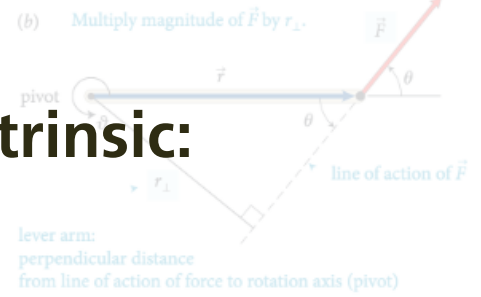
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motivating factors

Intrinsic:



- social interaction

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Extrinsic:

- assessment (fully automated)

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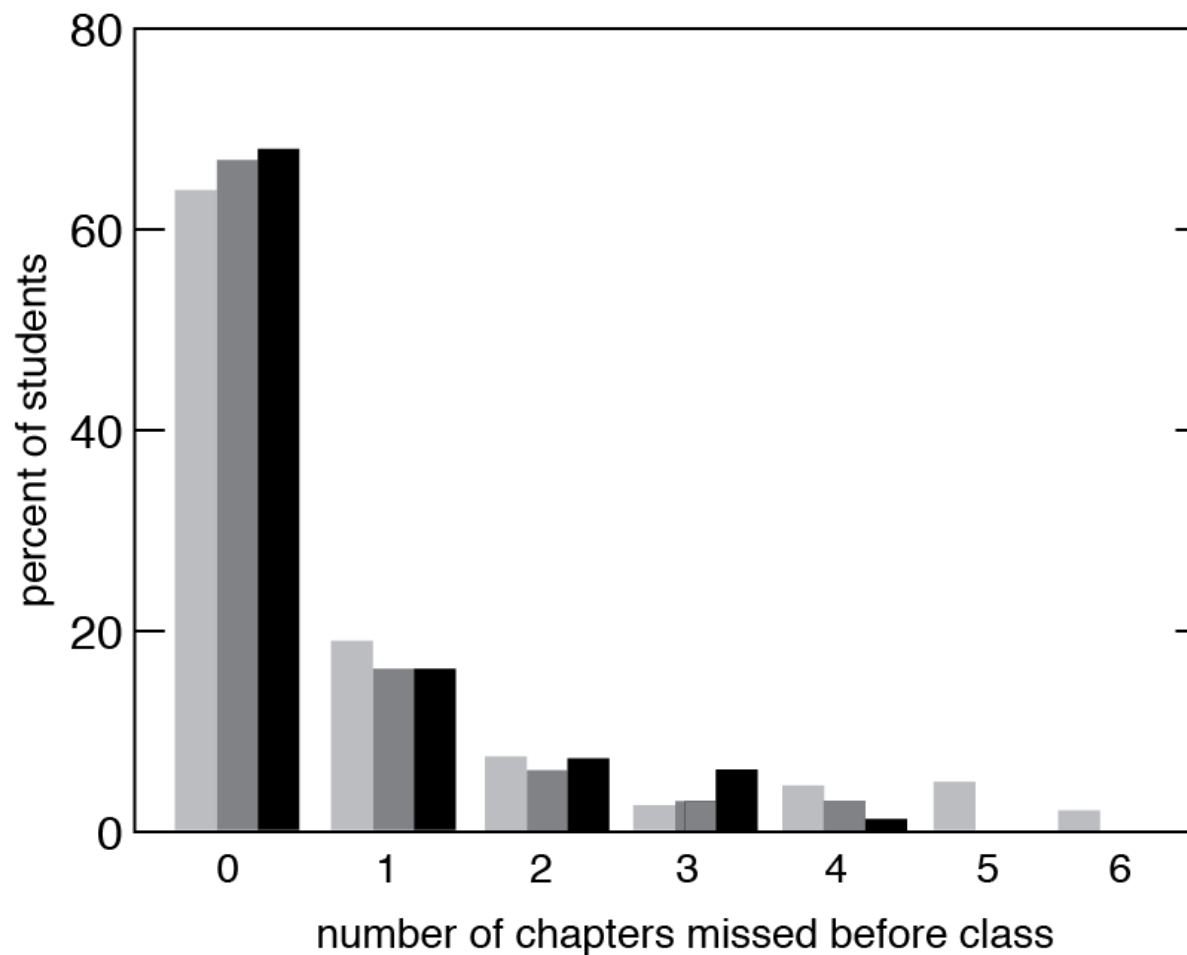
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reference point

