EVALUATING ACADEMIC READINESS FOR APPRENTICESHIP TRAINING

Revised for

ACCESS TO APPRENTICESHIP

SCIENCE SKILLS
FORCE AND NEWTON'S LAWS OF MOTION

AN ACADEMIC SKILLS MANUAL
for
The Metal Work Trades

This trade group includes the following trades:
Heat & Frost Insulator, Iron Worker,
Precision Metal Fabricator, Sheet Metal Worker, and
Welder & Fitter

Workplace Support Services Branch
Ontario Ministry of Training, Colleges and Universities

Revised 2011

In preparing these Academic Skills Manuals we have used passages, diagrams and questions similar to those an apprentice might find in a text, guide or trade manual.

This trade related material is not intended to instruct you in your trade. It is used only to demonstrate how understanding an academic skill will help you find and use the information you need.

SCIENCE SKILLS
FORCE AND NEWTON'S LAWS OF MOTION

An academic skill required for the study of the Metal Work Trades

INTRODUCTION

The physical world is held together by shifting forces. Nuclear forces hold an atomic nucleus together, while electrical forces pull electrons and protons towards each other to form atoms and molecules. Gravitational forces hold galaxies together and keep us firmly planted on earth. We can't see these forces at work but we can see the work done by mechanical forces that function at the visible level.

On a work site, mechanical forces determine how things move. Knowing the reasons why things react in these familiar ways can lead you to understand the procedures that enable you to work safely and effectively.

> **Example:** If you put a steel structure on a weak foundation, eventually the force of the structure will cause the foundation to crack.
>
> If you push on a loaded cart, it will start to move and it then keeps moving until friction slows it down.
>
> When you are driving a heavily loaded vehicle, it accelerates more slowly going up a hill. To stop, you exert a force on the brakes. If you do this too quickly, you and any load you are carrying will slide forward. When you want to go around a corner, the vehicle will tend to keep moving in a straight line. You have to exert a turning force on the wheels through the steering wheel to keep the vehicle moving in a curved direction.

Objects usually react in these familiar ways to any force that acts on them. However, your experience might not be enough to provide you with a valid scientific explanation for these reactions. Isaac Newton observed the way applied forces cause objects to move. He developed three laws which explain what effect a force will have in a given situation. This skill manual looks at the following topics to explain the connections between force and the Laws of Motion:

- Motion
- Force
- Newton's First Law of Motion, including inertia and friction
- Newton's Second Law of Motion
- Newton's Third Law of Motion
- Centripetal force

MOTION

All objects on earth are in some kind of motion. Nuclear forces inside molecules cause them to constantly vibrate. Solid objects that seem to be at rest, like your workbench and the coffee cup on it, are actually moving relative to the moon and stars. Motion is such a regular part of the way matter behaves that it is the main term used to describe other basic concepts such as force and energy.

Motion *is defined as a continuing change of place, or position.* We also say motion occurs when an object undergoes a displacement.

- ***Displacement*** is a change in place, or position.
- An object moving in a straight line has ***linear motion***.
- An object moving in a circle or rotating around an axis has ***rotary motion*.**

The ***speed*** *of an object is its rate of motion, or how fast it is moving*. When you travel to work, you go a certain distance in a certain amount of time. If you know the distance and the time, you can find the average speed. The distance divided by the time gives the average speed:

$$\text{average speed} = \frac{\text{distance traveled}}{\text{time elapsed}}$$

Average speed is measured in kilometers per hour (km/hr) or meters per second (m/s) in the metric system. In the imperial system, speed is measured in miles per hour (mph) or feet per second (ft/s).

Direction is an important part of the outcome of motion in many situations.

- If you are working in Sudbury and you need to pick up supplies 400 kilometers away in Toronto, you can’t just head out, drive for 400 k at 100 k/hr and expect to get there in 4 hours.
- You have to drive at 100 k/hr *in a southerly direction* to be sure of arriving in Toronto.

Although speed and velocity are often used interchangeably, velocity actually has a more specific meaning. ***Velocity*** *is the rate of motion in a particular direction*. To describe the velocity of an object, you need to state both the speed and the direction of movement.

