Truncated Icosahedron (Soccer Ball)

By Steve Garrison ©2020

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Introduction

"Truncated Icosahedron (Soccer Ball)" is a 32-sided polyhedron composed of 12 regular pentagons, and 20 regular hexagons with 2 different bevel angles. Polyhedral construction was notoriously difficult and very unforgiving of errors. Not only do the polygons have to be perfect, but also the bevel angles – and the edge lengths also have to match. These instructions describe a new approach that I came up with using a digital microscope as an alignment tool, and an adjustable table saw sled I have designed.

Affordable Digital microscopes are now available that have a built-in screen and a video reticle in the center of the viewing area. By positioning the microscope reticle inline with the edge of the saw cut we can use it to align a pattern with the cut. The alignment is only a single point making it foolproof and extremely precise. We can slide the workpiece back and forth along the fence under the reticle to make the pattern line exactly parallel to the fence and cut path before making the cut by adjusting two points where the sled touches the fence. We can use patterns printed on paper and cut the polygons with as much precision as they are printed with which is very high coming from a drafting program. I have experimented with different ways to attach the pattern to the wood and found that permanent adhesive full sheet shipping labels work the best. Paper can shrink a small amount when adhesive is applied, but shipping labels already have the adhesive on them and any shrinkage has already happened long before being printed on, so nothing happens that could shrink the label before being stuck to the wood. After cutting the polygons the label can be peeled off in one piece with enough nail polish remover (acetone) to wet the paper. The wood will still feel sticky after removing the label, but can be removed with a little more solvent and rubbing or by sanding. I also recently found that a wire-wheel on a bench grinder also does a good job removing the label afterwards as long as the wood you use is hard enough to resist erosion. Be sure to wear safety glasses and/or a face shield, sometimes wire wheels shed while in use – ouch!

The Microscope

The particular microscope I bought has a metal stand with 2 screws holding the vertical rack and pinion column on the base. I reversed the screws so the base plate is rotated 180° and can be clamped to the table saw top using a home-made T-bolt and hold-down board. The base plate has rubber feet that I removed, and the 2 screws that hold the column protrude, so I glued a piece of ¼" plywood to the bottom of the base to provide a flat bottom with clearance for the heads of the screws. Another modification I made to the microscope was to cover the aperture with a piece of clear tape to keep sawdust from getting into the optics of the microscope; I also covered other holes on the microscope.

