

### III. Applications of Force and Motion Concepts

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## CONCEPT REVIEW

The subject of this chapter is the application of force and motion concepts. Many of these exercises will explore the characteristics and principles of gravitational force, friction, projectile motion and circular motion.

### 1. Gravitational Force and Weight

- a. Weight is a force caused by the gravitational attraction between an object and the very massive earth. The direction of weight is always downward.
- b. The acceleration due to gravity at the surface of the earth is independent of the body experiencing the force because the property causing the force of gravity is proportional to the property of matter that resists changes in motion. The first property is given the name gravitational mass and the second property is called inertial mass.
- c. The gravitational force near the surface of the Earth is treated as constant because both the mass of the earth and distance from the center of the earth to an object experiencing gravitational force are mostly constant. These two properties, plus the mass of the object, determine the magnitude of the gravitational force.

### 2. Friction

- a. Friction is a reactive force that always resists the motion of an object. It is caused by the forces of interaction between three-dimensional objects at a microscopic level.
- b. Experimentally, frictional force is proportional to a normal force acting on an object.
- c. There are three classes of frictional force: static friction, sliding (or kinetic) friction, and rolling friction. Static friction prevents a body from starting to move; kinetic friction and rolling friction cause a moving object to decelerate. The force of static friction between two surfaces tends to be larger than the force of sliding friction. Rolling friction is the smallest of the three, but the moving object must be round.

### 3. Projectile Motion

- a. Projectile motion describes the behavior of an object acting under a constant acceleration (both magnitude and direction) while it is moving in two dimensions. The path of a projectile as it travels through the air, called its trajectory, is a parabola.
- b. An object experiencing only the force of gravity near the surface of the earth will behave as an ideal projectile. The projectile moves with constant velocity in the horizontal direction and with the constant acceleration of gravity in the vertical direction.
- c. The motion of a projectile in the accelerated direction is independent of the motion of the object in the non-accelerated direction. That means that the motion of the object in the

vertical direction has no effect on the motion of the object in the horizontal direction, and vice versa. The two 'one-dimensional' motions are linked by the variable they have in common, the time,  $t$ .

- d. The velocity vector of a projectile may be described by two components, a horizontal one and a vertical one, and the magnitudes of these components may be determined from the magnitude and angle of the velocity vector using trigonometry.
- e. The time that a projectile is in the air is determined by the vertical component of the velocity vector. The vertical component also determines the maximum height reached by the projectile.
- f. The distance the projectile travels, called the range is the product of the horizontal component of the initial velocity vector and the time the object is in the air. It can be shown that trajectories fired with the same speed at the complementary angles (the two angles add to 90 degrees) have the same range, but not the same times in the air. The greatest range is achieved from a 45 degree launch angle. The greatest height is obtained for a 90 degree (vertical) launch.

#### 4. Circular Motion

- a. Newton's first law of motion implies that the motion of an object along any curved path, including a circular one, requires the application of a net force.
- b. An object traveling in a circular path with a constant speed experiences an acceleration that is constant in magnitude and always directed radially, or toward the center of the circle. The centripetal (center-pointing) acceleration is always orthogonal to the velocity vector, which is tangential to the circular path at the point of motion.
- c. Centripetal acceleration is equal to the square of the speed divided by the radius of the circular arc:

$$a_c = v^2 / r$$

Since an object moving at a constant speed around a circle is traveling at a constant radius, centripetal acceleration changes the direction of the velocity vector only, and not its magnitude.

- d. A centripetal force causes a centripetal acceleration. Newton's second law of motion implies that centripetal force is equal to the product of the mass of the object and its centripetal acceleration. Therefore, centripetal force is a function of a body's mass and speed, and radius of the circular path it is following:

$$F_c = m v^2 / r$$

- e. Centripetal force does not exist as an independent entity: it results from real external force is acting on the object. Some examples of forces that can cause circular motion are friction (a car circling a track), tension (a ball swung on a string), and gravity (the orbits of planets).

## CONFLICTING CONTENTIONS

### 1. Airplane Drop

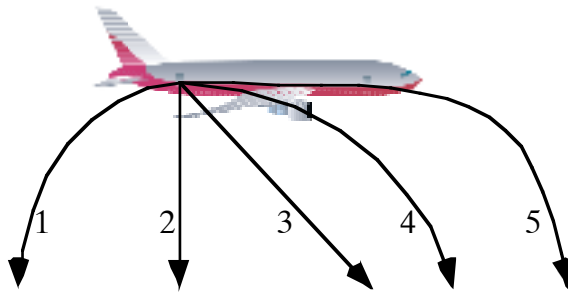
#### *The Situation*

All of the students were very curious to see Mr. Nicholls standing on a chair in the front of the room when class started. He was busily setting up a toy airplane on a guide wire.