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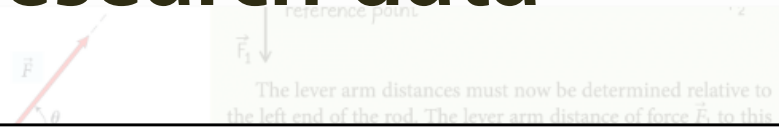
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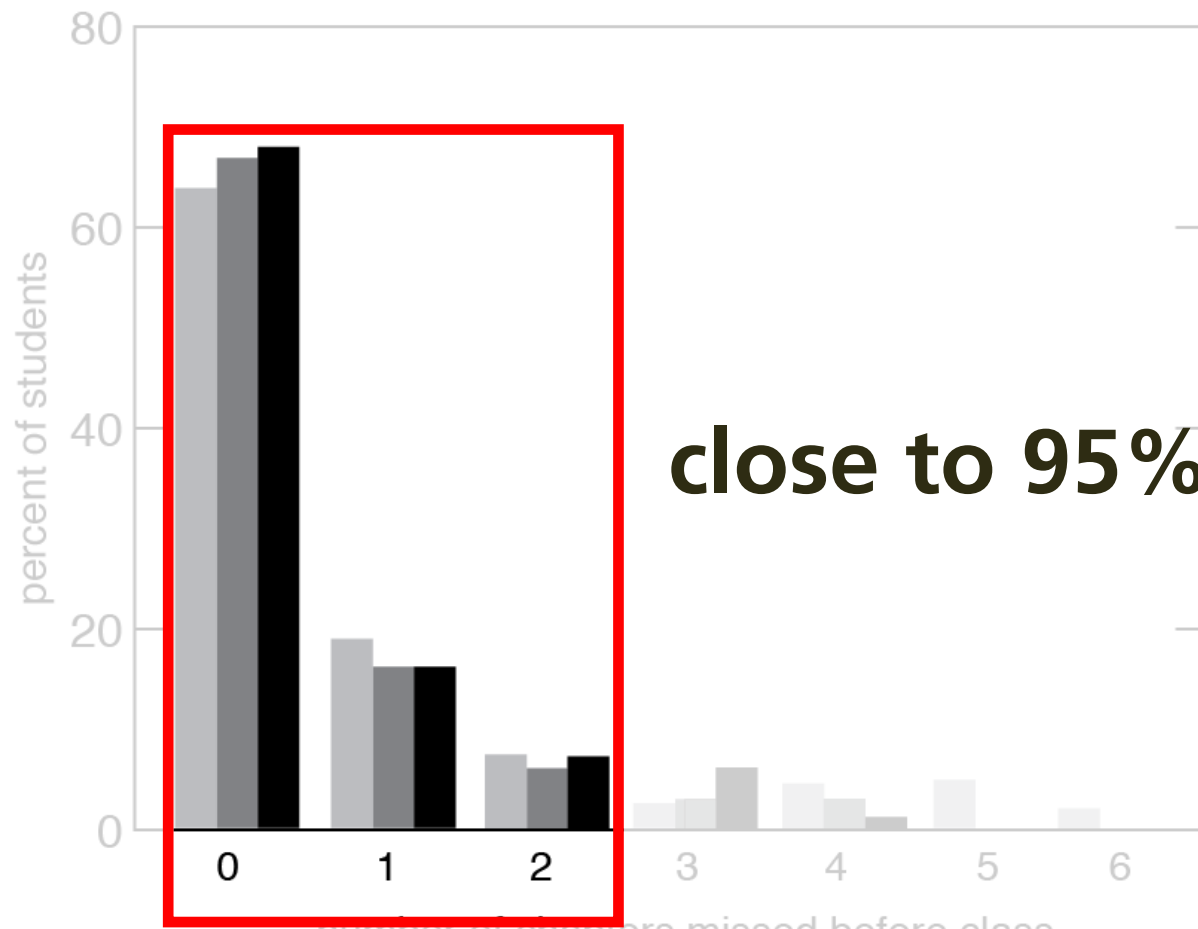
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research data

