3.1.1.2: Newton's Three Laws

Newton came up with several important laws of physics, three of which we may find useful for the physics of sound.

First Law: Objects continue at rest or in straight-line motion with constant velocity unless an unbalanced force acts on them. You might think that if no forces act the object is stationary. But this is only one case; the first law also says that if all the forces add to zero the object could still be moving at constant velocity. So why do you need to run the motor in your car if you are going down the road in the same direction at the same speed? The motor supplies enough force to overcome friction. Not more force than friction but a force *exactly equal* to friction so that the total force is *exactly zero* and you continue moving at a constant velocity. Similarly, a performer playing a wind instrument must continue to supply force on the air in the instrument to overcome friction as the air passes through the instrument. ***Inertia*** is the term used for the property of an object that causes it continue in straight line motion unless acted on by an unbalanced force.

Second Law: Forces cause accelerations (forces do not cause velocity but *changes* in velocity). The second law is also known as $F = ma$ where F is the total force acting on mass m, and a is the acceleration of the mass. Note that as was stated in the first law, a net total force is not needed to maintain a constant velocity; the first law says once something is moving it will keep moving unless a force (for example friction) acts to stop it. When you accelerate your car there is a net force on it. But when you reach cruising speed the net force goes to zero (the motor force exactly cancels resistance forces). In this case (when the net force adds to zero) the object (your car) obeys Newton's 1st law and you continue moving in a straight line at constant velocity.

Third Law: Anytime one object exerts a force on a second object, the second object exerts an equal force (but in the opposite direction) back on the first object. Forces always act in pairs on two different objects; an action force acting on one object and a reaction force acting on the second object. Another way to say this is you cannot touch something without it touching you back, and just as hard as you touched it. This seems simple if you are pushing on the wall; the wall obviously pushes back with the same force. But what about the force on a baseball as you throw it (before release)? Is the force pushing back by the baseball the same as the force you apply? YES! The laws of physics are always true with no exceptions. So how can you throw the baseball if the two forces are equal in magnitude but opposite in direction? The key is to realize the action and reaction forces act on different objects. Your force on the ball makes it go forward until it leaves your hand. The equal reaction force back from the ball acts on your hand (not the ball) so you can feel the ball as you throw it.

Video/audio examples:

- Newton's first law: egg drop.
- Newton's first law (car crash testing) one, two, three. Watch the movement of the dummy's body and head when the car suddenly stops. Because there is no force acting on the head, it keeps moving, according to Newton's 1st law.
- Newton's first and second law: sky diving. If you understand this example you have a good idea of how Newton's laws work.
- Newton's first, second and third law applied to a bicycle.
- Newton's third law: examples on the space station.

Questions on Newton's First Law:

1. If you are sitting at a stop sign and get hit from the rear, your head seems to fly back and hit the headrest. Explain, using Newton’s law of inertia, what really happens.
2. If you are standing in a bus and it suddenly stops, you feel like you are being thrown forward. Using Newton’s law of inertia, explain what is really happening.
3. Using Newton’s law of inertia, explain why a headrest prevents whiplash.
4. Using Newton’s law of inertia, explain why using a seatbelt in a car, plane, rollercoaster, etc. is a good idea.
5. Once a satellite is in orbit it doesn’t need to fire any rockets to stay there. Why not? What keeps it going?
6. What keeps the earth going around the sun?
7. A magic trick you can preform at home is to pull the tablecloth out from under some dishes on a table by giving the tablecloth a very quick horizontal jerk. Explain why the dishes don’t move.
8. Bowling balls slow down slightly as they roll down the lane. Explain why this does not violate Newton’s law of inertia?
9. If you quit pushing a shopping cart it stops. Explain how this does not violate Newton’s law of inertia.
10. The earth is rotating such that objects on the surface are traveling at close to 1000 km per hour (this is slightly different depending on latitude). Using Newton’s law, explain why you don’t get slammed by the wall if you jump straight up into the air.
11. When you are traveling in an airplane at cruising altitude, why does an object that is dropped not fly to the back of the plane?

12. A person drops a wrench from the top of the mast of a sailboat that is moving forward at constant velocity. Where does the wrench land relative to the mast if the boat has a speed of 10 m/s and the mast is 20 m high?
13. A driver heading towards a left curve encounters some ice on the road. Describe the motion of the car (drawing a picture will help) assuming the ice prevents any friction force from acting on the car. Which of Newton's laws tells you what will happen?
14. A small ball rolls in a frictionless tube that is flat on a table shown from above in the drawing. Draw the trajectory of the ball when it leaves the tube and justify your answer.

