# 6 Momentum

6.1 Momentum
6.2 Impulse
6.3 Impulse Changes Momentum
    Case 1: Increasing Momentum
    Case 2: Decreasing Momentum Over a Long Time
    Case 3: Decreasing Momentum Over a Short Time
6.4 Bouncing
6.5 Conservation of Momentum
6.6 Collisions
6.7 More Complicated Collisions

Rising physics star Derek Muller rises to the occasion in the first of the photos that open this chapter. And the personal profile is of Derek also. The second photo is of friend from school days, physics teacher Howie Brand. The physics he shows applies nicely to the Pelton wheel. The photo below is of grandson Alex.

This chapter begins where Chapter 5 leaves off. Newton's 2nd and 3rd laws lead directly to momentum and its conservation. We emphasize the impulse-momentum relationship with applications to many examples that have been selected to engage the students' interest. In your classroom I suggest the exaggerated symbol technique as shown in Figures 6.5, 6.6, and 6.8. Draw a comparison between momentum conservation and Newton's 3rd law in explaining examples such as rocket propulsion. You might point out that either of these is fundamental—i.e., momentum conservation may be regarded as a consequence of Newton's 3rd law, or equally, Newton's 3rd law may be regarded as a consequence of momentum conservation.

The increased impulse that occurs for bouncing collisions is treated very briefly and is expanded in the next chapter. Angular momentum is postponed to Chapter 8.

Interesting fact: The time of contact for a tennis ball on a racquet is about 5 milliseconds, whether or not a player "follows through." The idea that follow-through in tennis, baseball, or golf appreciably increases the duration of contact is useful pedagogy and gets the point of extended time across. But it is not supported by recent studies. Follow-through is more important in guiding one's behavior in applying maximum force to supply the impulse.

The swinging ball apparatus (Newton's cradle) shown in the sketch is popular for demonstrating momentum conservation. But any thorough analysis of it ought to be postponed to the next chapter when energy is treated. This is because the question is often raised, "Why cannot two balls be raised and allowed to swing into the array, and one ball emerge with twice the speed?" Be careful. Momentum would indeed be conserved if this were the case. But the case with different numbers of balls emerging never happens. Why? Because energy would not be conserved. For the two-balls-one-ball case, the KE after would be twice as much as the KE before impact. KE is proportional to the square of the speed, and the conservation of both momentum and KE cannot occur unless the numbers of balls for collision and ejection are the same. Consider postponing this demo until the next chapter.

A system is not only isolated in space, but in time also. When we say that momentum is conserved when one pool ball strikes the other, we mean that momentum is conserved during the brief duration of interaction when outside forces can be neglected. After the interaction, friction quite soon brings both balls to a halt. So when we isolate a system for purposes of analysis, we isolate both in space and in time. System identification is developed in *Systems*, in the Practicing Physics Book.

You may want to assign an “Egg Drop” experiment. Students design and construct a case to hold an egg that can and will be dropped from a three-or-four story building without breaking. The design cannot include means to increase air resistance, so all cases should strike the ground with about the same speed. By requiring the masses of all cases to be the same, the impulses of all will be the same upon impact. The force of impact, of course, should be minimized by maximizing the time of impact. Or do as Peter Hopkinson does (Think and Explain 56), and simply have students toss eggs into cloth sheets, suspended so the eggs don’t hit the floor after impact. Either of these projects stir considerable interest, both for your students and others who are not (yet?) taking your class.

In 2009 40-year old Paul Lewis from the UK survived a 10,000-foot skydiving fall after his parachute failed to open. Amazingly, he landed on the roof of an aircraft hanger that broke his fall and flexed sufficiently to reduce impact. That’s a wonderful $Ft = \Delta mv$ in action!

An economy air track is available from Arbor Scientific (P4-2710).

**Practicing Physics Book**:
- Changing Momentum
- Systems

**Problem Solving Book**:
Many problems on impulse, momentum, and the impulse-momentum relationship

**Laboratory Manual**:
- Bouncy Board *Impact Time and Impact Force* (Activity)

**Next-Time Questions** include:
- Car Crash
- Ice Sail craft
- Ball Catch

**Hewitt-Drew-It! Screencasts**:
- *Momentum*
- *Conservation of Momentum*
- *Fish-Lunch Problem*
- *Freddy-Frog Momentum Problem*

This chapter is important in its own right, and serves as a foundation for the concept of energy in the next chapter.

## SUGGESTED LECTURE PRESENTATION

### Momentum

Begin by stating that there is something different between a Mack truck and a roller skate—they each have a different inertia. And that there is still something different about a moving Mack truck and a moving roller skate—they have different momenta. Define and discuss momentum as inertia in motion.

