# Motion

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# Introduction to the Motion Subsystem

The Motion Subsystem comprises all the components in the VEX Robotics Design System which make a robot move. These components are critical to every robot. The Motion Subsystem is tightly integrated with the components of the Structure Subsystem in almost all robot designs.

In the VEX Robotics Design System the motion components are all easily integrated together. This makes it simple to create very complex systems using the basic motion building blocks.

The most fundamental concept of the Motion Subsystem is the use of a square shaft. Most of the VEX motion components use a square hole in their hub which fits tightly on the square VEX shafts. This square hole – square shaft system transmits torque without using cumbersome collars or clamps to grip a round shaft.
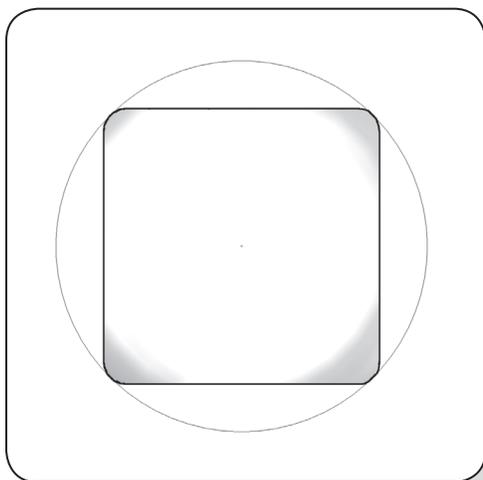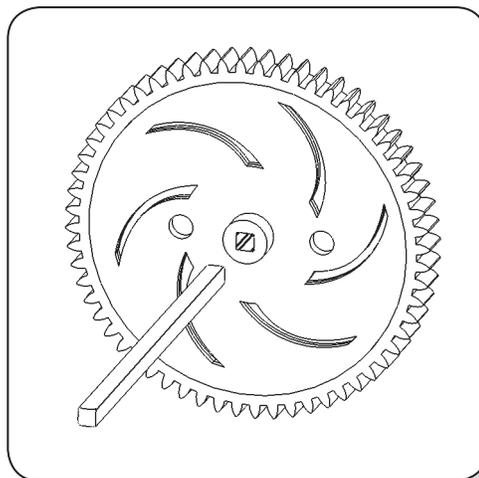
The square shaft has rounded corners which allow it to spin easily in a round hole. This allows the use of simple bearings made from Delrin (a slippery plastic). The Delrin bearing will provide a low-friction piece for the shafts to turn in.

These VEX Delrin bearings come in two types, the most common of which is a Bearing Flat. The Bearing Flat mounts directly on a piece of VEX structure and supports a shaft which runs perpendicular and directly through the structure.

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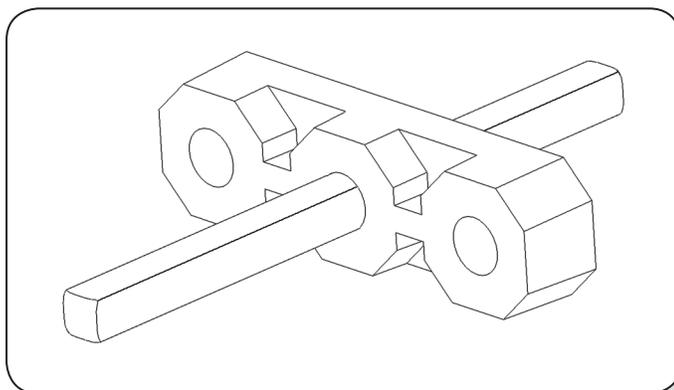
# Introduction to the Motion Subsystem, continued
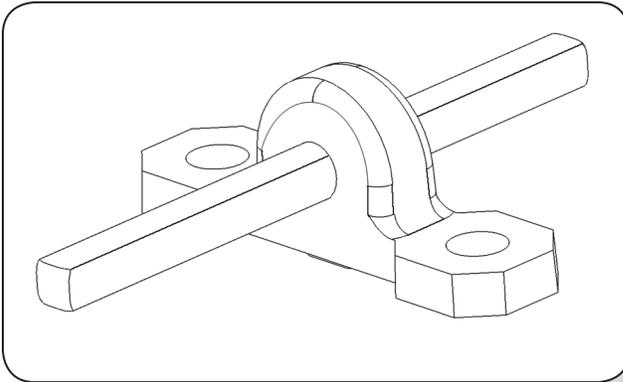
Another type of bearing used in the VEX Motion Subsystem is a Bearing Block; these are similar to the "pillow-blocks" used in industry. The Bearing Block mounts on a piece of structure and supports a shaft which is offset either above, below, or to the side of the structure.

Some bearings can be mounted to VEX structural components with Bearing Pop Rivets. These rivets are pressed into place for quick mounting. These Rivets are removable; pull out the center piece by pulling up on the head of the Rivet to get it to release.
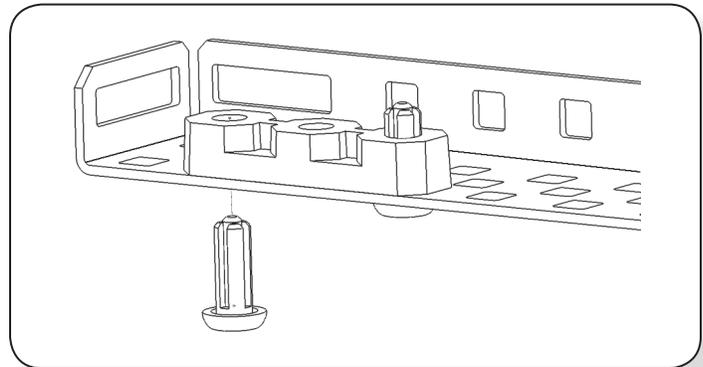
**HINT**:
It is also possible to to convert the square hole(s) in some Motion Subsystem Components to a round hole by using a drill (approximately 0.175'' diameter) to create a round hole that replaces the part's original square hole. A VEX square shaft can then spin freely in the newly created round hole. This is useful for some specialty applications.

**VEX Square Shaft Hole**

**Drilled Center Hole**
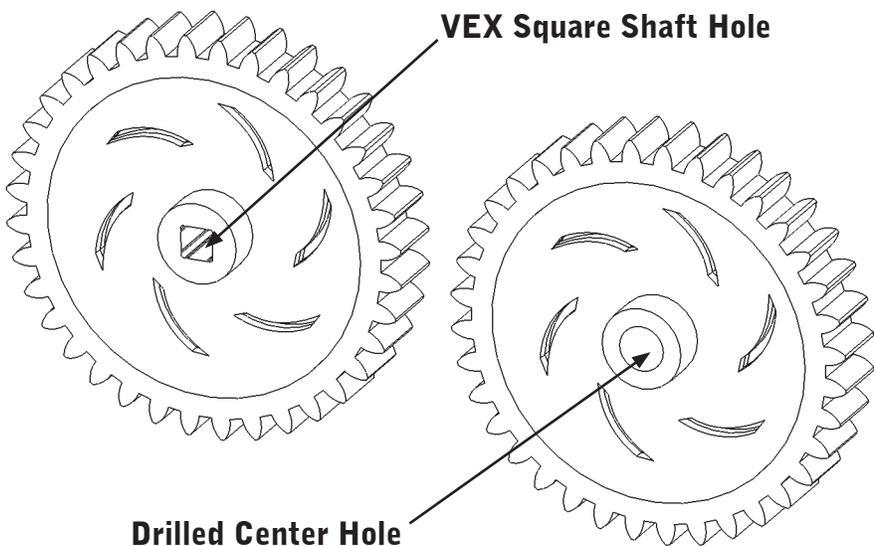
# Introduction to the Motion Subsystem, continued
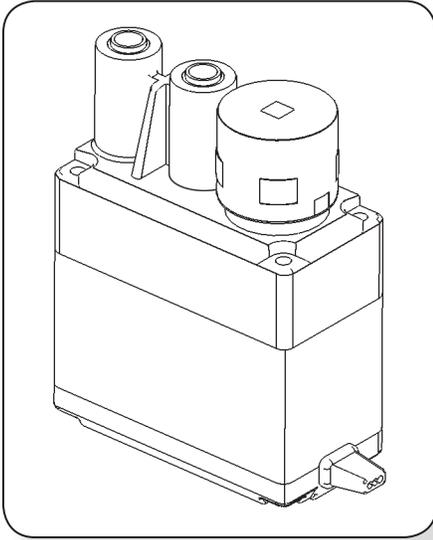
The key component of any motion system is an actuator (an actuator is something which causes a mechanical system to move). In the VEX Robotics Design System there are several different actuator options. The most common types of actuators used are the VEX Continuous Rotation Motors and the VEX Servos. (For more information on Motors & Servos refer to the "Concepts to Understand" section of this chapter.)

Each VEX Robotics Motor & Servo comes with a square socket in its face, designed to connect it to the VEX square shafts. By simply inserting a shaft into this socket it is easy to transfer torque directly from a motor into the rest of the Motion Subsystem.

**WARNING**:
VEX Motors include a clutch assembly which is designed to prevent damage to the internals of the VEX Motor in the event of a shock-load. Motors can be used without clutches, but it is not recommended. For more information on VEX Clutches refer to the "Concepts to Understand" section of this chapter.
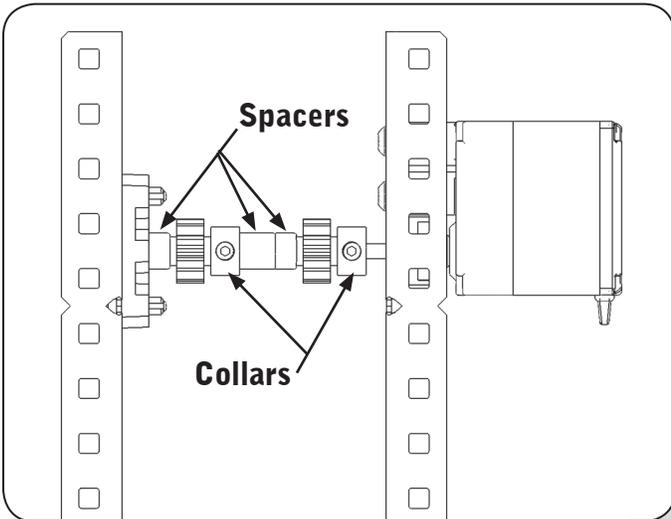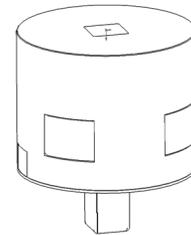
**Spacers**

**Collars**

The Motion Subsystem also contains parts designed to keep pieces positioned on a VEX shaft. These pieces include washers, spacers, and shaft collars. VEX Shaft Collars slide onto a shaft, and can be fastened in place using a setscrew. Before tightening the setscrew, it is important to slide the Shaft Collars along the square shafts until they are next to a fixed part of the robot so that the collar prevents the shaft from sliding back and forth.