- The velocity of an aircraft can be described as 615 km/hr southwest.
- The velocity of the car going from Sudbury to Toronto is described as 100km/hr south

Any quantity that requires both magnitude (an amount that can be measured) and direction for a complete description is called a ***vector quantity***. Velocity is a vector quantity because it includes both speed and direction.

- We describe the vector of the above aircraft as *southwest at 615 km/h*.
- We describe the vector of the car as *south at 100 km/hr*.

Motion can be uniform or variable. When an object's change in position is the same during each identical time unit, the velocity is uniform. If the speed or the direction of an object changes as it moves, the velocity is variable.

- When you drive along a road, your velocity is seldom uniform. You constantly slow down, speed up, turn corners or stop for red lights.

When you speed up or increase your velocity, you accelerate. ***Acceleration** is the rate of change in velocity*. Like velocity, acceleration is a vector quantity; it has both speed and direction.

- Acceleration which results in a slowing down of an object is called negative acceleration or *deceleration*. You can be traveling forward but if your rate of speed is slowing, you are decelerating.

To find the average acceleration (a), the original velocity is subtracted from the final velocity. The answer is divided by the time elapsed.

$$a = \frac{(\text{final velocity - original velocity})}{\text{time}}$$

Acceleration is usually measured in meters per second per second (m/s^2) or feet per second per second (ft/s^2).

FORCE

*A **force** is anything that produces or prevents motion, or that causes stress in an object.* It is usually felt by the object as a push or pull in a certain direction.

- ♦ If a force is strong enough, a free object receiving the force will move in the direction that the force is applied.
- ♦ If the object is not free to move, the push or pull is felt as a stress that can break the object.

Example: If a sheet of metal roofing is given a tap with a hammer to adjust its position, it will move. If it is already attached to the rafters and it is struck with a hammer, the force causes a stress in the sheet that will bend it.

The units commonly used to measure mechanical force are ***newtons (n)*** in the metric system and ***pounds (lb)*** in the imperial system. Because force is described by both its magnitude (size) and direction, it is a vector quantity. The different forces acting on an object at the workplace can be complex:

- ♦ Usually more than one force acts on an object.
- ♦ These different forces can act in different directions.
- ♦ *All the forces, with their directions, are added together to find the **resultant force**.*

Examples: When a machine is lifted by a hoist, the force of gravity pulls the load downward. The mechanical force of the hoist lifts the load upwards. Because the force exerted by the hoist is stronger than the force of gravity, the machine is lifted to where it is needed.

An aircraft flying through the air is affected by both the forward thrust of its engines and by the wind. An aircraft flying with a tail wind experiences a larger resultant force, resulting in a faster velocity, than if the same plane were flying into a headwind, or into a cross wind.

When several forces act on a free object, *the **resultant force** causes the object to move as if a single force with the magnitude and direction of the resultant force were acting on it.*

- All the forces with their directions are added together to find the force acting on the object.
- If the resultant force adds up to zero, the forces are balanced and the object acts as if no forces were being exerted on it.
- If the resultant force adds up to anything other than zero, the force will be an unbalanced force.
- An unbalanced force produces a change in the motion of the affected object in the direction of the resultant force. If the object is not free to move, it feels the resultant force as a stress.

If the forces acting on an object are equal and in opposite directions, they balance each other and there is no displacement (movement). When you lift a sheet of metal, the force of gravity pulls it down towards earth. Because you are strong enough to support the weight of the sheet, the mechanical force of your muscles balances the force of gravity. It doesn't fall. Because the forces are balanced, we say that the metal is in ***equilibrium***.

When more than one force acts on an object, the object only moves when the forces are unbalanced. See Figure 1.