> CHECK QUESTION: After stating that a Mack truck will always have more inertia than an ordinary roller skate, ask if a Mack truck will always have more momentum than a roller skate. [Only when *mv* for the truck is greater than *mv* for the skate.]

Cite the case of the supertanker shown in Figure 6.2, and why such huge ships normally cut off their power when they are 25 or so kilometers from port. Because of their huge momentum (due mostly to their huge mass), about 25 kilometers of water resistance are needed to bring them to a halt.

### Impulse and Momentum

Derive the impulse-momentum relationship. In Chapter 3 you defined acceleration as $a = \Delta v/t$ (really $\Delta t$, but you likely used $t$ as the "time interval"). Then later in Chapter 4 you defined acceleration in terms of the force needed, $a = F/m$. Now simply equate; $a = a$, or $F/m = \Delta v/t$, with simple rearrangement you have, $Ft = \Delta mv$ (as in the footnote in the textbook on page 92).

Then choose your examples in careful sequence: First, those where the objective is to increase momentum—pulling a slingshot or arrow in a bow all the way back, the effect of a long cannon for maximum range, driving a golf ball. Second, those examples where small forces are the objective when decreasing momentum—pulling your hand backward when catching a ball, driving into a haystack versus a concrete wall, falling on a surface with give versus a rigid surface. Then lastly, those examples where the objective is to obtain large forces when deceasing momentum—karate. Karate is more properly called "tae kwon do."

Point of confusion: In boxing, one "follows-through" whereas in karate one "pulls back." But this is not so—a karate expert does not pull back upon striking his target. He or she strikes in such a way that the hand is made to *bounce* back, yielding up to twice the impulse to the target (just as a ball bouncing off a wall delivers nearly twice the impulse to the wall than if it stuck to the wall).

> CHECK QUESTION: Why is falling on a wooden floor in a roller rink less dangerous than falling on the concrete pavement? [Superficial answer: Because the wooden floor has more "give." Emphasize that this is the beginning of a fuller answer—one that is prompted if the question is reworded as follows:] Why is falling on a floor with more give less dangerous than falling on a floor with less give? [Answer: Because the floor with more give allows a greater time for the impulse that reduces the momentum of fall to zero. The greater time occurs because Δ*momentum* means less force.]

The loose coupling between railroad cars (Think and Discuss 88) makes good lecture topic. Discuss the importance of loose coupling in bringing a long train initially at rest up to speed, and its importance in braking the train as well. In effect the time factor in impulse is extended. The force needed to produce motion is therefore decreased.
(I compare this to taking course load in proper sequence, rather than all at once where for sure one's wheels would likely spin.)

### Conservation of Momentum

Distinguish between external and internal forces and progress to the conservation of momentum. Show from the impulse-momentum equation that no change in momentum can occur in the absence of an external net force.

> DEMONSTRATION: Show momentum conservation with an air-track performance. Doing so can be the focus of your lecture presentation.

### Defining Your System

Momentum is not conserved in a system that experiences an external net force. This is developed in *Systems* in the Practicing Physics book (next page, which is credited to Cedric Linder, the instructor profiled in Chapter 2). The momentum of a system is conserved only when no external impulse is exerted on the system. As the example of the girl jumping from the Earth's surface suggests, momentum is always conserved if you make your system big enough. Likewise when you jump up and down.
The momentum of the universe is without change.

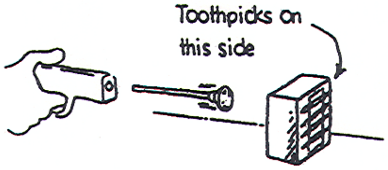
The numerical example of lunchtime for the fish in Figure 6.17 should clarify the vector nature of momentum—particularly for the case of the fishes approaching each other. Going over this should be helpful—Think and Solve 35, and Think and Rank 42 on pages 104 and 105, for example. Vehicles, rather than fish, are treated similarly.

**Bouncing**
When discussing bouncing, tell how the inventor of the Pelton wheel, Lester Pelton, made a fortune from applying some simple physics to the old paddle wheels. Fortunately for him, he patented his ideas and was one of the greatest financial beneficiaries of the Gold Rush Era in San Francisco.

Bouncing does not necessarily increase impact force. That depends on impact time. Point out that bouncing involves some reversing of momentum, which means greater momentum change, and hence greater impulse. If the greater impulse is over an extended time (bouncing from a circus net), impact force is small. If over a short time (plant pot bouncing from your head), impact force is large. Damage from an object colliding with a person may depend more on energy transfer than on momentum change, so in some cases damage can be greater in an inelastic collision without bouncing.