**HINT**: The setscrews used in VEX Shaft Collars are 8-32 size threaded screws; this is the same thread size used in the rest of the kit. There are many applications where it might be beneficial to remove the setscrew from the Shaft Collar and use a normal VEX screw.

**If a setscrew is lost any other VEX 8-32 screw can be substituted although the additional height of the screw head must be considered!**

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# Introduction to the Motion Subsystem, continued

In some applications excessive loads can damage the components of the VEX Motion Subsystem. In these cases there are often ways to reinforce the system to reduce the load each individual component will experience, or so that the load is no longer concentrated at a single location on any given component.

**EXAMPLE**:

Gear Train 1

One example of a component failure is fracturing gear teeth. Another example is rounding out the square hole the shaft goes through. If either of these situations exists an easy way to fix it is to use multiple gears in parallel. Try using two gear trains next to each other to decrease the load on each individual gear.
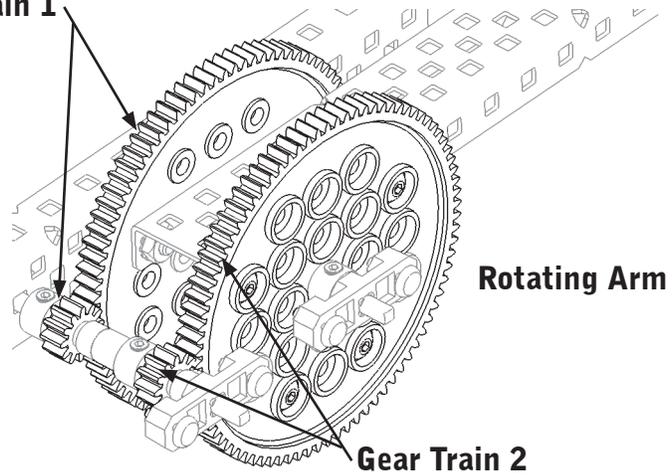
Rotating Arm

Gear Train 2

There are several ways to transfer motion in the VEX Robotics Design System. A number of Motion Subsystem accessory kits are available with a variety of advanced options. The primary way to transfer motion is through the use of spur gears. Spur gears transfer motion between parallel shafts, and can also be used to increase or decrease torque through the use of gear ratios.
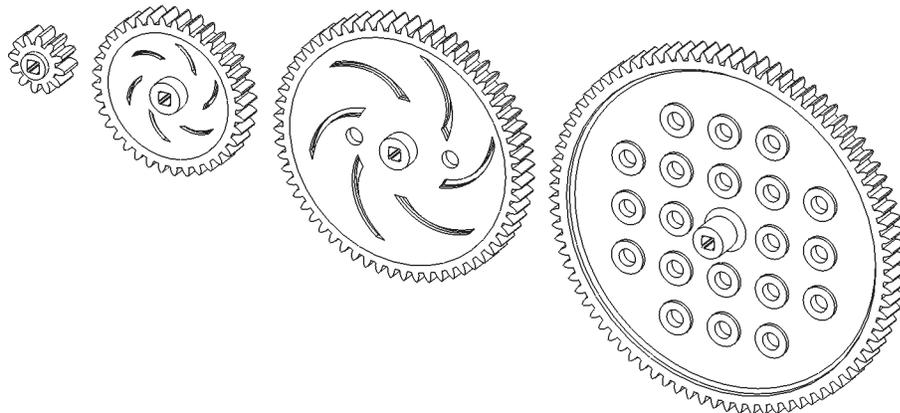
These gears can also be combined with sprocket & chain reductions, and also with advanced gear types to create even more complex mechanisms.
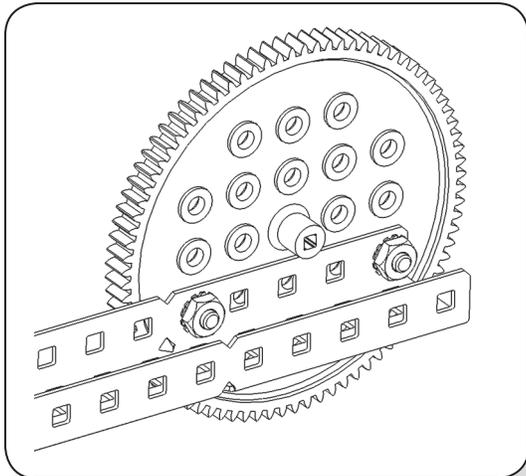
It is easy to drive components of the VEX Structure Subsystem using motion components in several different ways. Most of the VEX Gears have mounting holes in them on the standard VEX 1/2'' hole spacing; it is simple to attach metal pieces to these mounting holes. One benefit of using this method is that in some configurations, the final gear train will transfer torque directly into the structural piece via a gear; this decreases the torque running through the shaft itself.

Another option to drive structural pieces using the Motion Subsystem is through a Lock Bar. These pieces are designed such that they can bolt onto any VEX structural component using the standard VEX 1/2'' pitch. In the center of each piece there is a square hole which matches the VEX square shaft. As such, any VEX component can be ''locked'' to a shaft using the Lock Bar so that it will spin with the shaft. Note that the insert in each Lock Bar is removable and can be reinserted at any 15° increment.

**Lock Bar**
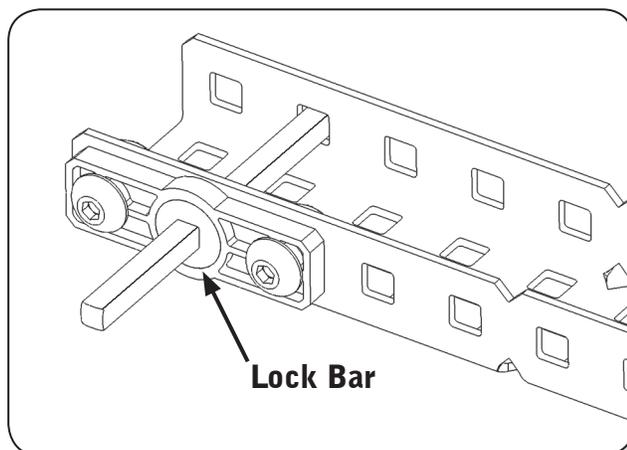
Intake Rollers can be used in a variety of applications. These components were originally designed to be rollers in an intake or accumulator mechanism. The ''fins'' or ''fingers'' of the roller will flex when they contact an object; this will provide a gripping force which should pull on the object.

**HINT:**
Try cutting off some of the fins of an Intake Roller for better performance on some objects.
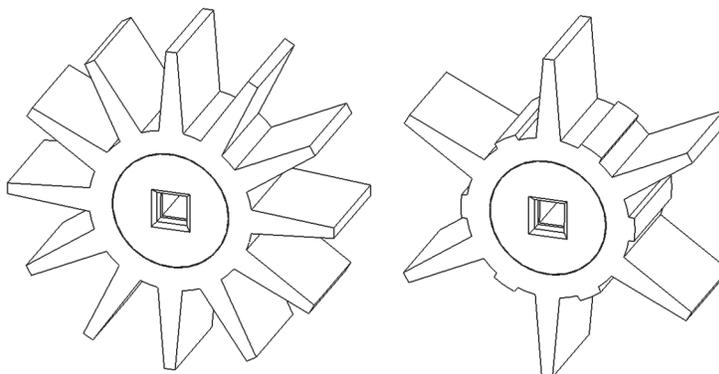
The VEX Motion Subsystem contains a variety of components designed to help make robots mobile.  This includes a variety of wheel sizes, tank treads, and other options.  Robots using these in different configurations will have greatly varying performance characteristics.
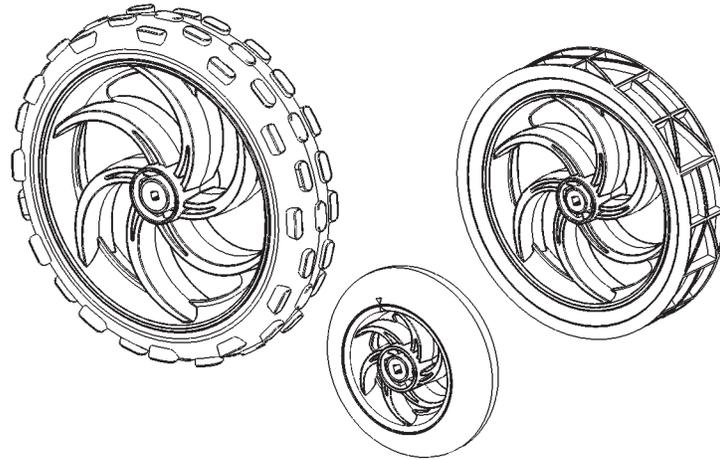
Tank Tread components and wheels can also be used to construct intake mechanisms and conveyor belts.  These are frequently used on competition robots.

When designing the Motion Subsystem of a robot it is important to think about several factors:
- First, it needs to be able to perform all the moving functions of the robot.
- Second, it needs to be robust enough to survive normal robot operation; it also needs to be robust enough to survive some abnormal shock loads.
- Third, it needs to be well integrated into the overall robot system.

The Motion Subsystem combines with the Structure Subsystem to form the primary physical parts of the robot.  The motion components will be used throughout a robot's construction, and will likely be part of every major robot function.  As such, this Subsystem needs to be well thought out in advance.

# Concepts to Understand

## Motors and Servomotors

**Motors are devices that can transform electrical energy into mechanical energy.** That is, they take electrical power, and create physical motion. In the VEX system, they are further divided into two main types: standard motors and servomotors.

The main difference is very clear and straightforward. Standard motors spin the attached axle around and around, while servomotors turn the axle to face a specific direction within their range of motion (120 degrees for the VEX servo module).

Note also that given the same transmitter command, the VEX motor modules and VEX servo modules rotate their shafts in opposite directions. This minor difference is due to the internal motor designs of the two different modules.

