Interactive Learning: Technology in the Classroom

@eric__mazur

IAP Symposium
Cambridge, MA
20 June 2016
• no ON/OFF button
• only last “click” counts
• display shows recorded answer
unique ID on back of clicker

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Think of something you are good at
Think of something you are good at

*How did you become good at this?*
Became good at it by:

1. trial and error
2. lectures
3. practicing
4. apprenticeship
5. other
better pay attention!
What happens in a lecture?
some people talk in their sleep
some people talk in their sleep

lecturers talk while other people are sleeping

(Albert Camus)
education
The result?
Lack of learning
Lack of learning
Lack of retention
not transfer but assimilation of information is key
1. transfer of information
1. transfer of information

2. assimilation of that information
1. transfer of information (in class)
2. assimilation of that information
1. transfer of information (in class)

2. assimilation of that information (out of class)
1. transfer of information (in class)

2. assimilation of that information (out of class)

Should focus on THIS!
1. transfer of information (in class)

2. assimilation of that information (out of class)
1. transfer of information (out of class)

2. assimilation of that information (in class)
1. transfer of information (out of class)

2. assimilation of that information (in class)
question
question

think
question

think

poll

discuss
question → think → poll → discuss → repoll
1 education

2 PI
Let's try it!

1 education
2 PI
thermal expansion

1 education
2 PI
education  PI
education

PI
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
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…
Before I tell you the answer, let’s analyze what happened.
Before I tell you the answer, let’s analyze what happened.

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.
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 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

1  education
2  PI
3  test
Greater learning gains
Greater learning gains
Better retention
in a lecture, students...
in a lecture, students...

1. don’t pay utmost attention
in a lecture, students...

1. don’t pay utmost attention

2. think they know it
in a lecture, students...

1. don’t pay utmost attention

2. think they know it

3. are not confronted with misconceptions
in a lecture, students...

1. don’t pay utmost attention
2. think they know it
3. are not confronted with misconceptions

false sense of security
education  PI  test
an illusion...
Education is not just about:

• transferring information

• getting students to do what we do
Education is not just about:

- transferring information
- getting students to do what we do

active participation a must!
PLEASE RETURN CLICKER
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CLASS
1st exposure
ROOM
deeper understanding
CLASS
1st exposure
ROOM
deeper understanding
ROOM
1st exposure
CLASS
deeper understanding
CLASS
1st exposure
ROOM
deeper understanding
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1st exposure
CLASS
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
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 will move shorter distance, and the surfaces are also quite smooth, it may be a daily 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.

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 not easily accomplished in practice, but the effect of the cushion of air can be simulated in the laboratory. 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:

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log in through social network
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...opens chat window

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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 $F_1$ to this point is zero, and so the torque caused by that force about the left end of the rod is zero. If $F_2$ causes a negative torque about the left end of the rod, the force $F_2'$ exerted by the pivot causes a positive torque about the left end of the rod. The lever arm distance of $F_2'$ about the left end of the rod is $r_1 + r_2$; that of $-F_2'$ is $r_2$. Because the rod is at rest, the magnitude of the force exerted by the pivot is equal to the sum of the forces $F_1$ and $F_2$. 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.

_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 $F_1$ and $F_2$ are equal in magnitude, and the magnitude of $F_3$ 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?
The lever arm distances must now be determined relative to the left end of the rod. The lever arm distance of $F_1$ 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, $F_2$ causes a negative torque about the left end of the rod; the force $F_2'$ exerted by the pivot causes a positive torque about the left end of the rod. The lever arm distance of $F_2'$ about the left end of the rod is $r_1 + r_2$ that of $F_2''$. Since the rod is at rest, the magnitude of the force exerted by the pivot is equal to the sum of the forces $F_1$ and $F_2$. 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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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.

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 lever 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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The lever arm distances must now be determined relative to the left end of the rod. The lever arm distance of $F_1$ 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, $F_2$ causes a negative torque about the left end of the rod; the force $F_2'$, exerted by the pivot causes a positive torque about the left end of the rod. The lever arm distance of $F_2'$ about the left end of the rod is $r_1 + r_2$; that of $F_2''$ 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 $F_1$ and $F_2$. 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 as 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.

**12.2 Torques on lever**

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 $F_1$ and $F_2$ are equal in magnitude, and the magnitude of $F_3$ 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?
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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.

View conversation
This comment helps my understanding
email notifications

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option 1: reply
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option 2: view chat

View conversation  This comment helps my understanding
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If this helps your understanding, click the button below. If you want to respond, simply reply to the conversation! You can also mark this comment as answered.

option 3: mark as answered
how to get students to participate?
use combination of intrinsic and extrinsic motivation drivers
rubric-based assessment

• quality (thoughtful reading & interpretation)
rubric-based assessment

- **quality** (thoughtful reading & interpretation)

- **quantity** (minimum 10)
rubric-based assessment

- **quality (thoughtful reading & interpretation)**
- **quantity (minimum 10)**
- **timeliness (before class)**
rubric-based assessment

• quality (thoughtful reading & interpretation)
• quantity (minimum 10)
• timeliness (before class)
• distribution (not clustered)
rubric-based assessment

- quality (thoughtful reading & interpretation)
- quantity (minimum 10)
- timeliness (before class)
- distribution (not clustered)

over 20,000 annotations!
rubric-based assessment

- quality (thoughtful reading & interpretation)
- timeliness (before class)
- distribution (not clustered)

how do you process all of that??