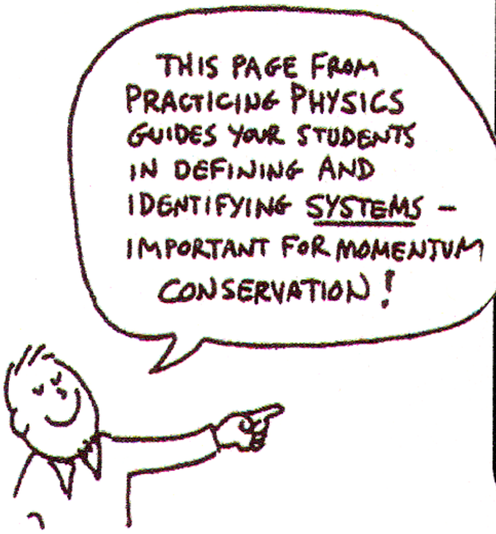
Consider the demo of swinging a dart against a wooden block, as Howie Brand does in the photo that opens this chapter, showing the effect of bouncing. A weak point of this demonstration is the fact that if the dart securely sticks to the block, then the center of gravity of the block is changed to favor non-tipping. This flaw is neatly circumvented by the following demo by Rich Langer of Beaumont High School in St. Louis, MO, which considers sliding rather than tipping.

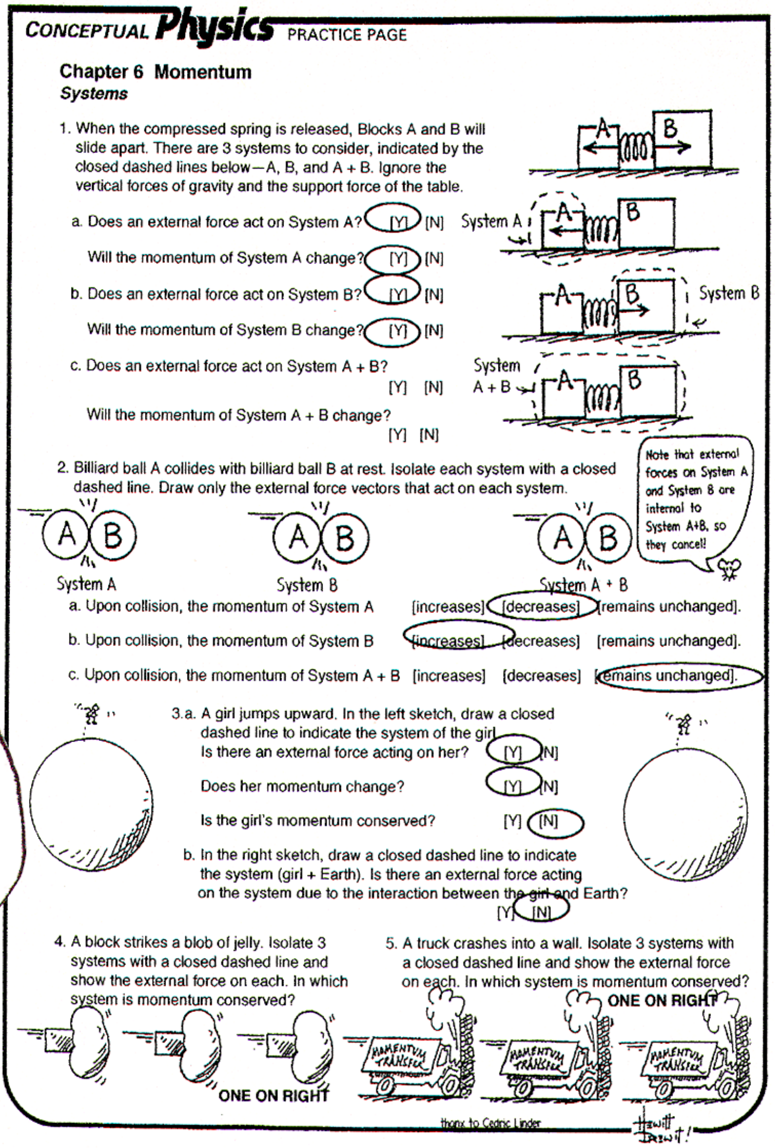
> DEMONSTRATION: Toy dart gun and block of wood. Tape some toothpicks to only one side of the block, so a suction-cup dart won't stick to it. First fire the dart against the smooth side of the block. The dart sticks and the block slides an observed distance across the table. Then repeat, but with the block turned around so the dart hits the toothpick side. When the dart doesn't stick but instead bounces, note the appreciably greater distance the block slides!



Or do as Fred Bucheit does and fashion a pendulum using the "happy-unhappy" rubber balls and let them swing into an upright board. When the less-elastic ball makes impact, with very little bounce, the board remains upright. But when the more-elastic ball makes impact, it undergoes a greater change in momentum as it bounces. This imparts more impulse to the board, and it topples.

