5 Newton's Third Law of Motion

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The opening photos begin with Darlene Librero and Paul Doherty, my two dear friends at the Exploratorium, Darlene goes back to the earliest days at the Exploratorium when she worked with Frank Oppenheimer. Paul has been the senior scientist there since the 80s. The caption of the tennis ball and racquet makes an important point, often overlooked by many: The racquet cannot hit the ball *unless* the ball simultaneously hits the racquet! Toby Jacobson, who pushes on the pair of scales with wife Bruna, sat with his mom on my Exploratorium Conceptual Physics class when he was 13 years old. Today, both with physics PhDs, Toby and Bruna continue in their love of physics. The touching photo is of my son Paul and his daughter, my granddaughter Gracie. Hooray for Newton's third law!

The personality profile is of the Exploratorium's senior scientist and good friend Paul Doherty.

Up to here a force is seen as a push or a pull. Newton's third law defines it better—as part of an interaction between one body and another. As the tennis ball and racquet attests, you cannot exert a force on something—*unless*, and I pause, that something exerts an equal and opposite force on you. So you can't hit a ball *unless* the ball hits back. You can't exert a force on the floor when you walk, *unless* the floor exerts the same amount of force back on you, etc. In discussing action and reaction emphasize the word "between," for example, the forces *between* Earth and the Moon.

This chapter continues with a treatment of vectors. Trigonometry, no. The parallelogram rule, yes! Vector components are also treated, which will be needed when projectiles are covered in Chapter 10. Treatment of vectors continues in the Practice Book.

Practicing Physics Book:
- Action and Reaction Pairs
- Interactions
- Vectors and the Parallelogram Rule
- Velocity Vectors and Components
- Force and Velocity Vectors
- Force Vectors and the Parallelogram Rule
- Force-Vector Diagrams
- More on Vectors

Problem Solving Book:
Sample Problems and more, also with optional section on trigonometry instruction

Laboratory Manual:
- The Force Mirror *Quantitative Observations of Force Pairs* (Tech Lab)
- Blowout *Newton's Three Laws* (Demonstration)

Next-Time Questions (in the Instructors Resource DVD):
- Reaction Forces
- Apple on a Table
- Scale Reading
- Tug of War
- Tug of War 2
- Leaning Tower of Pisa Drop
- Apple on Table
- Atwood Pulley
- Airplane in the Wind
- No-Recoil Cannon

Hewitt-Drew-It! Screencasts:
- *Newton's Third Law*
- *Newton's Laws Problem*

SUGGESTED LECTURE PRESENTATION

Forces and Interactions

Hold a piece of tissue paper at arms length and ask if the heavyweight champion of the world could hit the paper with 50 pounds of force. Ask your class to check their answer with their neighbors. Then don't give your answer. Instead, continue with your lecture. Reach out to your class and state, "I can't touch you, without you touching me in return—I can't nudge this chair without the chair in turn nudging me—I can't exert a force on a body without that body in turn exerting a force on me." In all these cases of contact there is a *single* interaction between *two* things—contact requires a *pair* of forces, whether they be slight nudges or great impacts, between *two* things. This is Newton's 3rd law of motion. Call attention to the examples of Figure 5.7.

Newton's Third Law of Motion

Extend your arm horizontally and show the class that you can bend your fingers upward only very little. Show that if you push with your other hand, and thereby apply a force to them, or have a student do the same, they will bend appreciably more. Then walk over to the wall and show that the inanimate wall does the same (as you push against the wall). State that everybody will acknowledge that you are pushing on the wall, but only a few realize the fundamental fact that the wall is simultaneously pushing on you also—as evidenced by your bent fingers.

Do as Linda E. Roach does and place a sheet of paper between the wall and your hand. When you push on the paper, it doesn't accelerate—evidence of a zero net force on the paper. You can explain that in addition to your push, the wall must be pushing just as hard in the opposite direction on the paper to produce the zero net force. Linda recommends doing the same with an inflated balloon, whereupon your class can easily see that both sides of the balloon are squashed.

