FRC TEAM 610

The Design Tutorials

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INTRODUCTION

Engineering is, quite simply, problem solving. It is the process of designing solutions to problems and then executing those solutions. There is never one correct way to do something, rather each solution is unique and holds its own value. Design can't be taught from a book, but is rather learned from experience and failure. This set of tutorials merely serves as a guideline for designing your own solutions. It is not a recipe for designs but teaches the essential techniques for everything from building gearboxes to lifts. Take great pride in what you build but always be open to critique.

These tutorials assume a reasonable understanding of SolidWorks, some basic physics (torque, gear ratios, etc.). Also, keep in mind that ideas are cultivated on pen and paper and in CAD, and not with a sledgehammer and drill. Work through these tutorials, and by the end hopefully you will have the tools to tackle any challenge the GDC throws at you.

Important tips before you get started:

1. Use the Design Library. It has everything from sprockets to motors and will save you lots of time looking for off-the-shelf parts.
2. Use off-the-shelf parts when convenient. For example, order spacers when possible – machining a dozen spacers takes time, resources, and is no fun.
3. Make things generic lengths and use standard parts. Make parts to fractions of an inch (e.g. 1/8" = .125; 3/8"= .375) so they are easier to machine, and you will be more likely to find an off-the-shelf part. Also, don't use weird stock sizes or rare/special parts as they will be hard to find.
4. NAME YOUR FILES PROPERLY! REMEMBER TO SAVE! DON'T FORGET WHERE YOU SAVED IT!
5. Always ask for help if you need it.
6. As cliché as this is: never give up.

FASTENERS

You should probably know enough by now to know that to attach two parts together, you are probably going to be using a screw.

This basically covers all of the screw sizes you will ever use:

4-40

- Essentially the smallest screw we use
- Low stress applications (e.g. panels, covers, trays, sensor mounts)
- Rarely use this size

6-32

- Most commonly used on VEX Motors
- Usually only used when an 8-32 is too big
- Not bad for tapping

8-32

- Most common screw in VEX – used to attach essentially everything
- Fairly common for assembling smaller FRC components (e.g. pneumatic tank mounts, electrical boards)
- Not bad for tapping

10-24

- Most common screw used
- Used for assembling the shooter, battery mounts, intakes, etc.
- Too big to tap the sides of thinner sheet metal/plastic but can still be tapped on thicker material

10-32

- Used almost exclusively to mount the CIM motors

¼-20

- Used when a 10-24 is too small and/or for higher load applications (e.g. while assembling the drive frame)

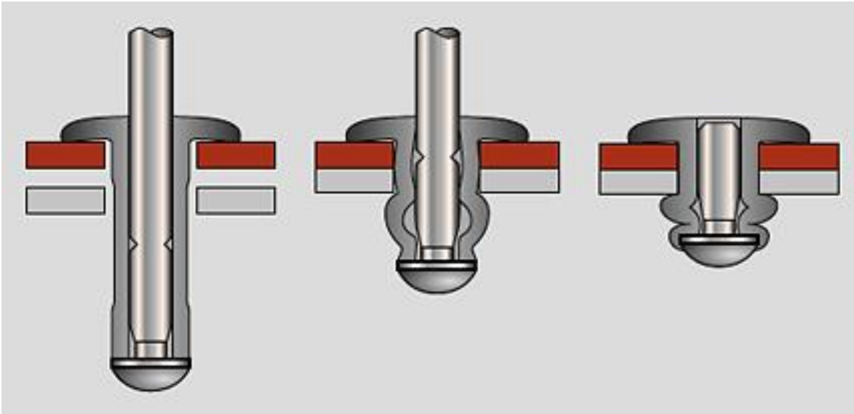
Larger sizes do exist but we don’t use them very often. Sometimes, a larger screw like a 3/8 may be used as an axle. Most screws and nuts are steel, although they do come in other materials such as nylon and aluminium.

Some Special Nut Types:

Keps Nut		These nuts have a special face that grips the material that it is holding to prevent it from coming loose.
Lock Nut		They have a nylon insert that doesn’t allow the nut to loosen or to come off. Must be used when a screw is being used as a pivot; if not, the nut will just undo itself. They are also commonly used in places where the nut will vibrate or shake off.
Pem Nut		A nut with a special face that you press into the part so that the nut stays attached to the part. Commonly pressed into a part before the part is assembled because without the nut already in the part, it would be difficult to put in once assembled. Must be pressed into the part ahead of time.

The above comprises >90% of the ways you will hold things together.

Rivets function like screws but work in a different fashion.



They are extremely convenient because you don’t need to have a nut (nuts can be problematic when access to the other side is limited). Rivets are also much lighter than screws because they are aluminium. While the weight of one screw may not seem like much, a whole robot’s worth of screws can add up. The disadvantage of rivets is that unlike a screw, they can’t be undone and put back together as easily. Removing a rivet involves drilling it out. The majority of our robots are held together with screws, but a fair amount of rivets can be found too.

They come in sizes such as 1/8’, 3/16’, and ¼’.

STOCKS AND RAW MATERIALS

The two main materials we use are plastics and metal. Of the metal, most of it is aluminium (6061 or 6063 and 7075), and most of our parts are machined from aluminium. Some steel is used, mainly in the form of shafts. We barely ever use steel, as it is harder to machine and much heavier than aluminium. Steel is stronger, but for most purposes aluminium will do. You will see some instances where aluminum would wear down too easily, such as in a dog gear. For plastics, we generally use either Lexan brand polycarbonate (a transparent plastic material that does not crack and is incredibly strong), or Delrin (a low friction plastic). Some occasional Teflon, nylon, ABS, and acrylic end up in the shop for special applications.

Metals and plastics come in the forms of sheet, an extrusion, or, rarely, in a block, and the stock is machined down to size.

Always check shop for stock availability. Go to “www.mcmaster.com” to search McMaster-Carr for full stock options. These are just general guidelines.

1) Metal (Aluminum only unless specified)
    a) Sheet or a rectangular Bar
        i) 1/16” Thick (.0625)
        ii) 1/8” Thick (.125)
        iii) 3/16” Thick (.1875)
        iv) ¼” Thick (.25)

b) Extrusions
   i) Shafts [aluminum and steel] (OD = Outer Diameter)
      (1) 3/16” OD (.1875) –round only
      (2) ¼” OD (.25) –round only
      (3) 3/8” OD (.375) –hex and round
      (4) 1/2” OD (.5) –hex and round
   ii) Tubes
      (1) Essentially any OD of generic size (1/2”, 1”, 2” etc.) with either 1/8” or 1/16” walls.
   iii) Box, C and L Channel
      (1) Essentially any combination of .5”x .5” up to 4”x 4” OD. Either 1/8" or 1/16” walls.
   iv) Blocks
      (1) Check shop

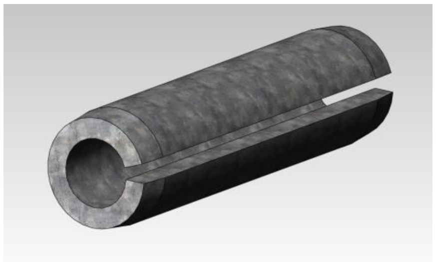
2) Plastics
   a) Sheet
      i) 1/16” Thick (.0625)
      ii) 1/8” Thick (.125)
      iii) 3/16” Thick (.1875)
      iv) ¼” Thick (.25)
      v) 5/8 Thick (.625) Delrin
   b) Other
      i) Check shop stock

Always check to see if your stock size is available. If it is not, try to see if you can use something else. If not, order it. Stick to the generic stock sizes.

ROLL PINS

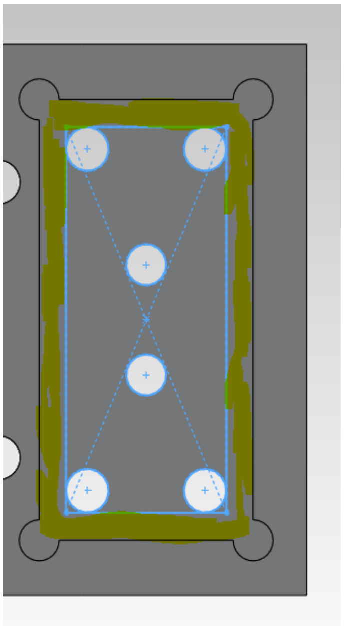
These are metal pins that are pressed into part.

Here is what it looks like.



This one is designed to fit into a 3/16’ hole, but is actually slightly larger than that.

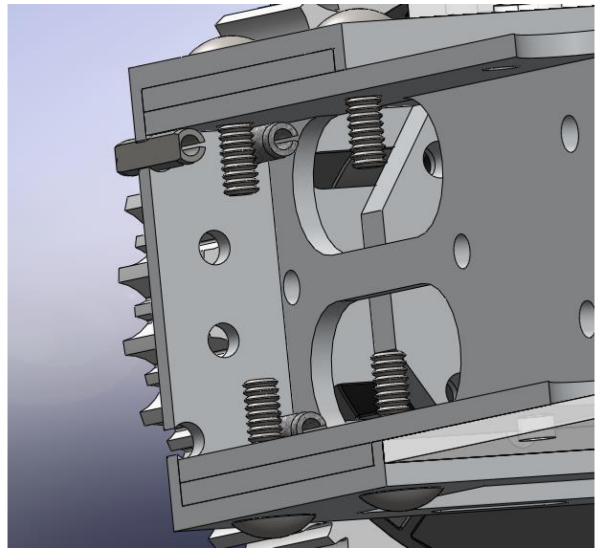
These pins are pushed into the metal and stay in because it is a tight fit.



The pins can be used in many ways, but one of the ways we use them is to join a square tube perpendicular to a flat surface.

Here we have a cross bar for a drive train being joined with the drive train.

Looking head-on, the yellow region is the space occupied by the perpendicular tube.

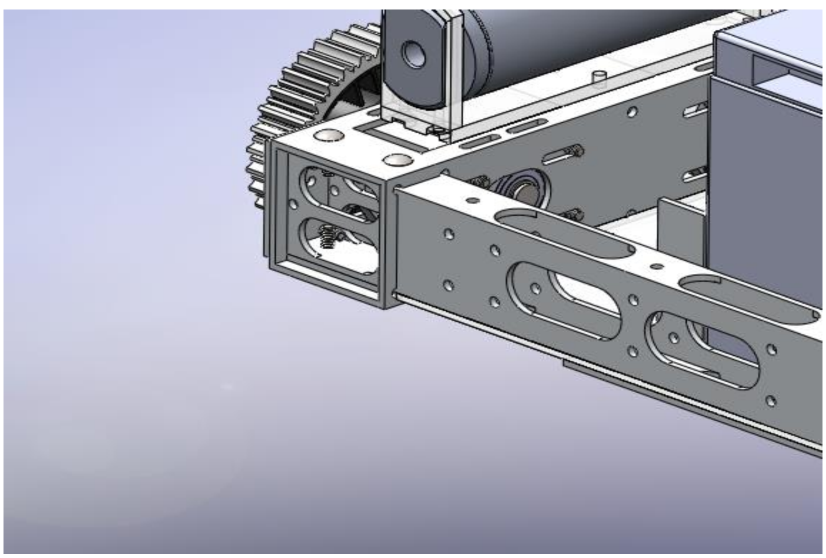


Tangent to the tube are 3 roll pins. (Note: the centre two holes are irrelevant)

In the 4th (empty) hole, a piece of threaded rod runs from one end to the other. Nuts on both sides keep the tube from sliding out, while the pins keep it from rotating or moving.

In this particular case there are also 4 screws that secure it from top and bottom. Notice the insert sandwiched between the 2 tubes. That piece is there to prevent the tube from caving in when the screw is being tightened. Over-tightening the screw can cause the screw to vice and warp the metal.

Also, notice how on the side that the perpendicular tube runs through, the rectangle has its four corners drilled out. This is because we can't cut perfect 90° inside corners. The 4 corners are drilled out so that the part fits in smoothly. The alternative is an army of filers – but that's no fun.



Screws are also shown in this case. In general, you don't need to put those into your CAD unless you have too much time or the amount of available space is in question. Screws take up space too! It might be very little, but if you can't get them in, it's no good.

TAPS

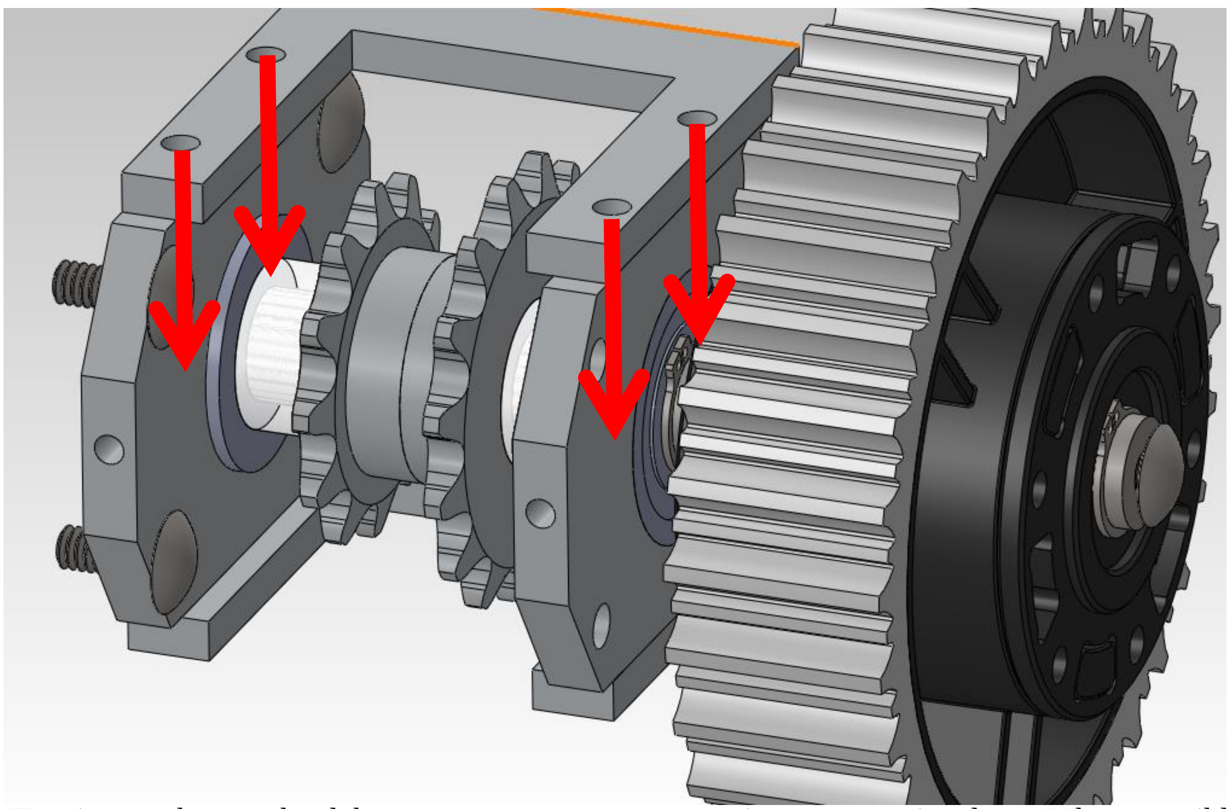
In places where you need to join 2 pieces of metal together but a nut will not fit or a rivet will not do, there is the tap. Tapping essentially involves giving a hole in a part threads such that the part itself acts like a nut and keeps the screw in.

This is what a tap looks like. It basically cuts a thread into a hole.

To tap a hole; first drill a hole slightly smaller into the part, then turn the tap into the part as if you were screwing it in.

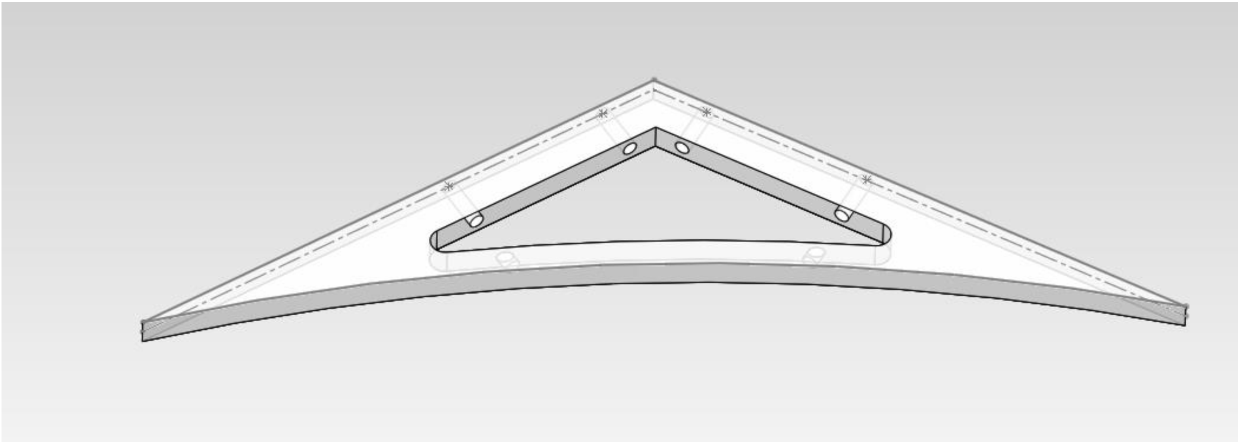
Taps are delicate (the tool and the threads) and break easily. When they break, you need a new part. Tapping is also very laborious and time consuming.

This bearing block (we will talk about these later) has a roof piece that needs to attach to the side piece. In this particular piece, a section of L channel will not do because the assembly needs to be small enough to fit into the drive tube. Typically, taps are used to connect something to the side of a sheet of material, where you can't put a nut or fit a gusset.



Tapping can be very hard, but taps are not as strong as using a conventional nut. Where possible, avoid taping.

This part is designed to hold two plates perpendicular to it at an angle. To avoid tapping, a slot was cut into the middle so that a nut could be placed there instead.



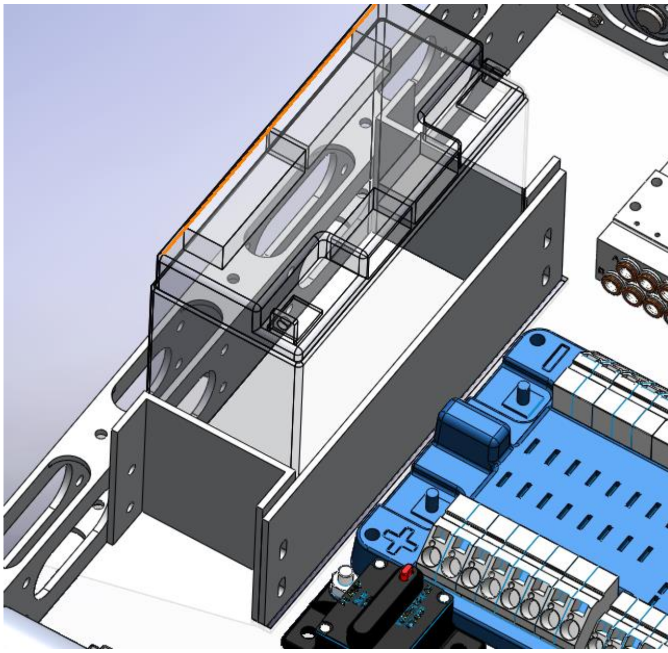
THREADED INSERTS

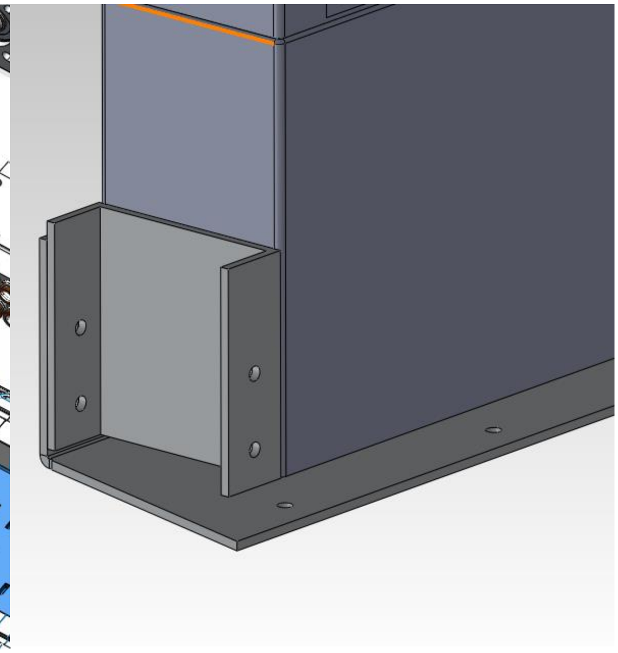
Quite simply, these are shoved into the ends of round tubes. To connect the end of the tube perpendicular to something, pound the insert into the end of the tube, and secure a perpendicular plate to the end by putting a screw through it. (Similarly to how a base flange works for a pipe.)

They come in sizes such as a 10-24 thread for a 1" pipe.

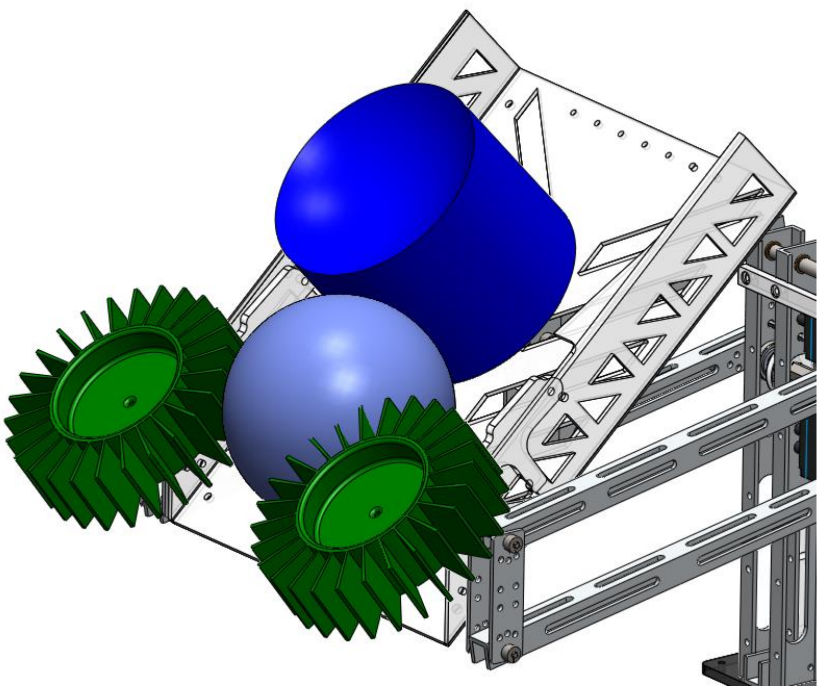
SHEET METAL

Instead of cutting two separate sheets and connecting them with a third piece, sometimes it is easier to make one part and bend it.