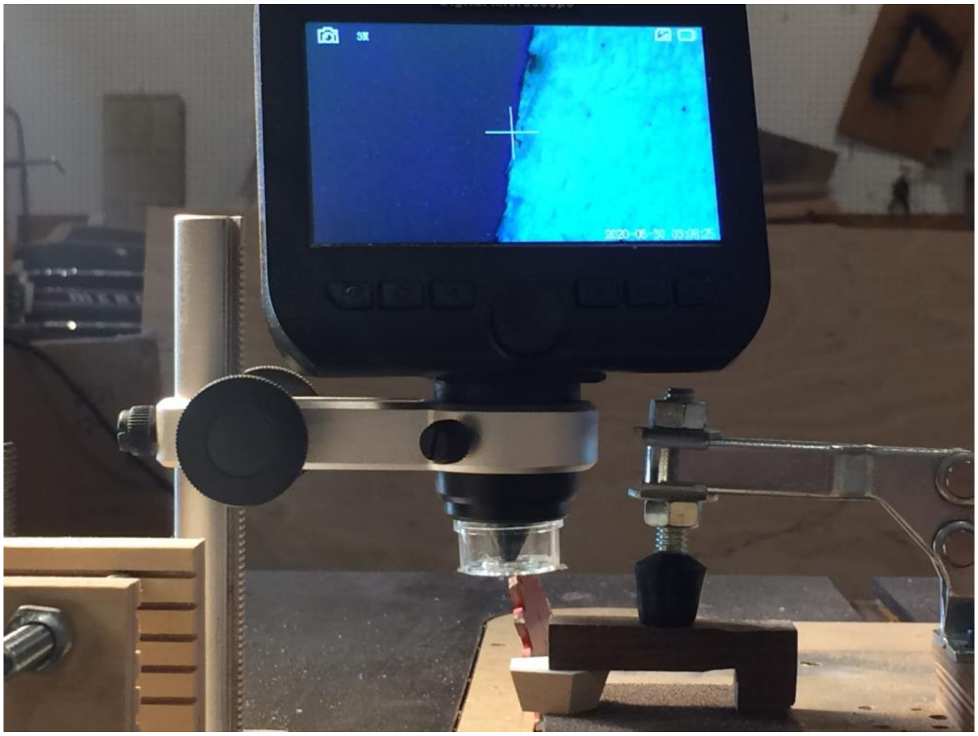

Photo 1. The view through the microscope of the edge of a polygon after being cut. The cross-hair reticle is aligned with the cut edge. A simple “shoe” made from a piece of hardwood is placed between the toggle clamp pad and the part instead of using the toggle clamp directly.

The Coarse Reticle

You will need to make a reticle and holder to get the pattern close enough to make fine adjustments in the 2-step alignment. This part goes in front of the microscope (closer to the saw operator). The reticle is a fine dashed line scratched into a piece of glass. I made a simple tool from a diamond rotary bit to scratch the glass with; it is a small piece of wood with 1/8” hole drilled to insert the shank of the diamond bit and works the same as a marking gauge except it has diamond abrasive instead of a pencil or scriber. The wood block is held against the edge of the glass (from a cheap dollar store picture frame), and the edge of the glass guides the marking tool so the scratched line is parallel to the edge of the glass perhaps a ¼” or so from the edge (bit is pulled out slightly for clarity). The scratched line should be made as a dashed line so the pattern line can be seen between the dashes. Use a permanent marker to blacken the scratch, and then remove the excess ink around the scratches using fine steel wool.

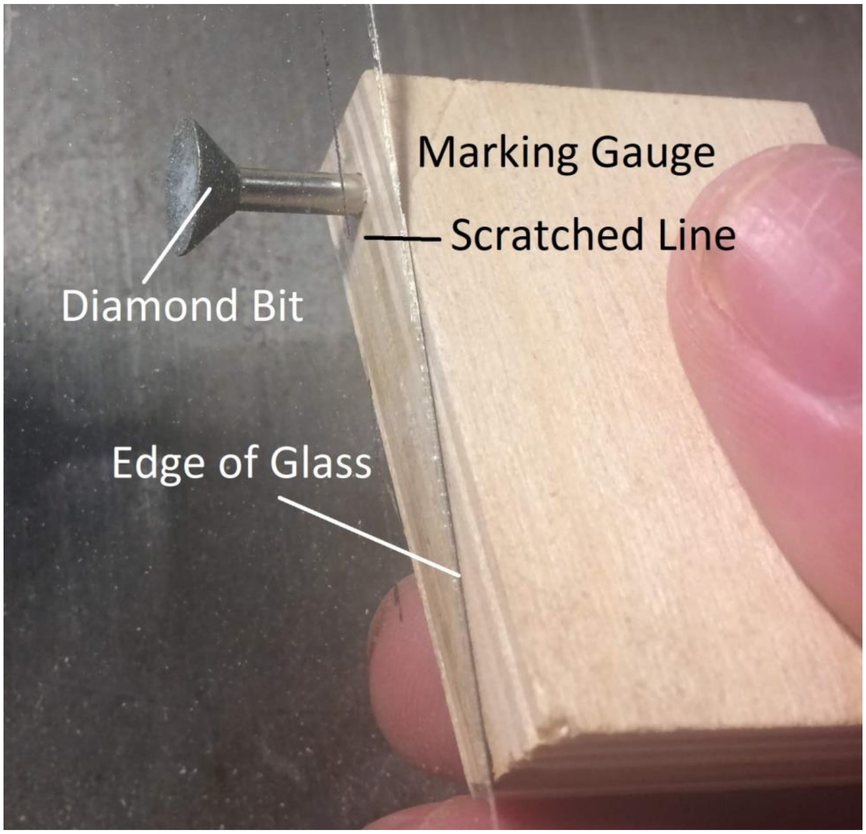

Photo 2. A simple marking gauge for scratching a reticle line into a piece of glass. The edge of the glass acts as a guide for a straight line. The diamond bit is pulled out for clarity.