For more information on radio control operation, see the Control Subsystem section of the Inventor's Guide.

| TRANSMITTER COMMAND | MOTOR BEHAVIOR | SERVOMOTOR BEHAVIOR |
|---|---|---|
|  |  |  |
|  |  |  |
|  |  |  |
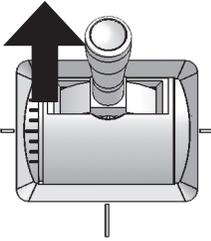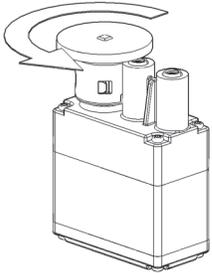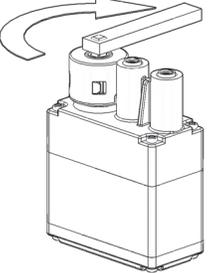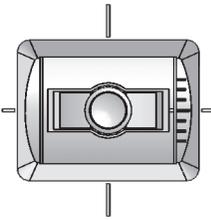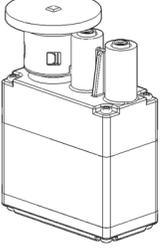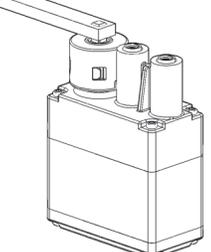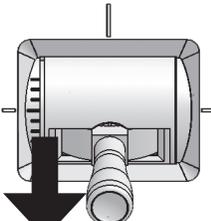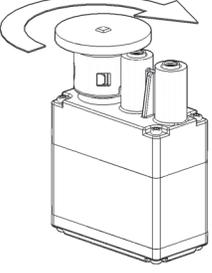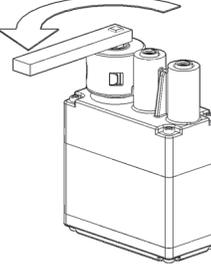
**Note: The easiest way to tell the difference between a VEX Motor and a VEX Servo is to read the text on the back. They are labeled "Motor Module" and "Servo Module".**

## Concepts to Understand, continued

### Motors and Servomotors, continued

**Using Motors and Servos**
While similar in appearance, motors and servomotors are suited to distinctly different types of tasks.

Motors should be used whenever continuous rotation is needed, such as in a robot's main drive system.

Servomotors can only be used in cases where the boundaries of motion are well-defined, but have the invaluable ability to self-correct to maintain any specific position within those boundaries.

**Motor Example:
Main Drive Motors**
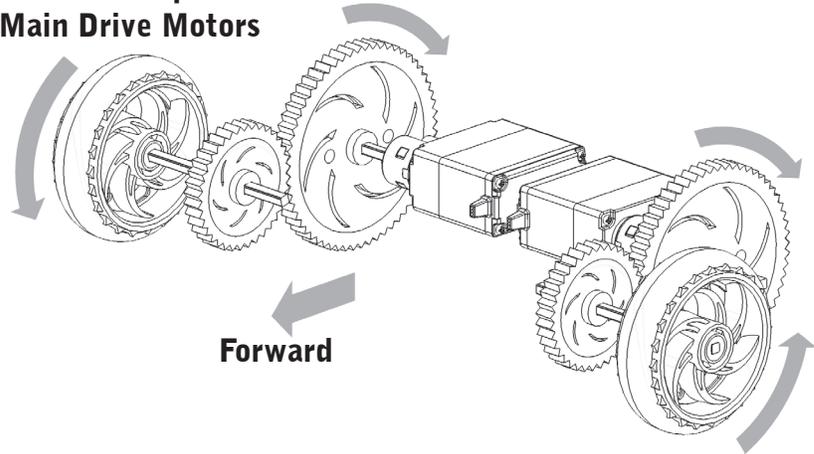
**Forward**

Use motors to power the robot's drive wheels. The wheels need to make continuous full rotations, which is exactly the kind of motion provided by the motors. Rotation for forward motion is shown.

**Servomotor Example:
Directable Attachment Mounting**

**120° of Rotation**

Use a servomotor to control the aim of a platform on top of the robot (shown with a wireless camera for illustrative purposes).

The servomotor allows you to turn the platform to face a specific direction relative to the robot, and will automatically hold that position until the controls are released.
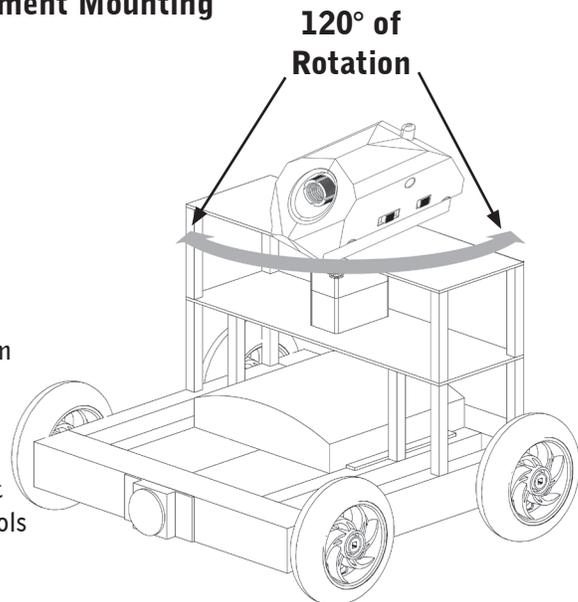
**Note: The easiest way to tell the difference between a VEX Motor and a VEX Servo is to read the text on the back. They are labeled "Motor Module" and "Servo Module".**

# Concepts to Understand, continued

## Speed vs. Torque

**A motor can generate a set amount of power;** that is, it can provide a specific amount of energy every second—this energy is most commonly used to make a wheel spin. Since there is only so much energy to go around, however, there is an inherent trade-off between *Torque*—the force with which the motor can turn the wheel—and *Speed*—the rate at which the motor can turn the wheel.

The exact configuration of torque and speed is usually set using gears. By putting different combinations of gears between the motor and the wheel, the speed-torque balance will shift.

## Gears

### Gear Ratio
You can think of gear ratio as a "multiplier" on torque and a "divider" on speed. If you have a gear ratio of 2:1, you have twice as much torque as you would if you had a gear ratio of 1:1, but only half as much speed.

Calculating the gear ratio between a pair of gears is simple. First, identify which gear is the "driving" gear, and which is the "driven" gear. The "driving" gear is the one that is providing force to turn the other one. Often, this gear is attached directly to the motor axle. The other gear, the one that the driving gear is turning, is called the "driven" gear.

To find gear ratio, you just need to count the number of teeth on the "driven" gear, and divide it by the number of teeth on the "driving" gear.

**12 Tooth Driving Gear**

**12 Tooth Driven Gear**

**Gear Ratio = 12:12 = 1:1**

| Torque | 1x |
| Speed | 1x |

### Mechanical Advantage –
The ratio of the force a machine can exert to the amount of force that is put in. Mechanical advantage can also be thought of as the "force multiplier" factor that a mechanical system provides.

If a vehicle has a gear train with a mechanical advantage of 2, for instance, it has twice as much force available to it, enabling it to go up hills that are twice as steep, or tow a load that is twice as heavy.

**36 Tooth Driving Gear**

**12 Tooth Driven Gear**

**Gear Ratio = 12:36 = 1:3**

| Torque | 1/3x |
| Speed | 3x |

**12 Tooth Driving Gear**

**36 Tooth Driven Gear**

**Gear Ratio = 36:12 = 3:1**

| Torque | 3x |
| Speed | 1/3x |

This additional force is never "free." It always comes at the expense of something else, such as speed. Also note that mechanical advantages are frequently fractional, indicating that force is being sacrificed for speed or some other similar performance factor in a system.

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## Concepts to Understand, continued
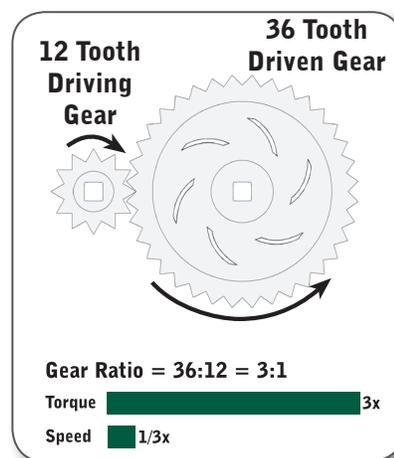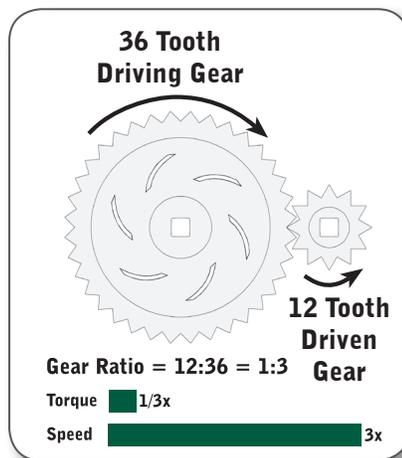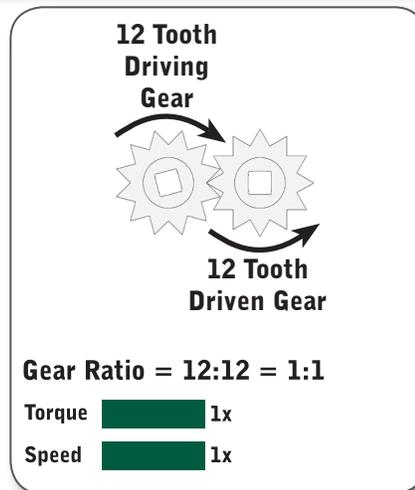
### Gears, continued

**Idler Gears**

Gears can be inserted between the driving and driven gears. These are called idler gears, and they have no effect on the robot's gear ratio because their gear ratio contributions always cancel themselves out (because they are a driven gear relative to the first gear, and a driving gear relative to the last gear—you would first multiply by the number of teeth on the idler gear and then divide by the same number, which always cancels out).

However, idler gears do reverse the direction of spin. Normally, the driving gear and the driven gear would turn in opposite directions. Adding an idler gear would make them turn in the same direction. Adding a second idler gear makes them turn in opposite directions again.

Idler gears are typically used either to reverse the direction of spin between two gears, or to transmit force from one gear to another gear far away (by using multiple idler gears to physically bridge the gap).