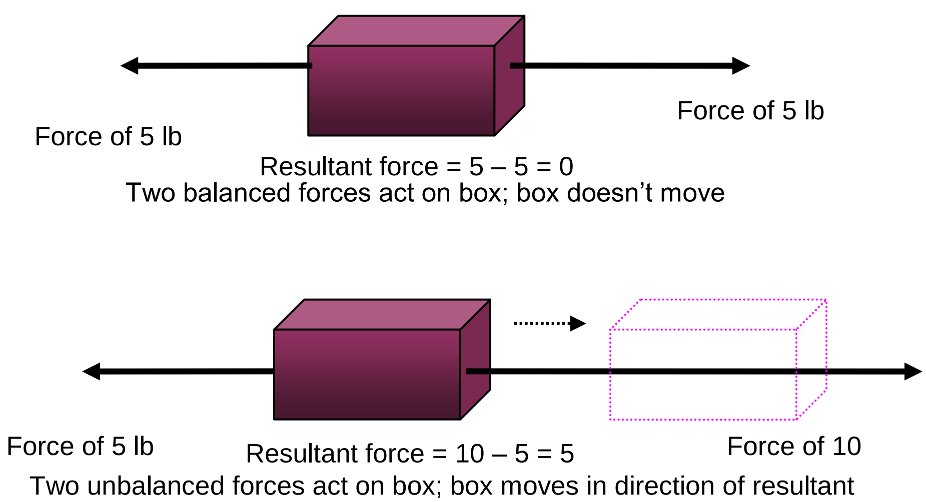

FIGURE1: Finding the Resultant Force

If you push a machine to a different spot, your muscles exert a force on it. The force acts directly on the machine because your hands are in physical contact with it. There are other forces, such as gravity, magnetism and electrical forces, which act on objects through space without being in physical contact with them.

Gravity works to hold objects on the earth even though we can't see anything making contact with the objects. A compass needle will point to the north as a result of the invisible pull of the North Pole.

The Force of Gravity
All objects on earth have mass. ***Mass*** is the amount of "stuff" an object has. An object's mass is determined by the number and type of molecules that form the object.

- The mass of an object is measured by comparing its mass to that of a known standard mass.
- The basic units of mass are the ***gram*** and the ***kilogram*** in the metric system and the ***pound*** in the imperial system.

Anything with mass feels the force of gravity and friction.

- ***Friction*** is the force that resists motion when an object moves over the surface of another object.
- ***Gravity*** is a universal force of attraction between all bodies in the universe.

*The measure of the force of the earth's gravitational pull on the mass of an object is the **weight** of that object.*

- In the imperial system, the unit of weight is the ***pound (lb)***.
- In the metric system, the unit of weight is the ***newton (n)***. However, we often use the units of mass - the gram and kilogram - to describe metric weight in everyday usage.
- These units can be used to measure any mechanical force.

On the earth's surface, the weight and mass of an object are the same. It is only further from the earth that weight will differ from mass. This is because the pull of gravity gets weaker the further away an object is from the earth. The closer an object is to the surface of the earth, the stronger the pull of gravity. So the weight of an object, which depends on the pull of gravity, can vary with its distance from the earth. An object's weight is greatest when it is sitting on the earth's surface.

Forces in Metal and Wood
Metals are subject to different types of forces. When you put a weight on a piece of metal, the top is pushed closer together while the bottom is pulled apart. *The force pushing the metal together is called **compression** and the force pulling it apart is called **tension**.* If the tension becomes too great, the metal will permanently bend.

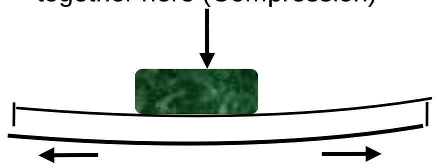

FIGURE 2: Weight On A Piece of Metal Produces Forces Of Compression And Tension

Metal can be bent a certain amount in response to an applied force and then return to its original shape. We say it has some *elasticity*. It also has *stiffness*. This is a measure of the amount of force required to bend it in the first place. Because metal is fairly stiff, it takes quite a bit of force to bend it (depending on the thickness). Because it has some elasticity, it can be bent and then return to its original shape. These characteristics make metal a good structural material.

Metal components must be *strong* enough to withstand the loads (forces) placed on them without breaking. Strength is proportional to the *thickness* if the other dimensions of length and width are the same. This means the greater the thickness, the greater the strength. Strength is inversely proportional to the *length*, if the other dimensions are the same. This means the shorter the piece of metal for its thickness, the stronger it is.