A single continuous plate holds the battery from underneath and in the front.

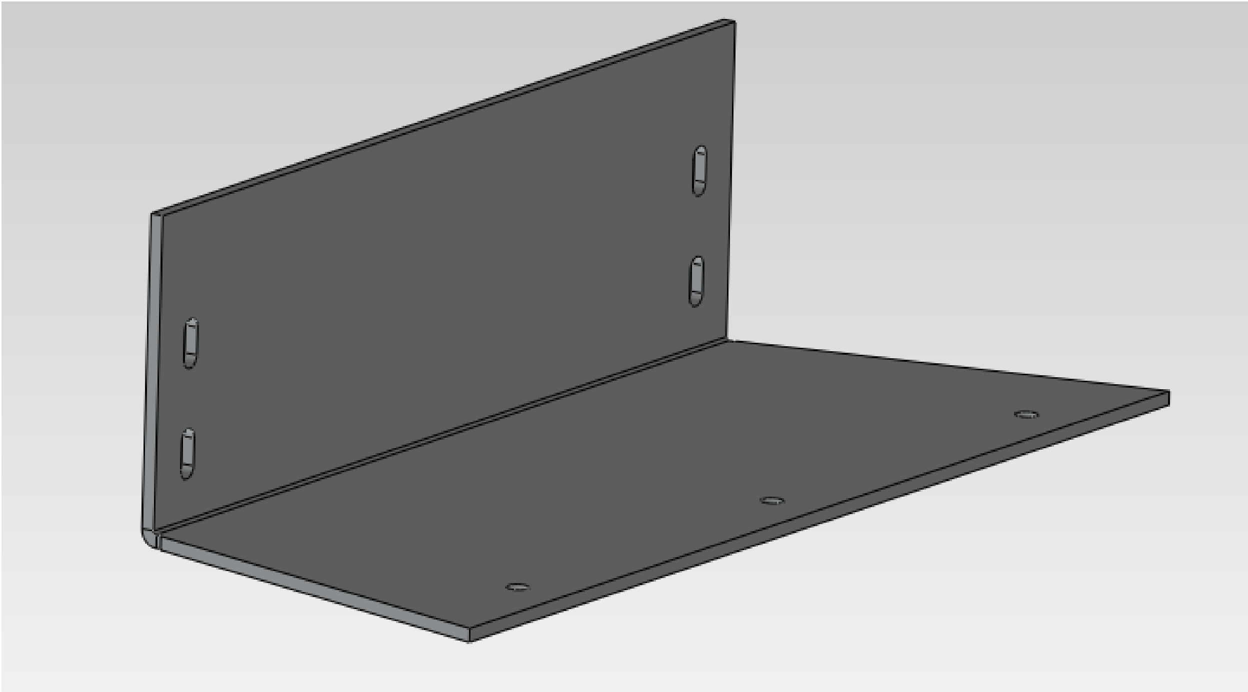


Giving parts a flange (bending the sides) can also increase its strength (think of C and L channels, and I beams)

Take this tray for example; (made from 1/8" polycarbonate) without the side flanges (ignoring the fact that the pieces would fall out), it would flex and bend back a lot.

In general, things are much more rigid when they have a bend in them.

A problem with sheet metal however, is that we cannot accurately place bends with our bender.

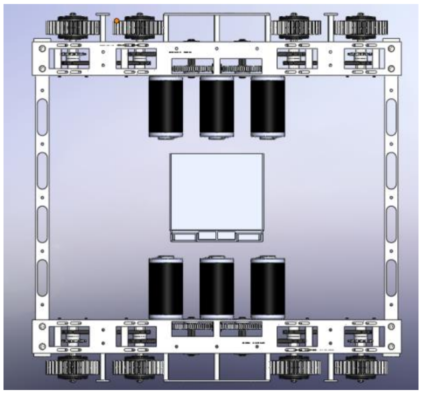


Take this part, for example. Since we cannot precisely control the position of the bend, the height of the flange could be too low or too high, causing the holes to not line up (hence the slots you see there). For parts like this where accuracy is a non-issue, we just put slots in. However, anything that needs to be precise can only be so on one side of the bend. Keep this in mind when designing with sheet metal!

DESIGN CHALLENGE

This is a basic revision of how to assemble things. Find the folder called: "Drive Base Battery Assignment". Open the Assembly called: "Drive Base".

Your Task:



1. The battery MUST go there and cannot be moved (don't ask why it is in the middle of nowhere – that's the challenge)
2. Build a mount that will secure the battery (remember it weighs ~15lbs.)
3. Assume the drive train has already been built and assembled (why it would be built without a battery mount is irrelevant) and you may not modify any components, you may only add.
4. Common sense applies. Remember to try to keep it as light, simple, and easy to machine as possible.

POWER TRANSMISSION (ROTARY)

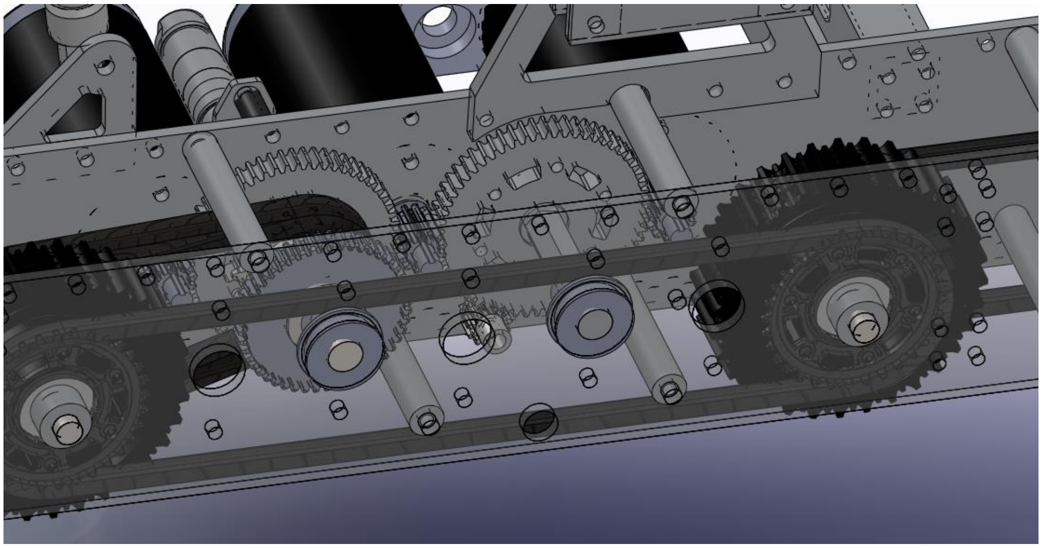
Batteries provide all the power for the robot. In general, everything on the robot is powered by motors (rotary motion) or pistons (linear motion) which run off of compressed air. Here, we will be dealing strictly with motors and getting power from the motors to a winch, arm, roller, or whatever you want to power.

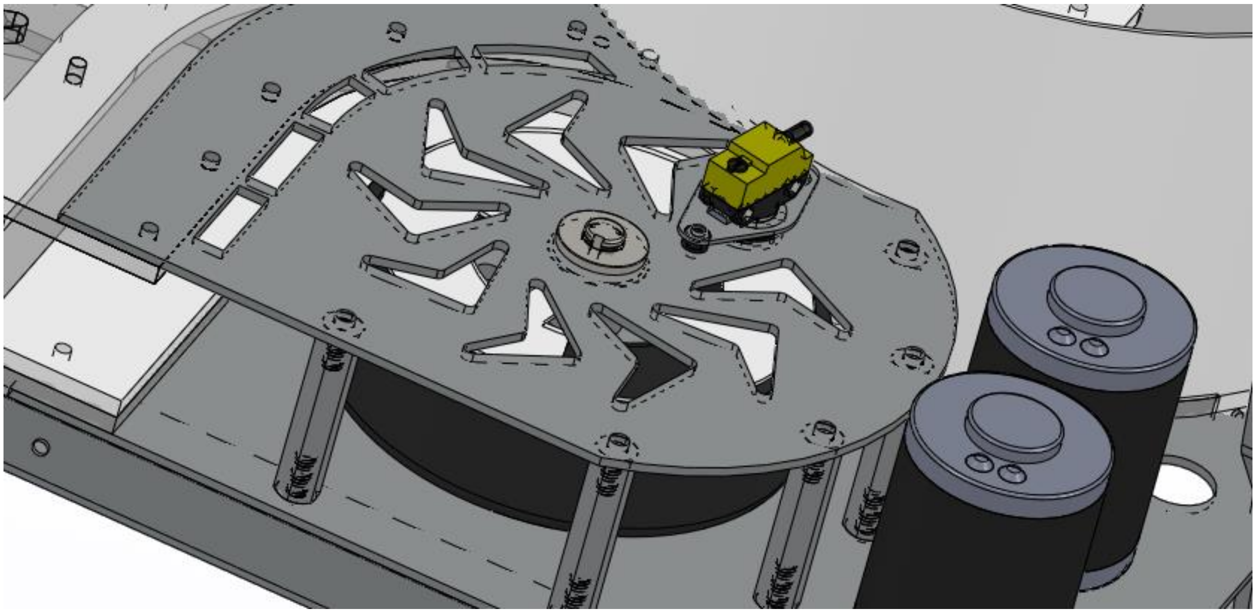
BEARINGS

This is a bearing. Essentially, bearings hold shafts in place and allow the shaft to spin freely with low friction. Anywhere that you have a spinning shaft you will need to put a bearing to hold it in place.

Most bearings that we use are for a ½ inch or ⅜ inch shaft, although we occasionally do use some other sizes such as ¼ inch or 3/16 for smaller applications. There other types known as sleeve bearings which are bearings without balls. They are just made of out a material that allows the shaft to spin with little friction. They don't allow the shaft to spin as well, but the advantage is that sleeve bearings are much smaller and can take much higher loads (not that we will ever come close to needing that).

Here we see two bearings in the side plate, holding in place shafts for the gear box. The bearings keep the shaft in place, but allow it to spin smoothly.

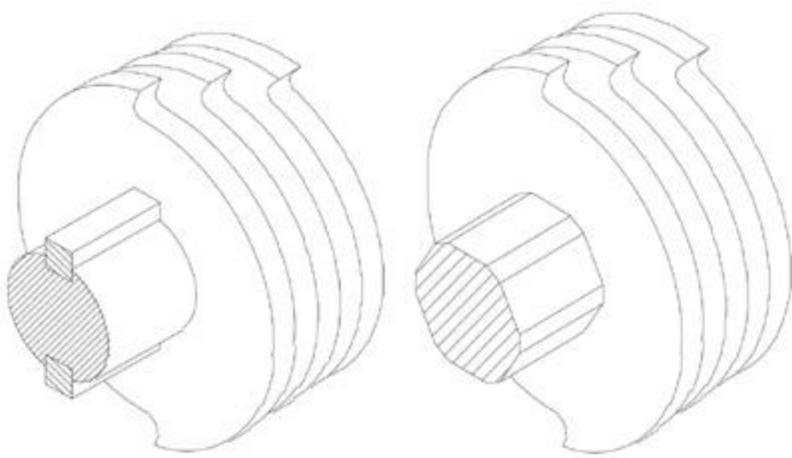




Here on the shooter wheel, it is the same story. The shaft on which wheel spins is held in place with a bearing. Typically, to put bearings in, we just press them into the stock.

SHAFTS

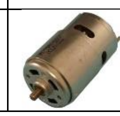
Shafts are used to transmit power. They are considered either live or dead axle. Live axle means that power is being transmitted through the axle, whereas dead axle means that the shaft is not transmitting the power; they are just there to hold the gear. An easy way to tell if an axle is dead or live is to ask this: If an axle were perfectly round and not spinning, would power still be transmitted to an appendage on the end? If the answer is yes, then it is a dead axle. If it is no, then it is a live axle. Also, a live axle will always have to have one of; a keyway, hex, or set screw to transmit the power.



We would normally only put one key/keyway in an axle (not two as shown in the picture).

MOTORS

Here are the motors we typically use:

Name	Primary Application	Picture
CIM	The drive train is the main application for these (allowed up to six). Most robust motor. Used for the most strenuous tasks. Many teams will run four of these on the drive. You also find them on mechanisms that require lots of torque, such as hangers.	
Mini CIM	Smaller CIM motor that is usually used for medium sized tasks such as shooters and arms.	
Bag Motor	Even smaller CIM motor that is often used to power rollers, feeders and smaller arms. Also known as a “baby CIM”. A combination of up to four of these and Mini CIMs is allowed.	
BaneBot RS550	Comparable power output to some of the larger motors. However, its smaller and more compact design means it is worse at thermal distribution (i.e. it overheats more easily). They are also not as reliable or as robust as CIMs. You will often find these on lifts, rollers, and feeders.	
Bane Bot RS775	Slightly more powerful than the RS550 but significantly less reliable.	

There are many more, but these are probably the four that you want to stick to make your life easy. Other motors include the “window motor” which has a built in worm gear so it is not back drivable, the AndyMark 9015, and the Fisher Price Motor. Reminder: models of all of these motors are in the design library and they have their weight already set. Use them!

Know that these motors spin at incredibly high RPM so quite often large reductions are needed. We could build large gearboxes for these motor but often we buy planetary gear boxes that fit right onto the face of the motor. VEX Pro VersaPlanetary gear boxes can fit on any motor (changeable face plate on the gear box) and can be configured up 100:1.

GEARS & CHAIN

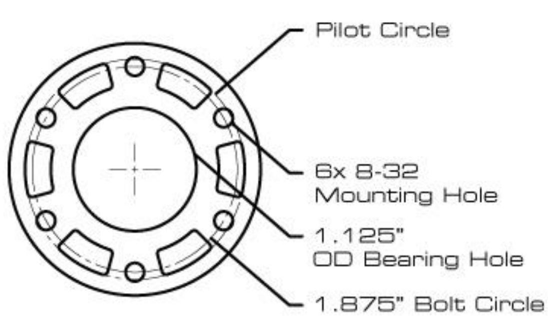
I don’t think I will have to explain what gears and chain are. In FRC, the gears we use are 20DP with a 14.5 degree pressure angle. You can’t mix gears with different DPs or pressure angles, but everything we use is the same. 20DP means that the number of teeth on the gear is 20 times the pitch diameter. In other words, if I have 20 teeth on the sprocket, the pitch diameter is 1 inch. The pitch diameter is the distance at which you want to mount the gear to other gears. If I have a 20 tooth and a 60 tooth, their pitch diameters are 1 and 3 inches, so their centres should be 2 inches apart (add their pitch radii). The chain we use in

FRC is either #25 chain (also known as ¼ pitch chain because each link is .25 inches) or #35 chain (3/8 pitch or .375" long). #25 chain is sufficient in most cases, including drive trains, which usually take the highest load. Sometimes the drive train will be designed with #35 chain. #25 chain has never broken on us but does rarely derail (rarely is about once in a season or not even once in a season; it derails in the off season). #35 is fatter and wider so it is much harder to derail; the disadvantage is that it weighs much more. In 2011 we used a #35 chain drive, but in both 2012 and 2013 we used #25. You will also find #35 chain on the 30pt. hanger gearbox for our 2013 robot. To get the size of a pitch diameter, you are probably better off looking it up than calculating it. Andy Mark has a list of their sprockets and their respective pitch diameters. To calculate the sprocket distance and the number of links you will have to do something different.

For sprockets of the same size, the centre distances should be a multiple of the chain's pitch. The number of links is the number of teeth on one of the sprockets (the two halves of the two sprockets) plus the distance between the 2 sprockets' centres times two. For sprockets of different sizes don't bother with the math. Use this: http://www.islandpondrailroad.com/chain.htm

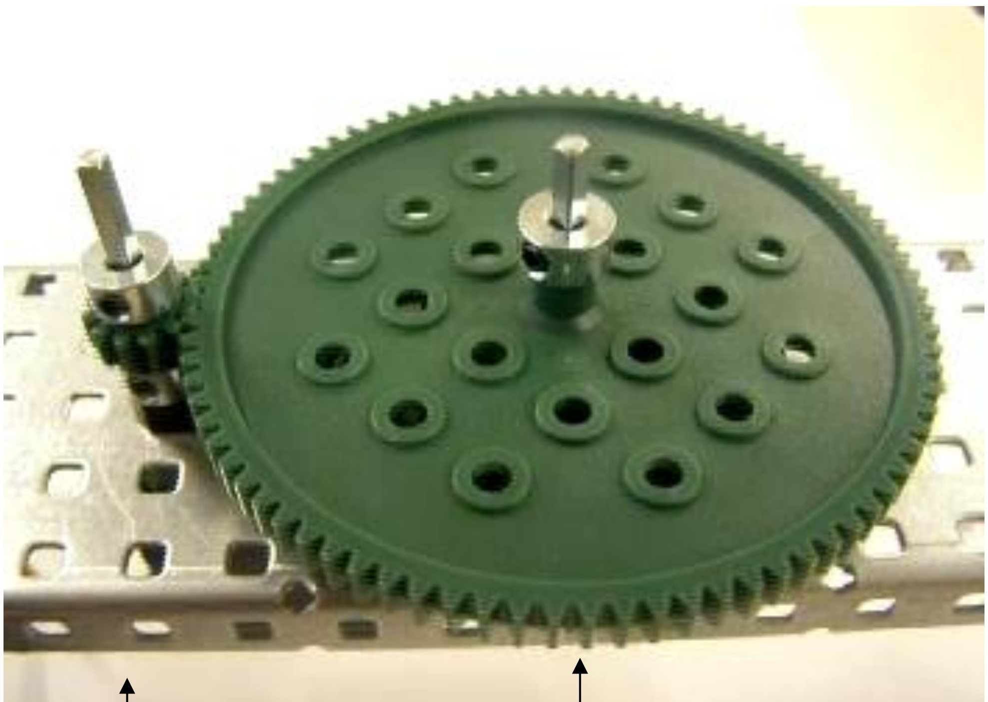
We usually get all of our sprockets and gears from VEX Pro and AndyMark. VEX Pro generally has better ones, the gears from VEX Pro are also aluminum, and thus lighter.

Further, there are hub sprockets and plate sprockets. Hub sprockets are designed to be put on shafts (they are either hex or keyed). Plate sprockets are dead axle and have a hole pattern that allows them to be easily bolted to a wheel or an arm.



GEAR AND SPROCKET RATIOS

Due to the nature of motors, they typically spin at high speeds and low torque. For most applications, we want high torque (i.e. lots of force) and will sacrifice speed.



Driving Gear

Driven (Follower) Gear

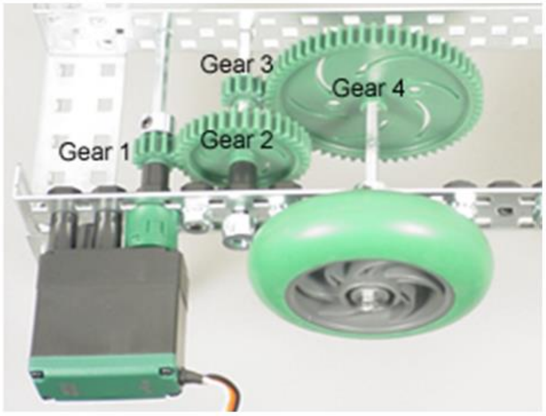
The driving gear is the gear that is being directly powered, and the follower gear is powered by the driven gear.

In this picture, the driven gear, which is attached to the motor behind, is a 12 tooth gear, and the follower is a 72 tooth gear.

For every 1 rotation of the driving gear, the follower will also rotate 12 teeth. Only, on the follower, 12 teeth is a fraction its total, so the 12 teeth on the follower translates to only 1/6 of a rotation. In other words, the driving gear must rotate seven times before the large gear rotates once. The gear ratio would be called a 6:1 gear ratio because for every seven rotations you put in, you get one out.

In this way, a motor with a free speed (the speed that the motor runs at with no load) of 100 rpm geared down 6:1 will have an output rotation speed 16.7 rotations per minute, or rpm (100/6).

Let’s say we were using an RS550 whose free speed is about 19000rpm. Now we would use a VersaPlanetary Gearbox with a 100:1 gear ratio and that would bring it down to 190 rpm. Now, let’s say we weren’t using a planetary gearbox and wanted a 100:1 reduction. We can’t easily find a 100 tooth gear and a 1 tooth gear, and a 10 tooth gear paired with a 1000 tooth gear sounds equally as obscure. In order to achieve higher gear ratios, we compound them together as follows.