> CHECK QUESTION: Identify the action and reaction forces for the case of a bat striking the ball.

Action and Reaction on Different Masses

Discuss walking on the floor in terms of the single interaction between you and the floor, and the pair of action and reaction forces that comprise this interaction. Contrast this to walking on frictionless ice, where no interaction occurs. Ask how one could get off a pond of frictionless ice. Make the answer easy by saying one has a massive brick in hand. By throwing the brick there is an interaction between the thrower and the brick. The reaction to the force on the brick, the recoiling force, sends one to shore. Or without such a convenient brick, one has clothing. Or if on clothing, one has air in the lungs. One could blow air in jet fashion. Exhale with the mouth facing away from shore, but be sure to inhale with the mouth facing toward shore.

> CHECK QUESTION: Identify the force that pushes a car along the road. [Interestingly enough, the force that pushes cars is provided by the road. Why? The tires push on the road, action and the road pushes on the tires, reaction. So roads push cars along. A somewhat different viewpoint!]

Most people say that the Moon is attracted to Earth by gravity. Ask most people if Earth is also attracted to the Moon, and if so, which pulls harder, Earth or the Moon? You'll get mixed answers. Physicists think differently than most people on this topic. Rather than saying the Moon is attracted to Earth by gravity, a physicist would say there is an attractive gravitational force between Earth and the Moon.

Asking if the Moon pulls as hard on Earth as Earth pulls on the Moon is similar to asking if the distance between New York and Los Angeles is the same as the distance between Los Angeles and New York. Rather than thinking in terms of two distances, we think of a single distance *between* New York and Los Angeles. Likewise there is a single gravitational interaction between Earth and the Moon.

Support this point by showing your outstretched hand where you have a stretched rubber band between your thumb and forefinger. Ask which is pulling with the greater force, the thumb or the finger. Or, as you increase the stretch, which is being pulled with more force toward the other—the thumb toward the finger or the finger toward the thumb. After neighbor discussion, stress the single interaction between things that pull on each other. Earth and the Moon are pulling on each other. Their pulls on each other comprise a single interaction. This point of view makes a moot point of deciding which exerts the greater force, the Moon on Earth or Earth on the Moon, or the ball on the bat or the bat on the ball, et cetera. Pass a box of rubber bands to your class and have them do it.

> DEMONSTRATION: Tug-of-war in class. Have a team of women engage in a tug-of-war with a team of men. If you do this on a smooth floor, with men wearing socks and women wearing rubber-soled shoes, the women will win. This illustrates that the team who wins in this game is the team who pushes harder on the floor. This is featured at the bottom of page 80.

Discuss the firing of a bullet from a rifle, as treated in the chapter. Illustrate Newton's 3rd law with a skit about a man who is given one last wish before being shot, who states that his crime demands more punishment than being struck by a tiny bullet, who wishes instead that the mass of the bullet match the magnitude of his crime (being rational in a rigid totalitarian society), that the mass of the bullet be much much more massive than the gun from which it is fired—and that his antagonist pull the trigger!

Return to your question about whether a heavyweight boxer could hit a piece of tissue paper with a force of 50 pounds or so. Now your class understands (hopefully) that the fist can't produce any more force on the paper than the paper exerts on the fist. The paper doesn't have enough mass to do this, so the answer is no. The fighter can't hit the paper any harder than the paper can hit back. Consider solving Think and Solve 27 in the end matter here.

Philosophically we know that if you try to do one thing, something else happens as a result. So we say you can never do only one thing. Every equation reminds us of that—change a term on one side of an equation and a term on the other correspondingly changes. In this chapter we similarly see that you can never have only one force.

Defining Your System

Discuss the different systems of orange and apple as in Figures 5.8 - 5.11. This is also treated in the Hewitt-Drew-It! Screencast on *Newton's Third law*. Ask students to identify action and reaction parts of the systems of Figures 5.14–5.18. That's wife Lil and me in Figure 5.19. And continuing with the same important concept of "you can't touch without being touched", my brother Steve and his daughter Gretchen do the same in Think and Explain 35 in the back matter. A prior photo of them, when Gretchen was a child, occurred in previous editions. The pushed bricks in the road of Figure 5.20 can illicit class discussion. The photo is clear evidence that the bricks have been pushed, as they push the tires of automobiles!