There is also a *geometric quality* to stiffness. A piece of metal on its edge is stronger than one used on its face. The area where the force or load is placed on a metal part must be taken into consideration. The load can be concentrated at certain points or uniformly distributed. These factors illustrate some of the reasons for the size and strength requirements in parts design

In brief:

- A force always works in a certain direction.
- The sum of all forces acting on an object gives the resultant force on the object.
- If two equal, but opposite, forces act on an object, they balance each other and there will be no change in the object’s motion. When the forces acting on it are balanced, the object is in equilibrium and it doesn’t move.
- An unbalanced force usually causes an object to move. The force increase or decrease the object’s velocity, causing it to accelerate. This acceleration can change both the speed and the direction of the object.
- A force can be exerted on a heavy body but not be strong enough to move it, or the body might not be free to move. In both cases, the object feels a stress or pressure.

NEWTON'S FIRST LAW OF MOTION

Newton's First Law of Motion states: *An object continues in its state of rest or state of uniform motion unless an unbalanced force acts on it.*

In other words, if there are no forces acting on an object, it remains at rest or in uniform motion. This basic property of matter is also called inertia.

- ***Inertia*** is the tendency of an object to preserve its present state. If it is at rest, it resists being moved. If it is already moving, it resists a change in speed or direction.
  - Inertia is related to the mass of an object. The more mass an object has, the more inertia it has, and the harder it is to change its position or motion.
  - A heavily loaded vehicle takes more force to brake or to accelerate than the same vehicle without a load. The vehicle has more mass when it is loaded.

Moving objects on earth slow down as soon as we stop applying a force. If we take our foot off the accelerator, a truck gradually slows down and stops. This seems to contradict the principle of inertia. But, the first law of motion says that the vehicle will remain moving forward *unless another force acts on it.*

In fact, there are other forces acting on the truck that we can't see. The force from the friction of the road and the force of gravity both work to slow and eventually stop a coasting vehicle. Only in outer space, away from the friction from air and the earth's gravity, does a satellite continue to stay in unchanging motion.

All objects have inertia; therefore, a force must be applied in order to move a resting object or to change a moving object's velocity (to accelerate it). An object's mass gives it inertia. The more mass an object has, the greater the amount of inertia and, therefore, the greater the force that must be applied in order to change its motion.

If your car suddenly hits a telephone pole, the car stops; but your inertia will keep you moving until your head is stopped by the windshield. A seatbelt prevents that forward motion in case of an accident. If you are standing on a bus that suddenly speeds up, you fall backwards because your inertia tries to keep you in the same place. The engine is exerting a forward force on the wheels of the bus, but, at first, there is no forward force acting on you.

We have to overcome the inertia of an object at rest in order to get it moving. In Figure 2, we see a coin sitting on a piece of paper over a glass. The coin will drop into the glass if the paper is flicked away. The coin does not move with the paper *because of its inertia*.

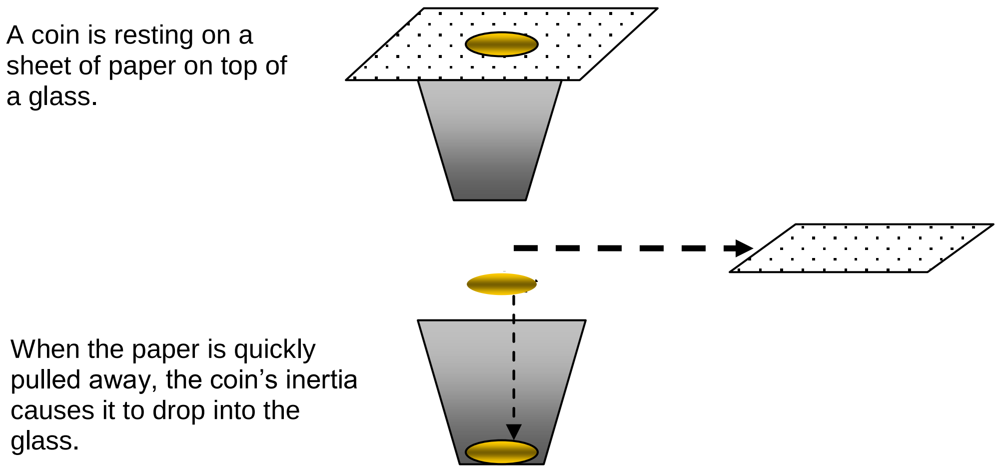

FIGURE 2: Inertia Causes A Coin At Rest To Stay At Rest

Whenever motion is considered, friction must also be considered because friction works to oppose or slow down motion. ***Friction** is a force that opposes the motion of one object in contact with the surface of another.* If you push or apply a force to a heavy load in order to get it moving, it will gradually slow down when you stop pushing. The opposing force of the friction of the ground acts to slow it down.