Gear 1 = 12 teeth

Gear 2 = 36 teeth

Gear 3 = 12 teeth

Gear 4 = 60 teeth

Gear 1 & Gear 2:

$$\frac{\text{follower}}{\text{driver}} = \frac{36}{12} = \frac{3}{1}$$

Gear 3 & Gear 4:

$$\frac{\text{follower}}{\text{driver}} = \frac{60}{12} = \frac{5}{1}$$

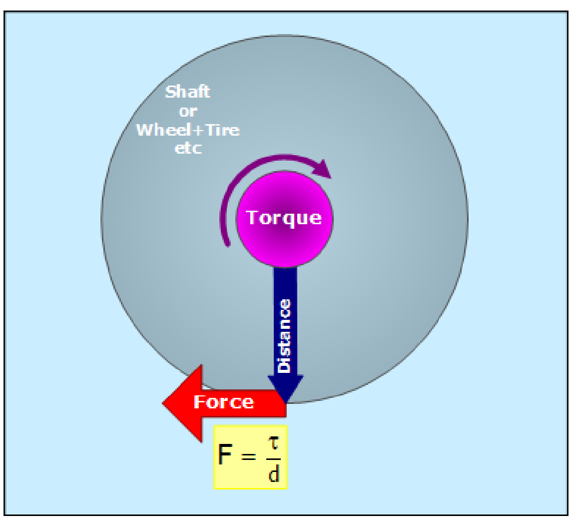
Multiply the gear ratios:

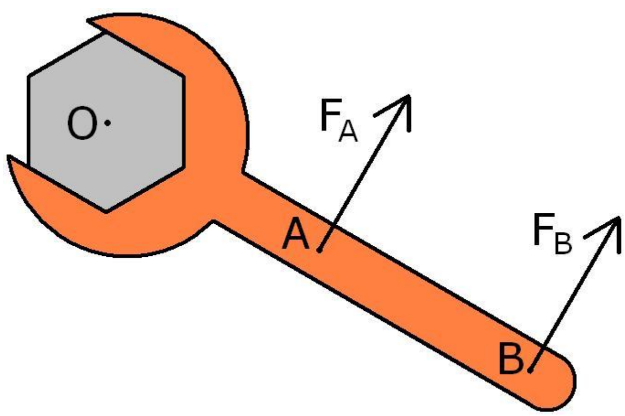
$$\frac{3}{1} \times \frac{5}{1} = \frac{15}{1} \longrightarrow 15:1$$

This way, if we use a 10:1 ratio and another 10:1 ratio, we can get a 100:1 gear ratio.

The advantage of gearing is that you can either speed things up or slow things down. When you speed things up, you trade torque (the amount of rotary force) for speed, and when you gear down, you essentially trade speed for torque.

Torque is measured in inches*pounds, or inch-pounds. There are other units for torque too, such as Newton-meters, but we mostly use inches and pounds, so inch-pounds makes sense. Torque is basically a measure of how much rotary force or twisting force there is. As the units, suggest torque is dependent on how much force you push with and the length of the distance the force acts on.

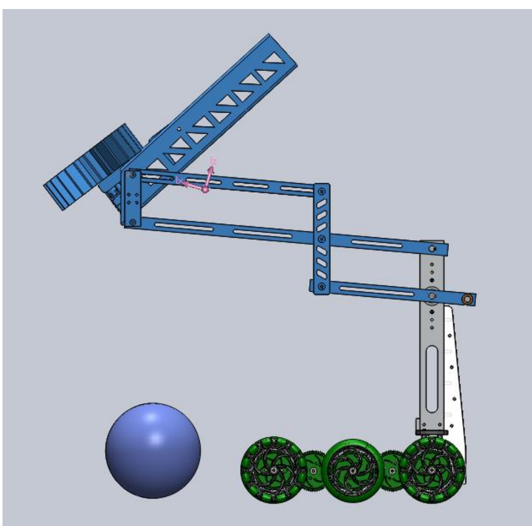




Similar to the idea of a lever arm, pulley, etc., if you push from point B and point A with the same amount of force, pushing from point B is going to yield a higher amount of torque on point O. This concept is very useful when we talk about how much force we need to rotate something

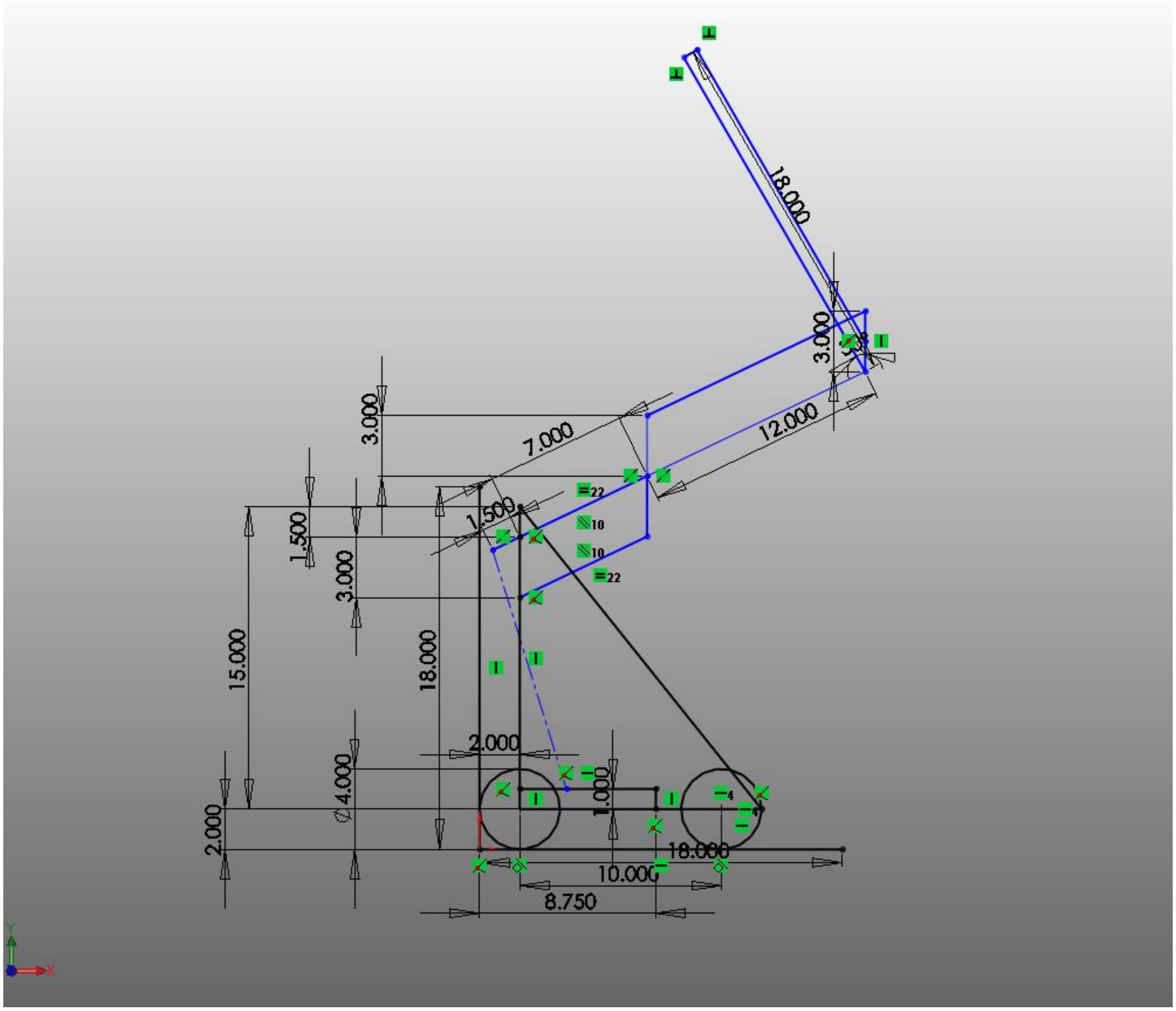
with and how much of a gear reduction we need from the motor to get the desired amount of force.

A CIM, for example, has a free speed of 5000 rpm, but a stall torque (the amount of torque required to stop the motor from spinning or the maximum amount of torque the motor can deliver) of only about 20 inch-pounds. In other words, if you were to put 4 CIMs on the drive train geared 1:1 with 6 inch wheels (3 inch radii), you won't have much force available for moving the robot. The maximum pushing force of 4 CIMs is just 4 times the stall torque of one, which is 80 inch-pounds. The wheels will try to spin at 5000 rpm but will only have 80 inch-pounds of torque. On the surface of the wheel 3 inches away, it will only have about 25 lb. of force (1/3 of 80: Remember that 80 inch-pounds means with a 1 inch radius drum winding in a rope, 80 lb. is the max weight you can lift. With a drum that is 3 times as big, the lever arm is 3 times a big and is working against you, so you can only use 1/3 of what you could originally). A robot with a weight of 120 lb. that can only push forwards with 20 lb. of force presents a problem. Gearing down gives us more torque. While it seems like we are getting something for nothing, it is similar in concept to how a pulley works. You arrange the pulleys such that you have to pull in twice the amount of string but only have to pull half as hard. In the case of gear reductions, you have to spin the shaft twice as many times but you only need half the torque.



Here is a VEX robot made out of custom parts. Its lift uses a 6-bar linkage. Basically, it is a clever series of joints that keeps the end (the tray) parallel to the ground as the tray moves up and down. If it were just a single pivot and the tray was fixed to the arm, the tray would change angle relative to the ground as the arm moves up and down.

Below is a 2D sketch of the robot. Often, this is the first thing we do before designing anything. The 2D allows us to easily play with the geometry of the robot and tells us how big or small we need to make everything.



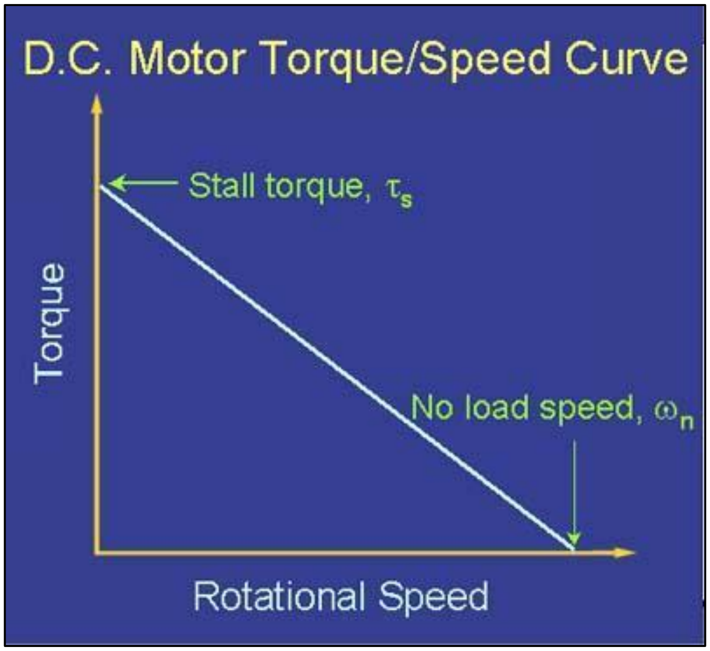
We know the total length of the arm is going to be around 19 in from the sketch above. We also know that the weight of each ball/barrel from VEX Gateway is about .5 lb, so in total the robot must lift 1.5lb (the tray can only hold 3 pieces).

Given this:

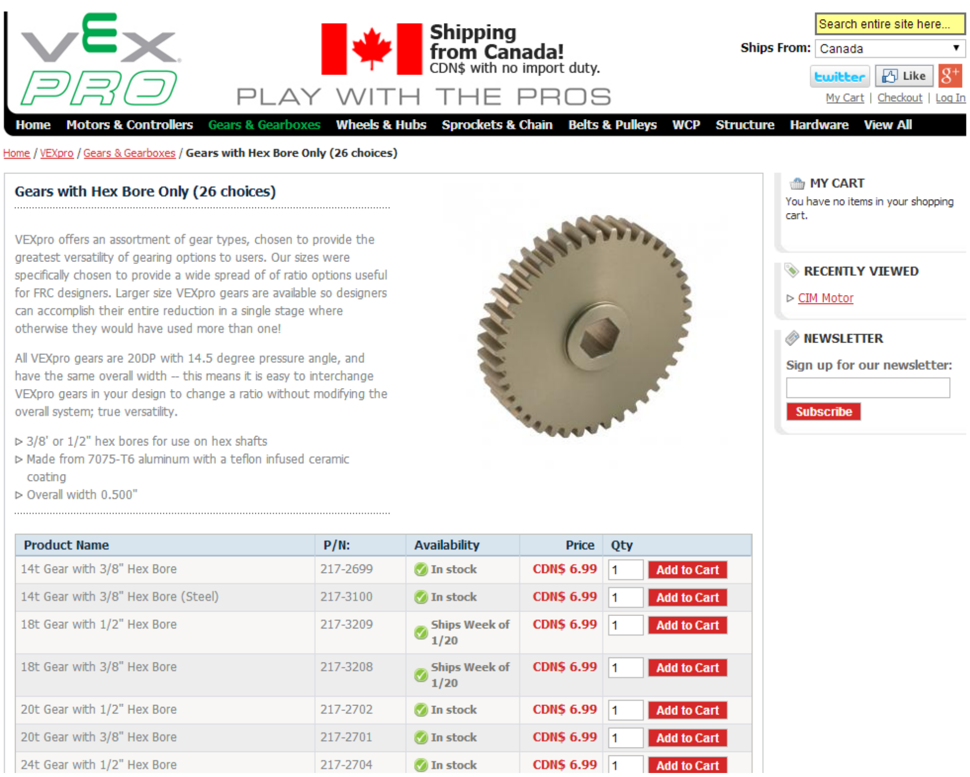
$$Torque = inch\ X\ pounds$$

$$T = 19in\ X\ 1.5\ lb$$

$$T = 28.5in * lb$$



For now, we will assume the weight of the lift itself is negligible. If we dedicate 2 VEX 393 motors to the lift, each motor has a stall torque of about 13in-lb and a free speed of 100 rpm. Remember that stall torque is how much torque will cause the motor to seize up or stop spinning. A general rule of thumb, you want to run your motors at about 50% of stall torque, which is about 50% of speed. Speed and torque are not exactly linearly related but it is a good approximation. If you are running at about 75% of stall torque, you will be at about 25% of the free speed of the motor. Thus, if we have two motors and want to run both motors at about 50%, we have a total of 13in-lb coming out of the motors. However, we need about 30 in.-lb. to get the lift to move the game objects up. With a gear ratio of about 3:1, it will have about 39 in-lb of torque (13*3). The speed of the lift will be about 50% of the motor's speed divided by 3 because we have geared it down 3:1. Assuming the lift must lift 90 degrees, that takes about half a second to one second (100rpm / 3 / (60 seconds / minute)), which is pretty good in this scenario.



This is a VEX robot, so we would have simply used a 12 tooth gear and a 36 tooth gear to create a 3:1 gear ratio.

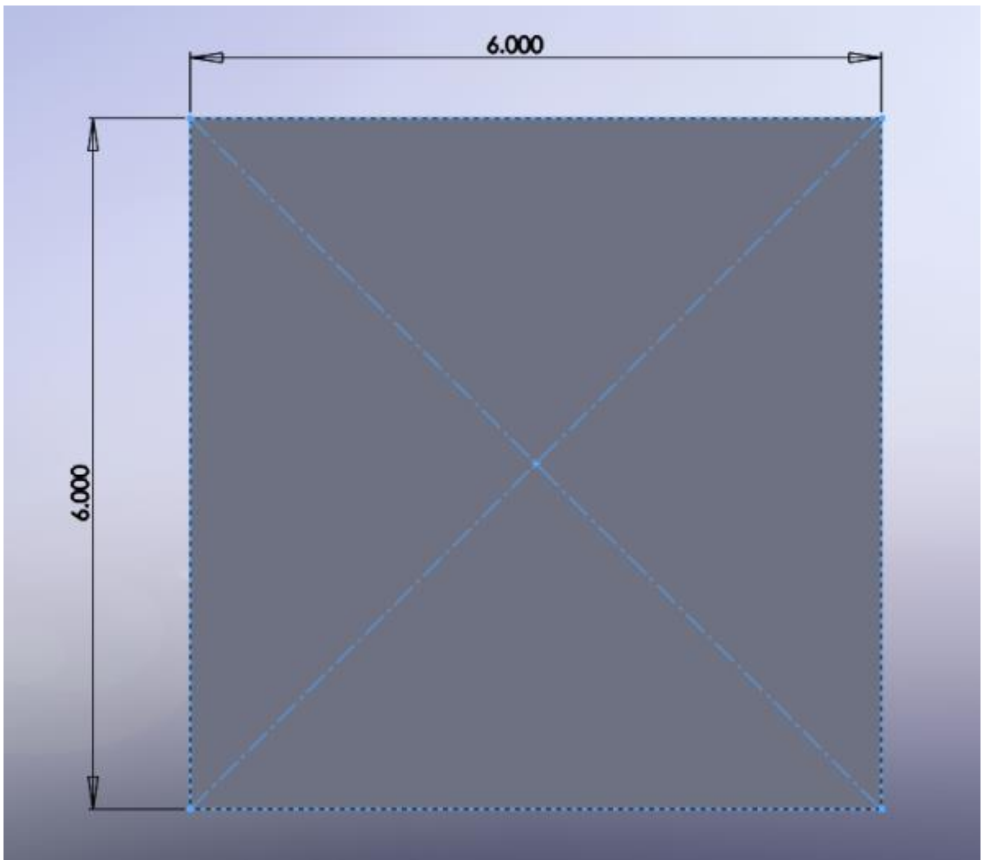
When we design mechanisms in FRC, we usually go to VEX Pro to get our gears, as they have a lot of options.

GEARBOXES & INTRODUCTION TO 2D SKETCHES

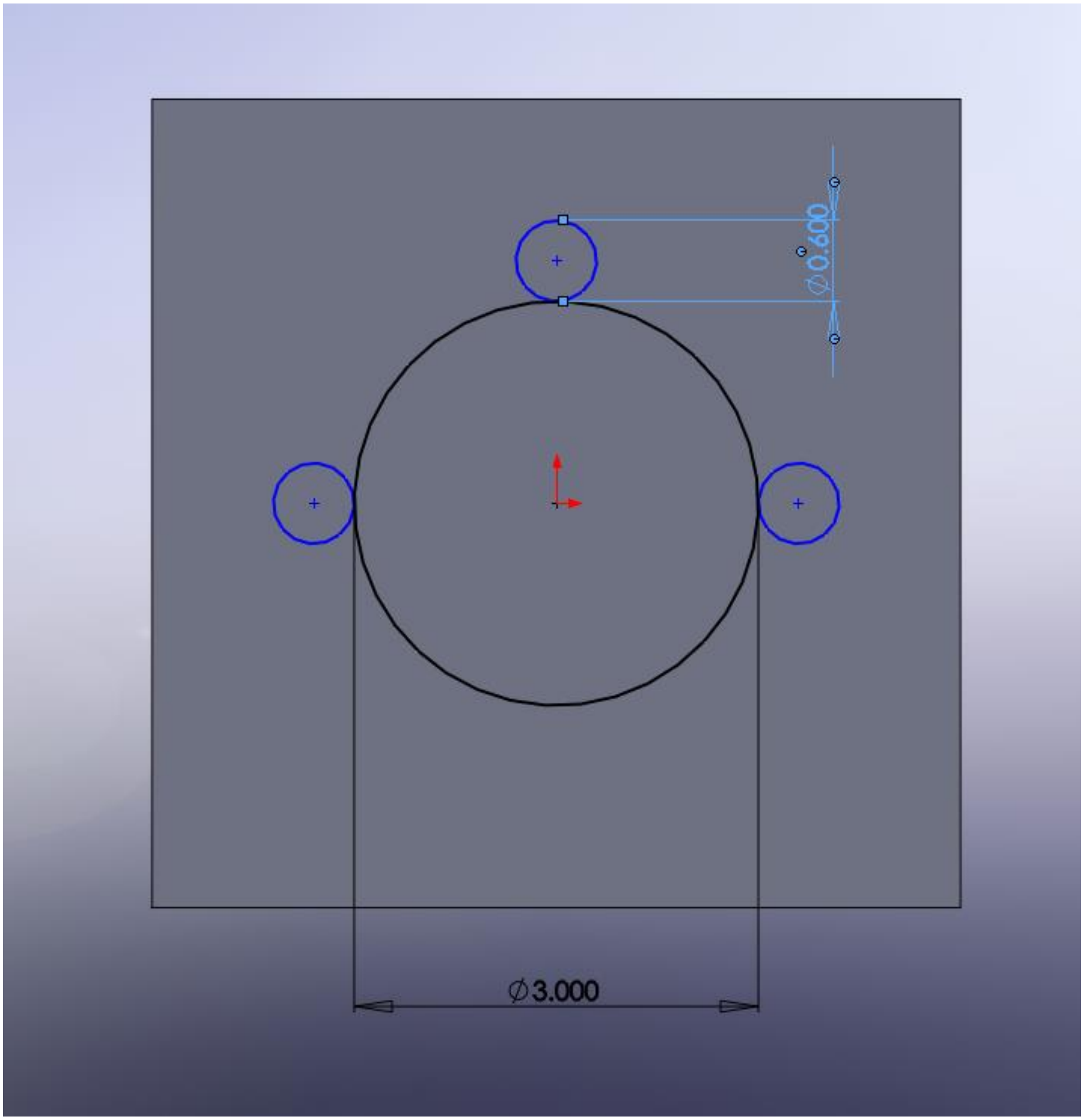
While you can often just buy a gearbox, sometimes a custom one better suits your needs. In this part of the tutorial it is recommended that you follow along with the instructions to create a gearbox for a drivetrain. Here we are going to use 6 CIMs (3 per gearbox).

An overall reduction of around 10:1 is a good amount for a drivetrain gearbox. You can go to: G:\Upper School\Robotics\Design and find the document called Drive Train Calculations and there are some parameters that you can play with, but for now we will assume approximately a 10:1 ratio. Go to the VEX Pro website (or the design library and find a matchup of gears that will get you around 10:1. In this example, we will use a 12:60 ratio followed by a 24:50 ratio to give an overall reduction of 10.4:1. The gears you choose don't really matter, however depending on what type of space you have to work with, you may have to use bigger or smaller gears and fewer or more stages.