Vectors and their Components

Section 5.4 illustrates vectors and their components. The physics can be clearly seen without the use of trigonometry. My assumption is that most readers of Conceptual Physics are not trig literate. You can take physics time to teach some trigonometry, but my advise is that you resist that impulse and use class time for the exciting physics beyond this chapter. If your school is typical, there are many math classes, and perhaps your class is the only one focused on physics. In that case, learning trig can occur in the math classes. Your math teaching colleagues are unlikely to teach much physics in their math classes! Since you're the physics person, go physics! ☺

You'll note examples involving vectors are simple ones. Why? Before one gets deeply into any subject, they are better off with an understanding of the simplest examples first. When challenge comes, it should be welcomed. It won't be welcomed if the basics are missing. So go basics!

Think and Discuss 80 in the back matter, of the strongman pulled in opposite directions, is treated in the screencast on *Newton's Third law*. The situation elicits class discussion.

Force and Velocity Vectors

Have your students have a go at the vector exercises in the Practicing Physics book. Take care to avoid force *and* velocity vectors on the same diagram. Having both on a vector diagram is an invitation to confusion—what you don't need.

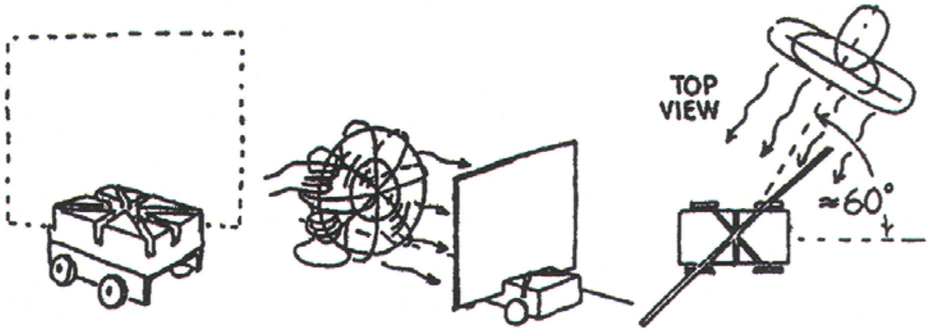
Components of Vectors

For components of vectors, again, the Practicing Physics worksheet on page 27 is instructive. The notion of component vectors will be useful in following chapters, particularly Chapters 6 and 10.

> DEMONSTRATION: To highlight the parallelogram rule for vectors, here's a good one: Have two students hold the ends of a heavy chain. Ask them to pull it horizontally to make it as straight as possible. Then ask what happens if a bird comes along and sits in the middle (as you place a 1-kg hook mass on the middle of the chain!). What happens if another bird comes to join the first (as you suspend another 1-kg mass)? Ask the students to keep the chain level. Now what happens if a flock of birds join the others (as you hang additional masses). This works well!

Invoke the parallelogram rule to show that the chain must be directed slightly upward to provide the needed vertical components to offset the weight.

Appendix D nicely extends vectors, and describes the interesting case of a sailboat sailing into the wind. This and the crossed Polaroids later in Chapter 29 are to my mind, the most intriguing illustrations of vectors and what they can do. An interesting demo is the model sailboat which you can easily build yourself with a small block of wood and a piece of aluminum. Cut slots in the wood and mount it on a car (or ideally, on an air track). A square-foot sheet of aluminum serves as a sail, and wind from a hand-held fan is directed against the sail in various directions. Most impressive is holding the fan in front, but off to the side a bit, so that the cart will sail into the wind. This is indeed an excellent vehicle for teaching vectors and their components!