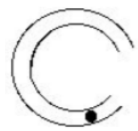

Figure $3.1.1.2.1$

Questions on Newton's Second Law:

1. Does a book at rest on the table have no forces acting on it? List and explain the forces that act on the book.
2. A car traveling North down the road at constant velocity has zero acceleration. The net force has to be zero since $F = ma$. Why then do you need to keep the engine running and the gas pedal pushed down?
3. Can you have an object traveling forward with a net force acting on it in the opposite direction? Explain and give an example.
4. You exert 800 N of force to push a box across the floor at a constant speed (zero acceleration). Is the friction force larger, smaller or exactly equal to 800 N? How do you know?
5. Can you make an object go around a curve without applying any force? Explain.
6. You jump out of an airplane and open your parachute. With the parachute open you travel at constant speed. How does the upward force of the parachute compare with the downward force of gravity?
7. A load of lumber in the back of a pickup truck accelerates at the same rate the truck does. What applies the force to make this happen? What happens if this force isn't large enough?
8. You throw a ball upward. Once it leaves your hand, what force acts on it on the way up? On the way down? What is the effect of this force on the way up? What is the effect of the force on the way down?
9. Explain why Newton's first law is really a special case of Newton's second law.
10. A car is traveling at a constant 55 mph in a straight line. What is the net force acting on the car?
11. An astronaut is in a spaceship far from the effects of gravity. She pushes with the same force on a baseball and a bowling ball. Indicate which of the following is true and explain why:
    a. they both accelerate with the same speed because they are weightless;
    b. they accelerate differently since their mass is different but they end up with the same terminal velocity;
    c. they have different accelerations.
12. The maximum tension on a guitar string is about 900 N (202 pounds of force). Suppose the peg holding the string weighs 0.002 kg and comes loose so that the 900 N causes the peg to accelerate. What will be the acceleration of the peg (in m/s^2)?
13. Is the acceleration in the previous problem dangerous? Hint: If the force acts over half the length of the guitar, say 0.20 m the final velocity will be $v = \sqrt{2ax}$ where a is the acceleration and x is the distance traveled.
14. Redo the previous two questions for the case of a piano string with 700 N of tension and a distance of 50 cm traveled. Assume the peg has the same mass.

Questions on Newton's Third Law:

1. Can you push on your left hand with a larger force using your right hand? Explain.
2. You tie a rope to a box in order to pull it across the floor. According to Newton's second law, the box pulls back on the rope with the same force that you pull on the rope. Explain how you can move the box if these forces are exactly equal and in opposite directions.
3. Explain the action and reaction forces when you push against the ground with your foot in order to take a step forward.
4. What are the action and reaction forces in these cases:
    a. a tennis racket hits a tennis ball;
    b. while walking, your foot pushes off from a curb;
    c. you push down on the pedal of a bicycle;
    d. during the windup of a baseball pitcher, up until he releases the ball?

5. For each case in the previous question, state which force is the larger force.
6. A force F pushes towards the left on a box. A friction force, f, between the floor and the box resists the movement of the box. These are the only forces acting in the horizontal direction. For the following three cases state which is bigger (or the same size), F or f and why.
   a. The box does not move.
   b. The box moves to the left with constant velocity.
   c. The box moves to the left and accelerates.
   d. The box moves to the left and decelerates.
7. A bowling ball collides with a tennis ball. Which object has the larger impact force on the other? Which has the greater acceleration? Explain.
8. Before space travel some people thought rockets would not work in space because there was no atmosphere for the rocket exhaust to push against. Explain the error in this thinking using Newton’s third law.
9. You are in a railroad car but the tracks are very smooth and the windows closed so you cannot tell if you are moving or not. You drop a tennis ball and it falls straight down and lands directly below your hand. What can you conclude about the motion of the car from this observation?
10. When you hit a xylophone bar with a mallet the mallet will bounce back. Which of Newton's three laws explains where the force comes from which causes the mallet to bounce back into the air?
11. A guitar string pulls on the peg mechanism with a tension of $600\ \mathrm{N}$ ($134\ \mathrm{lbs}$ of force). What minimum force must the mechanism be able to pull back with to avoid having the string change tension (which also changes the pitch)?
12. What force must a piano frame be able to withstand if the tension in the tightest string is $900\ \mathrm{N}$?