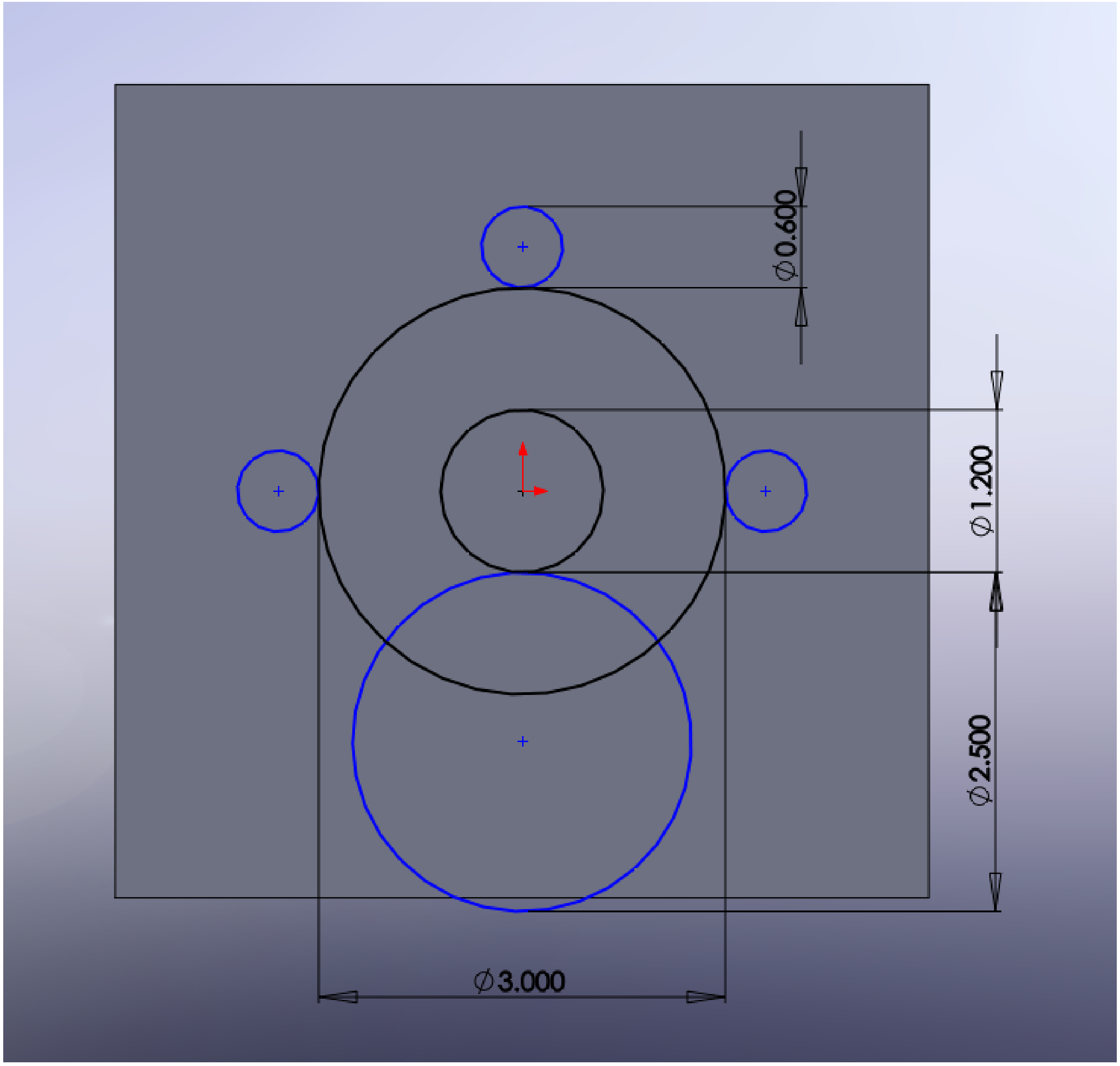
Start by drawing the side plate. You can start with an arbitrary size. It is a good idea to start with the origin in the centre.



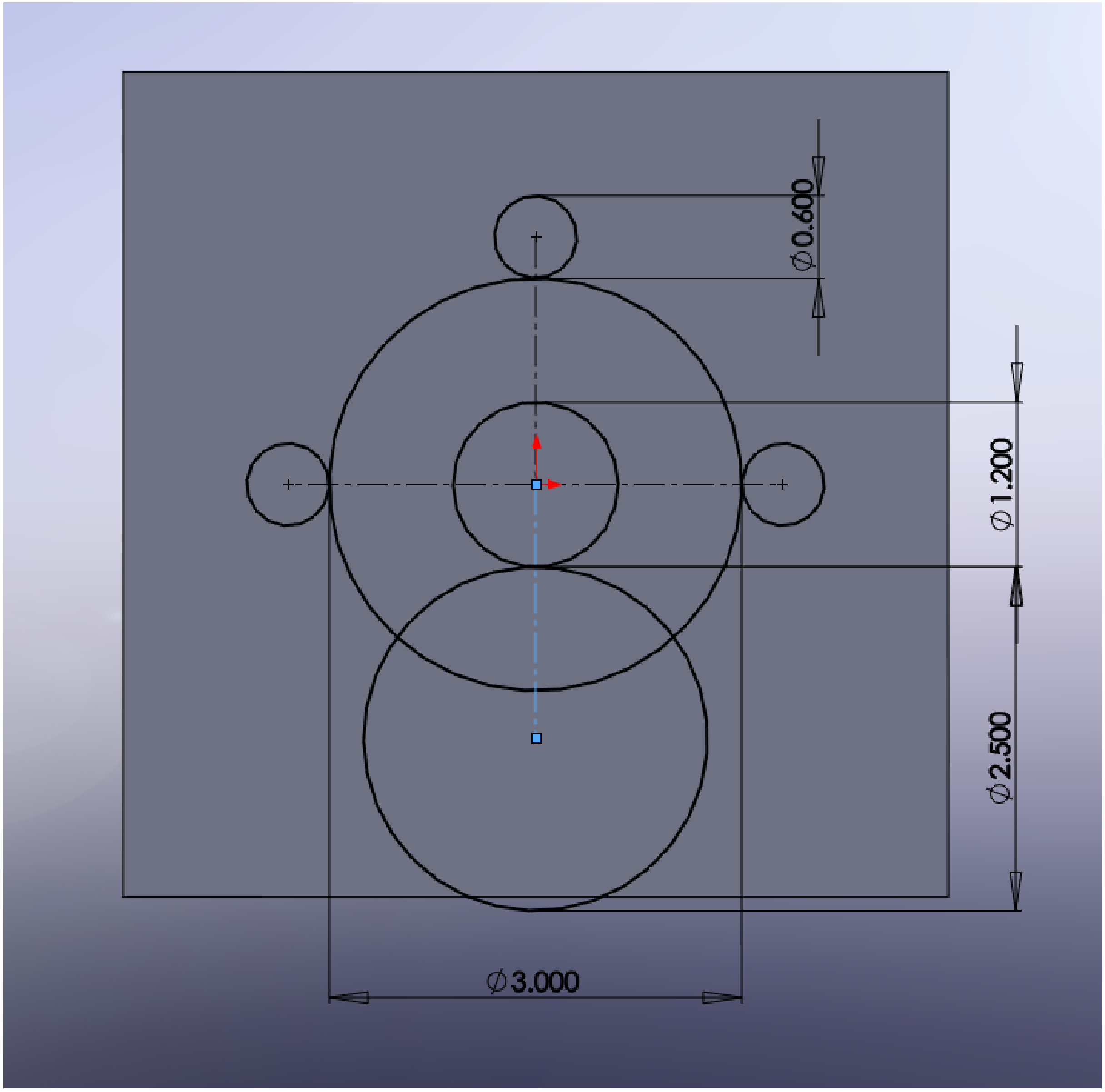
Before we start making the gearbox itself we are going to make a 2D sketch of the layout of the gearbox. This will come in handy later. Make a new sketch on the face of the part.



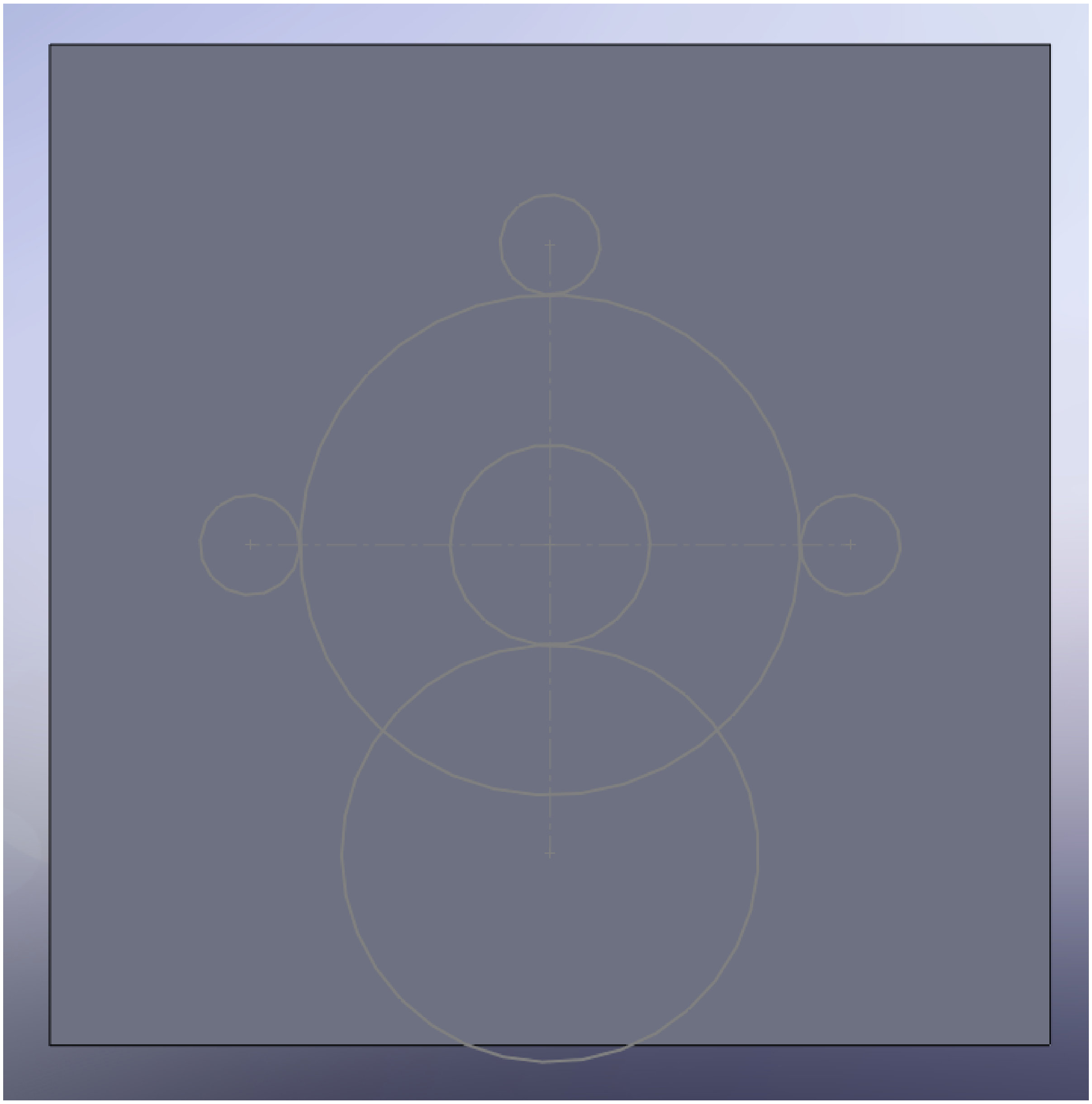
Represent each gear by its pitch diameter. The middle circle represents the 60 tooth gear and the 3 outer circles are the 12 tooth gears to which the CIMs are attached. Make the 12 tooth gears tangent to the centre 60 tooth gear. Ignore for now the fact that the gear is off the plate.



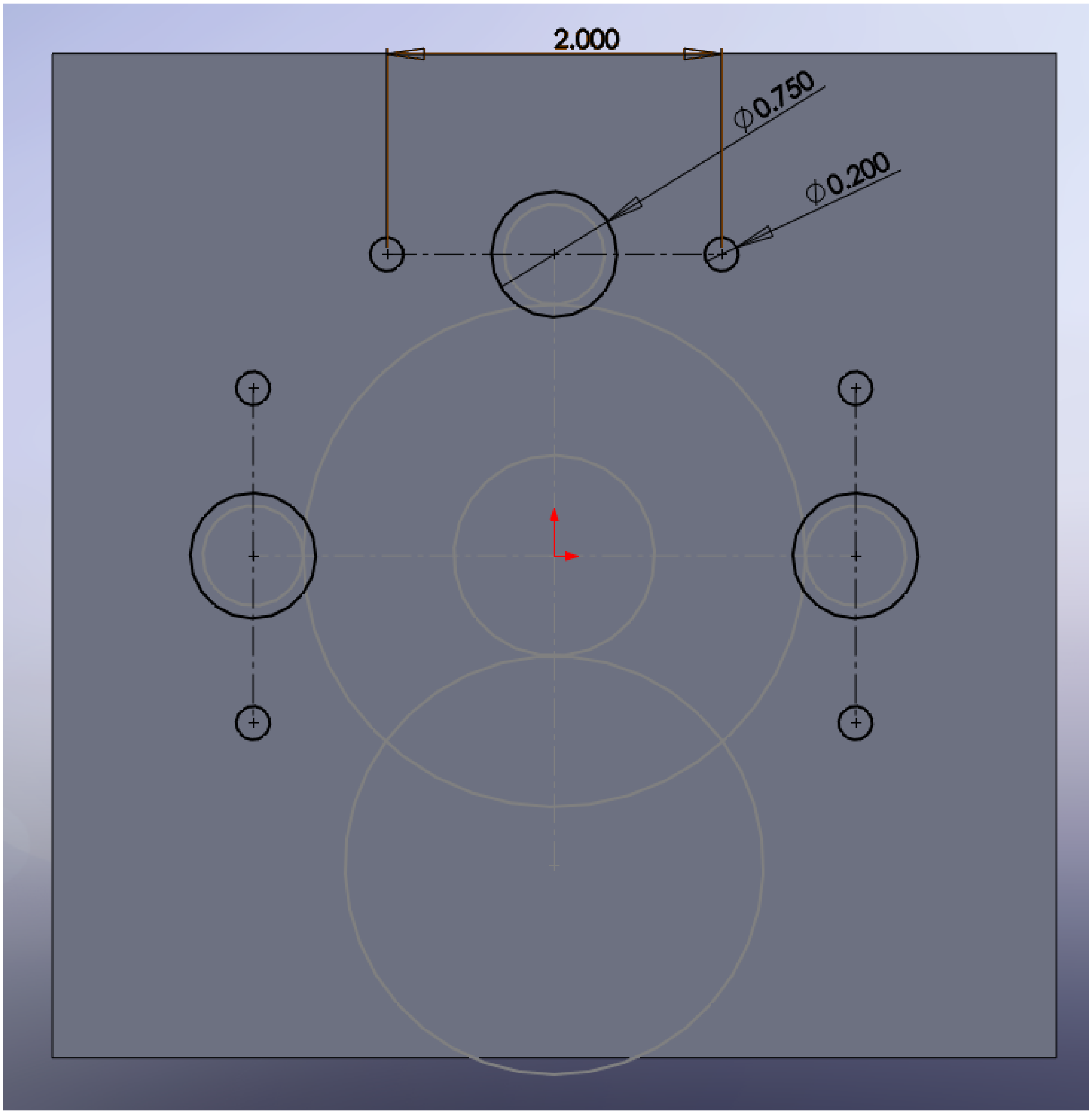
Next add the 24 tooth gear and make it concentric with the 60 tooth gear (concentric because they share the same shaft) and the 50 tooth gear tangent to the 24 tooth. Now you have added the second stage of the gearbox.



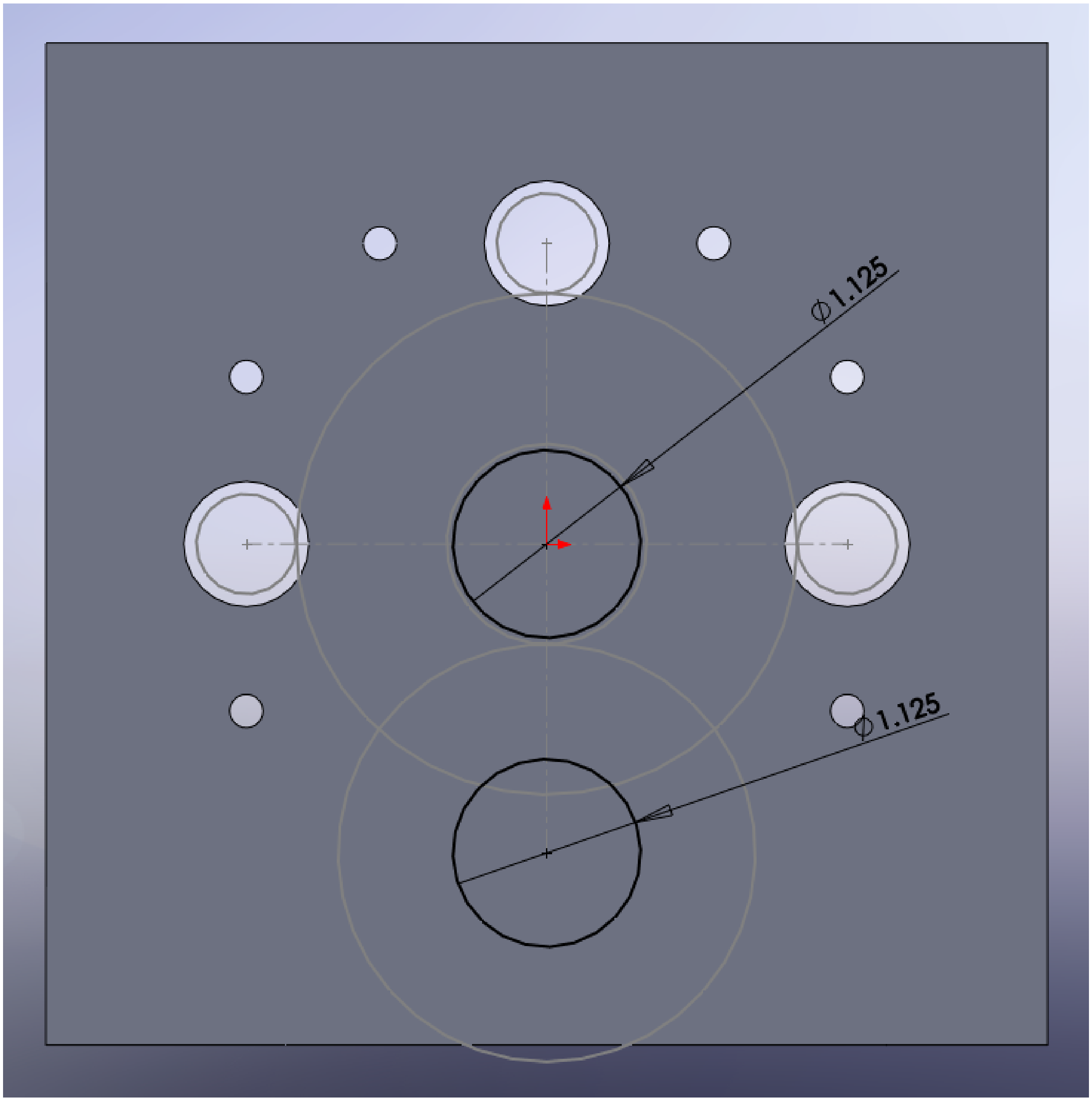
Fix the location of the gears and then close the sketch.



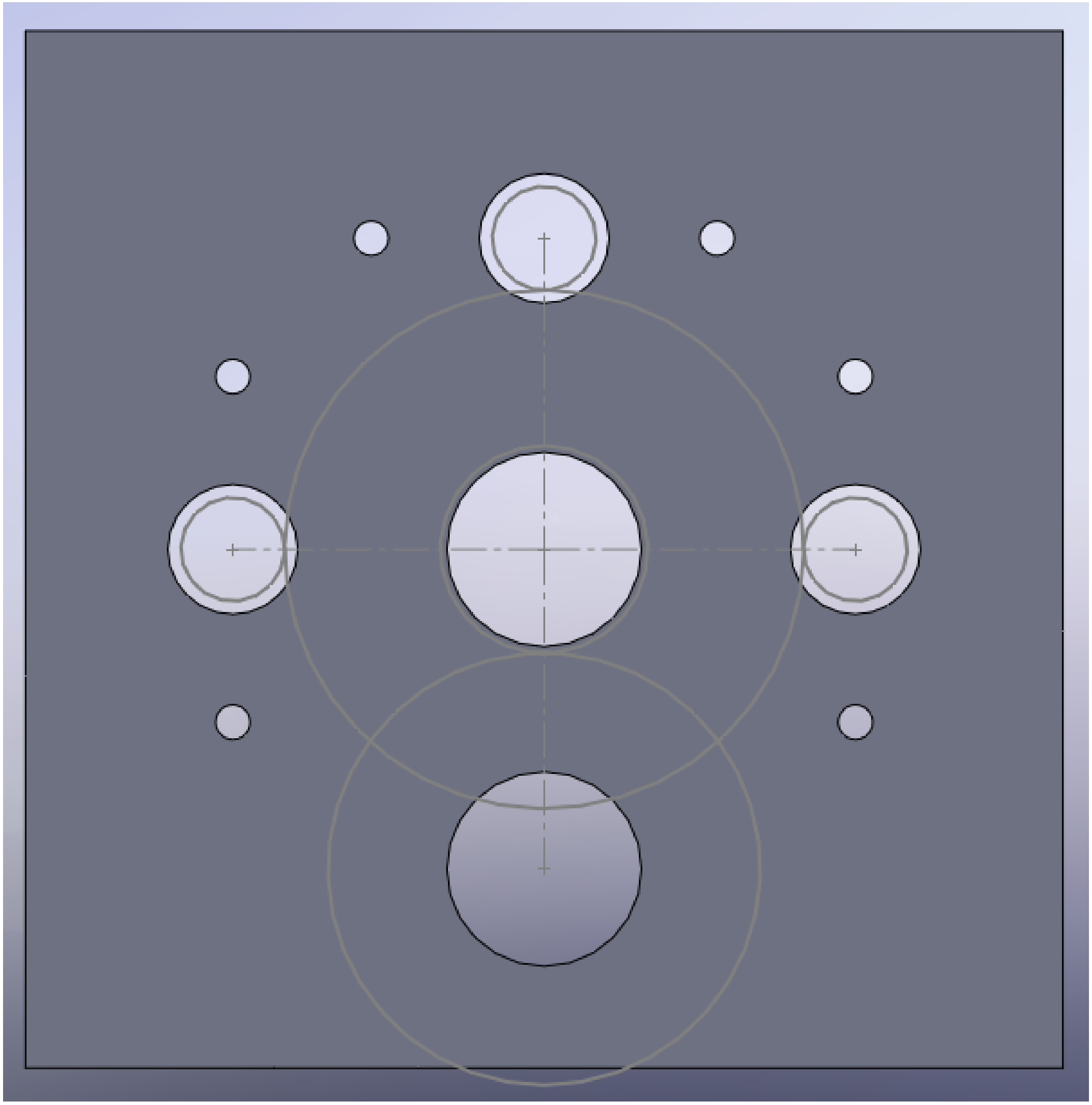
Now you have the layout of the gearbox drawn onto the face of the plate. Now, when you want to make holes for the bearings, you can reference this sketch. If you shift anything around, edit the layout and everything else will change with it.