Answers and Solutions for Chapter 5

Reading Check Questions

1. The force is the wall pushing on your fingers.
2. He can't exert much force on the tissue paper because the paper can't react with the same magnitude of force.
3. A pair of forces are required for an interaction.
4. Whenever one object exerts a force on a second object, the second object exerts and equal and opposite force on the first.
5. Action: bat against ball. Reaction: ball against bat.
6. Yes, and that external net force accelerates the orange system.
7. No, for the pair of forces are internal to the apple-orange system.
8. Yes, an external net force is required to accelerate the system.
9. Yes, the net force is provided by contact with your foot. If two opposite and equal forces act on the ball, the net force on it is zero and it will not accelerate.
10. Yes, you pull upward with the same amount of force on Earth.
11. The different accelerations are due to different masses.
12. The force that propels a rocket is the exhaust gases pushing on the rocket.
13. A helicopter gets its lifting force by pushing air downward, in which case the reaction is the air pushing the helicopter upward.
14. You cannot touch without being touched! And with the same amount of force.
15. The process of determining the components of a vector.
16. The magnitude of the normal force decreases.
17. The friction force has the same magnitude, with the sum of all forces being zero.
18. Moving upward, the vertical component of velocity decreases. The horizontal component remains constant, in accord with Newton's first law.
19. Inertia; acceleration; action and reaction.
20. Newton's third law deals with interactions.

Think and Do

21.Your hand will be pushed upward, a reaction to the air it deflects downward.

22. Each will experience the same amount of force.

Plug and Chug

23. 100 km/h – 75 km/h = 25 km/h north. 100 km/h + 75 km/h = 175 km/h north

24. R = $\sqrt{(100^2 + 100^2)}$ = 141 km/h

25. R = $\sqrt{(4^2 + 3^2)}$ = 5.

26. R = $\sqrt{(200^2 + 80^2)}$ = 215 km/h

Think and Solve

27. a. $a = \Delta v/\Delta t$ =(25 m/s)/(0.05 s) = **500 m/s^2**. b. $F = ma$ = (0.003 kg)(500 m/s^2) = 1.5 N, which is about $^1/3$ pound. c. By Newton's third law, the same amount, 1.5 N.

28.The wall pushes on you with **40 N**.
$a = F/m$ = 40 N/80 kg = **0.5 m/s^2**.

29.$a = F/m$, where $F = \sqrt{[(3.0\text{ N})^2 + (4.0\text{ N})^2]}$ = 5 N. So $a = F/m$ = 5 N/2.0 kg = **2.5 m/s^2**.

30. (a) From the 3rd law $F_{\text{on } 2m \text{ puck}} = F_{\text{on m puck}} \Rightarrow 2m(a_{2m}) = m(a_m) \Rightarrow 2m\dfrac{\Delta v_{2m}}{\Delta t} = m\dfrac{\Delta v_m}{\Delta t}$ Since the force acts for exactly the same Δt for each mass $\Rightarrow \Delta v 2m = \frac{1}{2}\Delta v_m$. Since both masses start out at rest $\Rightarrow v_{2m} = \frac{1}{2}v_m$.

(b) $v_{2m} = \frac{1}{2}v_m = \frac{1}{2}\left(0.4\,\frac{\text{m}}{\text{s}}\right) = 0.2\,\frac{\text{m}}{\text{s}}$.

Think and Rank

31. A = B = C
32. A, B, C; (b) B, C
33. (a) A = B = C; (b) C, B, A

Think and Explain

34. Action; hammer hits nail. Reaction; nail hits hammer. (b) Action; Earth pulls down on a book. Reaction; book pulls up on Earth. (c) Action; helicopter blade pushes air downward. Reaction; air pushes helicopter blade upward. (In these examples, action and reaction may be reversed—which is called which is unimportant.)

35. In accord with Newton's third law, Steve and Gretchen are touching each other. One may initiate the touch, but the physical interaction can't occur without contact between both Steve and Gretchen. Indeed, you cannot touch without being touched!

36. No, for each hand pushes equally on the other in accord with Newton's third law—you cannot push harder on one hand than the other.