The glass fits into grooves cut into the holder, and a nut and bolt (very gently) pull the sides of the holder in to hold the glass firmly by the edges to avoid having the glass rattle around or shift out of position. Multiple grooves are cut so the glass reticle can be at different heights according to the thickness of the wood being cut. The height of the clamping surface of the jig is about an inch above the saw table, so the bottom grooves should be slightly higher. Use a thin kerf 7¼" saw blade to cut the grooves with. The glass I used measures approximately 2" x 5" and I had to cut it to that size with a simple score and snap glass cutter and a straight edge. You might have noticed that the new glass reticle and holder is smaller than the one I used in my original video about making a dodecahedron. I wanted more room for the microscope, and didn't use the full length of the original reticle.

At the other end of the holder there is a ¼" carriage bolt going through a nut pressed into an undersized hole drilled in the end piece of the holder to act as an adjustment. The undersize hole should be larger than the flat-to-flat dimension of the nut, and smaller than the corner-to-corner measurement. Tap the nut in place with a hammer, or press it in with a strong clamp or vise. This bolt pushes a block of wood that fits between the bolt and the edge of the glass. The block has a shallow hole for the end of the bolt to fit in to loosely hold the bolt end in place. The purpose of the bolt is to allow side-to-side adjustment of the reticle when the bevel angle is changed. The line on the reticle should be in line with the cut. Simply make a test cut with the new bevel angle setting and slide it back under the reticle and adjust the reticle to align with the cut. The glass reticle is meant to be used as a coarse alignment to get the pattern line close enough to make fine adjustments with the two screws on the sled. I made the body of the reticle holder out of ½" Baltic birch plywood with the edges fitted and glued into dado grooves. The grooves for the glass are spaced about ¼" apart. The glass should be over and not touching the wood being cut, but do not make the distance between the bottom of the glass and the wood excessive. The body of the reticle holder should be clamped to the saw table using a T-bolt in the miter groove, make a slot in the base of the holder for the T-bolt to pass through. With the blade square to the table, the glass should stick out a few inches beyond the end of the holder, and then as the bevel angle is increased the glass will be moved to the left back into the holder.

While cutting the polygons you might notice that one end of the sled is adjusted farther away from the fence than the other after a few cuts. You can tweak the angle between the glass reticle and the fence by slightly rotating the reticle holder on the table to even out the adjustments, and have fewer adjustments to make to get parallel. The same thing applies if the pattern line is parallel but shifted left or right, in that case you should adjust the glass reticle with the adjusting screw. Be sure to check that the glass reticle is not able to rattle around in the holder.

Photo 3. If you need to obtain T-bolts to fit the miter slots of your saw, you can make them from a carriage bolt and a washer. The 5/16" T-bolt is made by pressing the square section below the head into a washer, and then grinding material from the top of the head until it fits the slot. Choose a washer that is too small to fit over the square section, and file two shallow notches 90° apart inside the hole with a chainsaw file so the square portion is a press-fit. Tap the bolt into the washer with a hammer on an open vise.