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close to 95%!

number of chapters missed before class

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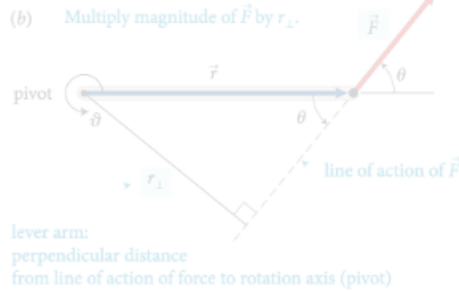
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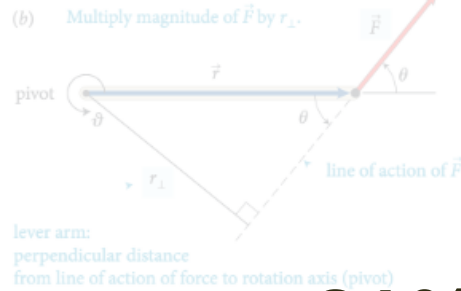
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every student prepared for every class

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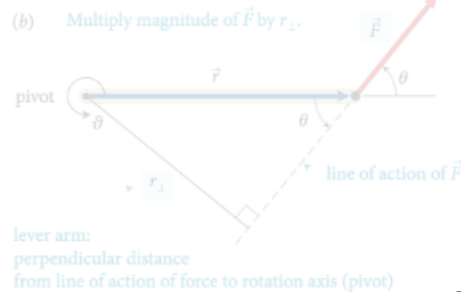
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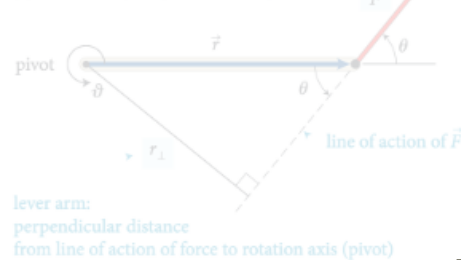
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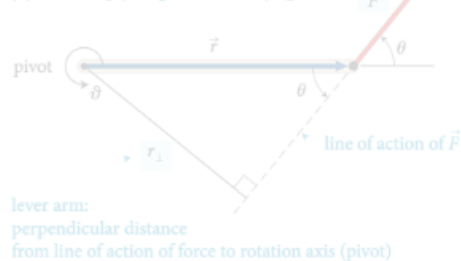
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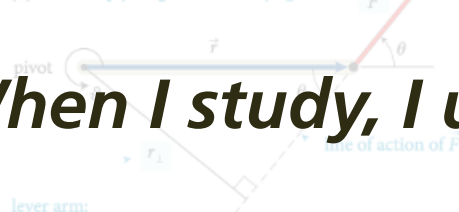
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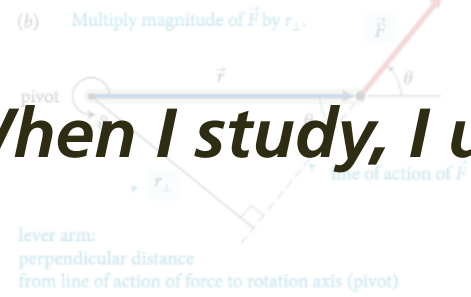
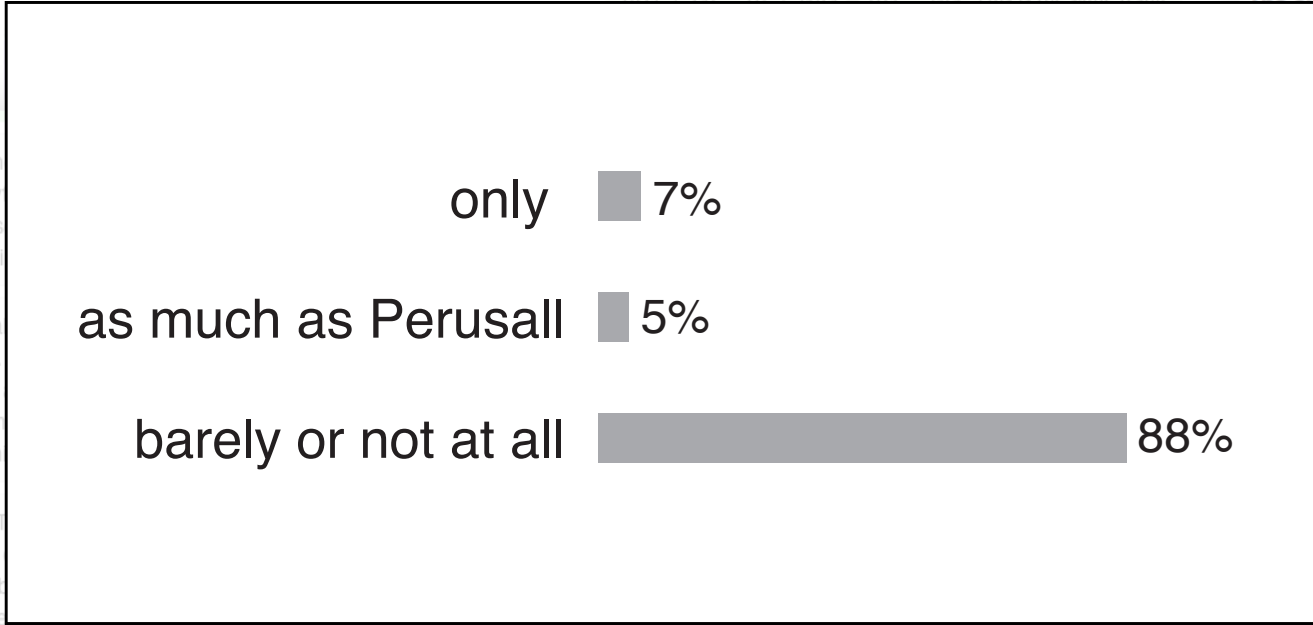
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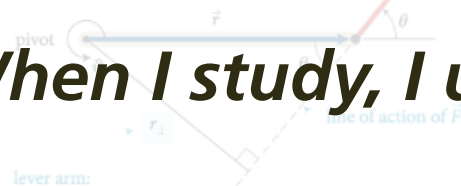
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in regards to "r" it can also be thought of as the radial vector. What this means is that this distance from the pivot points from the axis of rotation to the point where the force acts. In as previously mentioned, there is a general convention (the 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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continue to exert a force on the seesaw to keep the child on 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}_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° with the horizontal. Do these forces cause the lever to rotate about the pivot? If so, in which direction?