37. (a) Two force pairs act; Earth's pull on apple (action), and apple's pull on Earth (reaction). Hand pushes apple upward (action), and apple pushes hand downward (reaction). (b) With no air resistance, one force pair acts; Earth's pull on apple, and apple's pull on Earth.

38. (a) Action; Earth pulls you downward. Reaction; you pull Earth upward. (b) Action; you touch tutor's back. Reaction; tutor's back touches you. (c) Action; wave hits shore. Reaction; shore hits wave.

39. (a) While the bat is in contact with the ball there are two interactions, one with the bat, and even then, with Earth's gravity. Action; bat hits ball. Reaction; ball hits bat. And, action, Earth pulls down on ball (weight). Reaction; ball pulls up on Earth. (b) While in flight the major interactions are with Earth's gravity and the air. Action; Earth pulls down on ball (weight). Reaction; ball pulls up on Earth. And, action; air pushes ball, and reaction; ball pushes air.

40. In accord with Newton's first law, your body tends to remain in uniform motion. When the airplane accelerates, the seat pushes you forward. In accord with Newton's third law, you simultaneously push backward against the seat.

41. When the ball exerts a force on the floor, the floor exerts an equal and opposite force on the ball—hence bouncing. The force of the floor on the ball provides the bounce.

42. The billions of force pairs are internal to the book, and exert no net force on the book. An external net force is necessary to accelerate the book.

43. The friction on the crate is 200 N, which cancels your 200-N push on the crate to yield the zero net force that accounts for the constant velocity (zero acceleration). No, although the friction force is equal and oppositely directed to the applied force, the two do *not* make an action-reaction pair of forces. That's because both forces *do* act on the same object—the crate. The reaction to your push on the crate is the crate's push back on you. The reaction to the frictional force of the floor on the crate is the opposite friction force of the crate on the floor.

44. When the barbell is accelerated upward, the force exerted by the athlete is greater than the weight of the barbell (the barbell, simultaneously, pushes with greater force against the athlete). When acceleration is downward, the force supplied by the athlete is less.

45. The forces must be equal and opposite because they are the only forces acting on the person, who obviously is not accelerating. Note that the pair of forces do *not* comprise an action-reaction pair, however, for they act on the *same* body. The downward force, the man's weight, *Earth pulls down on man*, has the reaction *man pulls up on Earth*, not the floor pushing up on him. And the upward force of the floor on the man has the reaction of man against the floor, not the interaction between the man and Earth. (If you find this confusing, you may take solace in the fact that Newton himself had trouble applying his 3rd law to certain situations. Apply the rule, A on B reacts to B on A, as in Figure 5.7.)

46. When you pull up on the handlebars, the handlebars simultaneously pull down on you. This downward force is transmitted to the pedals.

47. When the climber pulls the rope downward, the rope simultaneously pulls the climber upward—the direction desired by the climber.

48. When you push the car, you exert a force on the car. When the car simultaneously pushes back on you, that force is on you—not the car. You don't cancel a force on the car with a force on you. For cancellation, the forces have to be equal and opposite and act on the same object.

49. The strong man can exert only equal forces on both cars, just as your push against a wall equals the push of the wall on you. Likewise for two walls, or two freight cars. Since their masses are equal, they will undergo equal accelerations and move equally.

50. As in the preceding exercise, the force on each cart will be the same. But since the masses are different, the accelerations will differ. The twice-as-massive cart will undergo only half the acceleration of the less massive cart.

51. In accord with Newton's 3rd law, the force on each will be of the same magnitude. But the effect of the force (acceleration) will be different for each because of the different mass. The more massive truck undergoes less change in motion than the Civic.

52. Both will move. Ken's pull on the rope is transmitted to Joanne, causing her to accelerate toward him. By Newton's third law, the rope pulls back on Ken, causing him to accelerate toward Joanne.

53. The winning team pushes harder against the ground. The ground then pushes harder on them, producing a net force in their favor.

54. The tension in the rope is 250 N. With no acceleration, each must experience a 250-N force of friction via the ground. This is provided by pushing against the ground with 250 N.