“As you can see,” he told them, “the toy airplane is carrying a golf ball. The wire is set at a slight angle, so that when I push the plane, it will slide down the wire at a mostly constant speed.

“When the plane is half-way through its trip, a trigger will cause it to let go of its load. I’ve drawn a picture of some possible paths of the golf ball after it is released. I want you to choose which path you think the golf ball will follow and then give me your reasons for choosing that path.

Which path do you think is the correct one? Can you give a reason why?



#### *The Predictions*

Daniel and Cathy were sure that the golf ball would drop straight downward, following path 2. According to Cathy, “Once it is released, there will be no other forces acting on the ball except gravity. Since the ball is in free fall, it should drop straight down.”

Beth disagreed. “I think this is another Newton’s First Law problem. Of course it’s going to fall, but it has a forward velocity, so it should follow the straight line path 3.”

“Wait a minute” John said, “what about Path 1? Isn’t that what you would see if your were in the airplane and watching the golf ball drop? After all, since the plane isn’t pulling it forward anymore, it must be moving backward to compensate.”

‘I think the golf ball will still be moving forward, but I’m not sure whether it’s path 4 or 5. Will the ball start dropping immediately, or will it have a ‘hang time’ and then start falling?’ asked Alonzo.

Have the opinions of these students caused you to change your mind? If so, record any changes in your prediction or reasoning.

### *The Answer*

“Well, the best way to find out the right answer is to see it for yourself,” Mr. Nicholls said, so he flew the plane, and the closest match to the real trajectory of the golf ball was Path 4.

Now that you know the right answer, can you figure out the errors in reasoning for the other four paths?

## 2. Moving Ball Toss

### *The Situation*

Mr. Nicholls has another demonstration for the class. It is a small car that shoots a ball vertically in the air.

“I’m going to roll the ball shooter at a constant speed, and when it passes over the triggering mechanism it is going to shoot the ball straight up into the air.”

“Will the car catch the ball, will the ball land in front of the car, or will it land behind the car?”

### *The Predictions*

Half the class predict the ball will land in the car, and half the class believe the ball will land behind the car.

What is your prediction? Can you give a plausible explanation for each prediction?

### *The Answer*

When Mr. Nicholls runs the demonstration, the car catches the ball.

Can you explain the error in reasoning for the prediction that the ball would land behind the car?

## 3. Galileo’s Argument

Here is an argument that Galileo used to show that the acceleration of an object due to gravity must be independent of its mass.

Suppose that the acceleration of an object due to gravity was proportional to its mass, so that an object with twice the mass had twice the acceleration of a lighter object.

Now suppose you had two objects with one twice the mass of the other and you tied them together with a string. What would be the acceleration of the system?

Show that a gravitational acceleration that is proportional to mass necessarily leads to two conflicting contentions about the acceleration of the combined masses, and therefore the assumption that the acceleration of an object acted on by gravity depends on its mass cannot be true.

HINTS: If gravitational force is proportional to mass, what should happen to the acceleration of the two objects when they are tied together to become one very large mass?

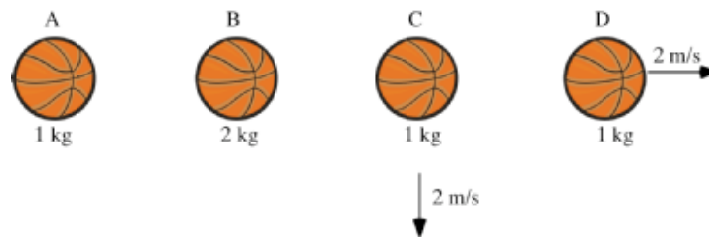
Now suppose instead you held a track race, with one fast runner and one slow runner. What would happen if you tied the fast runner to the slow runner with a rope?

### QUALITATIVE REASONING

#### 1. Dropping Balls

Four balls (labeled A, B, C, and D) are located two meters above the ground. All four balls are the same size and shape. Balls A, C and D all have the same mass of 1 kilogram; Ball B had a mass of 2 kilograms. There are no obstacles to their motion and air resistance can be ignored.