## No Idler – Opposite Direction

Driving Gear          Driven Gear
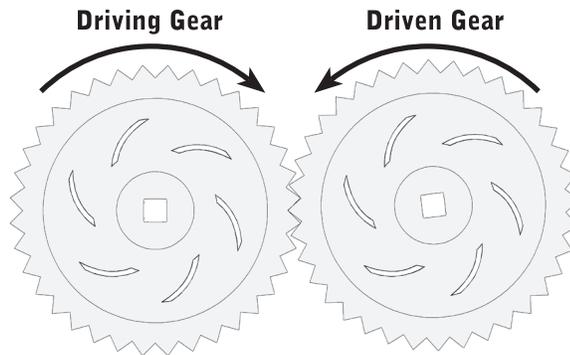
## One Idler – Same Direction

Driving Gear                    Driven Gear
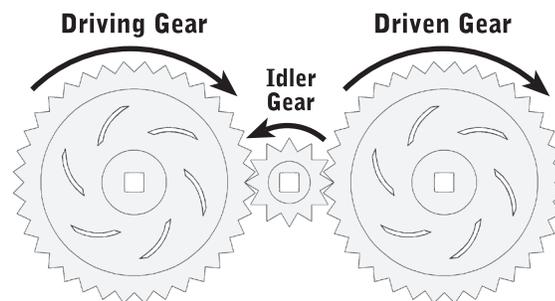
Idler Gear

## Two Idlers – Opposite Direction

Driving Gear                              Driven Gear

Idler Gear    Idler Gear
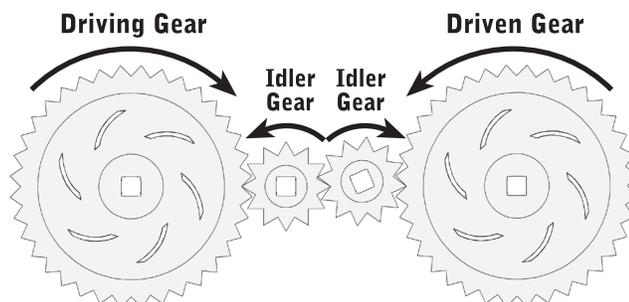
## Concepts to Understand, continued

### Gears, continued

**Compound Gear Ratio**
Compound gears are formed when you have more than one gear on the same axle. Compound gears are not to be confused with idler gears, as compound gears can affect the overall gear ratio of a system!

### Non-Compound Gear

**Driving Gear**

**Idler Gear**

**Driven Gear**

**Gear Ratio = 60:12 = 5:1**

Torque    1/5x

Speed    5x

In a compound gear system, there are multiple gear pairs. Each pair has its own gear ratio, but the pairs are connected to each other by a shared axle.

The resulting compound gear system still has a driving gear and a driven gear, and still has a gear ratio (now called a "compound gear ratio").

The compound gear ratio between the driven and driving gears is then calculated by multiplying the gear ratios of each of the individual gear pairs.

### Compound Gear

**Driving Gear**

**Linked by Shared Axle**

**Driven Gear**

**Compound Gear Ratio:**
**12:60 x 12:60 = 1:5 x 1:5 = 1:25**

Torque    1/25x

Speed    25x

Compound gears allow configurations with gear ratios that would not normally be achievable with the components available. In the example above, a compound gear ratio of 1:25 was achieved using only 12 and 60-tooth gears. This would give your robot the ability to turn an axle 25 times faster than normal (though it would only turn with 1/25th of the force)!

## Concepts to Understand, continued
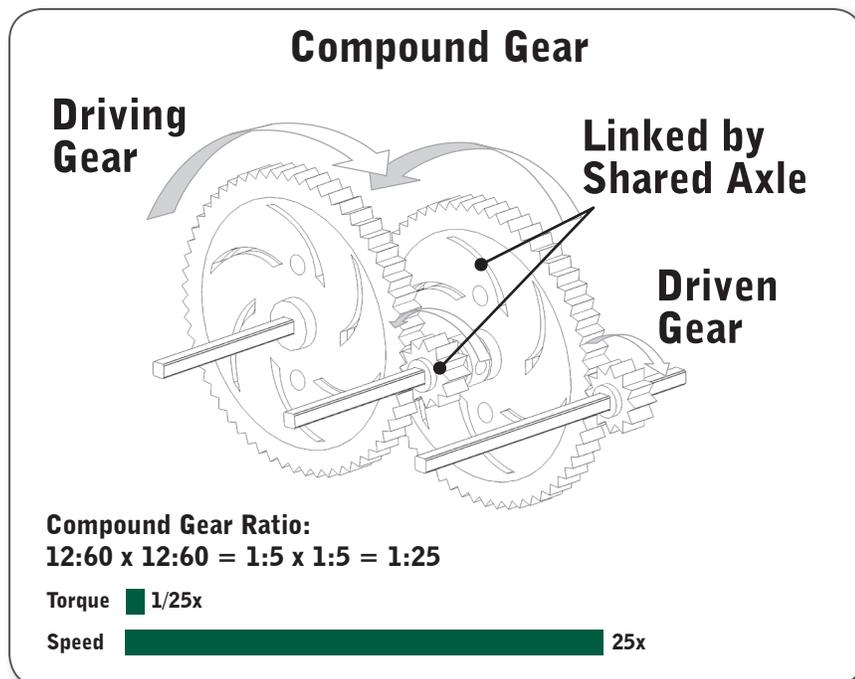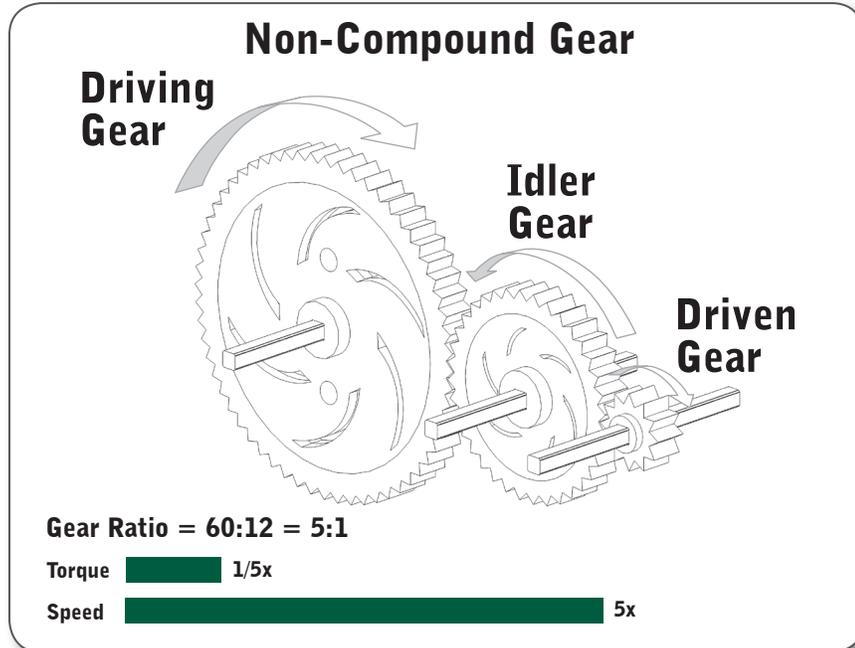
### Gears, continued

**Gear ratio with non-gear systems**

The real nature of gear ratios is a little more complex than just counting teeth on gears. Gear ratio is actually defined as the number of rotations that the driving axle needs to make in order to turn the driven axle around once. When dealing with toothed gears or sprockets, you can find the number of turns needed by counting teeth, as you have seen previously (see "Gear ratio").

With other types of systems, you can still find the "gear ratio" by measuring the number of rotations on the driven and driving axles. Some of these other drive types include belt-and-pulley drives and chain-and-sprocket drives.

Belt or chain drives are often preferred over gears when torque is needed to be transferred over long distances. Unlike spur gear reductions, Sprocket and Chain reductions do NOT reverse rotation.
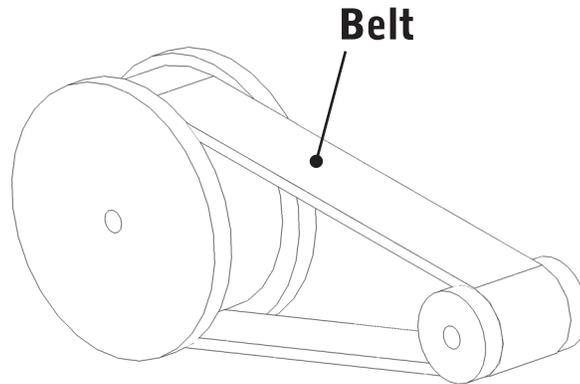
**Belt**

**Belt Drive**
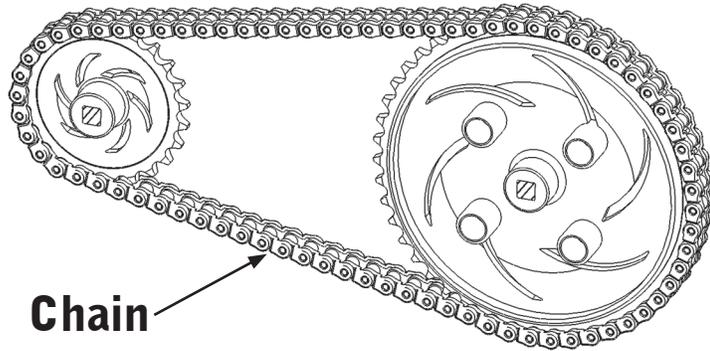
**Chain**

**Chain Drive**

# Concepts to Understand, continued

## Wheels

### Wheel Sizes

Often, the role of the Motion Subsystem on a robot will be to move the robot along the ground. The last step in the drive train, after the motors and gears, is the wheels.

Like motors and gears, different properties of the wheel will affect your robot's performance. The size of the wheels will be an important factor here, and will affect two distinct and different characteristics of the robot: its acceleration, and its top speed.

### Wheel Sizes and Acceleration

The relationship between wheel size and acceleration is simple: bigger tires give you slower acceleration, while smaller tires give you faster acceleration.

This relationship is the product of the physics of converting the spinning motion of a motor into the forward or reverse motion of the vehicle.



**Equal Torque** · **Large Radius** · **Small Radius** · **Fast Acceleration** · **Slower Acceleration**

Motors generate a "spinning" force (torque), which wheels convert into a "pushing" force at the point where they contact the ground. The larger this "pushing" force is, the faster the robot will accelerate.

The relationship between torque and force is:

$$\text{Force} = \frac{\text{Torque}}{\text{Wheel Radius}}$$

A larger radius will produce a smaller force for the same amount of torque, hence the larger wheel (which has the longer distance) has a smaller force, and hence the slower acceleration.