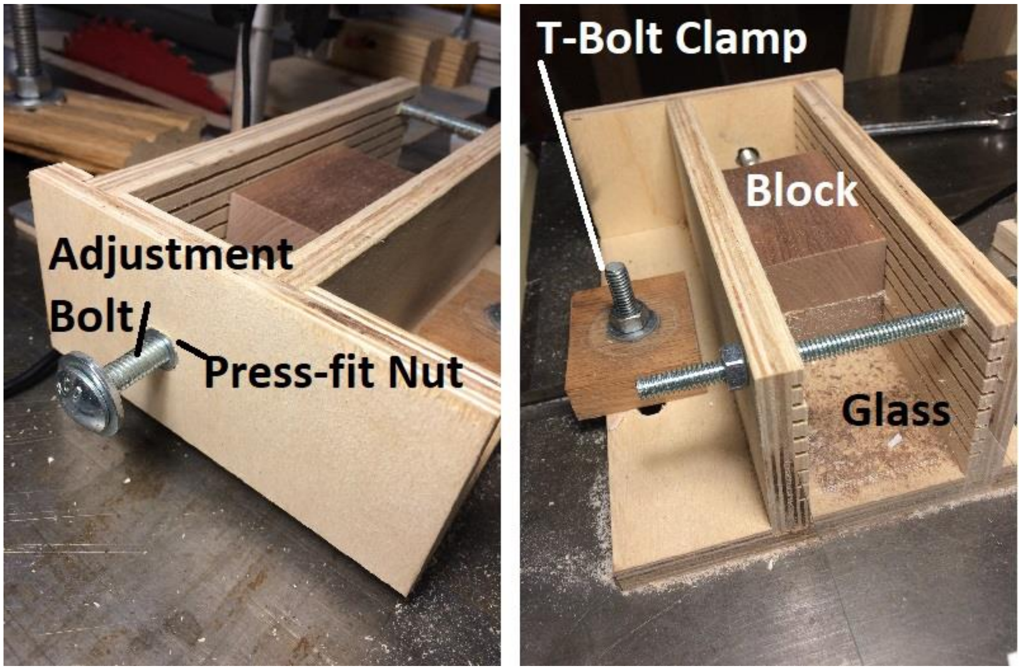

Photo 4. The coarse alignment glass reticle and holder. The glass is able to slide in the grooves like a drawer. Once the reticle is in correct position it is held in place by gently tightening the nut and bolt above the glass.

The Sled

The adjustable sled is guided along the saw fence instead of the miter grooves to make it more easily adjustable when you change the bevel angle. You'll want to keep the edge of the sled close to the blade for more support of small parts, but not too close that you might touch the metal part of the sled to the blade. The sled is made of ½" Baltic birch plywood measuring roughly 18" x 9" – or something such as mdf could also be used as long as it is very flat. The edge of the sled that rides along the fence is not the base, it is a pair of adjustable feet (see photo 5 below). Each foot is mounted on a pivot bolt that goes through the bottom of the sled. Each foot is adjustable by a round carriage bolt head that moves either the front or rear end of the sled closer to or away from the saw fence. A rubber band or spring keeps each foot in contact with the end of the adjusting bolts. The adjusting bolts form their own threads in undersized holes in a pair of wood blocks attached to the base of the sled, I used a pair of 4" long ¼"-20 carriage bolts. After threading the bolts through the wood blocks, bend the end of the bolts in a vise to form a handle. The length of the handles should be short enough so the base of the sled does not interfere with the rotation of the adjusting bolts. Cut off any excess length from the bent handle, and file any burs of the ends of the handles and wrap the ends with rubber bands or tape to soften them (you'll be adjusting them a lot). Leave perhaps an inch or so between the handle ends and the threaded wood blocks to allow for adjustment.