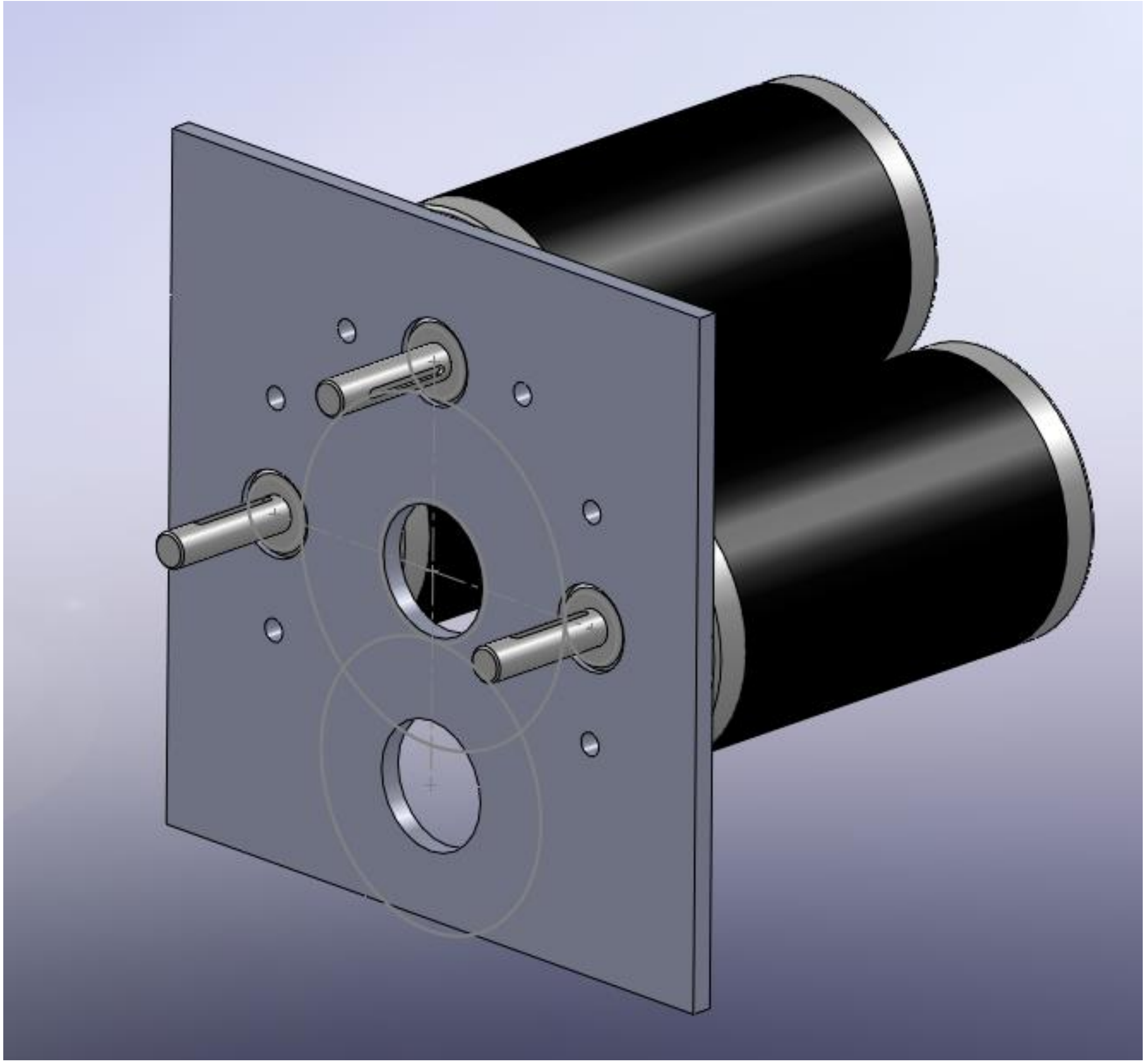
Make a new sketch on top and add a mounting feature for the CIM. Do not dimension the location of the holes. Reference the hole position to the location of the original sketch. Cut these holes out.



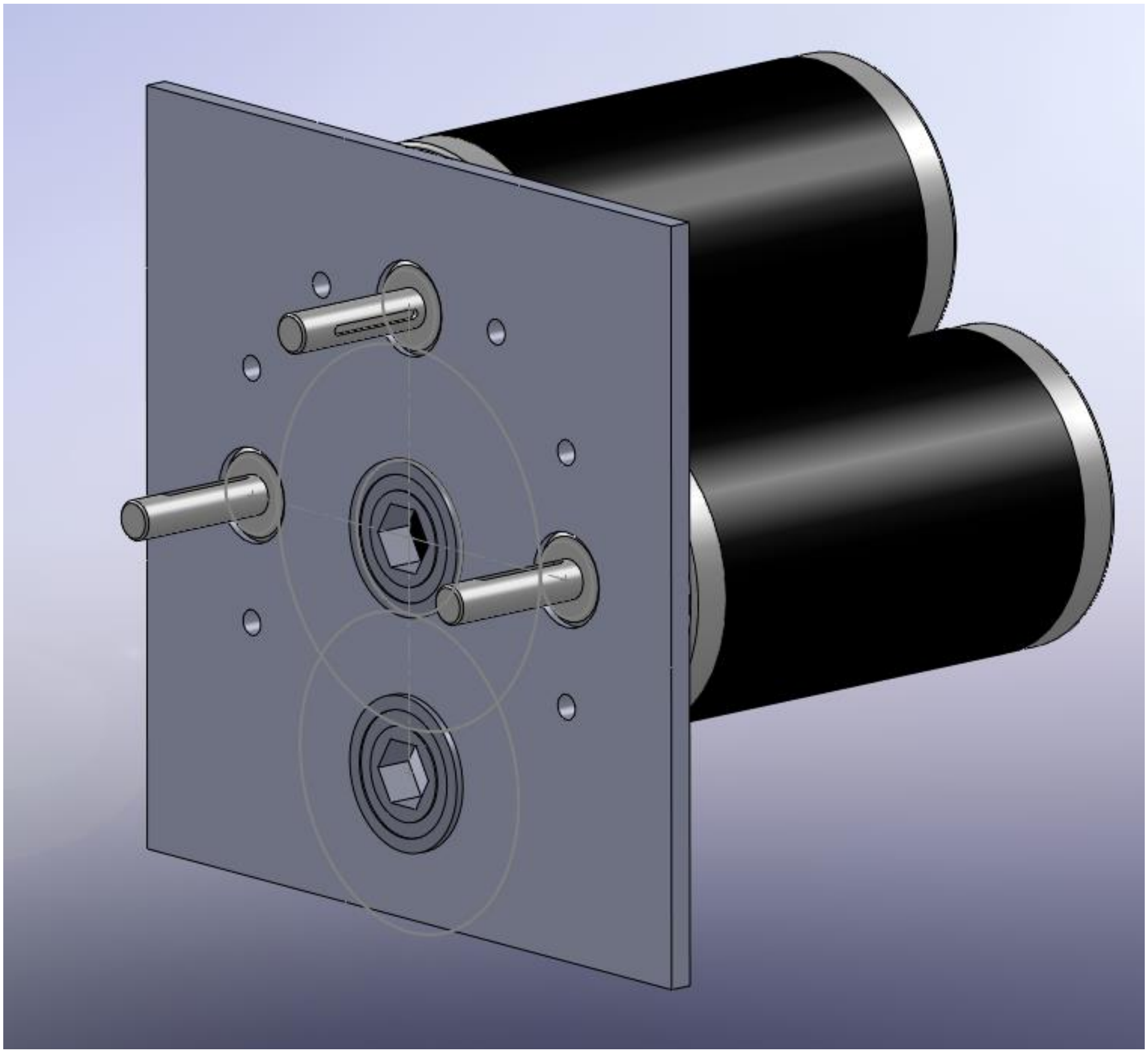
Make another sketch on top and make holes for the bearings. Cut these holes out too.



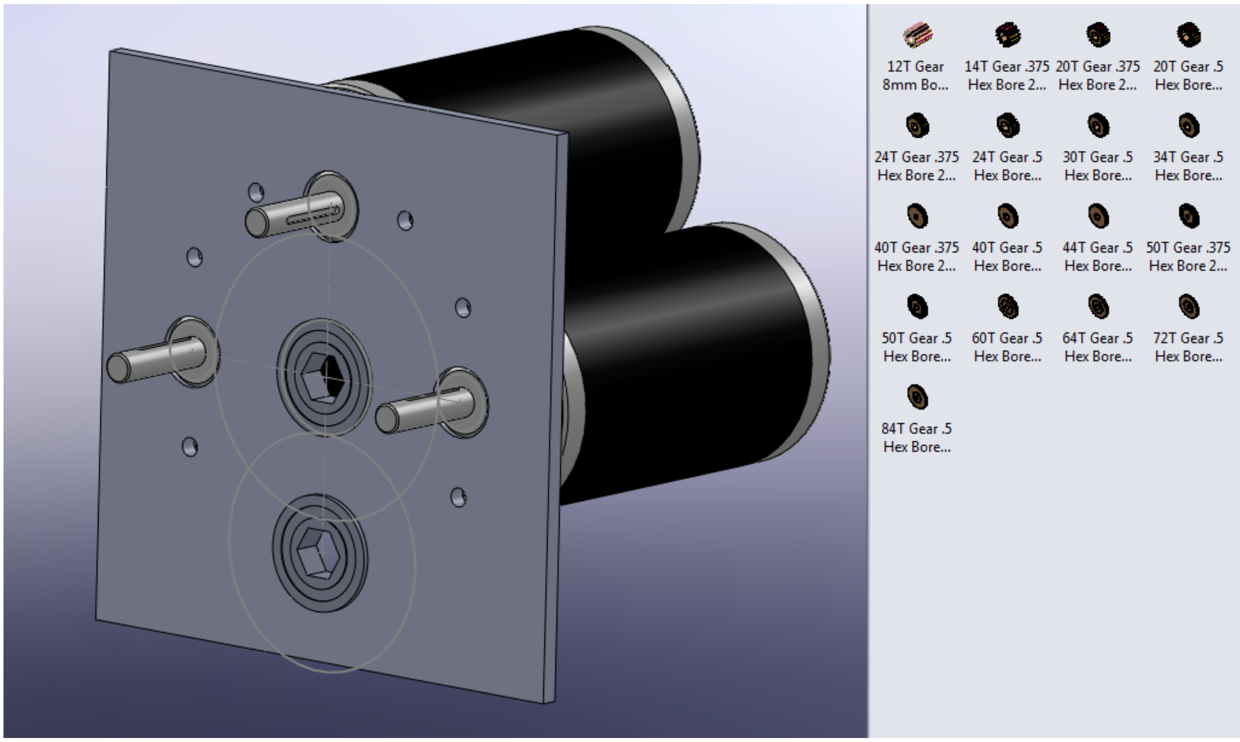
The part should look like this now. Save it and make a new assembly with it.



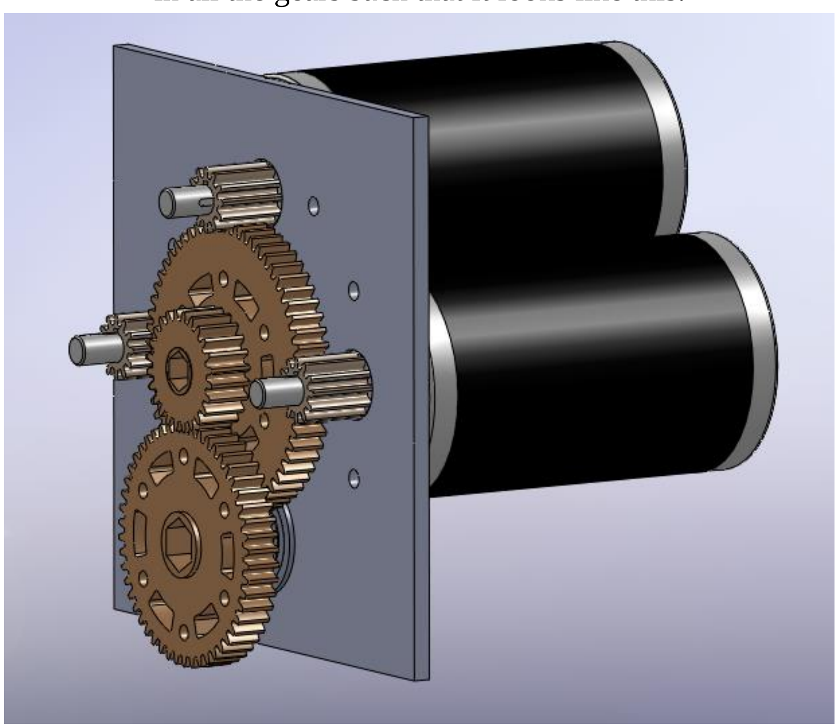
Mate the CIMs onto the plate. It should look like this.



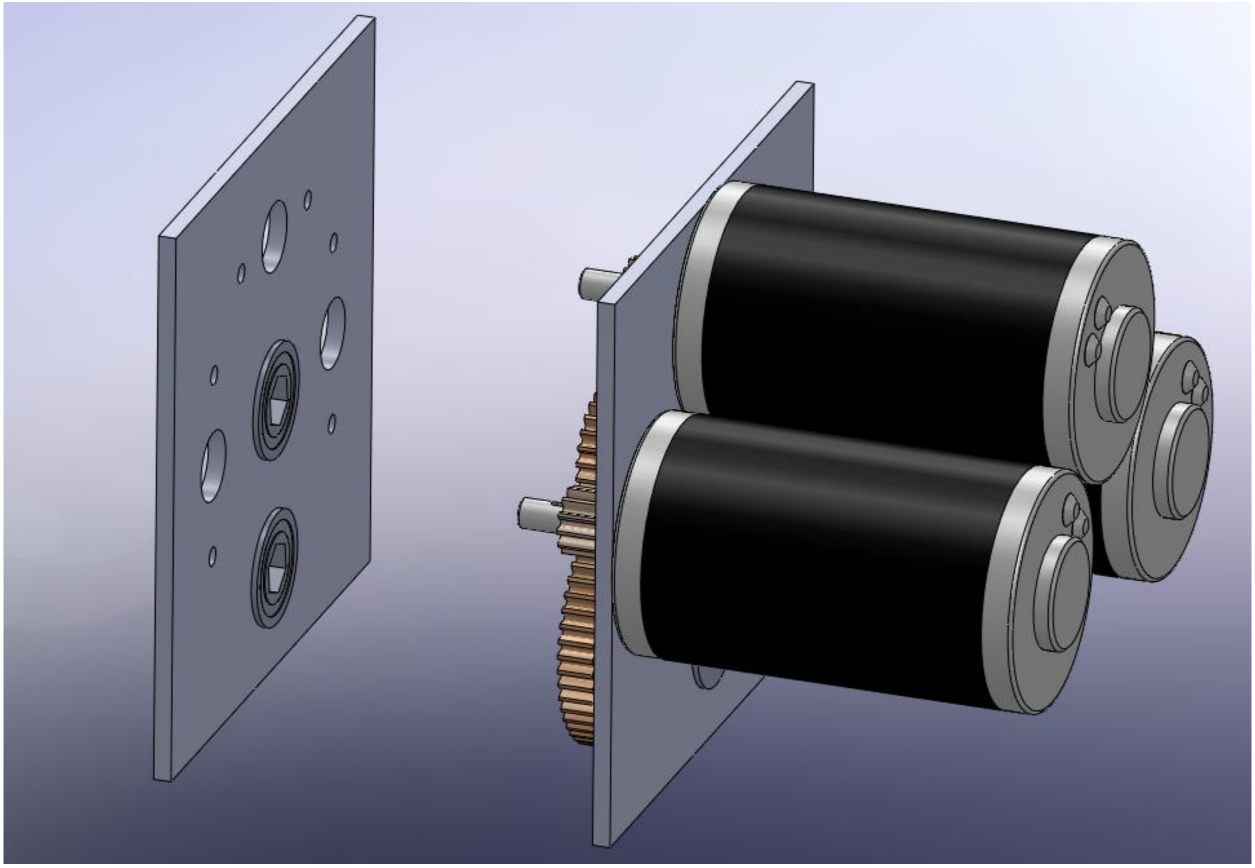
Put in two .5 hex bearings into the plate. Put the flanges on the inside; you will see why later.



Open up the design library and find the 12 tooth CIM gear. Put 3 of them on the 3 CIMs and add in all the gears such that it looks like this.

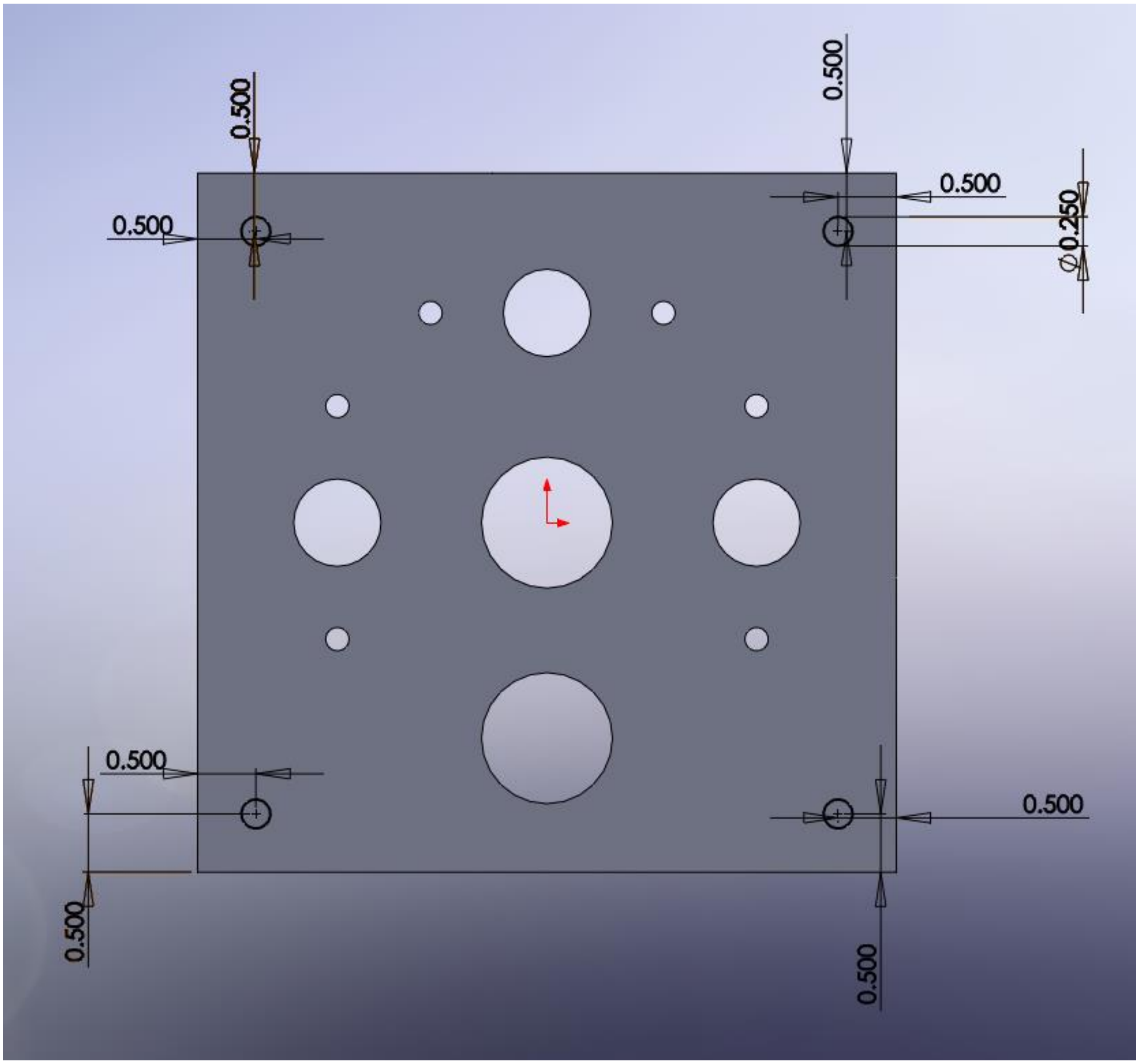


Don't worry about the spacing and fact that half of the stuff is free floating; we will deal with that later.

