# 2 Newton’s First Law of Motion—Inertia





The little girl with the Newton’s Cradle apparatus in the Part One opener is Charlotte Ackerman, of San Francisco. She appears later as a chapter opener in Chapter 20. Photo openers begin with a recent inertia demonstration of me on my back with a blacksmith’s anvil resting on my body, and friend Will Maynez who swings the sledge hammer. The photo of the balanced rock is by my friend Howie Brand, who retired to Thailand. Sweden friends Cedric and Anne Linder, profiled on the next page, pose with the vector demonstration. Karl Westerberg of CCSF shows one of my favorite demos with the suspended ball and strings.

Galileo was introduced in Chapter 1 and is also featured in this chapter. On August 25 in 1609 (405 years before 2014) he demonstrated his newly constructed telescope to the merchants of Venice, and shortly thereafter, aimed it on the skies. And as we know, his findings had much to do with the advent of science in those intellectual scary times.

Whereas the study of mechanics in earlier editions began with kinematics, we begin our study with a much easier concept for your students—forces. We postpone what I call the black hole of physics instruction—overemphasis on kinematics. You should find that starting a course off with forces first will lessen the initial roadblock that kinematics poses. Of particular interest to me is the Personal Essay in the chapter, which relates to events that inspired me to pursue a life in physics—my meeting with Burl Grey on the sign-painting stages of Miami, Florida. Relative tensions in supporting cables are what first caught my interest in physics, and I hope to instill the same interest with your students with this opening chapter. This story is featured on the first of the Hewitt-Drew-It screencasts, *Equilibrium Rule*, which nicely introduces vectors.

Force vectors are easier to grasp than velocity vectors treated in the following chapter. (More on vectors in Appendix A.)

Note that in introducing force I first use pounds—most familiar to your students. A quick transition, without fanfare, introduces the newton. I don’t make units a big deal and don’t get into the laborious task of unit conversions, which is more appropriate for physics majors.

The distinction between mass and weight will await the following chapter, when it’s needed in Newton’s second law. I see the key to good instruction as treating somewhat difficult topics only when they are used. For example, I see as pedagogical folly spending the first week on unit conversions, vector notation, graphical analysis, and scientific notation. How much better if the first week is a hook to promote class interest, with these things introduced later when needed.

**Practicing Physics Book**:

• Static Equilibrium
• The Equilibrium Rule: $\Sigma \mathbf{F} = 0$
• Vectors and Equilibrium

**Laboratory Manual**:
• Walking the Plank *Equilibrium Rule* (Experiment)

**Next-Time Questions** (in the Instructor Resource DVD):
• Ball Swing
• Pellet in the Spiral
• Falling Elephant and Feather

**Hewitt-Drew-It! Screencasts**:
• *Equilibrium Rule*
•*Net Force and Vectors*
•*Nellie's Ropes*
•*Force Vectors on an Incline*
• *Equilibrium Problems*
•*Nellie's Rope Tensions*
•*Force Vector Diagrams*

**SUGGESTED LECTURE PRESENTATION**

**Newton's 1st Law**
Begin by pointing to an object in the room and stating that if it started moving, one would reasonably look for a cause for its motion. We would say that a force of some kind was responsible, and that would seem reasonable. Tie this idea to the notion of force maintaining motion as Aristotle saw it. State that a cannonball remains at rest in the cannon until a force is applied, and that the force of expanding gases drives the ball out of the barrel when it is fired. (I have a 10-cm diameter solid steel sphere, actually a huge ball bearing, that I use in this lecture. Use one, or a bowling ball, if available.) But what keeps the cannonball moving when the gases no longer act on it? This leads you into a discussion of inertia. In the everyday sense, inertia refers to a habit or a rut. In physics it's another word for laziness, or the resistance to change as far as the state of motion of an object is concerned. I roll the ball along the lecture table to show its tendency to keep rolling. Inertia was first introduced not by Newton, but by Galileo as a result of his inclined-plane experiments.