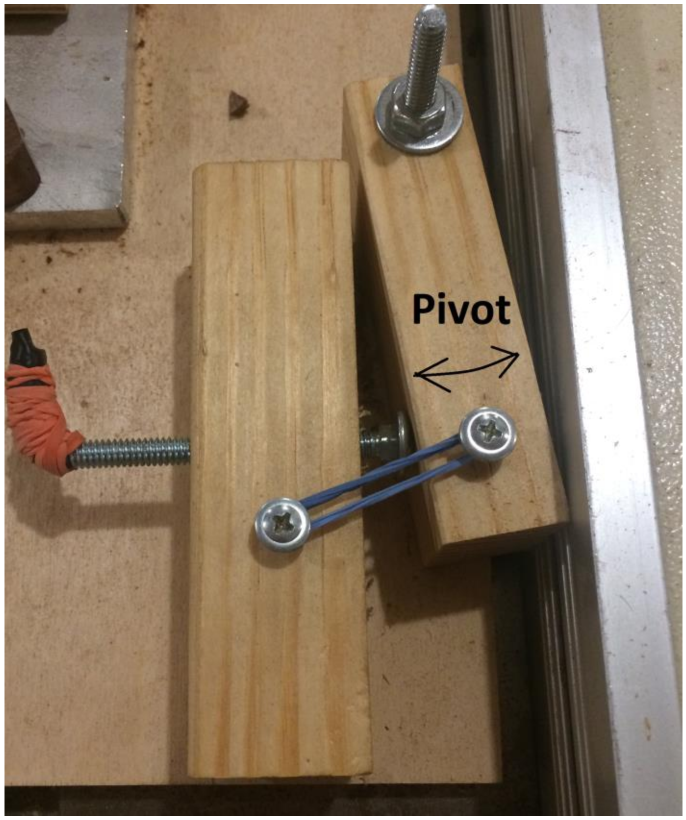

Photo 5. The sled has a pair of adjustment screws made from ¼" carriage bolts that pivot the feet that ride against the fence. This allows very fine tuning of each cut.

The sled uses a toggle clamp and a wooden "shoe" to hold the wood in place against a thick metal plate covered with coarse sandpaper. My first sled I made did not have the metal plate, and the force exerted by the toggle clamp was enough to warp the base board – which messes up the bevel angle. I reasoned that it would be better to make the clamp in a way so that any distortion caused by the clamping force would not affect the base of the sled. The metal plate I use is a piece of 3/8" thick aluminum that measures 6" wide x 8" inches long – overkill I know, but it works very well. I used aluminum instead of steel just in case I am not paying enough attention and it comes into contact with the blade. The left edge of the aluminum is beveled 45° to maximize supporting area under small pieces, and allow the sled to be closer to the blade. The safest way to make the beveled edge on the aluminum is with a band saw. If you have to make the cut with your table saw, do not cut all the way through in one pass. This will reduce the amount of hot, sharp metal flakes flying towards your face. Do not attempt without the proper safety gear of a face-shield, goggles, and long sleeve shirt. I cut my aluminum plate with my table saw with a blade specifically for aluminum. The toggle clamp is attached to the metal plate using Allen-head screws in drilled and tapped holes in the aluminum plate, and a wood spacer to have enough height capacity to clamp wood the thickness you want to use. The metal plate is attached to the base of the sled using 4 ¼"-20 machine screws through the bottom with counter-sunk heads to keep the base flat on the table without any protrusions. The bolts are trimmed flush with the top of the plate. There is a small gap between the aluminum plate and the base made by placing a flat washer on each of the four screws between the base and the aluminum plate. The reasoning for the gap is that if the plate distorts a little from the pressure of the toggle clamp, the gap will isolate the bend from the flat baseboard.

I made a wooden "shoe" to place between the wood being cut and the toggle clamp. The rubber tip of the toggle clamp will mash and shift the adhesive label. The shoe should have a heel that is just a little bit taller than the thickness of the wood being cut. The shoe not only is easier on the label, but it also gives more flexibility in where the part can be positioned relative to the tip of the clamp, and allows the aperture of the microscope to be closer to the wood and still have clearance for the toggle clamp. The area on the metal plate under the wood being cut is covered with coarse sandpaper glued down with spray adhesive. Something between 60 and 100 grit seems ideal, and reduces the amount of pressure needed from the toggle clamp to secure the wood.

Photo 6. A walnut "shoe". It is important that the heel is a little taller than the thickness of the wood that the parts are being made from. This piece should be made from hardwood.

Something I would do different if re-building the sled is to make the metal plate stick out a little farther than the edge of the base to allow more room for adjustment and be able to keep the metal plate closer to the blade without interference. The pieces for the polyhedron are rather small (especially on the last cut of each piece), and need all the support they can get to prevent having too much sticking out unsupported.