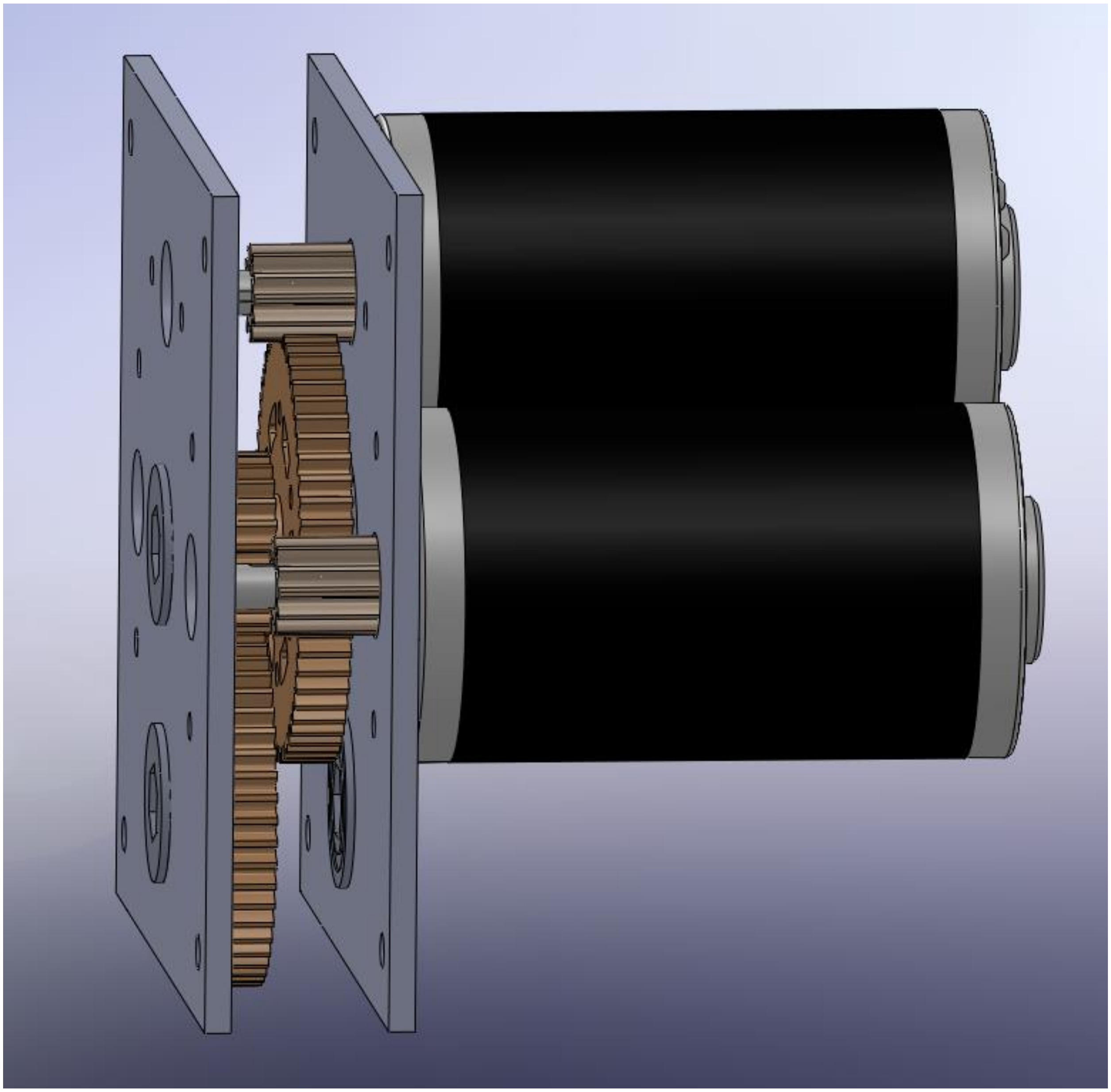


Put a second plate in (the same one). Sometimes you will have to make a different part, but in this example we will be using the same plate. Put bearings in the plate. Place the flanges facing the inside.

Go back to the original part and add 4 holes in the corners for standoffs.

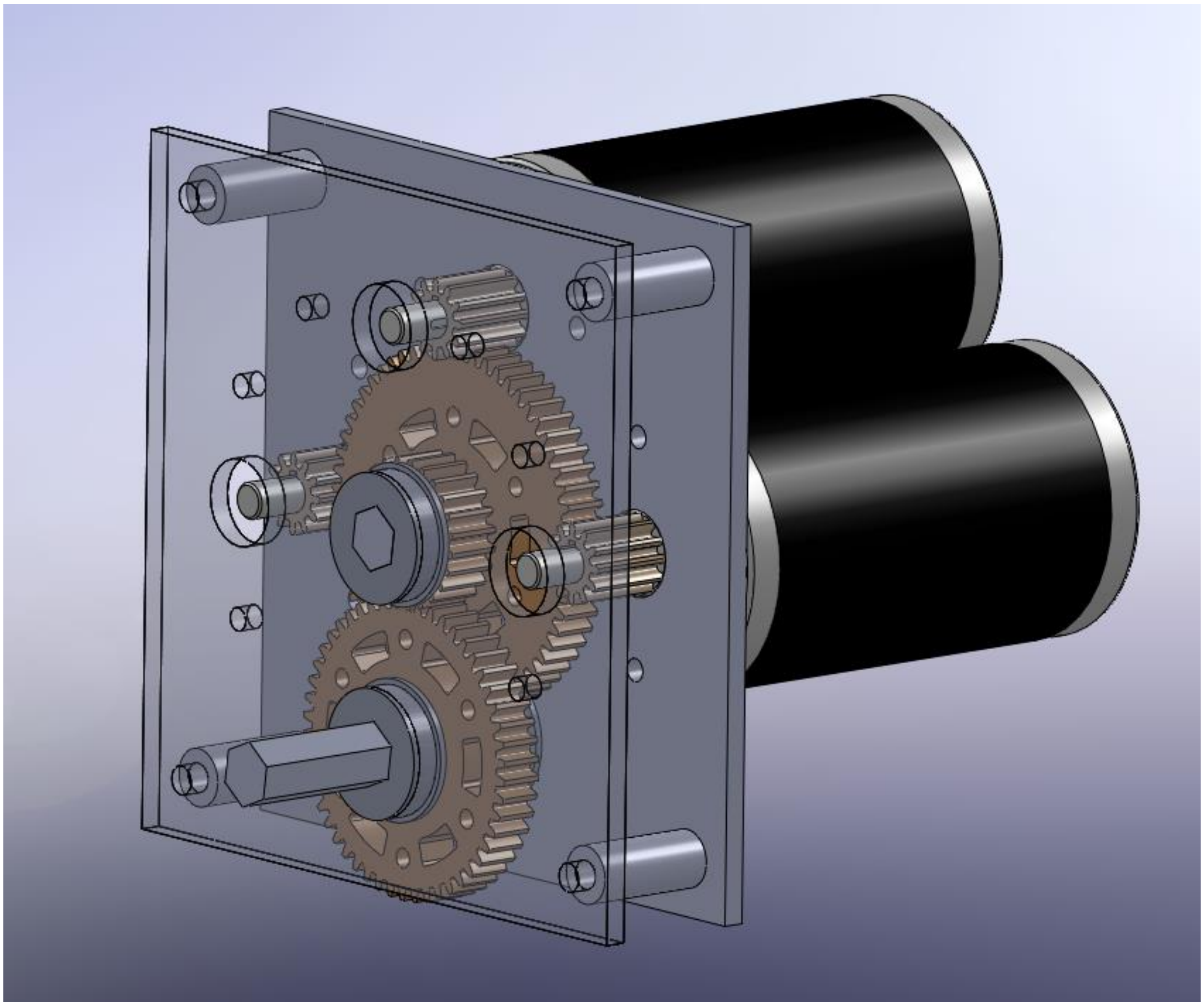


Mate the plate in so there is no space left over.



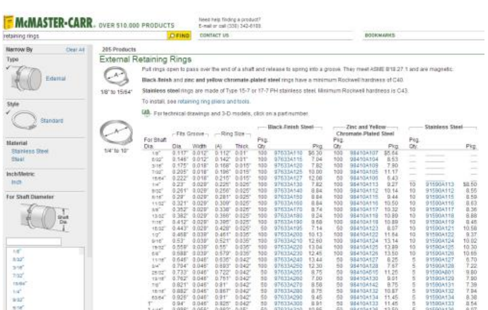
Now you have essentially all of the parts of the gearbox. Now add in some shafts and spacers and you are done…

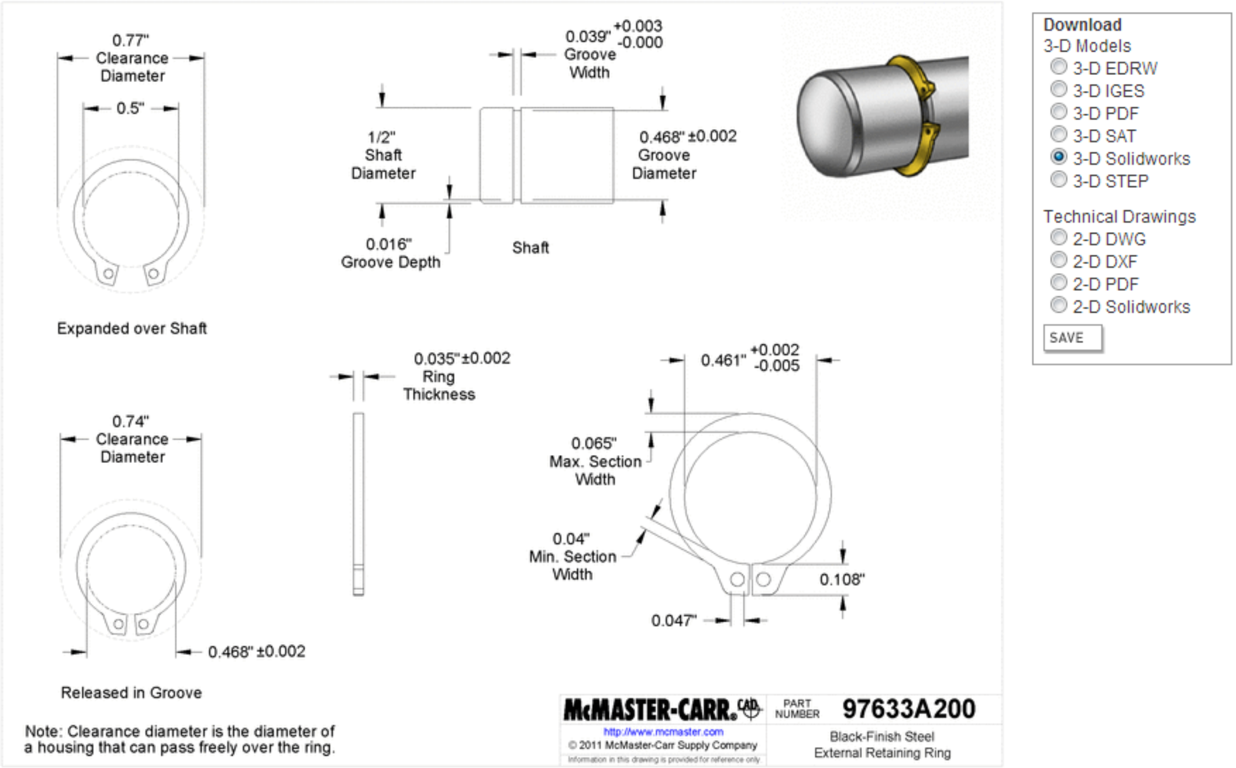
At this point you may think you are done, but you may have forgotten that your shaft can fall out and there is nothing keeping it in place.



One of the ways we can solve this is by extending the length of the shaft slightly and adding retaining rings to the shaft. Basically, a retaining ring is a ring that fits into a groove that you machine into the shaft that prevents the shaft from moving.

You can find them on McMaster-Carr.

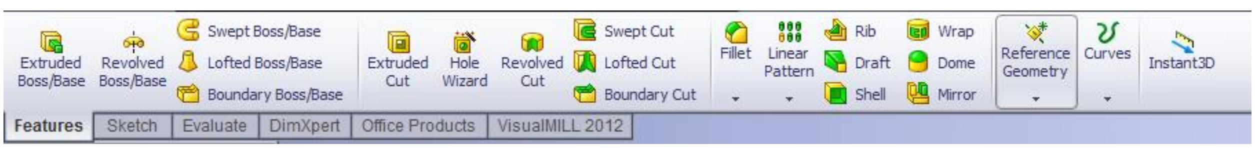




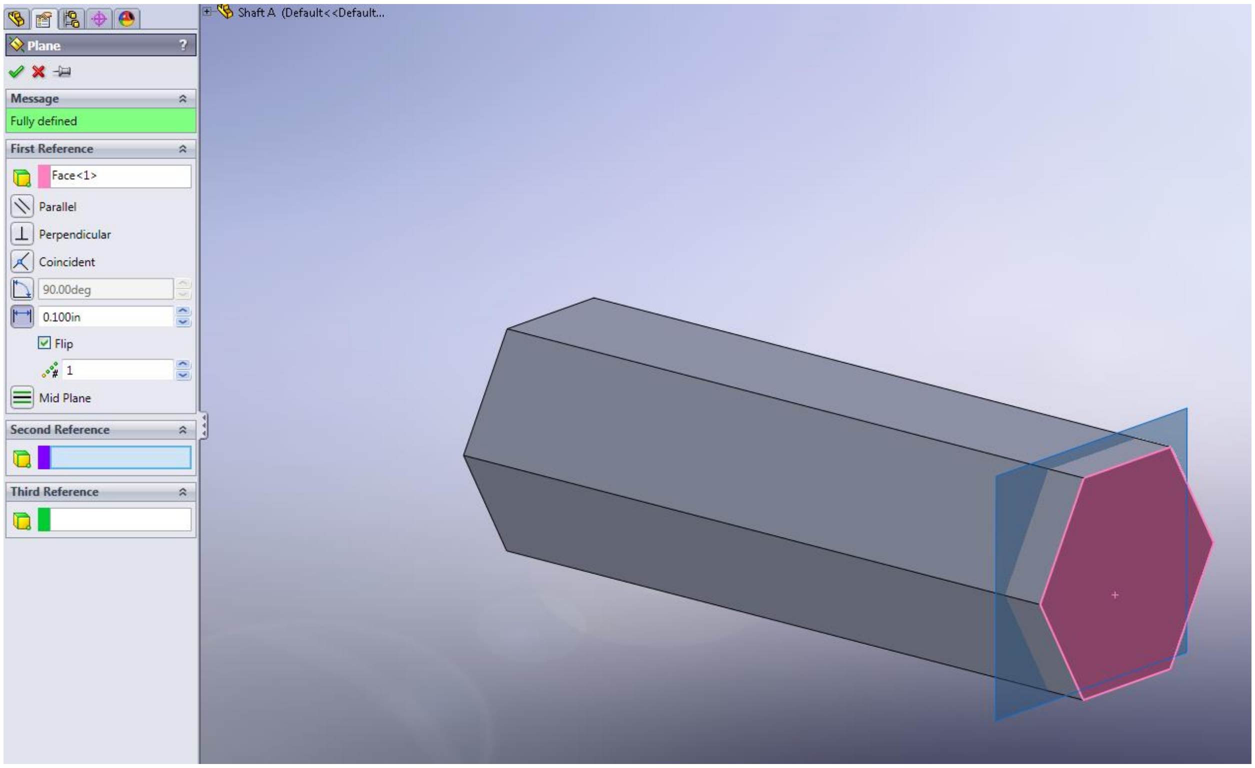
Click on the part number for the retaining ring size you would like. Then click on “CAD”. It will bring you to this drawing. Here it specifies the size of groove that you should make on the shaft. You can also download a CAD model for it.

There are multiple ways to make a retaining ring groove; this is one way.

Go to reference geometry and insert a plane.



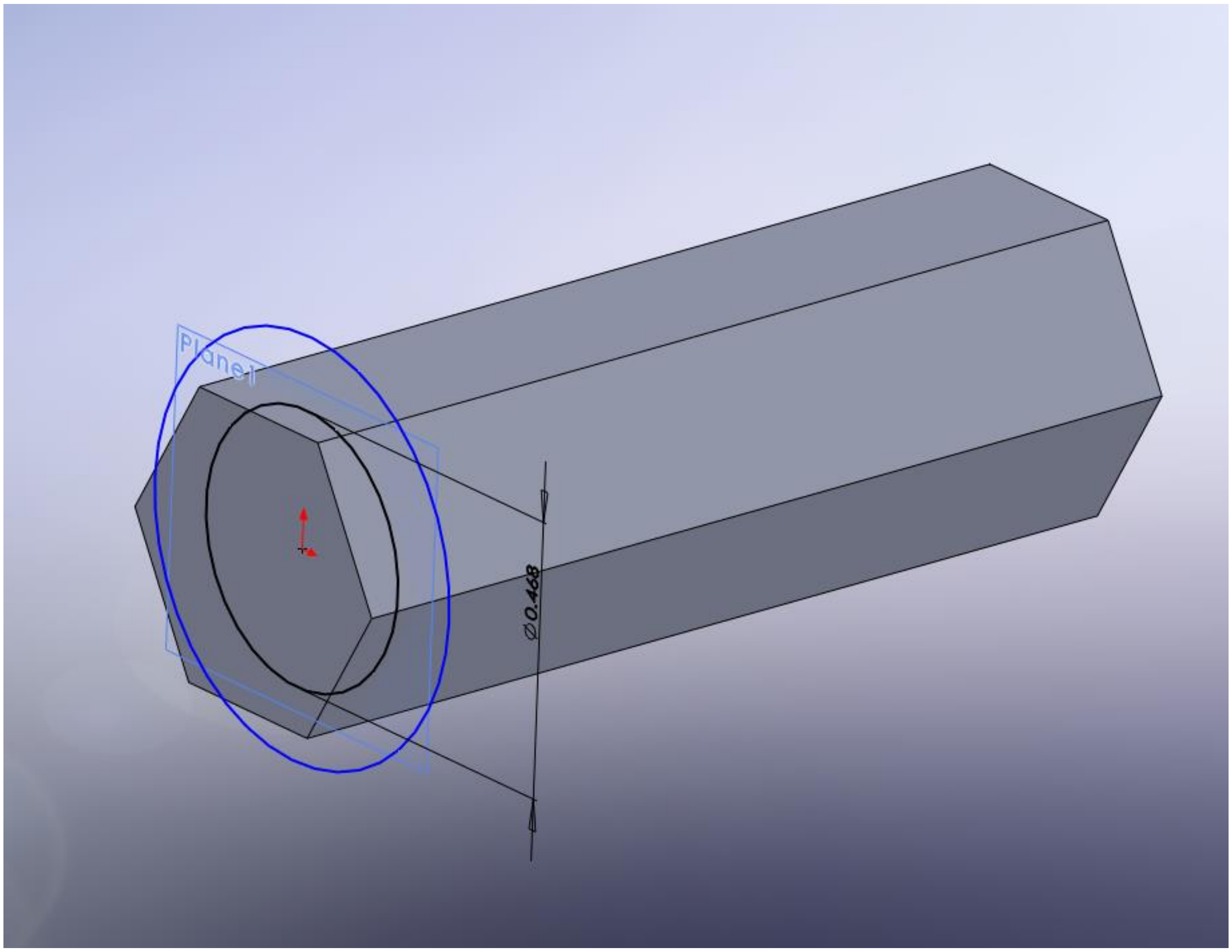
Click on plane. We are going to make a plane and cut the groove on that plane.



Set the distance away from the end of the shaft on which you want to place the retaining ring. You should probably leave at least 1/16 of an inch off the end of the shaft.

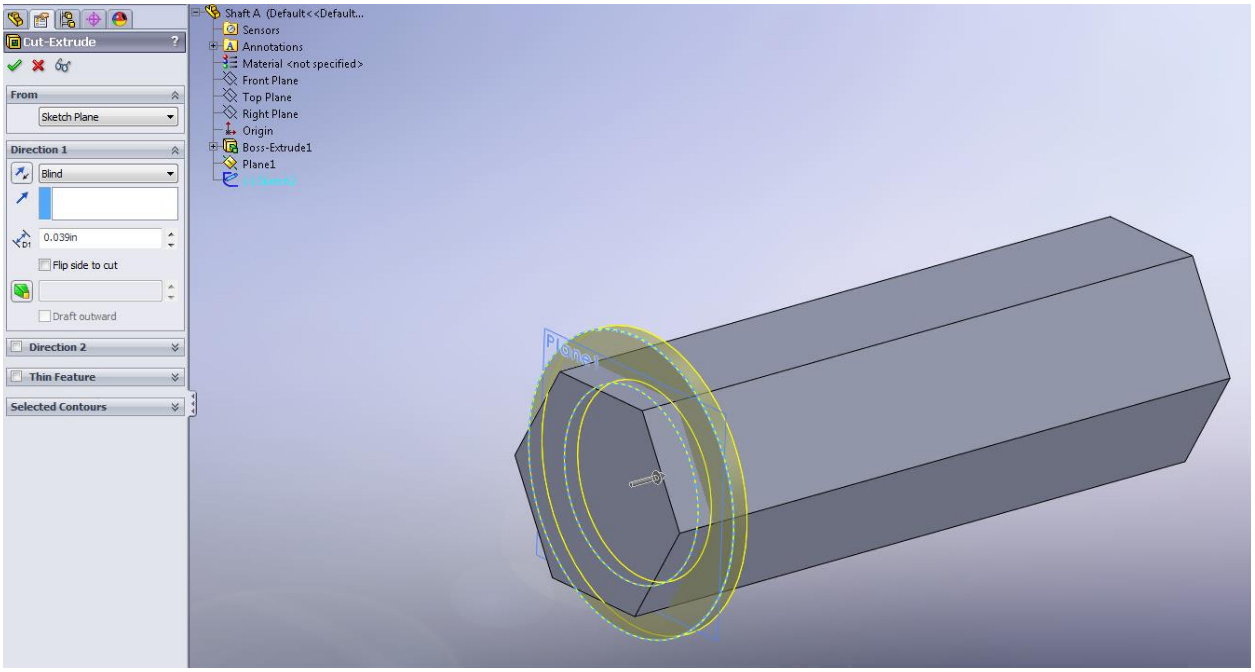
Click ok to make the plane.

Right click on the plane to make a sketch.