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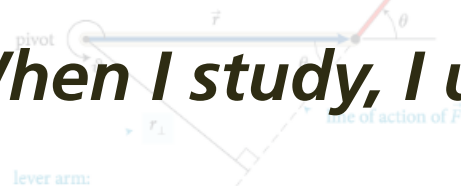
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(b) Multiply magnitude of \vec{F} by r_{\perp} .



lever arm:
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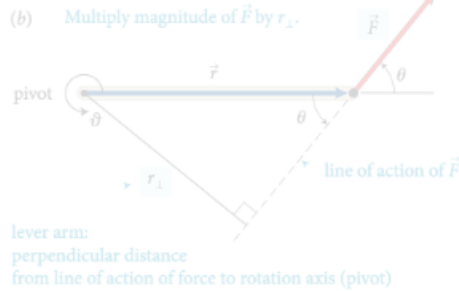
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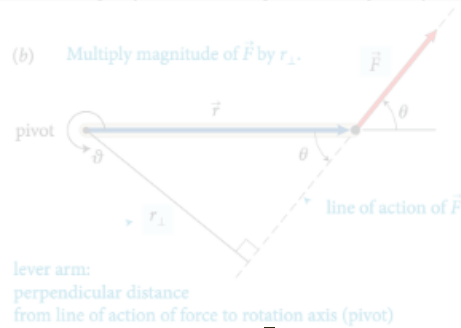
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This is a great question. To further elaborate on this, we can think of this in terms of the Torque equation. The equation for torque is $\tau = r \times F$, with r being the level arm distance and F being force. We know that force is a vector vector 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