DEMONSTRATION: Show that inertia refers also to objects at rest with the classic ***tablecloth-and-dishes demonstration***. [Be sure to pull the tablecloth slightly downward so there is no upward component of force on the dishes!] I precede this demo with a simpler version, a simple block of wood on a piece of cloth—but with a twist. I ask what the block will do when I suddenly whip the cloth toward me. After a neighbor check, I surprise the class when they see that the block has been stapled to the cloth! This illustrates Newton's zeroth law—be skeptical. Then I follow up with the classic tablecloth demo. Don't think the classic demo is too corny, for your students will really love it.

Of course when we show a demonstration to illustrate a particular concept, there is almost always more than one concept involved. The tablecloth demo is no exception, which also illustrates impulse and momentum (Chapter 6 material). The plates experience two impulses; one that first involves the friction between the cloth and dishes, which moves them slightly toward you. It is brief and very little momentum builds up. Once the dishes are no longer on the cloth, a second impulse occurs due to friction between the sliding dishes and table, which acts in a direction away from you and prevents continued sliding toward you, bringing the dishes to rest. Done quickly, the brief displacement of the dishes is hardly noticed. Is inertia really at work here? Yes, for if there were no friction, the dishes would strictly remain at rest.

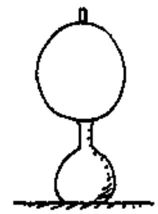
DEMONSTRATION: Continuing with inertia, do as Jim Szeszol does and fashion a wire coat hanger into an m shape as shown. Two globs of clay are stuck to each end. Balance it on your head, with one glob in front of your face. State you wish to view the other glob and ask how you can do

so without touching the apparatus. Then simply turn around and look at it. It's like the bowl of soup you turn only to find the soup stays put. Inertia in action! (Of course, like the tablecloth demo, there is more physics here than inertia; this demo can also be used to illustrate rotational inertia and the conservation of angular momentum.)

A useful way to impart the idea of mass and inertia is to place two objects, say a pencil and a piece of chalk, in the hands of a student and ask for a judgment of which is heavier. The student will likely respond by shaking them, one in each hand. Point out that in so doing the student is really comparing their inertias, and is making use of the intuitive knowledge that weight and inertia are directly proportional to each other. In Chapter 4 you'll focus more on the distinction between mass and weight, and between mass and volume.

CHECK QUESTION: How does the law of inertia account for removing snow from your shoes by stamping on the floor, or removing dust from a coat or rug by shaking it?

DEMONSTRATION: Do as Marshall Ellenstein does and place a metal hoop atop a narrow jar. On top of the hoop balance a piece of chalk. Then whisk the hoop away and the chalk falls neatly into the narrow opening. The key here is grabbing the hoop on the inside, on the side farthest from your sweep. This elongates the hoop horizontally and the part that supports the chalk drops from beneath the chalk. (If you grab the hoop on the near side, the elongation will be vertical and pop the chalk up into the air!)



**Units of Force—Newtons**:
I suggest not making a big deal about the unfamiliar unit of force—the newton. I simply state it is the unit of force used by physicists, and if students find themselves uncomfortable with it, simply think of "pounds" in its place. Relative magnitudes, rather than actual magnitudes, are the emphasis of conceptual physics anyway. Do as my influential pal Burl Grey does in Figure 2.13 and suspend a familiar mass from a spring scale. If the mass is a kilogram and the scale is calibrated in newtons, it will read 10 N (more precisely, 9.8 N). If the scale is calibrated in pounds it will read 2.2 pounds. State that you're not going to waste good time in conversions between units (students can do enough of that in one of those dull physics courses they've heard about).

CHECK QUESTION: Which has more mass, a 1-kg stone or a 1-lb stone? [A 1-kg stone has more mass, for it weighs 2.2 lb. But we're not going to make a big deal about such conversions. If the units newtons bugs you, think of it as a unit of force or weight in a foreign language for now!]

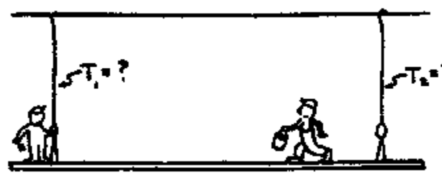
**Net Force**
Discuss the idea of more than one force acting on something, and the resulting net force. Figure 2.10 or Figure 2.12 captures the essence.