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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 any other point. 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:

1. For a stationary object, the sum of the torques is zero.
2. For a rotating object, the sum of the torques is not zero, but it is equal to the torque of the forces that cause the rotation.

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 exereted at the reference point. So, by setting the reference point at the point of zero sum of torques, we can eliminate that force from the calculation.

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rubric-based assessment

- quality (thoughtful reading & interpretation)
- quantity (minimum 10)
- timeliness (before class)
- distribution (not clustered)

How do you process all of that??

fully automated assessment
fully automated assessment

- specialized machine learning algorithm
- assesses intellectual content
- exceeds intercoder reliability

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 see that the result is the same. The lever arm is of the torques is not affected by the choice of the reference point. However, the sum of the torques is the zero point. In general, we can say:

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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 if torques cause objects to accelerate rotationally?

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# Gradebook

Click on a grade to see details about the student’s assignment.

<table>
<thead>
<tr>
<th>Student Name</th>
<th>Student ID</th>
<th>Chapter 1</th>
<th>Chapter 2</th>
<th>Chapter 3</th>
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</thead>
<tbody>
<tr>
<td>John Smith</td>
<td>3</td>
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<tr>
<td>Jane Doe</td>
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<td>Alice White</td>
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<tr>
<td>Robert grey</td>
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[Release to students]
Gradebook

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<td>6</td>
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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
connect pre-class and in-class activities
Confusion report for Chapter 24

right hand rule (11 questions)

- JB: Can someone in simpler terms explain the right-hand rule?
- 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?

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.
- AB: How can you determine which direction the magnetic field will point towards?
- 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?

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 earth's magnetic field? They kind of look similar to me.
Intrinsic:

- social interaction

motivating factors
motivating factors

Intrinsic:

• social interaction

• tie-in to in-class activity
motivating factors

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

Extrinsic:
- assessment (fully automated)
research data

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There is a graph showing the percentage of students who missed a certain number of chapters before class. The x-axis represents the number of chapters missed (0 to 6), and the y-axis represents the percent of students.
research data

close to 95%!
Every student prepared for every class.
Let's do a live demo together
• sign on to http://app.perusall.com
• enter access code WEBINAR
• click on “Chapter 4”
• scroll to second page
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.

[Diagram of velocity-versus-time graph]

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?
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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?
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.

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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_{bullet} = (0.010 \text{ kg})(1300 \text{ m/s}) = 13 \text{ kg} \cdot \text{m/s}
- p_{bowling} = (6.5 \text{ kg})(4.0 \text{ m/s}) = 26 \text{ kg} \cdot \text{m/s}.

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

\[ p_{ax,2} - p_{ax,1} + p_{bx,1} - p_{bx,2} = 0. \]  

If we write \( \Delta p_{ax} = p_{ax,2} - p_{ax,1} \) and \( \Delta p_{bx} = p_{bx,2} - p_{bx,1} \), Eq. 4.8 takes on the beautifully simple form

\[ \Delta p_{ax} + \Delta p_{bx} = 0. \]

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 \( v_{ax} = +0.032 \text{ m/s} \) and \( v_{bx} = -0.039 \text{ m/s} \), what are the inertias of the red and the blue carts?

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).

Figure 4.18  (a) Initial  \[ v_1 \]  \[ v_2 = 0 \]  \[ v_1' = v_2' = 0 \]  \[ v_3 ' \]  \[ v_4 ' \]  (b) Final
CHAPTER 4 MOMENTUM

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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 bumping across the floor at 4.0 m/s.

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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 \( \dot{v} = \dot{r} \).

\[
\text{Execute plan. Substituting the values given in the problem statement, I get}
\]

\[
p_{\text{bullet}} = (0.010 \text{ kg})(1300 \text{ m/s}) = 13 \text{ kg} \cdot \text{m/s}
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3. 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.

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

\[
\Delta p_{x,d} = p_{x,d} - p_{x,d'} = 0.
\]

If we write \( \Delta p_{x,i} = p_{x,i} - p_{x,i'} \) and \( \Delta p_{x,i} = p_{x,i} - p_{x,i'} \), Eq. 4.8 takes on the beautifully simple form

\[
\Delta p_{x,i} + \Delta p_{x,i'} = 0.
\]

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.

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CHAPTER 4  MOMENTUM

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

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

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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.