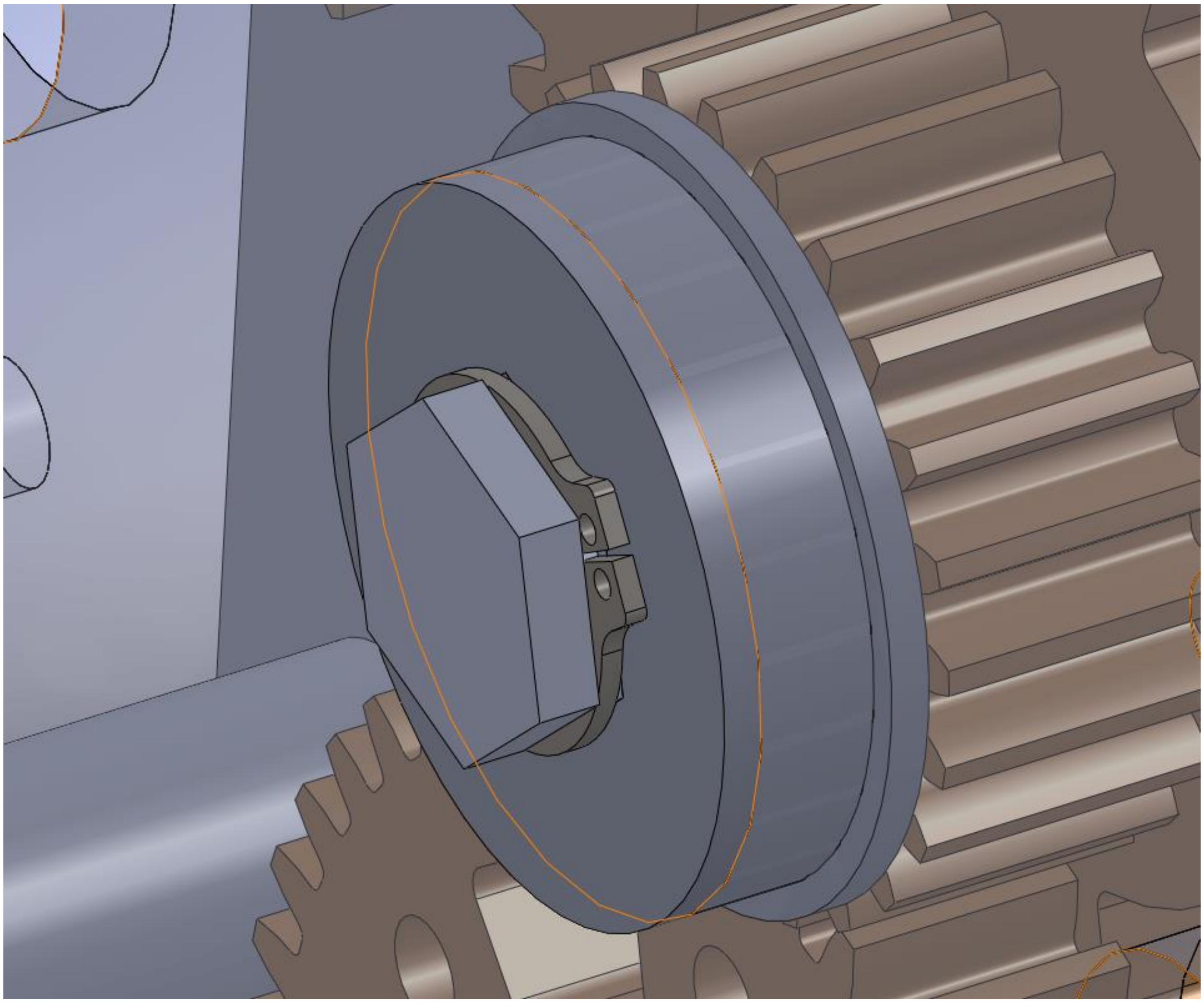


Sketch on the plane the inner groove diameter and a circle that is larger than the diameter of the shaft. The outer circle does not matter as long as it is bigger than the shaft.

Cut extrude the sketch.



Now you have a retaining ring groove.



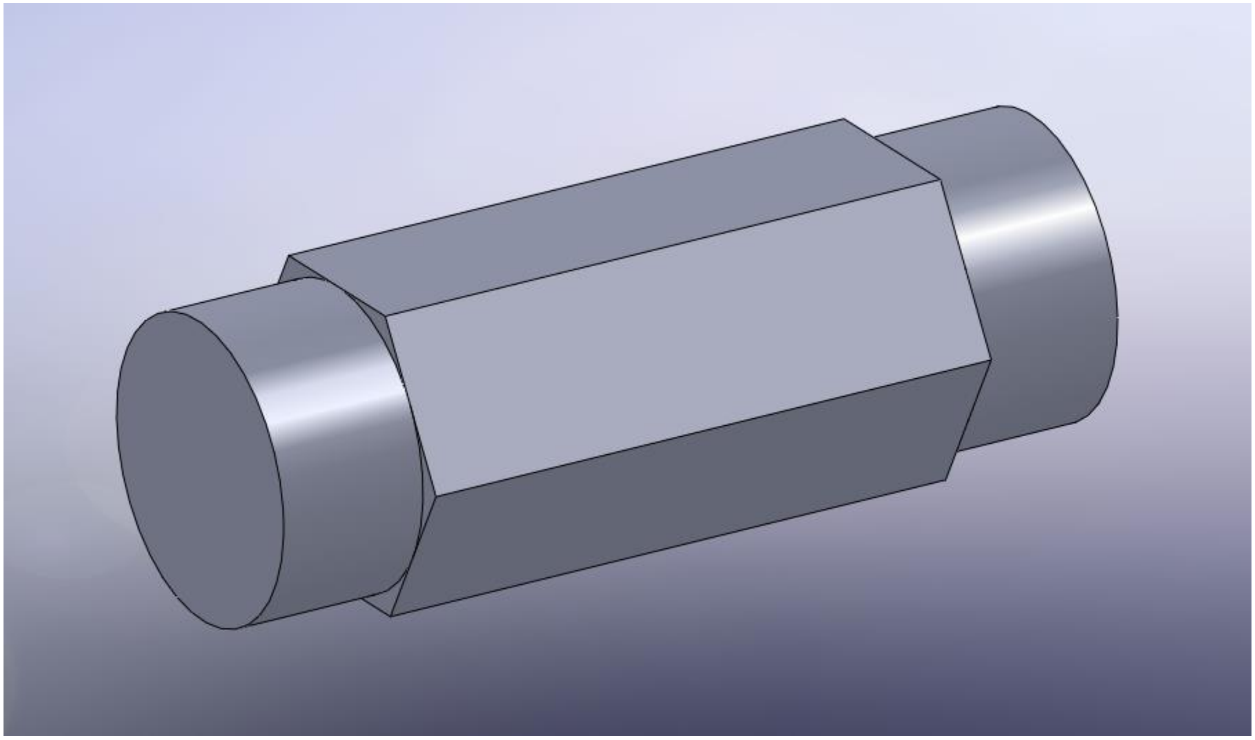
The end result will look like this.

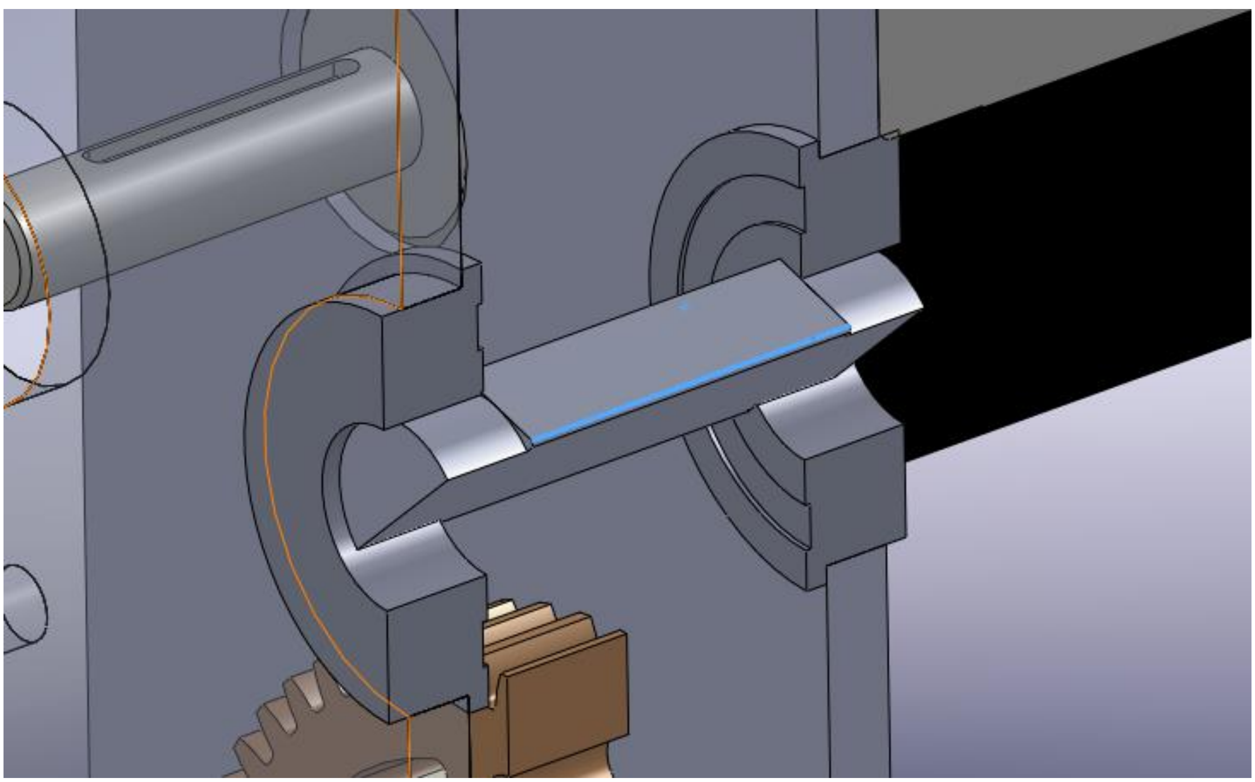
There is, however, an easier way to hold the shaft in.

Remember how you put the flanges in the inside. This is where it comes into play. Currently, you have “hex bearings” inside. These are bearings with a hexagon shape inside. Replace all of those bearings with round bearings for a 0.5 inch shaft.

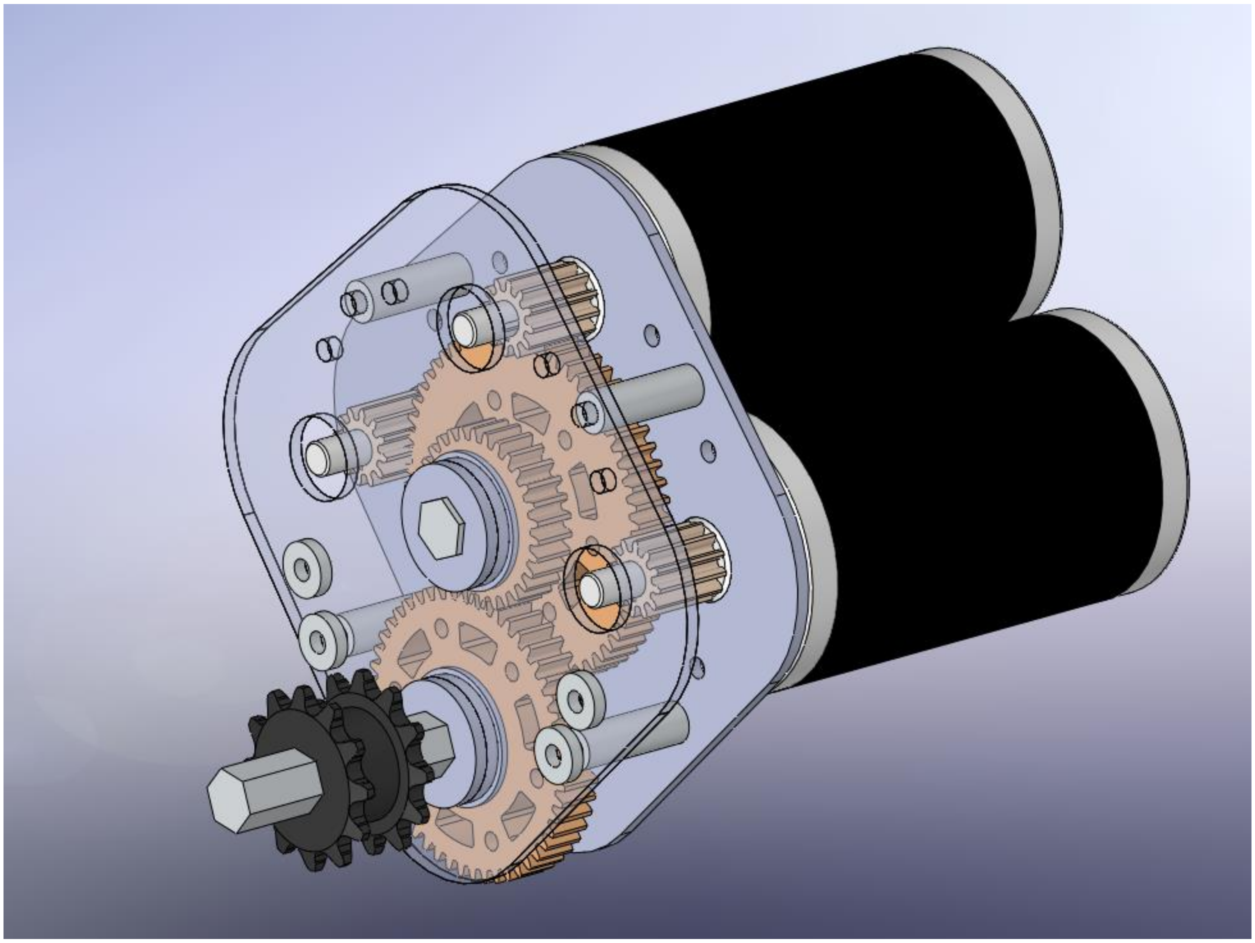
Instead of using a retaining ring, we are going to round off the ends of the hex shaft and use round bearings to keep the shaft from falling out.

Change the shafts so that they look like this:





Notice now how the "hexagon" part butts up against the round bearing keeping it from falling out. This method is often preferred as it doesn't require additional parts (the retaining rings) and is easier to machine. Either way is fine though. Add some mounting holes and now you are done.



You can round off the corners to save some weight and make it look nice. Whatever you end up powering (in this case, a double sprocket) goes on the output shaft. You have now just made a gearbox.

DESIGN CHALLENGE (ROTARY)

A 10 pound linear lift needs to lift a 5 pound game piece. The lift is driven up on a belt run. Given 2 Mini CIMs, build a gearbox that will get the 60 inch lift up to the top as quickly as possible and calculate how long it will take to reach the top.

<u>Mini CIM Specs:</u>

Free Speed: 6,200 rpm (+/- 10%)

Free Current: 1.5A

Maximum Power: 230 W

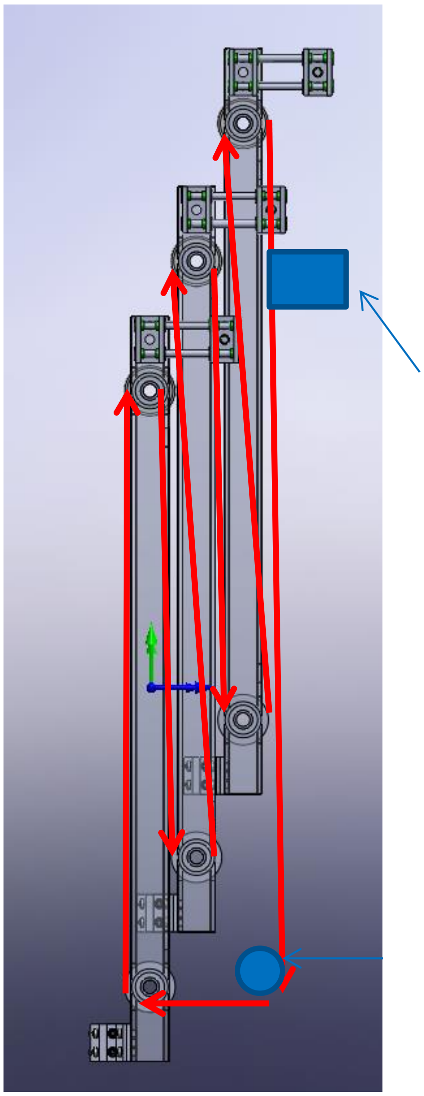
Stall Torque: 12.4 in-lbs [1.4 N-m]

Stall Current: 86A

Mounting Holes: (4) #10-32 tapped holes on a 2" bolt circle

The type of belt that would be used would be 5mm (GT2). You can find timing belt pulleys: https://sdp-si.com/eStore/Catalog/Group/217

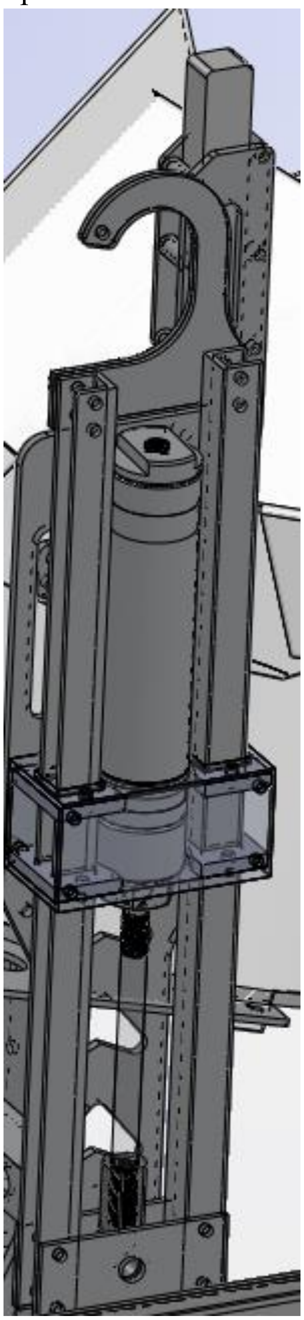
Note that they keep changing their website so this link probably won't work for long. The company is called Stock Drive Products.



LINEAR MOTION

Motors deal with rotary motion: pivoting arms, spinning wheels, etc. While it is possible to go between linear and rotary motion, it is often messy and inefficient. Linear motion in general is usually harder to design with but sometimes comes with benefits. Most linear motion is

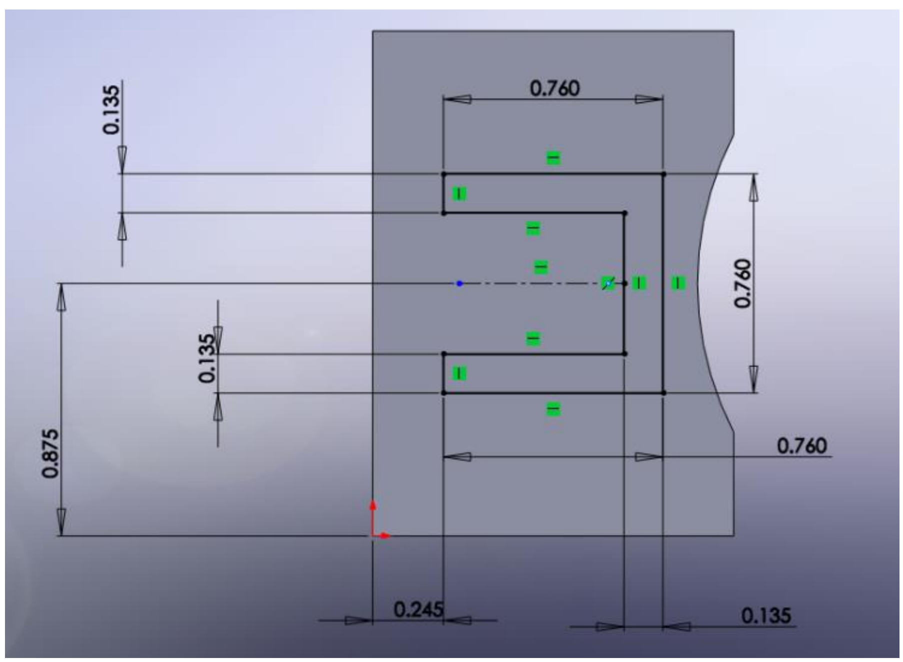
generated by pistons, but mechanisms such as "snail cams" and racks and pinions can be used to take a motor's "rotary" force and convert it to a linear movement. Typically, you will need some sort of a "linear bearing" to guide the thing in place. This can range from anything from an Igus rail (http://www.igus.com/), to a drawer slider, to little plastic rollers. We usually don't deal with linear motion that much, but the telescoping arm we used for LogoMotion (2011) and the 10 point hanger from Taz, (2013) are good examples of linear movement. The general rule is plastic on metal, metal on plastic. You don't want metal rubbing against metal. We typically use Delrin, a low friction plastic. VEX bearings are made of this and it is a relatively cheap and durable plastic. Teflon is nice but expensive. ABS isn't bad and Lexan isn't too good but will do for



cases where you don't really care how smooth it is. Of course, you can use perpendicular ball bearings but that often magnifies the size and complexity.

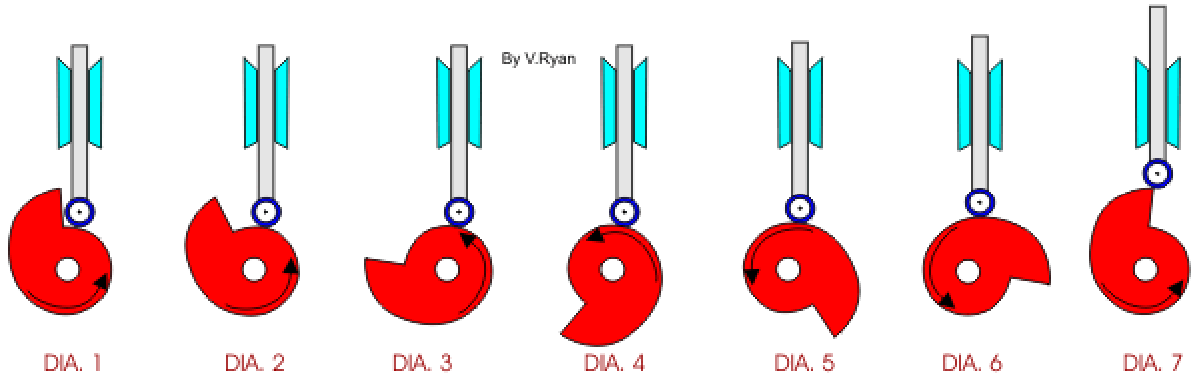
The 4 light grey blocks are Delrin pads cut from a 5/8" sheet and allow the c-channel to slide up and down freely. You can see how it would have been much more difficult to fit a bunch of ball bearings into this housing. Also, when the two pistons put out a combined force of 200lb, the friction of the Delrin pads is negligible. That being said, you still want the mechanism to move smoothly up and down. Keep in mind that when designing, you should add a few thousandths of an inch tolerance so that it is not super tight. In this case, we added .010 of an inch to the C channel profile to give the c-channel so wiggle room.

Most of the time, linear motion will be powered by pneumatics. However, cams and racks and pinions are also fairly common.



SNAIL CAMS

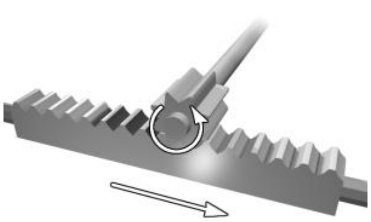
Below is a diagram of a snail cam.