**Support Force (Normal Force)**
Ask what forces act on a book at rest on your lecture table. Then discuss Figure 2.15, explaining that the atoms in the table behave like tiny springs. This upward support force is equal and opposite to the weight of the book, as evidenced by the book's state of rest. The support force is a very real force. Without it, the book would be in a state of free fall.

**Statics and the Equilibrium Rule**: Cite other *static* examples, where the net force is zero as evidenced by no changes in motion. Hold the 1-kg mass at rest in your hand and ask how much net force acts on it. Be sure they distinguish between the 10-N gravitational force on the object and the zero net force on it—as evidenced by its state of rest. (The concept of acceleration is introduced in the next chapter.) When suspended by the spring scale, point out that the scale is pulling up on the object, with just as much force as the Earth pulls down on it. Pretend to step on a bathroom scale. Ask how much gravity is pulling on you. This is evident by the scale reading. Then ask what the net force is that acts on you. This is evident by your absence of motion change. Consider two scales, one foot on each, and ask how each scale would read. Then ask how the scales would read if you shifted your weight more on one than the other. Ask if there is a rule to guide the answers to these questions. There is; $\Sigma F = 0$. For any object in equilibrium, the net force on it must be zero. Before answering, consider the skit in my Personal Essay.

**Sign painter Skit**: Draw on the board the sketch below, which shows two painters on a painting rig suspended by two ropes.

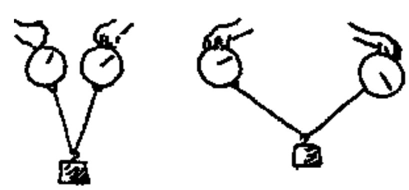
Step 1: If both painters have the same weight and each stands next to a rope, the supporting force of the ropes will be equal. If spring scales were used, one on each rope, the forces in the ropes would be evident. Ask what the scale reading for each rope would be in this case. [The answer is each rope will support the weight of one man + half the weight of the rig—both scales will show equal readings.]



Step 2: Suppose one painter walks toward the other as shown in the second sketch above, which you draw on the chalkboard (or show via overhead projector). Will the tension in the left rope increase? Will the tension in the right rope decrease? Grand question: Will the tension in the left rope increase *exactly* as much as the decrease in tension of the right rope? You might quip that is so, how does either rope "know" about the change in the other rope? After neighbor discussion, be sure to emphasize that the answers to these questions lie in the framework of the equilibrium rule: $\Sigma F = 0$. Since there is no change in motion, the net force must be zero, which means the upward support forces supplied by the ropes must add up to the downward force of gravity on the two men and the rig. So a decrease in one rope must necessarily be met with a corresponding increase in the other. (This example is dear to my heart. Burl and I didn't know the answer way back then because neither he nor I had a model for analyzing the problem. We didn't know about Newton's first law and the Equilibrium Rule. How different one's thinking is when one has or does not have a model to guide it. If Burl and I had been mystical in our thinking, we might have been more concerned with how each rope "knows" about the condition of the other—an approach that intrigues many people with a nonscientific view of the world.)

**Inertia and the Moving Earth**:
Stand facing a wall and jump up. Then ask why the wall does not smash into you as the Earth rotates under you while you're airborne. Relate this to the idea of a helicopter ascending over San Francisco, waiting motionless for 3 hours and waiting until Washington, D.C. appears below, then descending. Hooray, this would be a neat way to fly cross-country! Except, of course, for the fact that the "stationary" helicopter remains in motion with the ground below. "Stationary" relative to the stars means it would have to fly as fast as the Earth turns (what jets attempt to do).

**Forces at an Angle**:
This chapter introduces vectors as they relate to tensions in ropes at an angle. Other cases are developed in the Practicing Physics Book. As a demonstration, support a heavy weight with a pair of scales as shown. Show that as the angles are wider, the tensions increase. This explains why one can safely hang from a couple of strands of vertical clothesline, but can't when the clothesline is horizontally strung. Interesting stuff.