Think and Discuss 94-96 may need your elaboration if you wish to go this deep in your lecture. Simply removing the sail, as 94 suggests, is the option used by propeller-driven aircraft. Consider suddenly producing a sail in the airstream produced by the propeller of an airplane. The result would be a loss of thrust, and if bouncing of the air occurred, there would be a reverse thrust on the craft. This is precisely what happens in the case of jet planes landing on the runway. Metal "sails" move into place behind the engine in the path of the ejected exhaust, which cause the exhaust to reverse direction. The resulting reverse thrust appreciably slows the aircraft.





**CONCEPTUAL Physics** PRACTICE PAGE

## Chapter 6 Momentum

### *Systems*

1. When the compressed spring is released, Blocks A and B will slide apart. There are 3 systems to consider, indicated by the closed dashed lines below—A, B, and A + B. Ignore the vertical forces of gravity and the support force of the table.

   a. Does an external force act on System A? [✓ Y] [N]

   Will the momentum of System A change? [✓ Y] [N]

   b. Does an external force act on System B? [✓ Y] [N]

   Will the momentum of System B change? [✓ Y] [N]

   c. Does an external force act on System A + B? [Y] [N]

   Will the momentum of System A + B change? [Y] [N]

2. Billiard ball A collides with billiard ball B at rest. Isolate each system with a closed dashed line. Draw only the external force vectors that act on each system.

   a. Upon collision, the momentum of System A [increases] [✓ decreases] [remains unchanged].

   b. Upon collision, the momentum of System B [✓ increases] [decreases] [remains unchanged].

   c. Upon collision, the momentum of System A + B [increases] [decreases] [✓ remains unchanged].

3.a. A girl jumps upward. In the left sketch, draw a closed dashed line to indicate the system of the girl.

   Is there an external force acting on her? [✓ Y] [N]

   Does her momentum change? [✓ Y] [N]

   Is the girl's momentum conserved? [Y] [✓ N]

   b. In the right sketch, draw a closed dashed line to indicate the system (girl + Earth). Is there an external force acting on the system due to the interaction between the girl and Earth? [Y] [✓ N]

4. A block strikes a blob of jelly. Isolate 3 systems with a closed dashed line and show the external force on each. In which system is momentum conserved?

ONE ON RIGHT

5. A truck crashes into a wall. Isolate 3 systems with a closed dashed line and show the external force on each. In which system is momentum conserved?

ONE ON RIGHT

thanx to Cedric Linder

Hewitt Drew it!

# Answers and Solutions for Chapter 6

## Reading Check Questions

1. The moving skateboard has more momentum since only it is moving.
2. Impulse is force x time, not merely force.
3. Impulse can be increased by increasing force or increasing time of application.
4. More speed is imparted because the force on the cannonball acts for a longer time.
5. The impulse-momentum relationship is derived from Newton's second law.
6. For greatest increase in momentum, use both the largest force for the longest time.
7. Less force will occur if momentum is decreased over a long time.
8. When the momentum of impact is quick, less time means more force.
9. By rolling with the punch, more time of impact occurs, which means a less forceful punch.
10. Choice (c) represents the greatest change in momentum.
11. Choice (c) also represents the greatest impulse.
12. Only external forces produce changes in momentum, so sitting in a car and pushing on the dash is an internal force, and no momentum change of the car occurs. Likewise with the internal forces within a baseball.
13. Yes, the statement is correct.
14. To say a quantity is conserved is to say its magnitude before an event is the same as its magnitude after the event. Momentum in a collision, for example is the same before and after providing no external forces act.
15. Momentum would not be conserved if force, and therefore impulse, was not a vector quantity.
16. Momentum is conserved in both an elastic and an inelastic collision.
17. Car B will have the speed of Car A before the collision.
18. After collision, the cars will move at half the initial speed of Car A.
19. Since they are same-magnitude vectors at right angles to each other, the combined momentum is $\sqrt{2}$ kg·m/s.
20. The total momentum before and after collision is the same, $\sqrt{2}$ kg·m/s.

## Think and Do

21. Open ended.

## Plug and Chug

22. Momentum ($p$) = $mv$ = (8 kg)(2 m/s) = 16 kg·m/s.

23. $p = mv$ = (50 kg)(4 m/s) = 200 kg·m/s.

24. $I$ = (10 N)(2.5 s) = 25 N·s.

25. $I$ = (10 N)(5 s) = 50 N·s.

26. $I = \Delta mv$ = (8 kg)(2 m/s) = 16 kg·m/s = 16 N·s.

27. $I = \Delta mv$ = (50 kg)(4 m/s) = 200 kg·m/s = 200 N·s.

28. From $mv_{\text{bef}} + 0 = (m + m)v_{\text{aft}}$; $v_{\text{aft}} = mv_{\text{bef}}/2m = v_{\text{bef}}/2$ = (3 m/s)/2 = 1.5 m/s.