As you rotate the red piece counterclockwise, the follower arm is pushed up until it hits the highest point at which point it drops back down to the starting point. This mechanism is particularly used full for reloading and is often used in kickers, catapults, shooters, etc. The "winding" of the cam effectively "cocks the shooter" (e.g. pulling back on some spring or elastic) and the "drop off" allows the mechanism to fire (e.g. letting go of the sling shot). This is very useful because now only one mechanism is needed to cock and release the mechanism and it is continuous, with no "rest period" of any sort.

VEX has one for the VRC and you can probably buy one somewhere, but you could also machine your own out of a thick sheet of plastic or metal.

RACK AND PINION

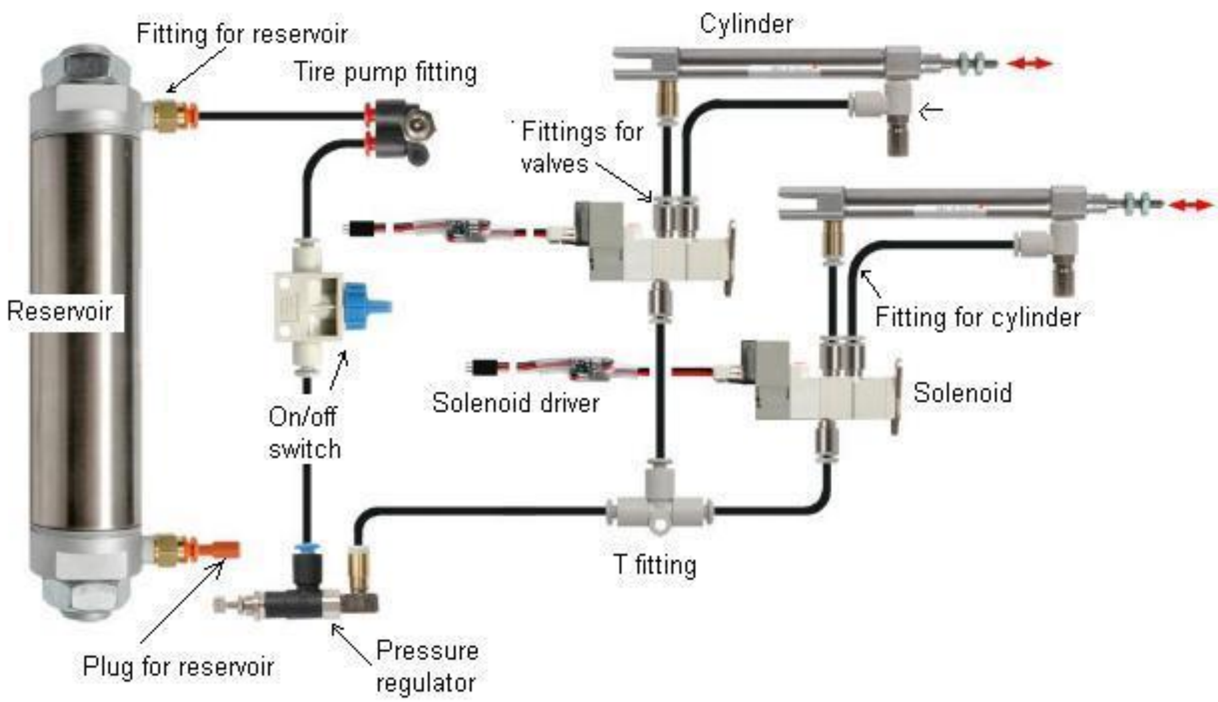


Think of a rack like a linear gear. Quite simply, rotating the pinion moves the rack up and down. Calculating the amount of force you get pushing from the rack is just the inch pounds of torque/radius of the gear. (Think back to the definition of an inch pound). Again, VEX has some rack and pinion kits. As for FRC we've never used one. They're usually not the most convenient option. A piston will usually suffice.

PNEUMATICS

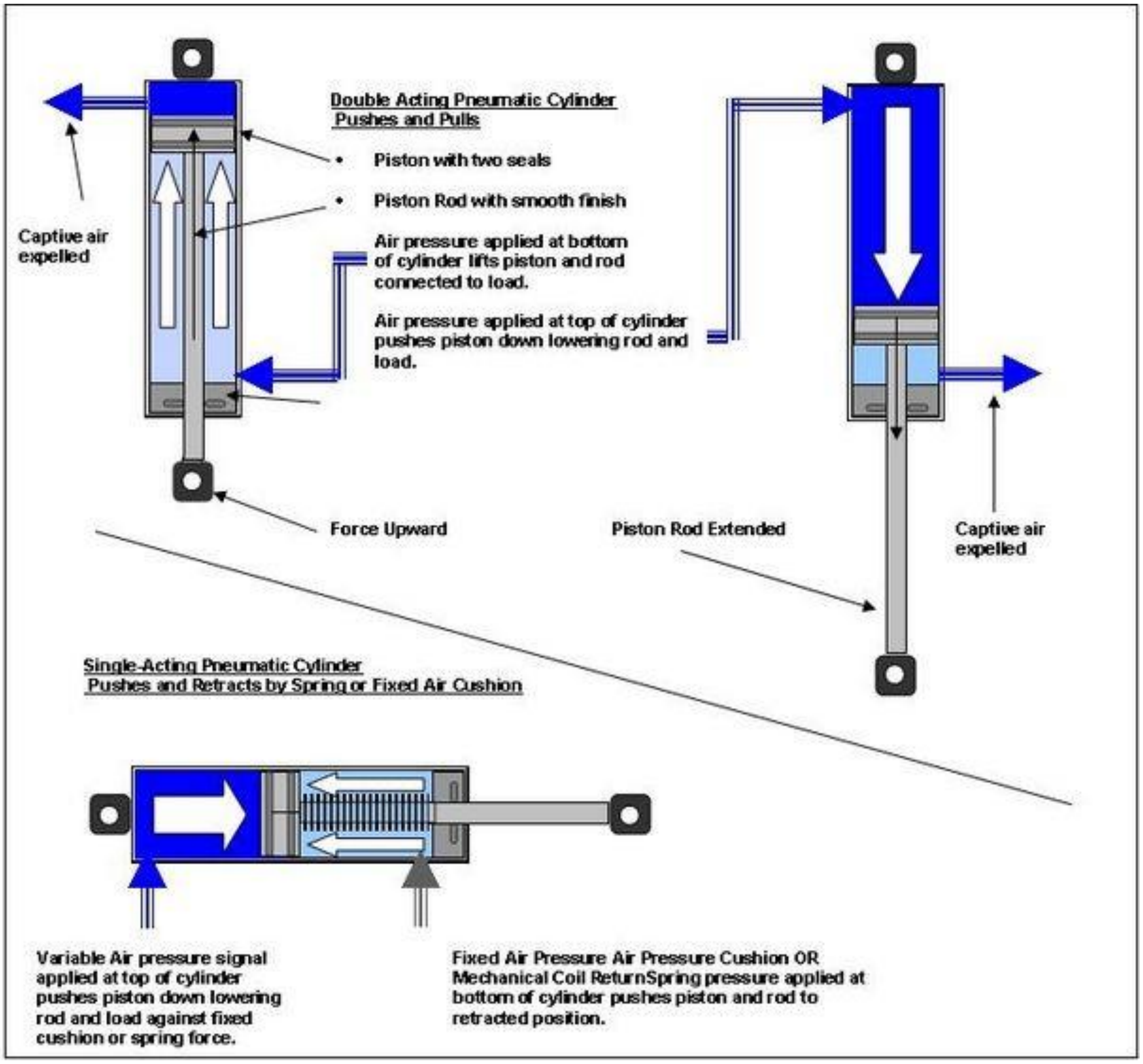
Pneumatics are basically the method of using pressurized gas to power a mechanism. We usually deal with it in the form of pistons.

This convenient and over-simplified diagram helps give a basic understanding of how it works.



Compressed air is stored in the air tank (reservoir). We won't worry about the tire pump fitting. That is basically where the bike pump connects to so you can pump it up with air; in FRC we use a compressor. The on/off switch is self-explanatory. As for the regulator, (this one is a bad example) they usually have a gauge that you set to a certain pressure and it only allows through the set amount of pressure. You might store you air at 120 psi but regulate it down to 30 so only 30 PSI passes through to the pistons. This both saves you air (as you are letting less air out) and is also a safety feature as sometimes you don't want too much force coming out of the pistons. The solenoid is a basically the "on/off" switch of the piston. Basically, it controls the flow of air to either the top portion or bottom portion of the piston which determines whether it is retracted or extended.

This diagram shows double acting pistons (i.e. pistons that pull and push). There are also single acting pistons (pistons that only push and rely on a small spring to retract it). Double acting pistons obviously require more air (because they need air to pull the rod back in as well as push out), but as you will see later, they have certain advantages.

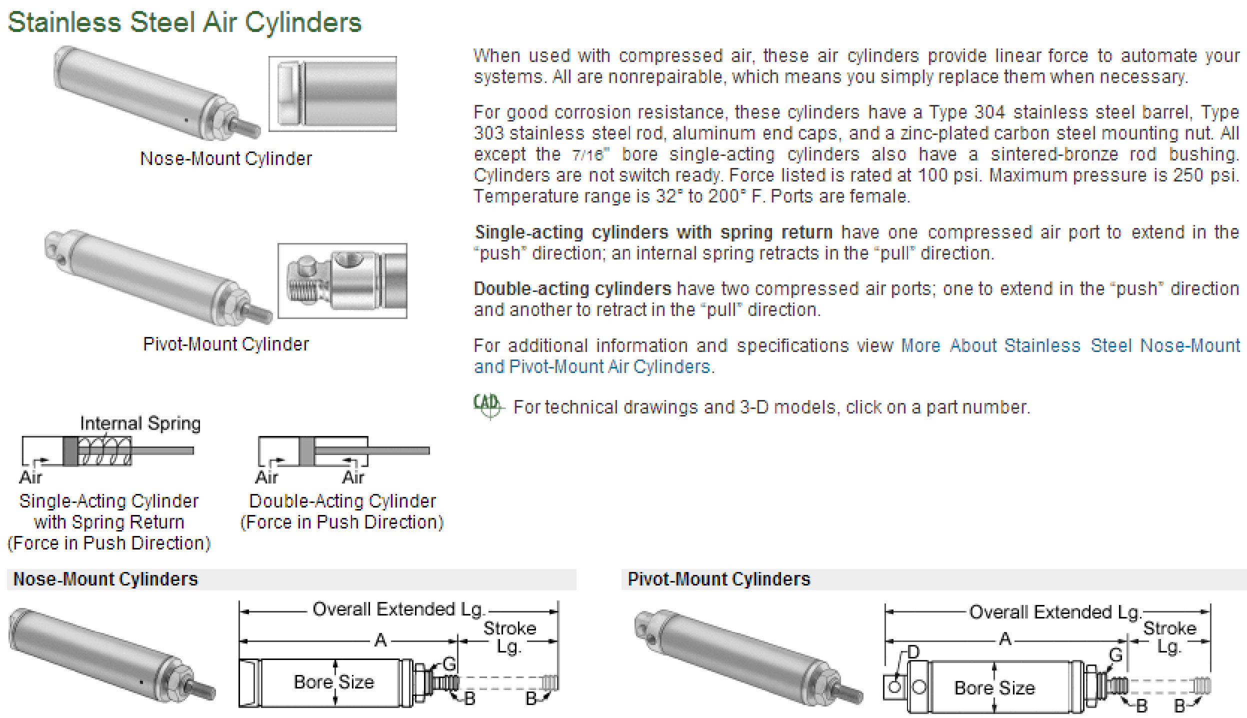


The term "psi" refers to "pounds per square inch". 1 psi means that for every square inch of surface area, the air is pushing back with 1 pound of force. In FRC we are allowed a maximum of 60 working psi. The air can be stored at up to 120 psi. Let us say we want to calculate the force of a piston with a 1 inch bore and ¼ rod that has a 5 inch stroke @60 psi.

Bore: Refers to the internal diameter of the piston which will be used to calculate force of the piston

Rod: The part that moves out; you will see later how this comes into effect.

Stroke: How far the piston extends.


Stainless Steel Air Cylinders

Nose-Mount Cylinder

Pivot-Mount Cylinder

Internal Spring
Air
Single-Acting Cylinder with Spring Return (Force in Push Direction)

Air Air
Double-Acting Cylinder (Force in Push Direction)

When used with compressed air, these air cylinders provide linear force to automate your systems. All are nonrepairable, which means you simply replace them when necessary.

For good corrosion resistance, these cylinders have a Type 304 stainless steel barrel, Type 303 stainless steel rod, aluminum end caps, and a zinc-plated carbon steel mounting nut. All except the 7/16" bore single-acting cylinders also have a sintered-bronze rod bushing. Cylinders are not switch ready. Force listed is rated at 100 psi. Maximum pressure is 250 psi. Temperature range is 32° to 200° F. Ports are female.

Single-acting cylinders with spring return have one compressed air port to extend in the "push" direction; an internal spring retracts in the "pull" direction.

Double-acting cylinders have two compressed air ports; one to extend in the "push" direction and another to retract in the "pull" direction.

For additional information and specifications view More About Stainless Steel Nose-Mount and Pivot-Mount Air Cylinders.

CAD For technical drawings and 3-D models, click on a part number.

Nose-Mount Cylinders

Pivot-Mount Cylinders

With a 1 inch bore, the surface area of the plate (on the inside of the piston connected to the rod, i.e. the part that the air is pushing on so it can expand):

$$SA = \pi r^2$$

$$SA = \pi(1in)^2$$

$$SA \cong 3.14in^2$$

So we know the plate has an area of 3.14 square inches and we know there are 60 psi or pounds per 1 square inch. Given that:

$$F = Area \times Pressure$$

$$F = 3.14in^2 \times 60lb/in^2$$

$$F \cong 188.4lb$$

Let's say this was a single acting piston: would the force of the single acting piston also be 188lb?

Will the return force (the retracting force of the piston) be the same 188lb?

Yes/No?

The answer is on the next page.

The answer is, in fact, no. Why? The return spring (the spring build into the single acting piston to pull the rod back) offers resistance. When dealing with tiny pistons the force is negligible, but when dealing with larger pistons sometimes the return spring can be quite significant so you should factor it in. Single acting pistons will save you air but will have less force for the same size bore as its double acting counterpart.

As for the return force question, the answer is also no.

Remember that we are only concerned with the area of the plate (the highlighted yellow region) because that is the part the compressed part tries to push out to give the air more volume.

When the pistons extends, it has the entire surface to push up against, however when it returns it has less room because some is being taken up by the rod. We must factor this into our calculations.

Thus, the surface area is the area of the plate minus the profile of the rod:

$$SA = \pi {r_1}^2 - \pi {r_2}^2$$

$$SA = \pi(1in)^2 - \pi(.125in)^2$$

$$SA \cong 3.09in^2$$

Force is the same:

$$F = Area \times Pressure$$

$$F = 3.09in^2 \times 60lb/in^2$$

$$F \cong 185lb$$

In this case it was only a loss of about 3 lb, but when the size of the rod increases, the difference can be significant. Ever wonder why on the 2013 world champion robot the hanger pistons seem to be pointed downwards? This is so that the retracting of the piston actually brings the hooks up and the expansion, which has more force, lifts the robot. It is also why the piston is a double and not a single, even though it required very little force to bring the piston up and we only need

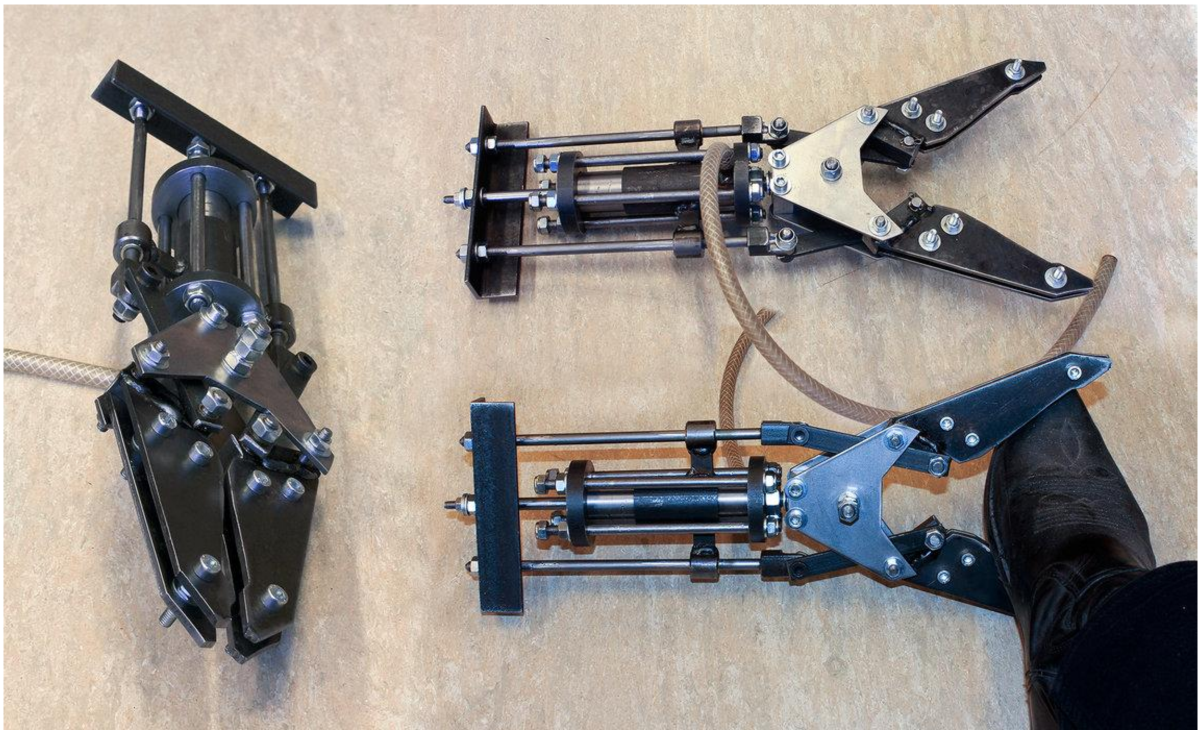
force pulling down. This is because the force of the return spring is too large and we would not get enough force pulling the robot up.

DESIGN CHALLENGE (LINEAR)

In physics, you were probably told about something called mechanical advantage. The farther you apply a force from a fulcrum, the easier it will be to push, and the closer the load is the fulcrum the easier it will be to lift. So why exactly do excavators, dump trucks, bobcats etc. often look like they are doing the opposite? While heavy machinery runs off hydraulics (pressurised liquid) as opposed to pneumatics (what we use in FRC and sometimes in VEX, pressurised air), pistons can deliver massive amounts of force. Take the 2013 10 point hanger. Those two pistons combined have a total output of about 200 pounds whereas if we geared a CIM 100:1 we would get about 88.5 ft-lbs. of torque. While this isn't the best comparison, pistons can deliver a large force over a small distance while motors can deliver comparatively less force but for a much larger distance. Thus when it comes to heavy machinery, the pistons can deliver more than sufficient force to do the job, but the stroke of the piston is not nearly long enough to provide the desired reach, thus the pivot is placed such that you effectively get more stroke of the arm and less force. In general, we don't really care that we are losing some force because of the immense force we are going to get. With motors we "gear down" to provide more force but go slower. With pistons we go farther but get less force, effectively the same as if we were to "*gear up*".

Pistons are nice when you want something to be binary (on/off and only two positions), and when you want a lot of force; which sometimes is helpful. Motors on the other hand can vary their speed and position, and while you could gear them down, to have an insane amount of torque it would probably end up being too slow. While motors might be better for an arm or intake roller, pistons might be preferred for an indexer or a gate.

For this design challenge you are going to build a pneumatic claw. How you do it doesn't matter, but the claw should clamp shut on a 1 inch steel pipe with about 100lb of force.



CLOSING

Many thanks to the mentors on team 610 who have taught me everything I know, and without whom I would not be the same. Many thanks to Rob Stehlik who has taught me everything I know about mechanical design, Shawn Lim for sharing his computer science and electronics know how, Don Morrison for running the entire robotics program, Marcella Fioroni for getting us to competition as well as making sure we are always having a good time and last but not least, David Grant who started the program so many years ago. Also, a big thank you to Jeff Adams and Ian Fisher for mentoring my FIRST Lego Team and getting me involved in robotics nearly a decade ago.

This book is dedicated to all the future members of 610 in hopes that they will learn something from it and carry the team on for many years to come.

APPENDIX A

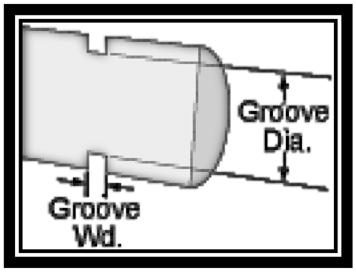
Imperial

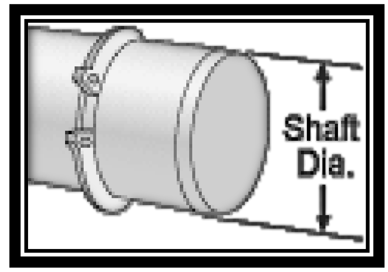
Screw Size	Recommended Clearance Hole Size	Closest Fractional Drill Size
#4-40	0.125”	1/8
#6-32	0.156”	5/32
#8-32	0.172”	11/64
#10-24	0.203”	13/64
¼-20	0.266”	17/64

Metric Screws

Screw Size	Recommended Clearance Hole Size	Closest Fractional Drill Size
M3	0.141”	9/64
M4	0.188”	3/16
M5	0.219”	7/32
M6	0.266”	17/64
M8	0.390”	25/64
M10	0.453”	29/64

APPENDIX B





Shaft Diameter	Groove Diameter	Groove Width
¼”	0.23”	0.029”
3/8”	0.352”	0.029”
½”	0.468”	0.039”
5/8”	0.588”	0.039”
¾”	0.704”	0.046”
1”	0.94”	0.046”

APPENDIX C

Tap Drill Holes Size

Screw	Holes Size (Fractional Approximation)	Tap Drill
4-40	5/64”	#43
6-32	3/32”	#36
8-32	1/8”	#29
10-24	9/64”	#25
¼-20	3/16”	#7