Example: If we push or apply a force to a heavy load in order to get it moving, it will gradually slow down when we stop pushing. The opposing force of the friction of the road acts to slow it down.

Example: Normally the platform on a scaffold is secured to the supports at its ends and can hold your weight. But if scaffolding is not secured properly and you move close to the edge, your weight will cause the scaffolding to tilt. If it tilts far enough, the force of gravity will pull you and the platform towards the ground, resulting in a fall.

Example: If we lift up one end of a board with a box sitting on it (see Figure 3), the force of gravity will pull the box in a downward direction, but the force of friction will prevent it from sliding. The forces on the box are balanced.

At some point, as you raise the board, the downward force of gravity will become greater than the force of friction holding the box in place. Because the force of gravity is now a greater force than that of friction, the forces become unbalanced. *Unbalanced forces usually result in motion*, so the box starts to slide down the board

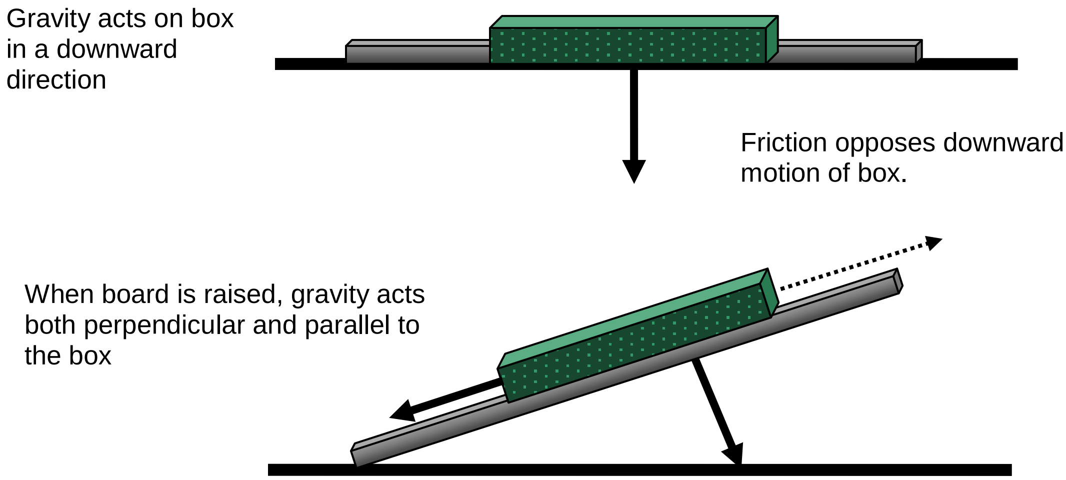

FIGURE 3: Forces Of Gravity And Friction Affect Inertia Of A Box

Inertia acts constantly on everything around us but we aren't usually aware of its influence on how objects move. However, it is an important property of matter that, along with gravity, actually regulates the position and motion of everything in the universe.

Because an object has mass and therefore, inertia, a force must act on it to change its position or motion. *The more mass an object has, the more force is required to overcome inertia.* This observation connects Newton's First Law with the Second Law of Motion.

NEWTON'S SECOND LAW OF MOTION

When a strong enough force is applied to an object that is at rest or moving at a uniform rate, the object accelerates (changes its rate and/or direction of motion). The object may speed up, slow down, stop, or change direction depending on the magnitude and direction of the force.

- The greater the force applied, the more the object accelerates.
- If the same amount of force is applied to two objects, the object with more mass will accelerate less than the object with a smaller mass.
- So both the size of the object's mass and the size of the force applied to it have an influence on the resulting change of motion or acceleration.

The relationship between the force applied and the mass of the object to the resulting acceleration can be measured. This relationship is expressed as Newton's Second Law of Motion.

Newton's Second Law of Motion states: *When an unbalanced force is exerted on an object, the object accelerates in the direction of the force. The acceleration produced is directly related to the force exerted on it and inversely proportional to the mass of the object*.