## Think and Solve

29. The bowling ball has a momentum of (10 kg)(6 m/s) = 60 kg·m/s, which has the magnitude of the impulse to stop it. That's 60 N·s. (Note that units N·s = kg·m/s.)
30. From $Ft = \Delta mv$, $F = \dfrac{\Delta mv}{t}$ = [(1000 kg)(20 m/s)]/10 s = 2000 N.
31. From $Ft = \Delta mv$, $F = \dfrac{\Delta mv}{t}$ = [(75 kg)(25 m/s)]/0.1 s = 18,750 N.
32. From the conservation of momentum,

Momentum$_{\text{dog}}$ = momentum$_{\text{Judy + dog}}$
(15 kg)(3.0 m/s) = (40.0 kg + 15 kg)$v$
45 kg m/s = (55 kg) $v$ , so $v$ = 0.8 m/s.

33. Momentum after collision is zero, which means the net momentum before collision must have been zero. So the 1-kg ball must be moving twice as fast as the 2-kg ball so that the magnitudes of their momenta are equal.

34. Let *m* be the mass of the freight car, and 4*m* the mass of the diesel engine, and *v* the speed after both have coupled together. Before collision, the total momentum is due only to the diesel engine, 4*m*(5 km/h), because the momentum of the freight car is 0. After collision, the combined mass is (4*m* + *m*), and combined momentum is (4*m* + *m*)*v*. By the conservation of momentum equation:

Momentum$_{\text{before}}$ = momentum$_{\text{after}}$

$$4m(5 \text{ km/h}) + 0 = (4m + m)v$$

$$v = \frac{(20m\cdot\text{km/h})}{5m} = 4 \text{ km/h}$$

(Note that you don't have to know *m* to solve the problem.)

35. Momentum$_{\text{before}}$ = momentum$_{\text{after}}$

$$(5 \text{ kg})(1 \text{ m/s}) + (1 \text{ kg})v = 0$$

$$5 \text{ m/s} + v = 0$$

$$v = -5 \text{ m/s}$$

So if the little fish approaches the big fish at 5 m/s, the momentum after will be zero.

36. By momentum conservation,

asteroid mass × 800 m/s = Superman's mass × *v*.

Since asteroid's mass is 1000 times Superman's,

$(1000m)(800 \text{ m/s}) = mv$

$v = 800{,}000$ m/s. This is nearly 2 million miles per hour!

37. Momentum conservation can be applied in both cases.

(a) For head-on motion the total momentum is zero, so the wreckage after collision is motionless.

(b) As shown in Figure 6.18, the total momentum is directed to the northeast—the resultant of two perpendicular vectors, each of magnitude 20,000 kg·m/s. It has magnitude 28,200 kg·m/s. The speed of the wreckage is this momentum divided by the total mass, $v = (28{,}200 \text{ kg·m/s})/(2000 \text{ kg}) = 14$ m/s.

38. (a,b) From $Ft = \Delta p = mv \Rightarrow F = \frac{mv}{t} = \frac{(1\text{ kg})(2\text{ m/s})}{(0.2\text{s})} = 10\text{ kg}\cdot\text{m/s}^2 = 10\text{ N}$.

## Think and Rank

39. a. B, D, C, A
    b. B, D, C, A
40. a. B=D, A=C
    b. D, C, A=B
41. a. A, B, C
    b. A, B, C
    c. C, B, A
    d. A, B, C
42. C, A, B

## Think and Explain

43. The momentum of a supertanker is enormous, which means enormous impulses are needed for changing motion—which are produced by applying modest forces over long periods of time. Due to the force of water resistance, over time it coasts 25 kilometers to sufficiently reduce the momentum.

44. When you are brought to a halt in a moving car, an impulse, the product of force and time, reduces your momentum. During a collision, padded dashboards increase the time of impact while reducing the force of impact. The impulse equals your change in momentum.

45. Air bags lengthen the time of impact thereby reducing the force of impact.

46. The extra thickness extends the time during which momentum changes and reduces impact force.

47.Stretching ropes extend the time during which momentum decreases, thereby decreasing the jolting force of the rope. Note that bringing a person to a stop more gently does *not* reduce the impulse. It only reduces the force.

48.The steel cord will stretch only a little, resulting in a short time of stop and a correspondingly large force. Ouch!

49.Bent knees will allow more time for momentum to decrease, therefore reducing the force of landing.

50.The time during which the stopping force acts is different for the different situations. Stopping time is least on concrete and most on water, hence the different impact speeds. So there are three concepts; speed at impact, time of impact, and force of impact—which are all related by the impulse-momentum relationship.

51.An extended hands allow more time for reducing the momentum of the ball to zero, resulting in a smaller force of impact on your hand.