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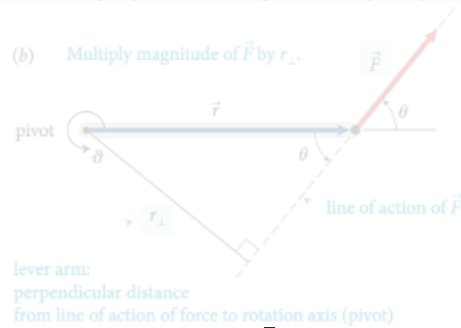
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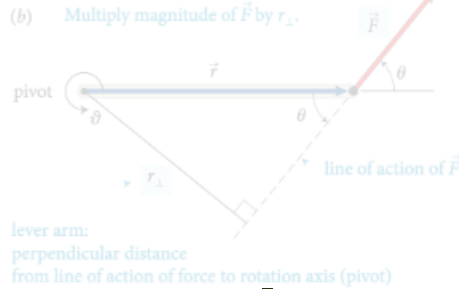
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Benefits

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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 its lever arm. It can be written equivalently as rF_{\perp} and $r_{\perp}F$.

Like other rotational quantities, torque is a vector that depends on the choice of reference point. In Figure 12.4, for example, the pivot tends to rotate in the clockwise direction, so the torque is negative. The sum of the torques is $r_1F_1 + (-r_2F_2)$. The magnitude of the net torque is zero, so the rod's rotational velocity and angular acceleration are zero.

In the situation shown in Figure 12.4, we used the pivot to calculate the net torque. This is a natural choice because the pivot is the point of contact between the object under consideration and the support. Torques also play a role for stationary objects. For example, a plank or bridge supported at several different points must be able 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}_3 exerted by the pivot causes a positive torque about the left end of the rod. The lever arm distance of \vec{F}_3 to the left end of the rod is $r_1 + r_2$; that of \vec{F}_2 to the left end of the rod is r_1 . If the rod is at rest, the magnitude of the net torque about the left end of the rod is zero. If the signs of the torques, we find that the net torque about the left end of the rod is $r_1F_1 - r_2F_2$. This is the same result as the net torque about the pivot, and so the sum of the torques about the pivot is zero. ✓

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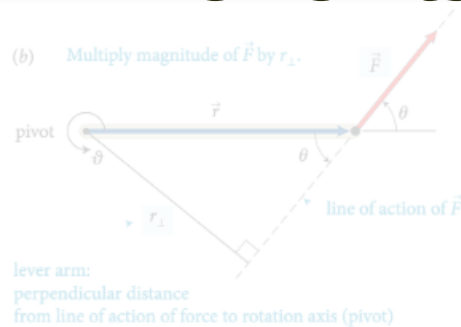
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CONCEPTS

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



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Like other rotational quantities, torque carries a sign that depends on the choice of direction for increasing ϑ . 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 ϑ 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.

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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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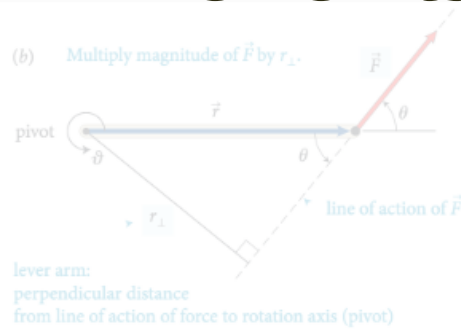


12.2 In the situation depicted in Figure 12.2a, you must continue to exert a force on the seesaw to keep the child off the ground. The force you exert causes a torque on the seesaw, and yet the seesaw's rotational acceleration is zero. How can this be if torques cause objects to accelerate rotationally?

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° 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} .



• 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 ϑ . 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 ϑ 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.