## Answers and Solutions for Chapter 2

### Reading Check Questions

1. Aristotle classified the motion of the Moon as natural.
2. Aristotle classified the motion of the Earth as natural.
3. Copernicus stated that Earth circles the Sun, and not the other way around.
4. Galileo discovered that objects in fall pick up equal speeds whatever their weights.
5. Galileo discovered that a moving object will continue in motion without the need of a force.
6. Inertia is the *name* given to the property of matter that resists a change in motion.
7. Newton's law is a restatement of Galileo's concept of inertia.
8. In the absence of force, a moving body follows a straight-line path.
9. The net force is 70 pounds to the right.
10. A description of force involves magnitude and direction, and is therefore a vector quantity.
11. The diagonal of a parallelogram represents the resultant of the vector pair.
12. The resultant is $\sqrt{2}$ pounds.
13. The tension in each rope would be half Nellie's weight.
14. Yes, although science texts favor the newton.
15. The net force is zero.
16. The net force is zero.
17. All the forces on something in mechanical equilibrium add vectorally to zero.
18. $\Sigma F = 0$.
19. The support force is 15 N. The net force on the book is zero.
20. Weight and support force have equal magnitudes.
21. Yes. The ball moving at constant speed in a straight-line path is in dynamic equilibrium.
22. An object in either static or dynamic equilibrium has a zero net force on it.
23. The force of friction is 100 N.
24. They had no understanding of the concept of inertia.
25. The bird still moves at 30 km/s relative to the Sun.
26. Yes, like the bird of Figure 2.18, you maintain a speed of 30 km/s relative to the Sun, in accord with the concept of inertia.

### Think and Solve

27. Since each scale reads 350 N, Lucy's total weight is 700 N.

28. 800 N on one scale, 400 N on the other. ($2x + x = 1200$ N; $3x = 1200$ N; $x = 400$ N)

29. From the equilibrium rule, $\Sigma F = 0$, the upward forces are 800 N, and the downward forces are 500 N + the weight of the scaffold. So the scaffold must weigh 300 N.

30. From the equilibrium rule, $\Sigma F = 0$, the upward forces are 800 N + tension in the right scale. This sum must equal the downward forces 500 N + 400 N + 400 N. Arithmetic shows the reading on the right scale is 500 N.

### Think and Rank

31. C, B, A
32. C, A, B, D
33. a. B, A, C, D
    b. B, A, C, D
34. a. A=B=C (no force)
    b. C, B, A
35. B, A, C
36. (a)

### Think and Explain

37. Aristotle favored philosophical logic while Galileo favored experimentation.

38. The tendency of a rolling ball is to continue rolling—in the absence of a force. The fact that it slows down is likely due to the force of friction.

39. Copernicus and others of his day thought an enormous force would have to continuously push the Earth to keep it in motion. He was unfamiliar with the concept of inertia, and didn't realize that once a body is in motion, no force is needed to keep it moving (assuming no friction).

40. Galileo discredited Aristotle's idea that the rate at which bodies fall is proportional to their weight.

41. Galileo demolished the notion that a moving body requires a force to keep it moving. He showed that a force is needed to *change* motion, not to keep a body moving, so long as friction was negligible.

42. Galileo proposed the concept of inertia before Newton was born.

43. Nothing keeps asteroids moving. The Sun's force deflects their paths but is not needed to keep them moving.

44. Nothing keeps the probe moving. In the absence of a propelling or deflecting force it would continue moving in a straight line.

45. If you pull the cloth upward, even slightly, it will tend to lift the dishes, which will disrupt the demonstration to show the dishes remaining at rest. The cloth is best pulled horizontally for the dishes to remain at rest.

46. The inertia of a whole roll resists the large acceleration of a sharp jerk and only a single piece tears. If a towel is pulled slowly, a small acceleration is demanded of the roll and it unwinds. This is similar to the hanging ball and string shown in Figure 2.5.

47. Your body tends to remain at rest, in accord with Newton's first law. The back of the seat pushes you forward. Without support at the back of your head, your head is not pushed forward with your body, which likely injures your neck. Hence, headrests are recommended.