At a certain instant, Balls A and B are dropped from rest, Ball C is thrown downward with a speed of 2 m/s, and Ball D is launched sideways with a speed of 2 m/s.



Use physics principles to answer the following questions. If two or more of the balls have the same value for any of these questions, then state that condition.

In what order do the balls strike the ground?

Which of the balls has the greatest and which has the least acceleration?

## 2. Spinning Bug

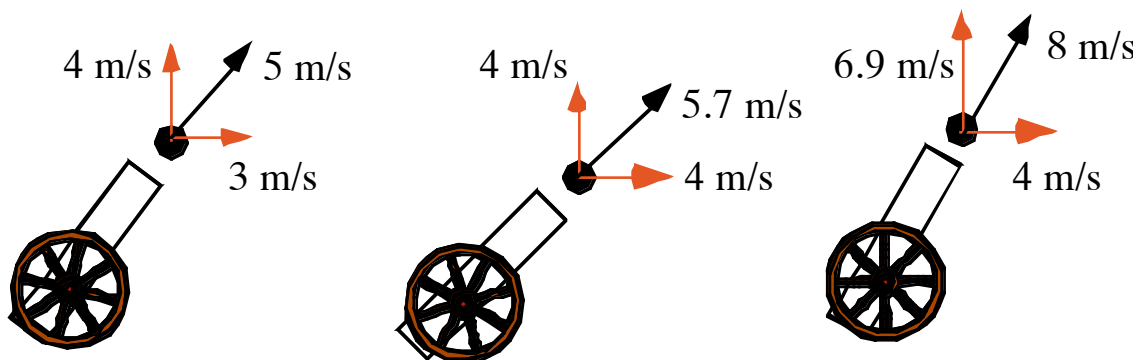
A ladybug sits at the center of a record player spinning at a constant  $33 \frac{1}{3}$  revolutions per minute. The bug spots a particular point on the edge of the turntable and begins a stroll radially outward towards that point. (From our point of view, the bug is spiraling outward.)

As our bug approaches the edge of the turntable, is it more likely, less likely, or equally likely to lose its grip and be swept off the record player?

What force acting on the ladybug is causing the centripetal force?

## 3. Cannon Ball Race — Part 1

Three cannon balls with the same mass are loaded into three identical cannons, but the initial velocities and angles are different, as shown in the figure.



The first cannon is set at an angle of 53 degrees and has an initial velocity of 5 m/s. As shown in the picture, that means that the vertical component of the velocity is 4 m/s and the horizontal velocity is 3 m/s.

The second cannon has an initial velocity of 5.7 m/s and a launch angle of 45 degrees. As shown in the picture, its vertical and horizontal velocity components are both 4 m/s.

The third cannon has a muzzle velocity of 8 m/s and is set at a 60 degree angle. Its horizontal velocity component is 4 m/s and its vertical velocity component is 6.9 m/s.

Note that the first two cannon balls have the same vertical velocity component, and the second and third cannon balls have the same horizontal velocity component.

All three cannon balls are shot simultaneously. Ignore air resistance.

- In what order do the cannon balls strike the ground? That is, which cannon ball stays in the air the longest? If two or more cannon balls travel through the air for the same length of time, then state that condition.

- b. Which cannon ball experiences the greatest and which experiences the smallest acceleration? If two or more cannon balls experience the same acceleration, then state that condition.
- c. Would any of your predictions change if the cannon balls were of different masses but had the same initial velocities, as given? Explain your answer.

#### 4. Cannon Ball Race — Part 2

Consider the cannon ball race of the previous problem. The initial velocities, angles, and masses are the same as in that problem. Once again, ignore air resistance; and if two or more cannon balls tie, then state that condition.

- a. Which cannon ball reaches the greatest and which one rises the least vertical height?
- b. Which cannon ball strikes the ground at the greatest and which one travels the shortest horizontal distance?
- c. Would any of your predictions change if the cannon balls were of different masses but had the same initial velocities, as given? Explain your answer.



#### 5. Galileo's Ramp — Again!

Galileo used an inclined plane as a 'gravity dilution device'. He calculated the constant acceleration of a ball rolling down an inclined plane for a series of steeper and steeper angles, and from that data estimated the acceleration of gravity.

- a. How did Galileo's ramp experiments support the idea that the acceleration of gravity is constant?
- b. What must have been Galileo's 'critical angle', where the acceleration down the ramp must equal the acceleration of gravity?
- c. Galileo also believed that the mass of an object should have no effect on its acceleration due to gravity. What experiment could Galileo perform on his inclined plane to support this contention?