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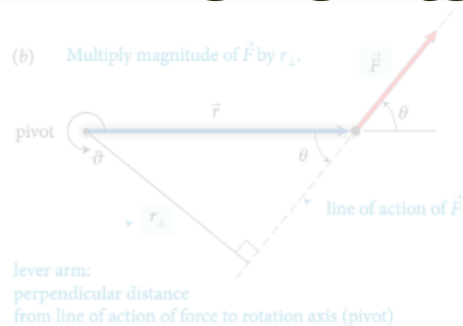


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lever arm:
perpendicular distance
from line of action of force to rotation axis (pivot)

- time recovery

- improved use of class time

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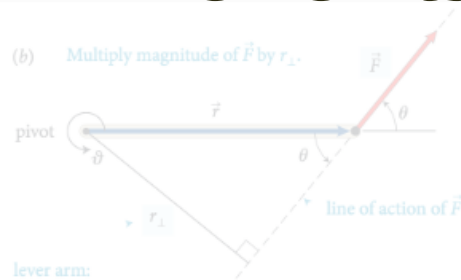


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- time recovery
- improved use of class time
- enhanced respect and understanding for students

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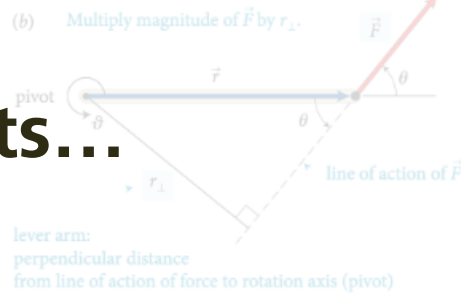
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Example 12.2 Torques on lever

Three forces are exerted on the lever of Figure 12.7. Forces \vec{F}_1 and \vec{F}_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° 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
- all at no cost & no additional effort!*

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_{\perp} and as $r_{\perp}F$.

Like other rotational quantities, torque carries a sign that depends on the choice of direction for increasing ϑ . 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 ϑ 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.

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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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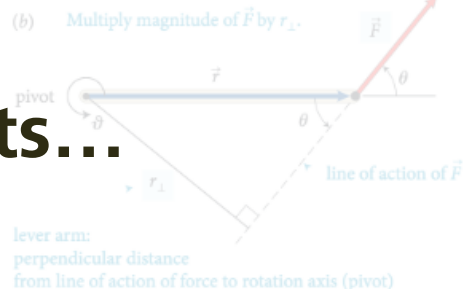
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Students...

- read the textbook



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Students...

- read the textbook
- learn how to read

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



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

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Students...

- read the textbook
- learn how to read
- learn how to read critically

CONCEPTS

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



lever arm:
perpendicular distance
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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
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Students...

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- learn how to read
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- participate in a collaborative experience
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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 $\tau = r_{\perp} F$. As a result, the torque depends on the angle θ . Figure 12.4 shows the torque caused by \vec{F}_1 about the pivot. The torque is in the direction of increasing θ , 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, in the case of the pivot, the distance from the pivot to the line of action of the force is the same. It also plays a role for stationary objects that are 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 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 equal in magnitude, the torque caused by \vec{F}_2 is $-r_2 F_2$ and the torque caused by \vec{F}_3 is $r_3 F_3$. The sum of the torques about the left end of the rod is then $\tau = -r_2 F_2 + r_3 F_3$. Because $r_3 = r_2$, the sum of the torques about the left end of the rod is zero.

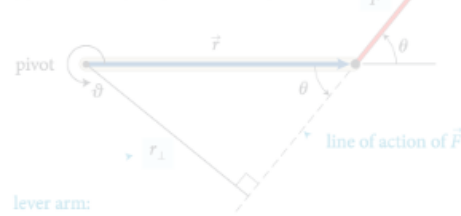
Example 12.1 shows that the sum of the torques about the left end of the rod is zero, just like the sum of the torques about the pivot. You can repeat the calculation for the torques about the right end of the rod or any other point, and each time you will find that the sum of the torques is zero. The 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 can be stated as follows:

Principle of Torques: If an object is not rotating about any reference point, the sum of the torques about that reference point is zero. It pays to choose a reference point that simplifies the calculation. As you have seen, we do not need to consider a force exerted at the reference point, because the lever arm distance from the reference point to the point of application of the force is zero, and so the torque is zero.

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° 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_{\perp} and as $r_{\perp}F$.

Like other rotational quantities, torque carries a sign that depends on the choice of direction for increasing ϑ . 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 ϑ 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.

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

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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. So, by putting the reference point at the point of application of a force, we can eliminate that force from the calculation.