48. In a bus at rest your head tends to stay at rest. When the bus is rear-ended, the car lurches forward and you and your head also move forward. Without headrest your body tends to leave your head behind. Hence a neck injury.

49. The law of inertia applies in both cases. When the bus slows, you tend to keep moving at the previous speed and lurch forward. When the bus picks up speed, you tend to keep moving at the previous (lower) speed and you lurch backward.

50. The maximum resultant occurs when the forces are parallel in the same direction—32 N. The minimum occurs when they oppose each other—8 N.

51. The vector sum of the forces equals zero. That means the net force must be zero.

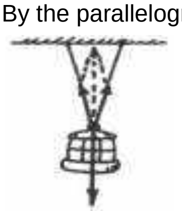
52. Vector quantities are force and acceleration. Age and temperature are scalars.

53. You can correctly say the vectors are equal in magnitude and opposite in direction.

54. A hammock stretched tightly has more tension in the supporting ropes than one that sags. The tightly stretched ropes are more likely to break.

55. The tension will be greater for a small sag. That's because large vectors in each side of the rope supporting the bird are needed for a resultant that is equal and opposite to the bird's weight.

56. By the parallelogram rule, the tension is less than 50 N.



57. The upward force is the tension in the vine. The downward force is that due to gravity. Both are equal when the monkey hangs in equilibrium.

58. By the parallelogram rule, the tension is greater than 50 N.

59.No. If only a single nonzero force acts on an object, its motion will change and it will not be in mechanical equilibrium. There would have to be other forces to result in a zero net force for equilibrium.

60.At the top of its path (and everywhere else along its path) the force of gravity acts to change the ball's motion. Even though it momentarily stops at the top, the net force on the ball is not zero and it therefore is not in equilibrium.

61.Yes. If the puck moves in a straight line with unchanging speed, the forces of friction are negligible. Then the net force is practically zero, and the puck can be considered to be in dynamic equilibrium.

62.You can say that no net force acts on your friend at rest, but there may be any number of forces that act—that produce a zero net force. When the net force is zero, your friend is in static equilibrium.

63. The scale will read half her weight. In this way, the net force (upward pull of left rope + upward pull of right rope − weight) = 0.

64.In the left figure, Harry is supported by two strands of rope that share his weight (like the little girl in the previous exercise). So each strand supports only 250 N, below the breaking point. Total force up supplied by ropes equals weight acting downward, giving a net force of zero and no acceleration. In the right figure, Harry is now supported by one strand, which for Harry's well-being requires that the tension be 500 N. Since this is above the breaking point of the rope, it breaks. The net force on Harry is then only his weight, giving him a downward acceleration of $g$. The sudden return to zero velocity changes his vacation plans.

65.The upper limit he can lift is a load equal to his weight. Beyond that he leaves the ground!

66.800 N; The pulley simply changes the direction of the applied force.
67. The force that prevents downward acceleration is the support (normal) force—the table pushing up on the book.

68.Two significant forces act on the book: the force due to gravity and the support force (normal force) of the table.

69.If the upward force were the only force acting, the book indeed would rise. But another force, that due to gravity, results in the net force being zero.

70.When standing on a floor, the floor pushes upward against your feet with a force equal to that of gravity, your weight. This upward force (normal force) and your weight are oppositely directed, and since they both act on the same body, you, they cancel to produce a net force on you of zero—hence, you are not accelerated.

71.Only when you are in equilibrium will the support force on you correctly show your weight. Then it is equal to the force of gravity on you.

72.Without water, the support force is $\boldsymbol{W}$. With water, the support force is $\boldsymbol{W} + \boldsymbol{w}$.

73.The friction on the crate has to be 200 N, opposite to your 200-N pull.

74.The friction force is 600 N for constant speed. Only then will $\Sigma F = 0$.

75.The support force on the crate decreases as the load against the floor decreases. When the crate is entirely lifted from the floor, the support force by the floor is zero. The support force on the workmen's feet correspondingly increases as the load transfers from the floor to them. When the crate is off the floor and at rest, its weight is transferred to the men, whose normal force is then increased.