Written as an equation, this relationship can be expressed as:

force = mass x acceleration

or

F = ma

Let's look at what this law explains. We know that an unbalanced force results in a change in the acceleration or the motion of an object. This acceleration *varies directly* with the force applied to the object.

When something "varies directly with" or "is directly proportional to" something else, it means that as one item changes*, the other changes in the same way*.

- If the force increases, the acceleration increases or gets larger.
- If the force decreases, the acceleration decreases or becomes less.

Example: If you put a more powerful engine in a truck, it will accelerate faster with the same load. If you put a less powerful engine in the same truck, it will accelerate at a slower rate.

When something "varies inversely with" or "is inversely proportional to" something else, it means that, as the first item changes, the second also changes, but in the opposite way. The word ***inversely*** means in *an opposite or reverse manner*. Acceleration varies inversely with mass.

- As the mass of an object increases, the acceleration (with the same force) becomes smaller.
- As the mass decreases, the acceleration increases.

Example: A truck with a heavy load will accelerate more slowly than the same truck with a light load.

NEWTON'S THIRD LAW OF MOTION

Forces always occur in pairs. Because you have weight, you exert a downward force on the floor where you are standing. This downward force is caused by the pull of gravity on your mass. However, you don't sink into the floor and disappear, because the floor is exerting an opposite force that is strong enough to hold your weight. Newton summed up this idea in his Third Law of Motion.

Newton's Third Law of Motion states: *Whenever one body exerts a force upon a second body, the second exerts an equal and opposite force back on the first.*

When you stand on the rung of a ladder, your weight exerts a downward force. You don't continue to move downward to the ground because the rung of the ladder is exerting an equal force back on your feet. The ladder in turn is exerting a force on the ground while the ground is exerting an equal force back on the ladder.

Remember that a force can cause acceleration in an object.

- Because of the force of gravity, we could say the earth causes a downward acceleration on the ladder.
- The ladder causes an equal acceleration back on the earth in an upward direction.
- Neither moves in this case, because the ladder is already resting on the earth and the acceleration acting on the earth is so small compare to the earth's mass that it has no effect.

This law also applies to objects that are free to move.

- A motor on an outboard pushes water away from the boat. In the opposite but equal reaction, the water pushes back against the boat, causing it to go forward.
- If you jump from a boat to a dock (see Figure 4), the force exerted by the boat as you push against it accelerates your body forward to the dock. The boat reacts by moving in the opposite direction. If the boat isn't tied up, it will move away from the dock, out of reach.

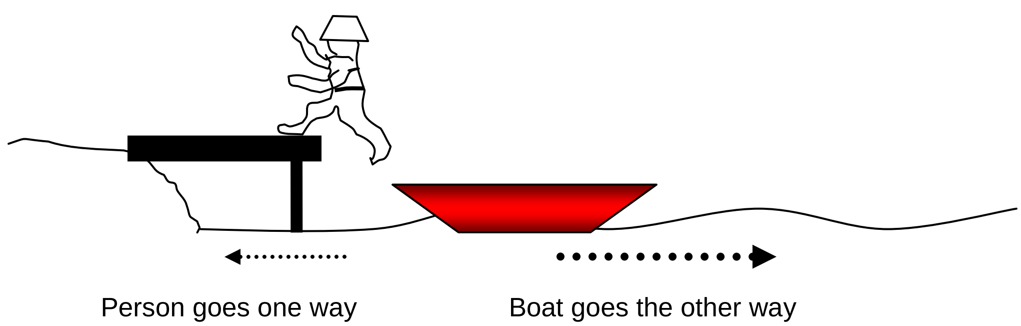

FIGURE 4: For Every Action, There Is An Equal And Opposite Reaction

Newton's Third Law means that all forces are interactions between objects and no force acts alone. If a force acts on one object, the other object exerts an equal but opposite force back. However, although the forces are equal, the acceleration produced can vary. The less massive object will accelerate more than the heavier object as stated in Newton's Second Law.

CENTRIPETAL FORCE

Newton's three laws of motion describe how forces affect the motion of any object. We generally think of forces combining to produce motion in a linear direction only. However, when different forces combine, more complex types of motion will occur.

- When a vehicle is driven around a curve, the property of inertia makes it tend to continue in a straight line. A force applied in a sideways direction to the vehicle will move it in a circular path.
- Remember, force, velocity and acceleration all have both magnitude and direction. If the vehicle is moving on a curve, its direction is constantly changing. Even if it is traveling at a constant speed, its velocity is constantly changing because its direction changes.