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\[
\Delta p_{\text{x,bul}} - \Delta p_{\text{x,ball}} + \Delta p_{\text{x,bul}} + \Delta p_{\text{x,ball}} = 0,
\]

If we write \( \Delta p_{\text{x,ul}} = p_{\text{x,ul}} - p_{\text{x,li}} \) and \( \Delta p_{\text{x,ul}} = p_{\text{x,ul}} - p_{\text{x,li}} \), Eq. 4.8 takes on the beautifully simple form

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Figure 4.18  (a) Initial \( \vec{v}_1 \) \( \vec{v}_2 = 0 \) (b) Final \( \vec{v}_1 \) \( \vec{v}_2 \)
CHAPTER 4: MOMENTUM

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If we write \( \Delta p_{\text{xf}} = p_{\text{xf}} - p_{\text{xi}} \) and \( \Delta p_{\text{xi}} = p_{\text{xf}} - p_{\text{xi}} \), Eq. 4.8 takes on the beautifully simple form

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4.2 Inertia
CHAPTER 4: MOMENTUM

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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
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.

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4.1 Friction

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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.

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:

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4.2 Inertia
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- **Engagement:** 81% spend 2–6 hrs/wk reading
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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 \( F_2 \) to this point is zero, and so the torque caused by that force about the left end of the rod is zero. If \( F_1 \) is chosen counterclockwise as the positive direction of rotation, \( F_2 \) causes a negative torque about the left end of the rod; the force \( F_2 \), exerted by the pivot causes a positive torque about the left end of the rod. The lever arm distance of \( F_2 \) about the left end of the rod is \( r_1 + r_2 \) that of \( F_1 \), \( r_2 \). Because the rod is at rest, the magnitude of the force exerted by the pivot is equal to the sum of the forces \( F_1 \) and \( F_2 \). Taking into account the signs of the torques, we find that the sum of the torques about the left end of the rod is

\[
( r_1 + r_2 ) F_2 - ( r_1 + r_2 ) F_1 = - ( r_1 - r_2 ) F_1 - r_2 F_2.
\]

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 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 Torques on lever

Three forces are exerted on the lever of Figure 12.7. Forces \( F_1 \) and \( F_2 \) are equal in magnitude, and the magnitude of \( F_3 \) is half as great. Force \( F_2 \) is horizontal, \( F_3 \) and \( F_2 \) 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?

### Orientation-based description

- On the very left, we see th...
- It's interesting that the white ...
- Is the reference frame i...
- How does force affect ... (2)
- I was curious about this, t...
- I understand partially w...
- In this class, we always em...
- Part before this wa...
- The extended free-body d...
- This just means the net ...
- I don't understand why ... (3)
- It is important to note that...
- This reminds me of when we ...
- Torque is the ability of a for...
- 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 ... (3)
- Orientation-based description...
- I don't really understa...
- How small is small? As ... (2)
- I think it would be slightly ...
- While I believe I underst...
- (a) The change in rotatinga...
- As we saw earlier in the chap...
- Objects executing motion ar...
- Generally, for rotating bod...
- Does torque have the s...
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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 $F_1$ 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, $F_1$ causes a negative torque about the left end of the rod; the force $F_2$, exerted by the pivot causes a positive torque about the left end of the rod. The lever arm distance of $F_2$ about the left end of the rod is $r_2 + r_1$ that of $F_1$, 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 $F_1$ and $F_2$. Taking into account the signs of the torque, we find that the sum of the torques about the left end of the rod is $r_1(F_1 + F_2) - (r_1 + r_2)F_2 = r_1 F_1 - r_1 F_2$. 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.

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12.2 In the situation depicted in Figure 12.2a, you must continue to exert a force on the seashore to keep the child off the ground. The force you exert causes a torque on the seashore and yet the seashore'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 $F_1$ and $F_2$ are equal in magnitude, and the magnitude of $F_3$ 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?
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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 $r F_1$ and as $r F$.

Like other rotational quantities, torque carries a sign that depends on the choice of direction for increasing $\theta$. In Figure 12.4, for example, the torque caused by $F_1$ about the pivot tends to rotate the rod in the direction of increasing $\theta$ and so is positive; the torque caused by $F_2$ is negative. The sum of the two torques about the pivot is then $r_1 F_1 + (-r_2 F_2)$. 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 $F_1$ 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, $F_1$ causes a negative torque about the left end of the rod; the force $F_2$, exerted by the pivot causes a positive torque about the left end of the rod. The lever arm distance of $F_2$ about the left end of the rod is $r_1 + r_2$ that of $F_1$. Because the rod is at rest, the magnitude of the force exerted by the pivot is equal to the sum of the forces $F_1$ and $F_2$. Taking into account the signs of the torques, we find that the sum of the torques about the left end of the rod is $\eta_1 F_1 + (r_1 + r_2) F_2 = r_1 F_1 - r_2 F_2$. This is the same result we obtained for the torque about the pivot, and so the sum of the torques about the left end is zero.

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