76. The net force on the rope is zero. The force exerted by the rope on each person is 300 N (in opposite directions).

77. Two forces must be equal and opposite so that the net force = 0. Then the parachutist is in dynamical equilibrium.

78. We aren't swept off because we are traveling just as fast as the Earth, just as in a fast-moving vehicle you move along with the vehicle. Also, there is no atmosphere through which the Earth moves, which would do more than blow our hats off!

### Think and Discuss

79. Your friend should learn that inertia is not some kind of force that keeps things like the Earth moving, but is the name given to the property of things to keep on doing what they are doing in the absence of a force. So your friend should say that *nothing* is necessary to keep the Earth moving. Interestingly, the Sun keeps it from following the straight-line path it would take if no forces acted, but it doesn't keep it moving. Nothing does. That's the concept of inertia.

80. You should disagree with your friend. In the absence of external forces, a body at rest tends to remain at rest; if moving, it tends to remain moving. Inertia is a *property* of matter to behave this way, not some kind of force.

81. The tendency of the ball is to remain at rest. From a point of view outside the wagon, the ball stays in place as the back of the wagon moves toward it. (Because of friction, the ball may roll along the cart surface—without friction the surface would slide beneath the ball.)

82. The car has *no* tendency to resume to its original twice-as-fast speed. Instead, in accord with Newton's first law, it tends to continue at half speed, decreasing in speed over time due to air resistance and road friction.

83. No. If there were no friction acting on the cart, it would continue in motion when you stop pushing. But friction does act, and the cart slows. This doesn't violate the law of inertia because an external force indeed acts.

84. An object in motion tends to stay in motion, hence the discs tend to compress upon each other just as the hammer head is compressed onto the handle in Figure 2.5. This compression results in people being slightly shorter at the end of the day than in the morning. The discs tend to separate while sleeping in a prone position, so you regain your full height by morning. This is easily noticed if you find a point you can almost reach up to in the evening, and then find it is easily reached in the morning. Try it and see!

85. No. If there were no force acting on the ball, it would continue in motion without slowing. But air drag does act, along with slight friction with the lane, and the ball slows. This doesn't violate the law of inertia because external forces indeed act.

86. Normal force is greatest when the table surface is horizontal, and progressively decreases as the angle of tilt increases. As the angle of tilt approaches 90°, the normal force approaches zero. When the table surface is vertical, it no longer presses on the book, then freely falls.

87. No. The normal force would be the same whether the book was on slippery ice or sandpaper. Friction plays no role unless the book slides or tends to slide along the table surface.

88. A stone will fall vertically if released from rest. If the stone is dropped from the top of the mast of a moving ship, the horizontal motion is not changed when the stone is dropped—providing air resistance on the stone is negligible and the ship's motion is steady and straight. From the frame of reference of the moving ship, the stone falls in a vertical straight-line path, landing at the base of the mast.

89. A body in motion tends to remain in motion, so you move with the moving Earth whether or not your feet are in contact with it. When you jump, your horizontal motion matches that of the Earth and you travel with it. Hence the wall does not slam into you.

90. The coin is moving along with you when you toss it. While in the air it maintains this forward motion, so the coin lands in your hand. If the train slows while the coin is in the air, it will land in front of you.

91. If the train rounds a corner while the coin is in the air, it will land off to the side of you. The coin continues in its horizontal motion, in accord with the law of inertia.

92. This is similar to Question 88. If the ball is shot while the train is moving at constant velocity (constant speed in a straight line), its horizontal motion before, during, and after being fired is the same as that of the train; so the ball falls back into the smokestack as it would have if the train were at rest. If the train increases its speed, the ball will hit the train behind the smokestack because the ball's horizontal speed continues unchanged after it is fired, but the speeding-up train pulls ahead of the ball. Similarly, on a circular track the ball will also miss the smokestack because the ball will move along a tangent to the track while the train turns away from this tangent. So the ball returns to the smokestack in the first case, and misses in the second and third cases because of the *change* in motion.