52. The time during which the ball stops is small, producing a greater force.

53.Crumpling allows more time for reducing the momentum of the car, resulting in a smaller force of impact on the occupants.

54.The blades impart a downward impulse to the air and produce a downward change in the momentum of the air. The air at the same time exerts an upward impulse on the blades, providing lift. (Newton's third law applies to impulses as well as forces.)

55.Its momentum is the same (its weight might change, but not its mass).

56.The egg hitting the sagging sheet has a longer impact time, which decreases the force that would otherwise break it.

57.The large momentum of the spurting water is met by a recoil that makes the hose difficult to hold, just as a shotgun is difficult to hold when it fires birdshot.

58.Not a good idea. The gun would recoil with a speed ten times the muzzle velocity. Firing such a gun in the conventional way would not be a good idea!

59.Impulse is force × time. The forces are equal and opposite, by Newton's third law, and the times are the same, so the impulses are equal and opposite.

60.The momentum of recoil of Earth is 10 kg m/s. Again, this is not apparent because the mass of the Earth is so enormous that its recoil velocity is imperceptible. (If the masses of Earth and person were equal, both would move at equal speeds in opposite directions.)

61. The momentum of the falling apple is transferred to the Earth. Interestingly, when the apple is released, the Earth and the apple move toward each other with equal and oppositely directed momenta. Because of the Earth's enormous mass, its motion is imperceptible. When the apple and Earth hit each other, their momenta are brought to a halt—zero, the same value as before.

62. There is usually greater speed and therefore impact on a catcher's mitt than the mitts of other players. That's why extra padding is used to prolong the time of the impulse to stop the ball and lessen the catching force.

63.The lighter gloves have less padding, and less ability to extend the time of impact, and therefore result in greater forces of impact for a given punch.

64. In jumping, you impart the same momentum to both you and the canoe. This means you jump from a canoe that is moving away from the dock, reducing your speed relative to the dock, so you don't jump as far as you expected to.

65.The swarm will have a net momentum of zero if the swarm stays in the same location; then the momenta of the many insects cancel and there is no net momentum in any given direction.

66. To get to shore, the person may throw keys, coins or an item of clothing. The momentum of what is thrown will be accompanied by the thrower's oppositely-directed momentum. In this way, one can recoil towards shore. (One can also inhale facing the shore and exhale facing away from the shore.)

67. If no momentum is imparted to the ball, no oppositely directed momentum will be imparted to the thrower. Going through the motions of throwing has no net effect. If at the beginning of the throw you begin recoiling backward, at the end of the throw when you stop the motion of your arm and hold onto the ball, you stop moving too. Your position may change a little, but you end up at rest. No momentum given to the ball means no recoil momentum gained by you.

68. Regarding Question 66: If one throws clothing, the force on the clothes will be paired with an equal and opposite force on the thrower. This force can provide recoil toward shore. Regarding Question 67: According to Newton's third law, whatever forces you exert on the ball, first in one direction, then in the other, are balanced by equal forces that the ball exerts on you. Since the forces on the ball give it no final momentum, the forces it exerts on you also give no final momentum.

69. Both recoiling carts have the same amount of momentum. So the cart with twice the mass will have half the speed of the less massive cart. That is, $2m(v/2) = mv$.

70. An impulse is responsible for the change in momentum, resulting from a component of gravitational force parallel to the inclined plane.

71. Momentum is not conserved for the ball itself because an impulse is exerted on it (gravitational force × time). So the ball gains momentum. Only in the *absence* of an external force does momentum not change. If the whole Earth and the rolling ball are taken together as a system, then the gravitational interaction between Earth and the ball are internal forces and no external impulse acts. Then the change of momentum of the ball is accompanied by an equal and opposite change of momentum of Earth, which results in no change in momentum.

72. A system is any object or collection of objects. Whatever momentum such a system has, in the absence of external forces, that momentum remains unchanged—what the conservation of momentum is about.

73. For the system comprised of only the ball, momentum changes, and is therefore not conserved. But for the larger system of ball + Earth, momentum is conserved for the impulses acting are internal impulses. The change of momentum of the ball is equal and opposite to the change of momentum of the recoiling Earth.

74. For the system comprised of ball + Earth, momentum is conserved for the impulses acting are internal impulses. The momentum of the falling apple is equal in magnitude to the momentum of the Earth toward the apple.

75. If the system is the stone only, its momentum certainly changes as it falls. If the system is enlarged to include the stone plus the Earth, then the downward momentum of the stone is cancelled by the equal but opposite momentum of the Earth "racing" up to meet the stone.

76. Yes, because you push upward on the ball you toss, which means the ball pushes downward on you, which is transmitted to the ground. So normal force increases as the ball is thrown (and goes back to equal $mg$ after the ball is released). Likewise, in catching the ball you exert an upward force while stopping it, which is matched by a downward force by your feet on the ground, which increases the normal force.