**Faster Acceleration**



**Slower Acceleration**

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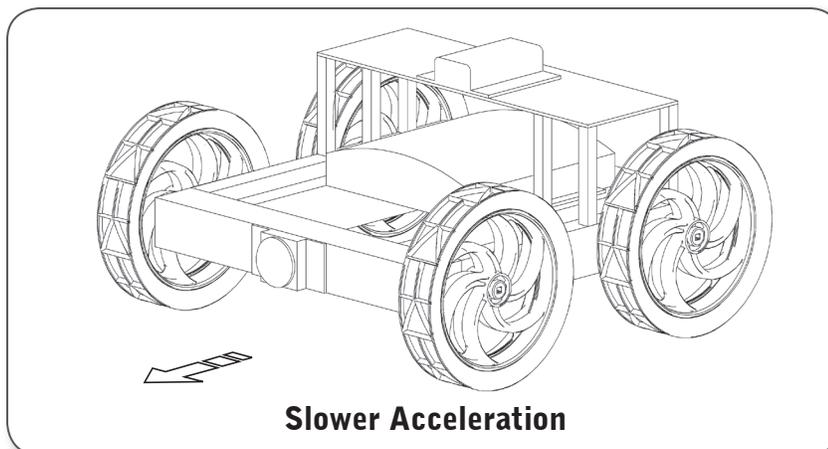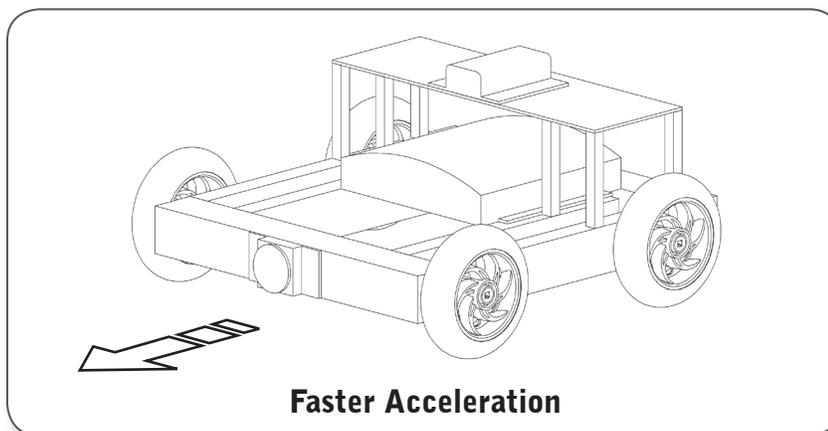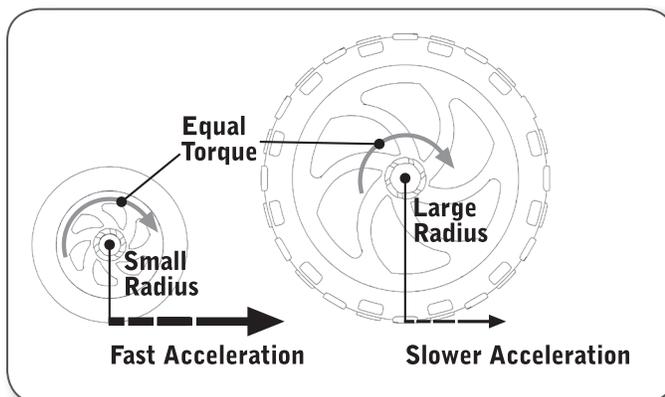
## Concepts to Understand, continued

### Wheels, continued

**Wheel Sizes and Top Speed**

Robots may take some time to reach their top speed, especially if they have high gear ratios (high gear ratio = low torque), but eventually, they tend to reach it, or at least come close.

When a wheel rolls along the ground, it is effectively "unrolling" its circumference onto the surface it is traveling on, every time it goes around. Larger wheels have longer circumferences, and therefore "unroll" farther per rotation.

Putting these two observations together, you can see that a robot with larger wheels will have a higher top speed. The robot with larger wheels goes farther with each turn of the wheels.  At top speed, robots with the same motor and gears will have their wheels turning the same number of times per second. Same number of turns times more distance per turn equals more distance, so the robot with larger wheels goes faster.

$$\text{Speed} = \text{Circumference} \times \frac{\text{turns}}{\text{second}}$$



Slower Top Speed    Faster Top Speed



**Small Circumference "Unrolling"**



**Large Circumference "Unrolling"**
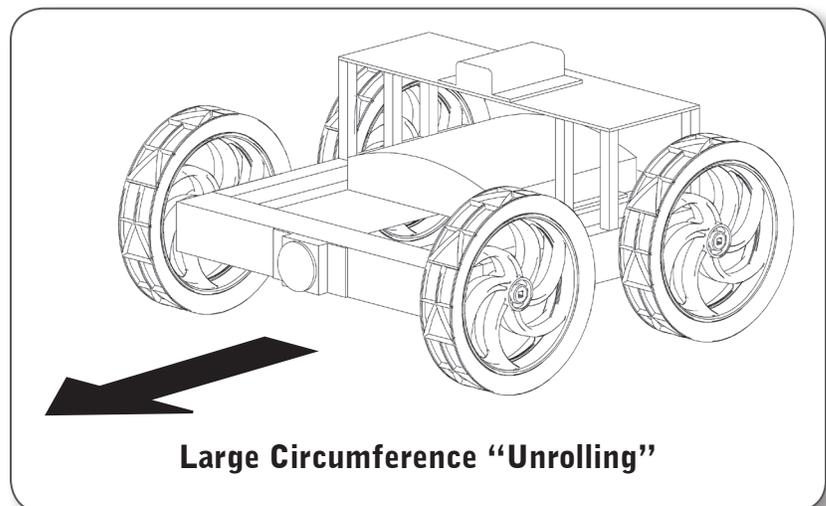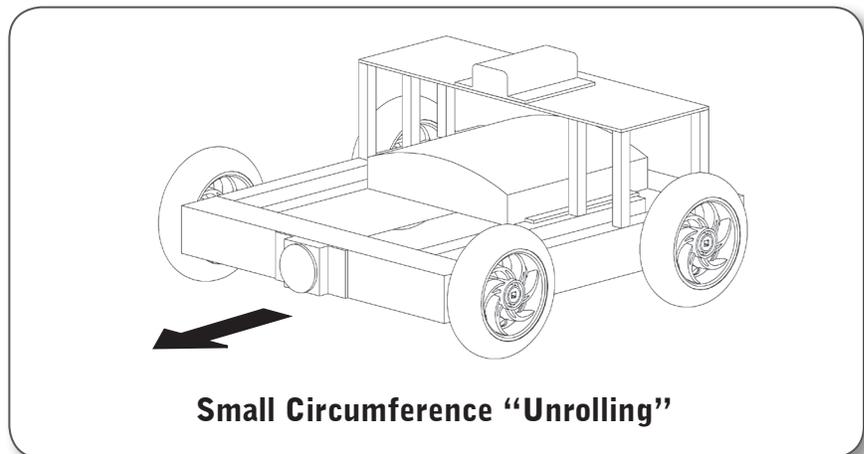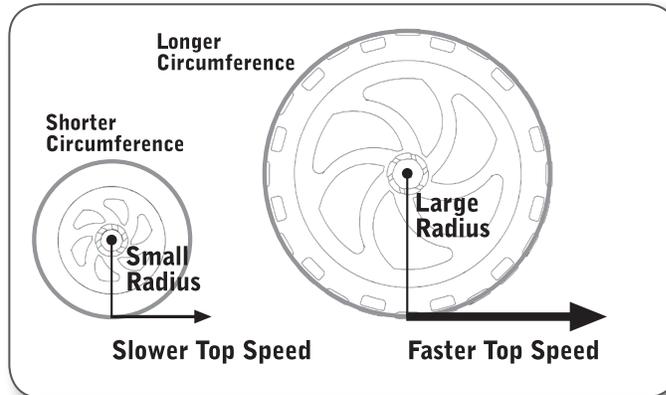
Notice that this sets up a tough design decision, since you need to decide on a balance between acceleration and top speed when choosing a wheel size. You can't have it both ways, so you'll need to plan ahead, decide which is more important to your robot, and choose wisely.

## Concepts to Understand, continued

### Wheels, continued

**Friction**

Friction occurs everywhere two surfaces are in contact with each other. It is most important when considering the wheels for your robot, however, because you will need to decide how much friction you want in order to maximize your robot's performance.

Wheel friction has both positive and negative consequences for your robot. On the one hand, friction between the wheel and the ground is absolutely essential in getting the robot to accelerate. Without friction, your robot would spin its wheels without going anywhere, like a car stuck on a patch of ice. Friction between the wheels and the ground gives the robot something to "push off" of when accelerating, decelerating, or turning.

On the other hand, wheel friction is also responsible for slowing your robot down once it is moving. A robot running over a sticky surface will go slower than one running over a smooth one, because the friction dissipates some of the robot's energy.

### For a Given Surface:
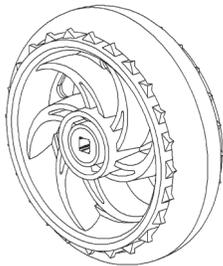
| 2.75" Wheel | 4" Wheel | 5" Wheel |
|---|---|---|
| Acceleration — Faster | Acceleration — Medium | Acceleration — Slower |
| Traction — Slippery | Traction — Medium | Traction — Heavy Grip |

Often there will be tradeoffs during wheel selection.

As shown above, wheel characteristics will vary greatly depending on the surface it is driving on. Some wheels which will perform well on carpet would not be as good on loose gravel.

The width, texture, and material of a tire all contribute to its friction characteristics. Again, there is no "best" solution. Rather it is a matter of picking the tire best suited to the robot's task, and the surface it will drive on.

05/08

## Concepts to Understand, continued

### Wheels, continued

**Terrain**
Sometimes robots will come across physical objects that must be traversed. Both the size of a tire and the amount of friction it generates will be very important in ensuring that you can successfully navigate over them. These obstacles may be numerous and complex, so you will need to plan for them, and test your solutions to make sure that they work reliably.

Drive trains can have a variety of functions. Be sure to design accordingly for what your robot will encounter. Remember the tradeoffs shown in this chapter and choose designs based on what your robot needs most.

**NOTE**: On some surfaces it is good to spread the robot load over multiple tires or a larger surface area to prevent it from sinking. Think of how snowshoes work.

**Example 1:**
**Robot attempting to climb a step**
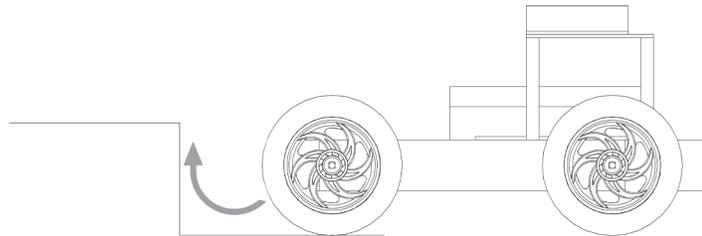
The robot with smaller wheels has a much steeper angle to climb – in fact, it's a sheer vertical face.
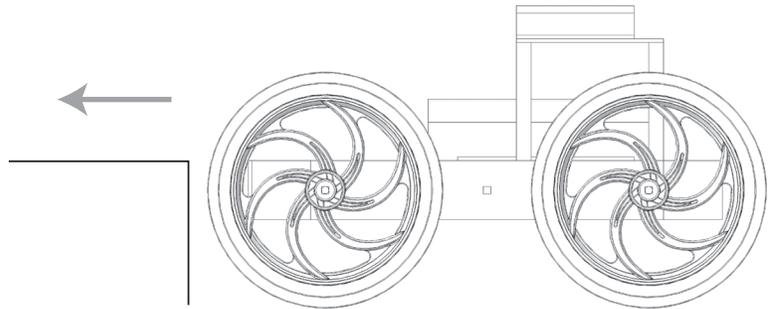
The robot with larger wheels has a much less difficult angle to climb to get up the step. This robot is much more likely to succeed.