- Because the friction of the road acts on the tires of the car, the wheels stay on the road and the car continues to move in a curve.

The uniform acceleration (change in velocity) caused by traveling in a circular path is called ***centripetal acceleration.*** The force that produces centripetal acceleration is called ***centripetal force.***

CONCLUSION

A look at the cycle of an internal combustion engine shows how the three laws of motion are related. To help you see these relationships we have included a diagram, Figure 5. As you read through this conclusion, follow the ideas on the diagram.

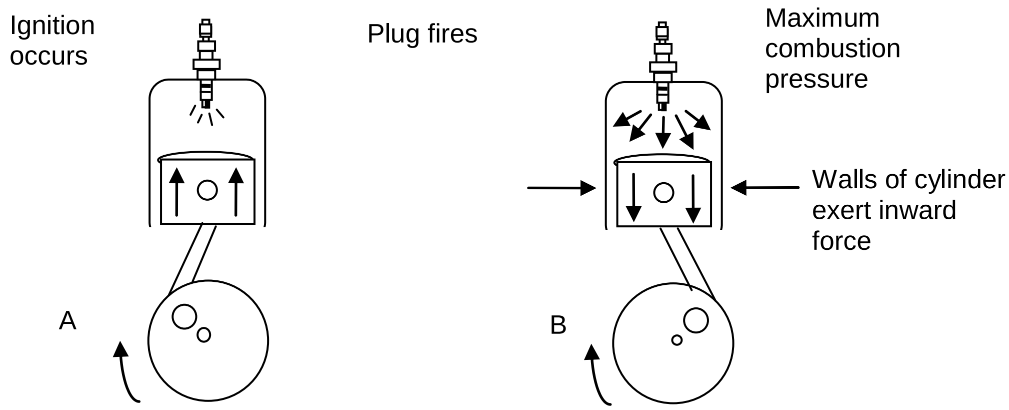

FIGURE 5: Combustion

When fuel molecules ignite in the cylinder, they push against the piston with a certain amount of force. The piston reacts to this force by moving down in the cylinder. The downward motion of the piston drives the crankshaft and the heavy flywheel attached to it. The *inertia* of the flywheel causes it to continue rotating (Figure 5A and 5B). The rotation of the flywheel drives the piston back up, ready for the next cycle. (*first law)*

The force of combustion drives the piston down with a certain *acceleration* (Figure 5B). The piston's acceleration depends on the *force* of the initial explosion of fuel and on the *mass* of the cylinder. *(second law)*

When the piston has traveled to the top of the cylinder, the gases trapped in the cylinder are ignited (Figure 5B). The pressure of this combustion exerts an explosive force downward on the piston which is free to move and so does.

The pressure of the combustion also exerts an outward forced on the immovable walls of the cylinder. Because the cylinder walls are immovable, they exert an equal but opposite force back on the gasses hitting them (*third law*) concentrating the gases in the cylinder and adding to the downward pressure on the piston.

Answer these questions based on Newton's Laws of Motion. Answers are on the last page.

1. The property of matter that causes things to stay at rest or in motion unless some force acts on them is called _________________.

2. When an object is in uniform motion, it is moving at a constant velocity. When a force acts to speed up the object, the force ____________________ the object.

3. _______________ is a force that opposes the motion of one object in contact with the surface of another object.

4. Force, velocity and acceleration are vector quantities. To completely describe these quantities, both their size and their ________________ must be stated.

5. The greater the force applied to an object, the ________________ the acceleration that results.

6. If the mass of an object is increased and the force remains the same, the acceleration of that object ___________________ .

7. Newton's Third Law of Motion states that whenever one body exerts a force upon a second body, the second exerts an _______________ but ________________ force on the first.

8. The force that produces circular motion in an object moving in a curved path is called _________________ force.

9. When you jump from a boat, the force exerted by the boat causes you to move forward. Your legs exert a force back against the boat that causes it to move in the opposite ______________.

Answer page

1. inertia
2. accelerates
3. Friction
4. direction
5. greater
6. decreases
7. equal but opposite
8. centripetal
9. direction