#### 6. Frictional Incline

Mr. Nicholls posed the following question to the class:

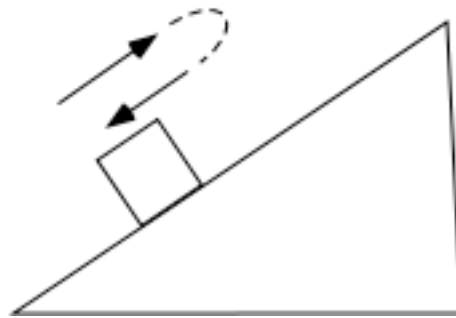
“Galileo demonstrated that a ball rolling down an inclined plane has a constant acceleration. We also know that a ball rolling down the incline and speeding up has the same acceleration magnitude and direction as a ball rolling up the incline and slowing down, just like a ball tossed in the air.

“Galileo used rolling balls to minimize frictional effects, but now we want to explore the effect of friction on the motion. Suppose we slide a box up the ramp, which has a lot of friction acting between its surface and the ramp.

“Because friction is a force, the acceleration of box sliding up the ramp will be less than the acceleration of the ball rolling up the ramp. But will the acceleration of the box down the ramp still be the same as the acceleration of the box up the ramp? Or will it be different?

“And if they aren’t the same, then which acceleration will have a larger magnitude? Would the acceleration vector change direction? And why, exactly, would friction cause the accelerations to be different, anyway?”

HINT: Frictional forces always act opposite to the direction of motion.



### CAN YOU EXPLAIN THIS?

#### 1. Centrifugal Force?

Daniel comes into class with a confused look on his face. Mr. Nicholls asks him what the problem is.

“Well,” he says, “I was just driving over to class and I went around the big curve on State Street. As I was rounding the curve to the right, I noticed that I was being pushed to the outside of the car, which was on the left.

“But centripetal force is supposed to be acting toward the center of the circle. So why did I feel a force pushing me away from the center and not toward it, which is the opposite direction from the one Newton predicted?”

Can you explain to Daniel what’s going on?

## 2. Words of Wisdom

Mr. Nicholls told the class about the time he visited a friend in the hospital who had broken his leg when he fell off a roof.

“Looks like you had a pretty bad fall”, he said. “Oh, the fall wasn’t too bad,” his friend said, “It was the landing that hurt.”

Can you explain what his friend meant using concepts of force and motion?

## 3. Why Doesn’t Weight Matter?

“Okay,” Cathy says, “explain this to me one more time. Weight is a force caused by gravity, so a ball with twice the weight has twice the gravitational force. So if I drop both balls at the same time, why doesn’t the heavier ball have twice the acceleration of the lighter one and hit the ground twice as quickly?”

Can you help Cathy understand why the acceleration of gravity isn’t affected by the weight of the object?

## 4. Body Mechanics

- a. Use Newton’s laws of motion to explain why is it important to bend your knees when landing on the ground after a jump. Why are you less likely to injure your knees or break a leg?
- b. Use Newton’s laws of motion to explain why it is important to lift a heavy object from a crouching position and ‘lift with your legs’ instead of bending over and picking up the object. Why are you less likely to hurt your back?
- c. Use Newton’s laws of motion to explain how a karate expert is able to break a board or a concrete block without breaking the hand. According to the Third Law, the force acting on the board is equal in magnitude to the force acting on the hand. If the force is great enough to break the board, why isn’t it great enough to break the hand?

## 5. Racing Around a Curve

Use physics concepts to explain why a truck exiting the circular exit ramp off an expressway must travel at a lower speed than a compact car exiting the same ramp to avoid skidding off the ramp.

Also, use the principles of physics to explain whether either vehicle should try to steer into a wider arc or into a sharper arc if it did start to skid in the turn. (Assume that, for some reason, slowing down is not a viable option.)

## 6. Swinging a Bucket

Try this yourself. Swing a bucket or a book in a vertical circle at a constant speed. The tension in your arm feels the greatest at the lowest point of the motion and least at the highest point in the motion. Can you explain why?

HINT: The centripetal force causes the bucket to move in a circle. Also, at each point of the motion, the real forces in the problem (the weight and the tension) must add up as vectors to equal the centripetal force. How do these two vectors add together at the highest and lowest points of the motion?