**Example 2:**
**Robots attempting to climb a gravel hill**

The robot with slippery tires cannot get enough traction to climb the hill and slides off.

The robot with wheels that dig into the gravel can make it up the hill.
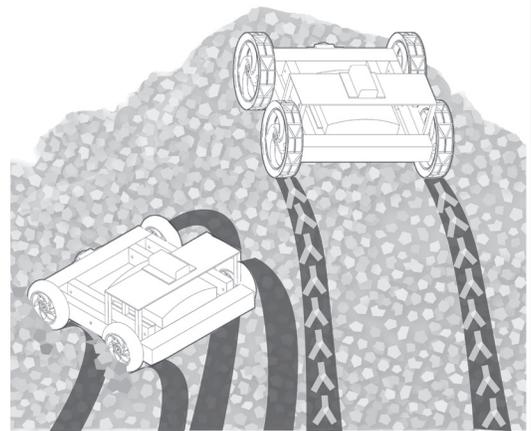
## Concepts to Understand, continued

### Clutches

**Clutches**

Every motor in the VEX Robotics Design System comes with a pre-attached clutch module. These clutch modules are designed to protect the gears internal to the motor from "shock-loads".

• The motor, even in a stall situation, CANNOT exert enough force to break the internal gears.

• The gears will break in some applications when the motor is under significant load, over a short duration of time (a shock-load).
  - The clutch is designed to absorb some of this energy in these situations by "popping" and giving way. This will protect the motor.
  - When a clutch "pops" it is briefly releasing the connection between the shaft and the motor.
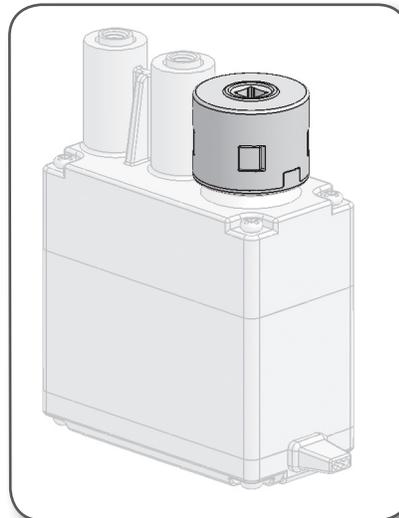
• **When a clutch pops, it is doing its job.**

• **When a clutch pops, it is a sign that there is something wrong with the robot design.**

• When a robot is designed such that the load on the motor is minimized (using gearing to reduce the load) there shouldn't be any popping clutches.

• Once a clutch pops for the first time, it is easier for it to pop every time after that; for some robotics applications it may be necessary to regularly replace clutches in key areas.

• There are some applications which do not need a clutch, however using a clutch is ALWAYS recommended. Any motor without a clutch is at risk of internal damage.

Spare clutches are available from **www.VEXrobotics.com**

## Concepts to Understand, continued

### Motion Part Features

**Hub and Tire**
Most wheels in the VEX Robotics Design System are actually two wheels in one. By pulling off the rubbery green tire surface, the grey hubs can be used directly in different applications on your robot.

**Hub**

**Tire**
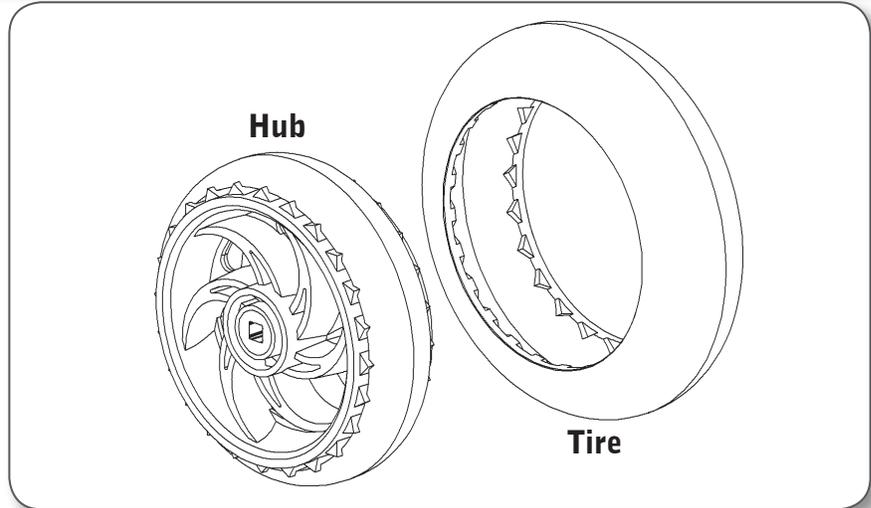
**Non-Axial Mounting Points**
In addition to the central hole for the gear shaft, some gears in the VEX Robotics Design System have a number of additional off-center mounting holes.

These mounting points have a number of applications. For instance, a larger structure could be built on top of the gear, which would rotate as the gear turned. Alternately, the ''orbiting'' motion of a non-axial mount can be used to create linear motion from rotational motion.

**Bar Oscillates**
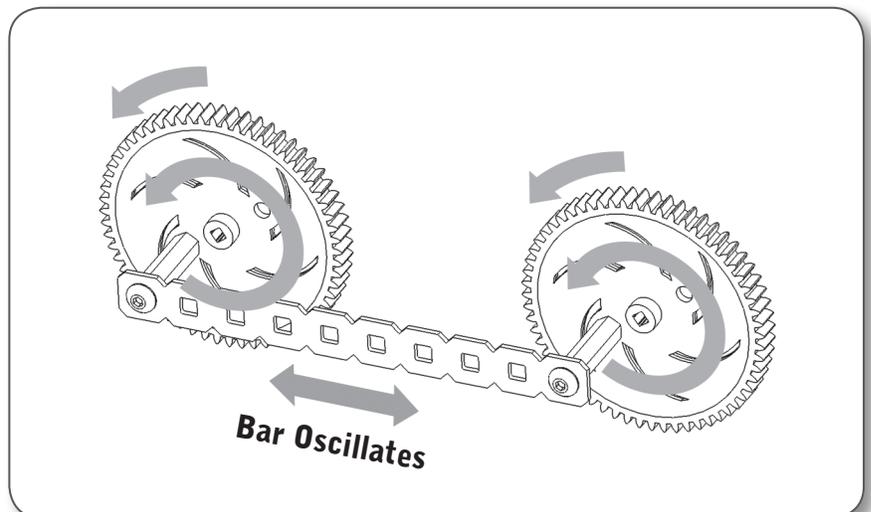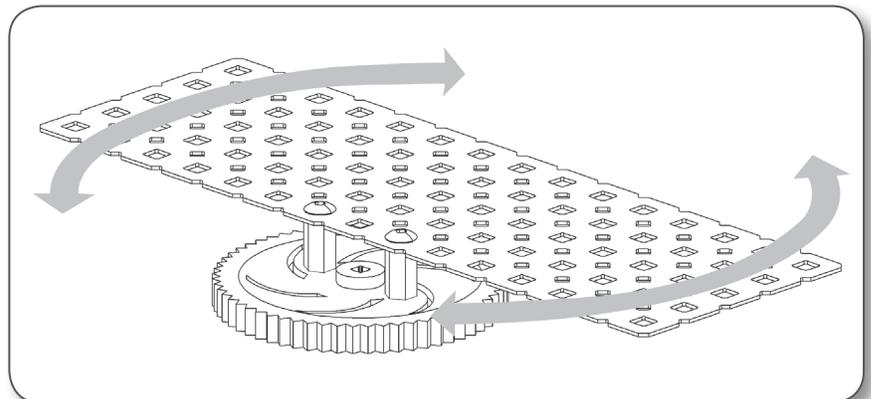
## Concepts to Understand, continued

### Motor Gear Replacement

**Gear Wear and Tear**

Gears often bear tremendous amounts of stress in a moving system. The gears inside the motors, in particular, are subjected to large amounts of wear and tear during use in robotics applications where they are frequently required to reverse direction quickly (to make the robot go the other way, for instance).

Inevitably, these gears will wear out and need replacement. Replacement gears come with Motor Kit and are also available from **www.VEXrobotics.com**, so you can perform the necessary repairs when needed.

To replace the gears in a motor or servo motor, follow these instructions:

1. (top of page) Remove the clutch and clutch post.

2. Remove the four screws in the corners of the front of the motor case.
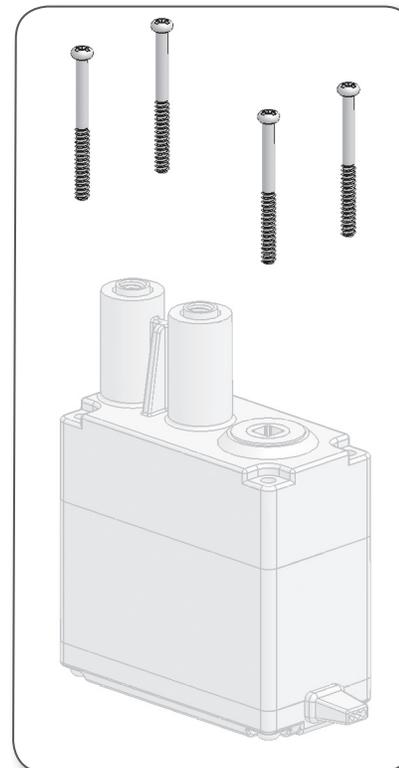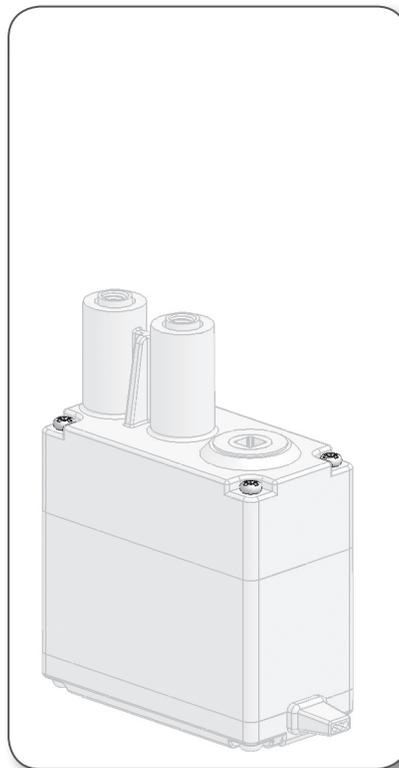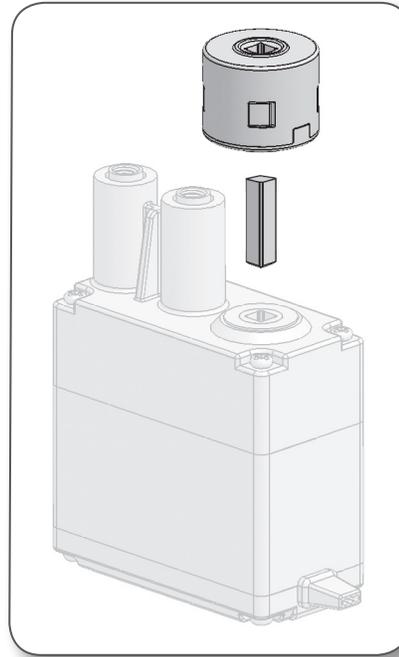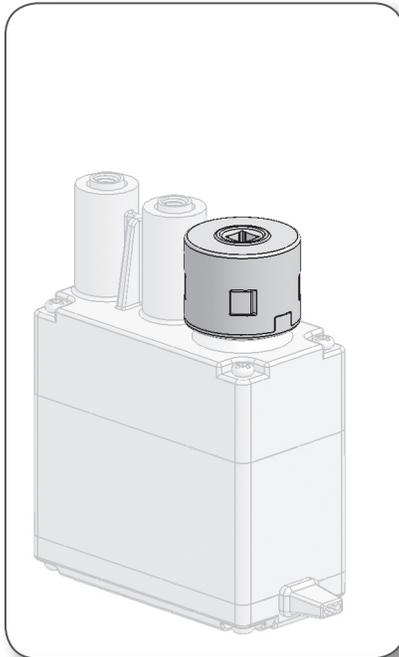
## Concepts to Understand, continued