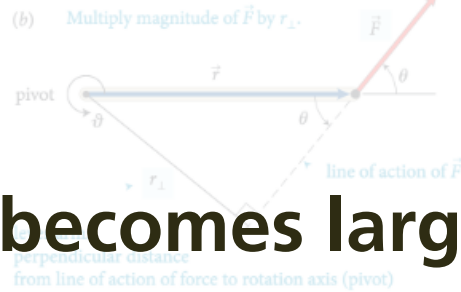


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action of the force and the axis of rotation. So, the torque caused by a force exerted on an object is the product of the magnitude of the force and its lever arm distance. It can be written equivalently as rF_{\perp} and as $r_{\perp}F$.

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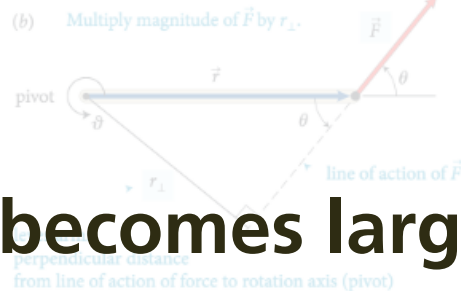


12.2 In the situation depicted in Figure 12.2a, you must continue to exert a force on the seesaw to keep the child off the ground. The force you exert causes a torque on the seesaw, and yet the seesaw's rotational acceleration is zero. How can this be if torques cause objects to accelerate rotationally?

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The 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}_{pit} exerted by the pivot causes a positive torque about the left end of the rod. The lever arm distance of \vec{F}_{pit} to the left end of the rod 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?

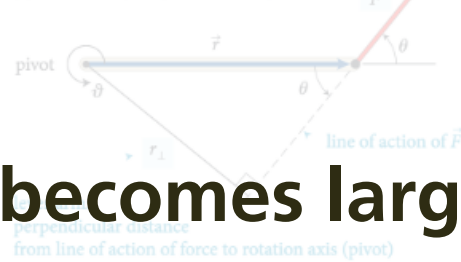
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Three forces are exerted on the lever of Figure 12.7. Forces \vec{F}_1 and \vec{F}_3 are equal in magnitude, and the magnitude of \vec{F}_2 is half as great. Force \vec{F}_1 is horizontal, \vec{F}_2 and \vec{F}_3 are vertical, and the lever makes an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

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CONCEPTS

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



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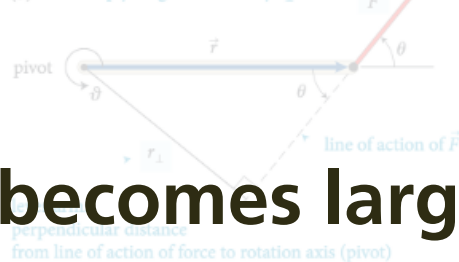
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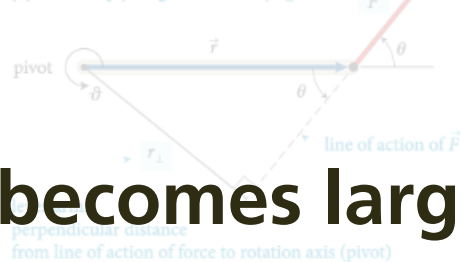
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Example 12.2 Torques on lever

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° with the horizontal. Do these forces cause the lever to rotate about the pivot? If so, in which direction?

21st century learning

A large, bright, modern classroom with a high ceiling and exposed wooden beams. The room is filled with students sitting at white tables, many of whom are using laptops. The atmosphere is collaborative and focused. The text "21st century learning" is overlaid in the center of the image.









Making learning fun again!

A group of four students are gathered around a wooden box containing a project. One student is using a soldering iron on a breadboard with electronic components. The others are looking on with interest and excitement. The scene is set in a bright, modern classroom or lab.

Education in 21st century is not just about:

- **transferring information**

- **getting students to do what we do**

A group of four students are gathered around a wooden box containing a project. One student is using a soldering iron on a circuit board. The others are looking on with interest and excitement. The scene is set in a classroom or workshop with other people and equipment visible in the background.

Education in 21st century is not just about:

- **transferring information**

- **getting students to do what we do**

social engagement in & out of classroom a must!

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