77. By Newton's 3rd law, the force on the bug is equal in magnitude and opposite in direction to the force on the car windshield. The rest is logic: Since the time of impact is the same for both, the amount of impulse is the same for both, which means they both undergo the same change in momentum. The change in momentum of the bug is evident because of its large change in speed. The same change in momentum of the considerably more massive car is not evident, for the change in speed is correspondingly very small. Nevertheless, the magnitude of $m\Delta V$ for the bug is equal to $M\Delta v$ for the car!

78. In accord with Newton's third law, the forces on each are equal in magnitude, which means the impulses are likewise equal in magnitude, which means both undergo equal changes in momentum.

79. The magnitude of force, impulse, and change in momentum will be the same for each. The MiniCooper undergoes the greater deceleration because its mass is less.

80. Cars brought to a rapid halt experience a change in momentum, and a corresponding impulse. But greater momentum change occurs if the cars bounce, with correspondingly greater impulse and therefore greater damage. Less damage results if the cars stick upon impact than if they bounce apart.

81. The direction of momentum is to the left, for the momentum of the 0.8-kg car is greater. By magnitude, net momentum = (0.5)(1) – (0.8)(1.2) = -0.46.

82. The combined momentum is √2 times the magnitude of that of each cart before collision.

83. Momentum conservation is being violated. The momentum of the boat before the hero lands on it will be the same as the momentum of boat + hero after. The boat will slow down. If, for example, the masses of the hero and boat were the same, the boat should be slowed to half speed; $mv_{\text{before}} = 2m(v/2)_{\text{after}}$. From an impulse-momentum point of view, when the hero makes contact with the boat, he is moved along with the boat by a friction force between his feet and the boat surface. The equal and opposite friction force on the boat surface provides the impulse that slows the boat. (Here we consider only horizontal forces and horizontal component of momentum.)

84. Yes, you exert an impulse on a ball that you throw. You also exert an impulse on the ball when you catch it. Since you change its momentum by the same amount in both cases, the impulse you exert in both cases is the same. To catch the ball and then throw it back again at the same speed requires twice as much impulse. On a skateboard, you'd recoil and gain momentum when throwing the ball, you'd also gain the same momentum by catching the ball, and you'd gain twice the momentum if you did both—catch and then throw the ball at its initial speed in the opposite direction.

85. The impulse will be greater if the hand is made to bounce because there is a greater change in the momentum of hand and arm, accompanied by a greater impulse. The force exerted on the bricks is equal and opposite to the force of the bricks on the hand. Fortunately, the hand is resilient and toughened by long practice.

### Think and Discuss

86. The impulse required to stop the heavy truck is considerably more than the impulse required to stop a skateboard moving with the same speed. The *force* required to stop either, however, depends on the time during which it is applied. Stopping the skateboard in a split second results in a certain force. Apply less than this amount of force on the moving truck and given enough time, the truck will come to a halt.

87. When a boxer hits his opponent, the opponent contributes to the impulse that changes the momentum of the punch. When punches miss, no impulse is supplied by the opponent—all effort that goes into reducing the momentum of the punches is supplied by the boxer himself. This tires the boxer. This is very evident to a boxer who can punch a heavy bag in the gym for hours and not tire, but who finds by contrast that a few minutes in the ring with an opponent is a tiring experience.

88. Without this slack, a locomotive might simply sit still and spin its wheels. The loose coupling enables a longer time for the entire train to gain momentum, requiring less force of the locomotive wheels against the track. In this way, the overall required impulse is broken into a series of smaller impulses. (This loose coupling can be very important for braking as well.)

89. The internal force of the brake brings the wheel to rest. But the wheel, after all, is attached to the tire which makes contact with the road surface. It is the force of the road on the tires that stops the car.

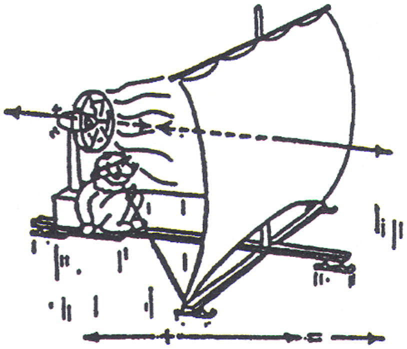
90. If the rocket and its exhaust gases are treated as a single system, the forces between rocket and exhaust gases are internal, and momentum in the rocket-gases system is conserved. So any momentum given to the gases is equal and opposite to momentum given to the rocket. A rocket attains momentum by giving momentum to the exhaust gases.

91. When two objects interact, the forces they exert on each other are equal and opposite and these forces act simultaneously, so the impulses are equal and opposite. Therefore their changes of momenta are equal and opposite, and the total change of momentum of both objects is zero.