### Motor Gear Replacement, continued

3. Gently lift off the top cover. Try to do so without disturbing the gears inside, so you can see the proper configuration for later reference.
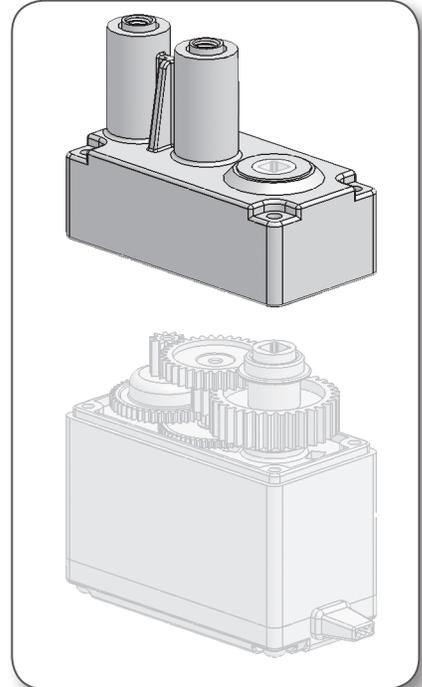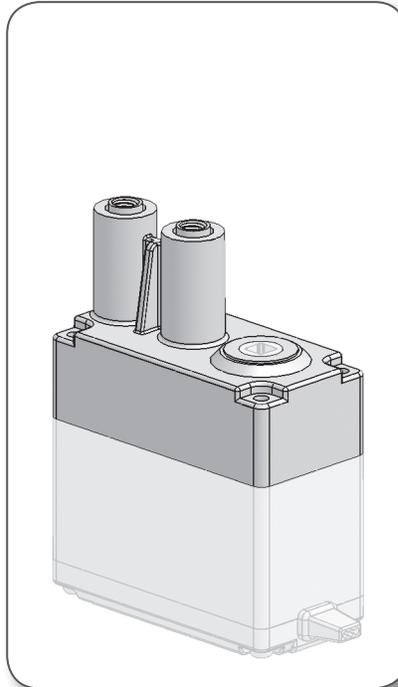


4. Remove the middle gear and the large shaft gear together.

*Be careful when handling gears, as they are coated with a layer of lubricant that helps them turn smoothly. Wash your hands after handling the gears!
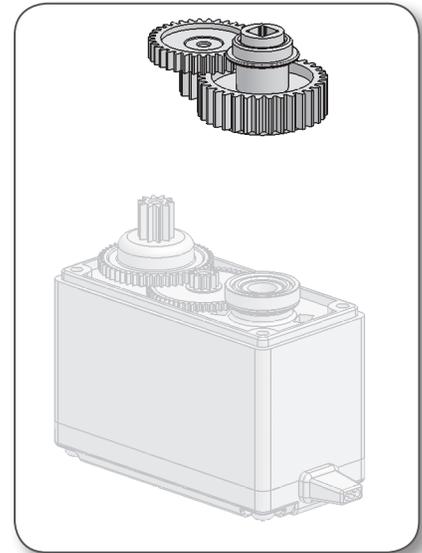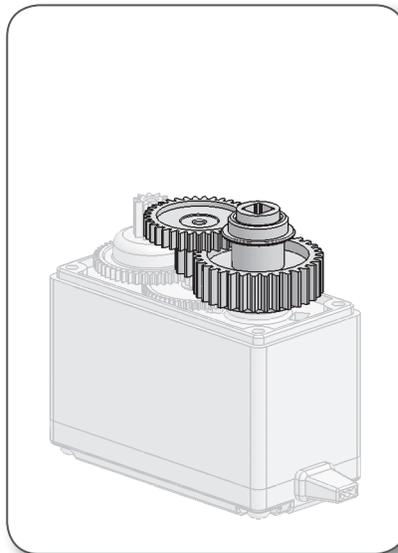
## Concepts to Understand, continued

### Motor Gear Replacement, continued

5. Remove the side gear.
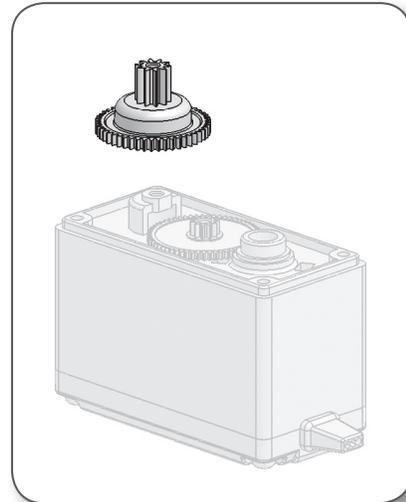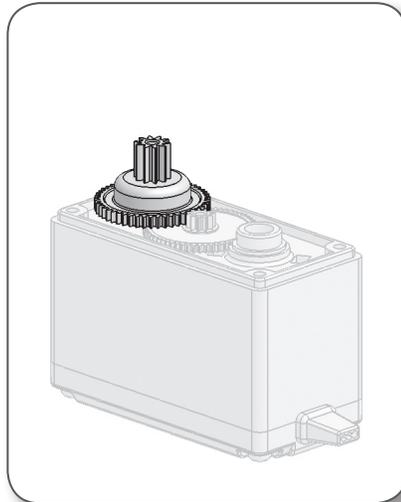
6. Remove the thin bottom gear, and carefully wipe the bottom gear deck and the inside of the top case to remove any remaining broken gear fragments.
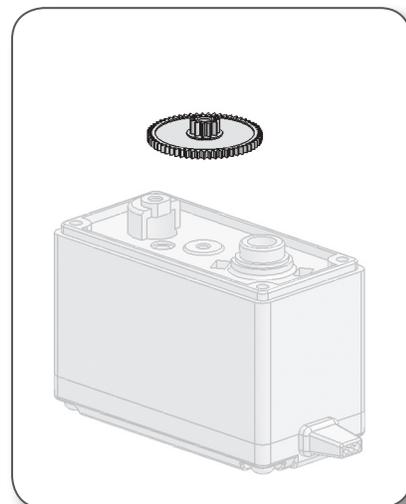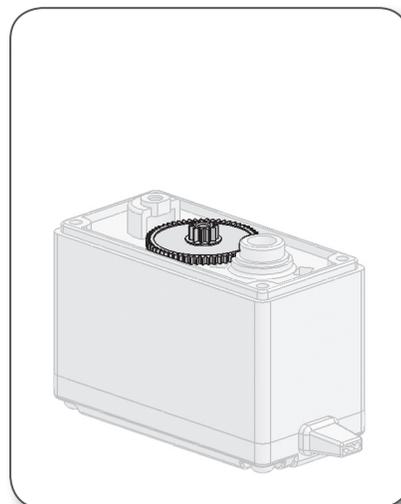
7. Open the packaging for the replacement gears. Take special care when handling the replacement gears, as they are very small and slippery (they come pre-greased).
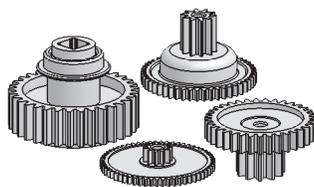
Note: The large black servo motor gear will have a black plastic key underneath the gear's metal bushing (Not shown).

## Concepts to Understand, continued

### Motor Gear Replacement, continued

8. Install the replacement thin bottom gear.
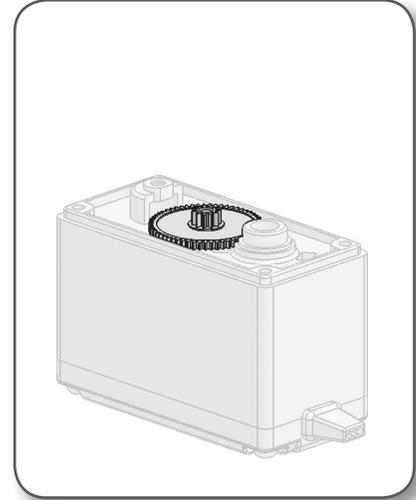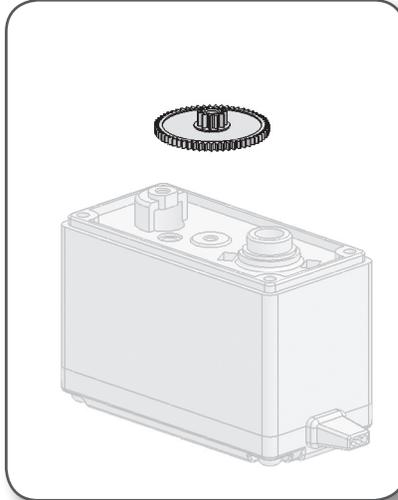