55. No. The net force on the rope is zero, meaning tension is the same on both ends, in accord with Newton's third law.

56. The forces on each are the same in magnitude, and their masses are the same, so their accelerations will be the same. They will slide equal distances of 6 meters to meet at the midpoint.

57. The writer apparently didn't know that the reaction to exhaust gases does not depend on a medium for the gases. A gun, for example, will kick if fired in a vacuum. In fact, in a vacuum there is no air drag and a bullet or rocket operates even better.

58. The slanted streaks are composed of two components. One is the vertical velocity of the falling rain. The other is the horizontal velocity of the car. At 45° these components are equal, meaning the speed of falling drops equals the speed of the car. (We saw this question back in Chapter 3.)

59. To climb upward means pulling the rope downward, which moves the balloon downward as the person climbs.

60. The other interaction is between the stone and the ground on which it rests. The stone pushes down on the ground surface, say action, and the reaction is the ground pushing up on the stone. This upward force on the stone is called the *normal force*.

61. (a) The other vector is upward as shown.
    (b) It is called the normal force.

62. (a) As shown.
    (b) Yes.
    (c) Because the stone is in equilibrium.

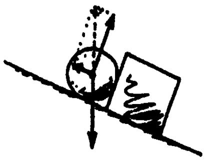
63. (a) As shown.
(b) Upward tension force is greater resulting in an upward net force.

64. As shown.

65. The acceleration of the stone at the top of its path, or anywhere where the net force on the stone is *mg*, is *g*, downward.

66. (a) Weight and normal force only.
(b) As shown.

67. (a) As shown.



(b) Note the resultant of the two normal forces is equal and opposite to the stone's weight.

68. Vector *f* will have the same magnitude as the vector sum of *mg* and *N*. If *f* is less, then a net force acts on the shoe and it accelerated down the incline.

69. The magnitudes of *mg* and *N* will be equal.

70. When the rope is vertical, *S* is zero. If the rope were vertical, *S* would be at an angle such that its vertical component would be equal and opposite to *mg*.

71. No force acts horizontally on the ball so the initial horizontal velocity remains constant as the ball moves through the air in accord with Newton's first law of inertia.

72. Earth pulls downward on the ball, action: the ball pulls upward on Earth, reaction. So the reaction force is the ball's upward pull on Earth. Acceleration all along the path is *g* ($a = F/m = mg/m = g$).

Think and Discuss

73. The answer is given in the equation $a = F/m$. As fuel is burned, the mass of the rocket becomes less. As m decreases as F remains the same, a increases! There is less mass to be accelerated as fuel is consumed.

74. Action: your foot against the ball. Reaction: the ball against your foot. Both forces have the same magnitude, in accord with Newton's third law.

75. Yes, it's true. The Earth can't pull you downward without you simultaneously pulling Earth upward. The acceleration of Earth is negligibly small, and not noticed, due to its enormous mass.

76. The scale will read 100 N, the same as it would read if one of the ends were tied to a wall instead of tied to the 100-N hanging weight. Although the net force on the system is zero, the tension in the rope within the system is 100 N, as would show on the scale reading.

77. Yes, a baseball exerts an external force on the bat, opposite to the bat's motion. This external force decelerates the oncoming bat.

78. The rapid deceleration of the speeding ball on the player's glove produces the force on the player's glove. In this sense, deceleration produces force (cause and effect can sometimes be a matter of interpretation).

79.The forces do not cancel because they act on different things—one acts on the horse, and the other acts on the wagon. It's true that the wagon pulls back on the horse, and this prevents the horse from running as fast as it could without the attached wagon. But the force acting on the wagon (the pull by the horse minus friction) divided by the mass of the wagon, produces the acceleration of the wagon. To accelerate, the horse must push against the ground with more force than it exerts on the wagon and the wagon exerts on it. So tell the horse to push backward on the ground.

80. Tension would be the same if one end of the rope were tied to a tree. If two horses pull in the same direction, tension in the rope (and in the strongman) is doubled.