92. Let the system be the car and the Earth together. As the car gains downward momentum during its fall, Earth gains equal upward momentum. When the car crashes and its momentum is reduced to zero, Earth stops its upward motion, also reducing its momentum to zero.

93. This exercise is similar to the previous one. If we consider Bronco to be the system, then a net force acts and momentum changes. In this case, momentum is not conserved. If, however we consider the system to be Bronco and the world (including the air), then all the forces that act are internal forces and momentum is conserved. Momentum is conserved only in systems not subject to external forces.

94. The craft moves to the right. This is because there are two horizontal impulses that act on the craft: One is that of the wind against the sail, and the other is that of the fan recoiling from the wind it produces. These impulses are oppositely directed, but are they equal in magnitude? No, because of bouncing. The wind bounces from the sail and produces a greater impulse than if it merely stopped. This greater impulse on the sail produces a net impulse in the forward direction, toward the right. We can see this in terms of forces as well. Note in the sketch there are two force pairs to consider: (1) the fan-air force pair, and (2) the air-sail force pair. Because of bouncing, the air-sail pair is greater. The net force on the craft is forward, to the right. The principle described here is applied in thrust reversers used to slow jet planes after they land. Also, you can see that after the fan is turned on, there is a net motion of air to the left, so the boat, to conserve momentum, will move to the right.



95. If the air is brought to a halt by the sail, then the impulse against the sail will be equal and opposite to the impulse on the fan. There will be no net impulse and no change in momentum. The boat will remain motionless. Bouncing counts!

96. Removing the sail and turning the fan around is the best means of propelling the boat! Then maximum impulse is exerted on the craft. If the fan is not turned around, the boat is propelled backward, to the left. (Such propeller-driven boats are used where the water is very shallow, as in the Florida Everglades.)

97. Bullets bouncing from the steel plate experience a greater impulse. The plate will be moved more by bouncing bullets than by bullets that stick.

98. In terms of force: When Freddy lands on the skateboard he is brought up to the skateboard's speed. This means a horizontal force provided by the board acts on Freddy. By action-reaction, Freddy exerts a force on the board in the opposite direction—which slows the skateboard. In terms of momentum conservation: Since no external forces act in the horizontal direction, the momentum after the skateboard catches Freddy is equal to the momentum before. Since mass is added, velocity must decrease.

99. Agree with the first friend because after the collision the bowling ball *will* have a greater momentum than the golf ball. Note that before collision the momentum of the system of two balls is all in the moving golf ball. Call this +1 unit. Then after collision the momentum of the rebounding golf ball is nearly –1 unit. The momentum (not the speed!) of the bowling ball will have to be nearly +2 units. Why? Because only then is momentum conserved. Momentum before is +1 unit: momentum after is (+2 – 1) = +1.

100. We assume the equal strengths of the astronauts means that each throws with the same speed. Since the masses are equal, when the first throws the second, both the first and second move away from each other at equal speeds. Say the thrown astronaut moves to the right with velocity $V$, and the first recoils with velocity $-V$. When the third makes the catch, both she and the second move to the right at velocity $V/2$ (twice the mass moving at half the speed, like the freight cars in Figure 6.14). When the third makes her throw, she recoils at velocity $V$ (the same speed she imparts to the thrown astronaut) which is added to the $V/2$ she acquired in the catch. So her velocity is $V + V/2 = 3V/2$, to the right—too fast to stay in the game. Why? Because the velocity of the second astronaut is $V/2 - V = -V/2$, to the left—too slow to catch up with the first astronaut who is still moving at $-V$. The game is over. Both the first and the third got to throw the second astronaut only once!

101. Impulse is greater for reflection, which is in effect, bouncing. The vanes therefore recoil more from the silvered sides. The vanes in the sketch therefore rotate clockwise as viewed from above. (This rotation is superseded by a counter rotation when air is present, which is the case for most radiometers. The black surface absorbs radiation and is heated, which warms the nearby air. The surface is pushed away from the warmed air resulting in a recoil that spins the vanes counterclockwise.)

102. Their masses are the same; half speed for the coupled particles means equal masses for the colliding and the target particles. This is like the freight cars of equal mass that collide as shown in Figure 6.14.

103. If a ball does not hit straight on, then the target ball flies off at an angle (to the left, say) and has a component of momentum perpendicular to the ball's initial momentum. To offset this, the striking ball cannot be simply brought to rest, but must fly off in the other direction (say, the right). It will do this in such a way that its sideways component of momentum is equal and opposite to that of the target ball. This means the total sideways momentum is zero—what it was before collision. (Inspect Figure 6.19 and see how the sideways components of momentum cancel to zero.)

104. The chunks have equal and opposite momenta, with the smaller-mass chunk having greater speed ($mV = -Mv$).