9. Install the replacement side gear.
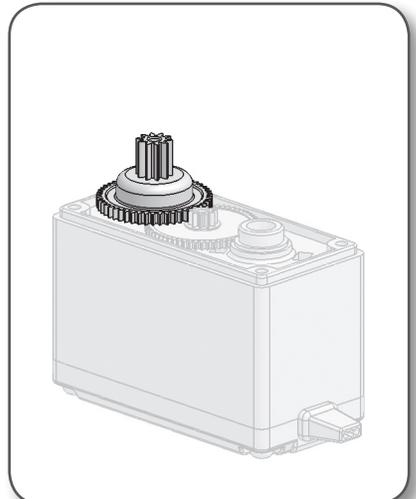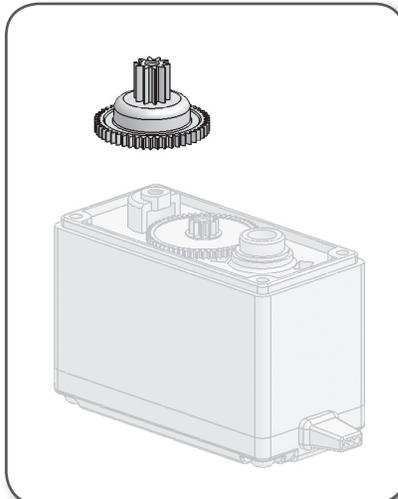


10. Install the replacement middle gear and the replacement large gear together, the same way you took them apart.
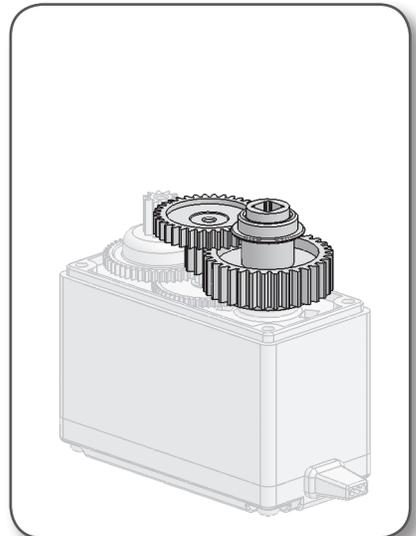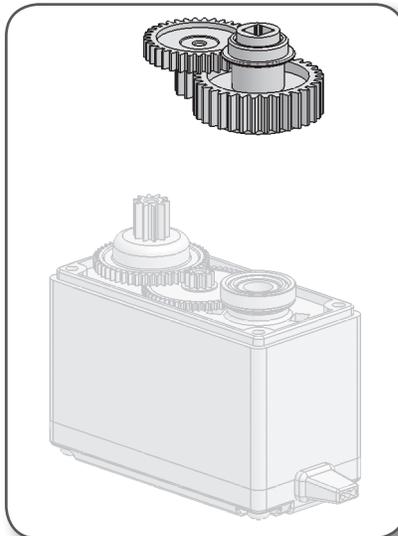
## Concepts to Understand, continued

### Motor Gear Replacement, continued

11. Carefully replace the top cover. Don't disturb the gears, or the motor may not turn properly.
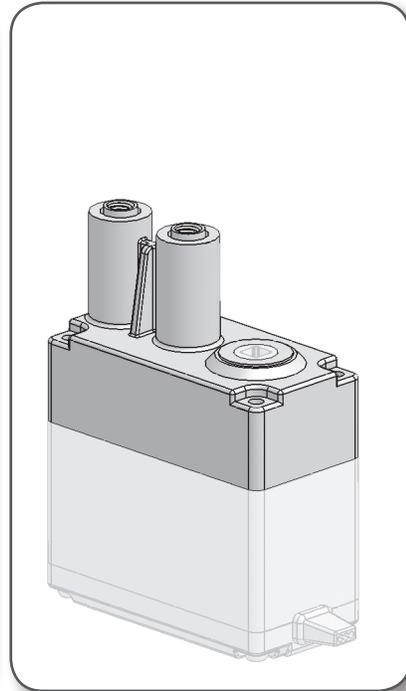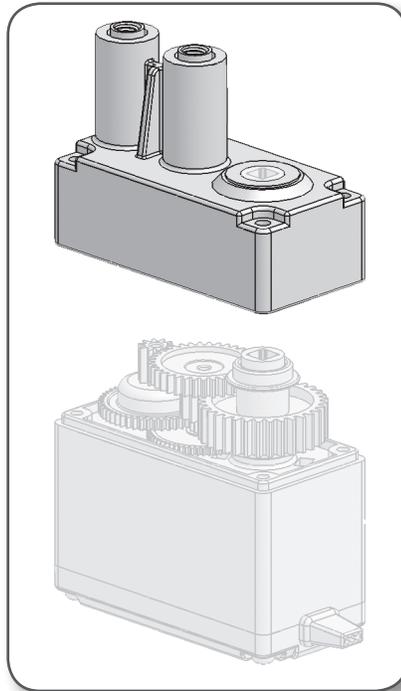




12. Replace the four corner screws.
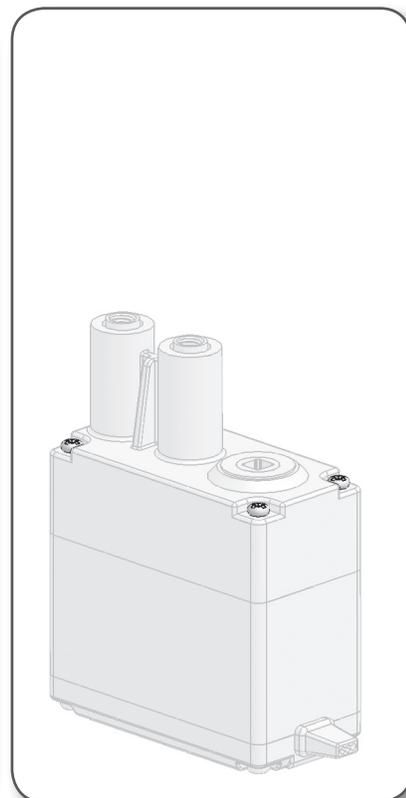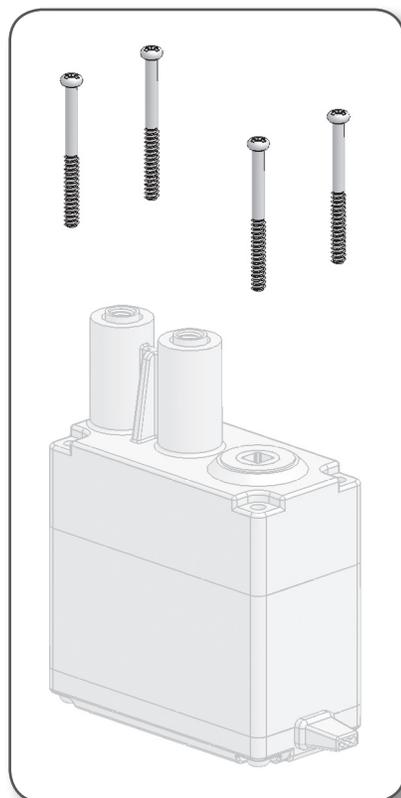
## Concepts to Understand, continued

### Motor Gear Replacement, continued

13. Replace the clutch and clutch post.
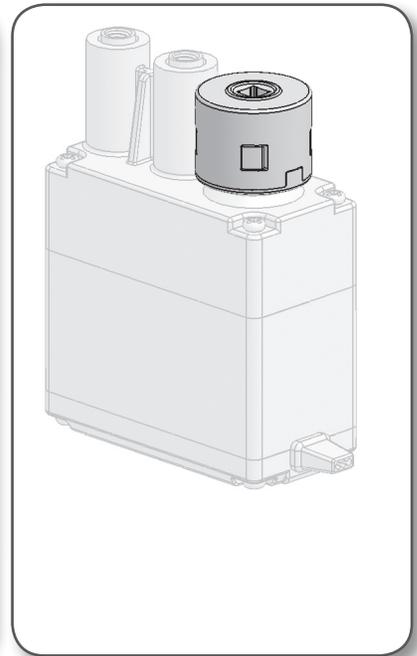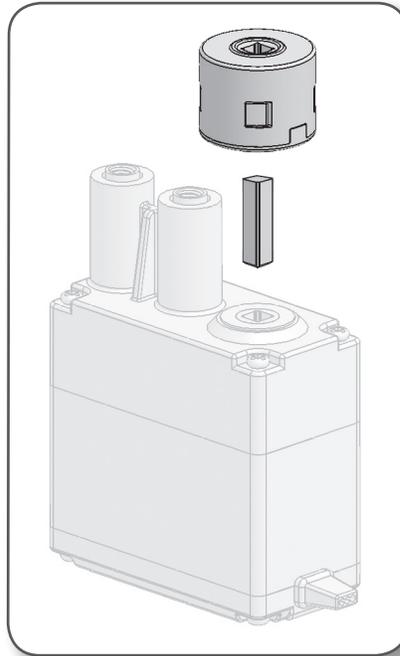
# Subsystem Interactions

**How does the Motion Subsystem interact with...**

## ...the Structure Subsystem?

• The motion and Structure Subsystems are tightly integrated in many robots designs. The Motion Subsystem can't be constructed without certain structural components (like the chassis rails) to provide support and positional reference. By the same token, the Structure Subsystem must be designed largely to accommodate the motion components.

## ...the Power Subsystem?

• The Motion Subsystem's motors and servomotors convert electrical energy into physical energy. This electrical energy is ultimately supplied by the Power Subsystem's battery, but the motors do not plug into the battery directly. Rather, the flow of power is directed by the Robot Microcontroller, which decides how much power is allowed to flow from the Power Subsystem to the Motion components.

## ...the Sensor Subsystem?

• Robots often have motors and other Motion components controlled by sensors (for instance, the emergency stop function stops the motors when the bumper switch sensor is pushed). However, the Sensor Subsystem does not directly control the Motion Subsystem. Instead, the Sensors provide information to a program running in the Microcontroller, which takes that information into account, and then decides what command to send to the Motion Subsystem.

## ...the Control Subsystem?

• Unlike radio-controlled cars, the VEX robot does not directly tie the Control Subsystem into the Motion Subsystem. The commands generated by the operator, using the Transmitter are sent to the RF receiver on the robot. From there the commands are given to a program running in the Microcontroller, which takes this and other information into account when deciding which command to give to the Motion components.

## ... the Logic Subsystem?

• The Motion Subsystem plugs into the Microcontroller, which is the main component in the Logic Subsystem. Though the Motion components are "controlled" to various degrees by user input (Control Subsystem) and sensor feedback (Sensor Subsystem), the final decision on what command is issued, as well as the actual flow of electricity (from the Power Subsystem) is all controlled by the Logic Subsystem. The Logic Subsystem governs everything the Motion components do.