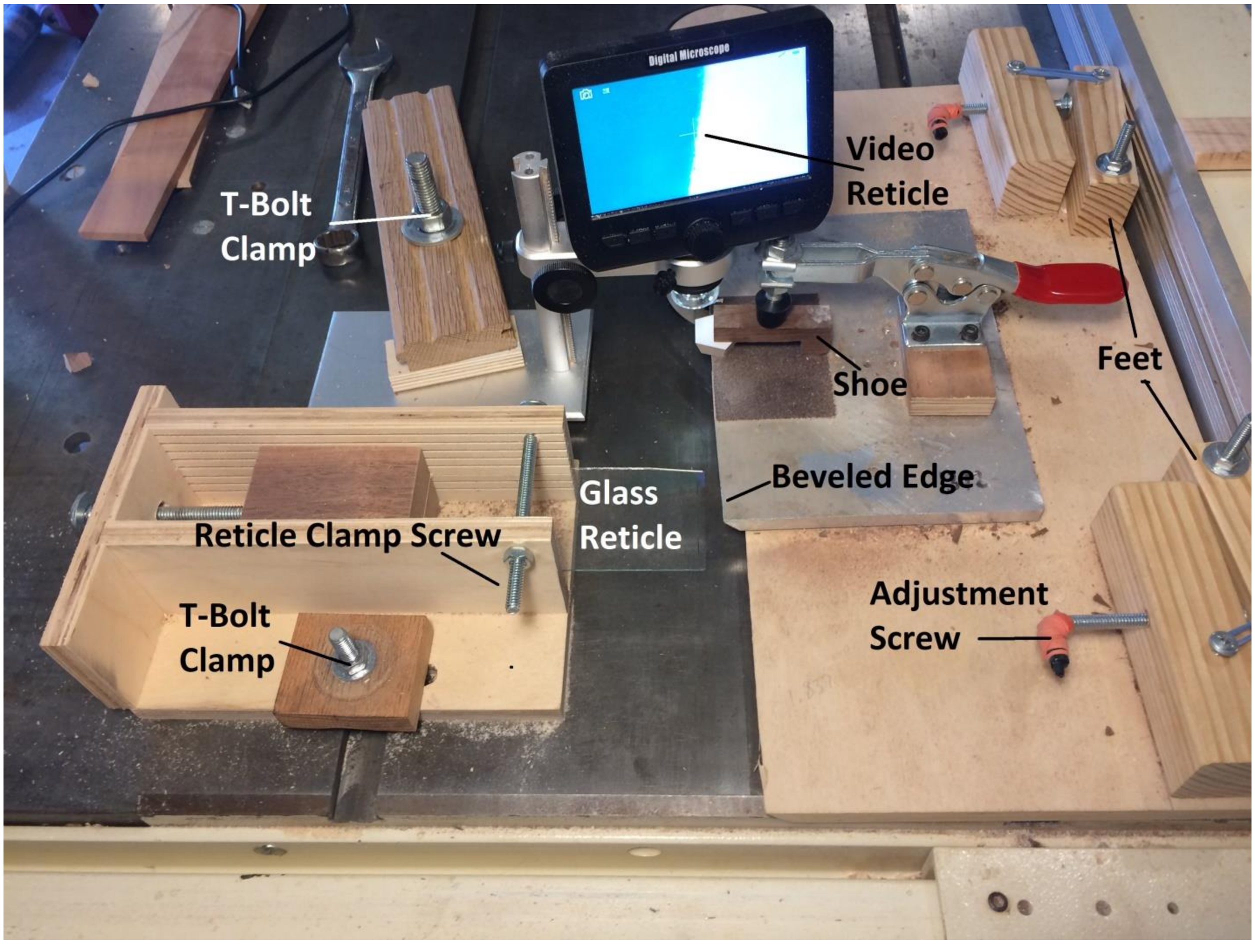

Photo 7. The components for cutting precision polygons for polyhedra.

Stock Preparation

Before getting your table saw all set up to make beveled cuts, you might need it to prepare the wood you will use for cutting polygons from. The wood will need to be wide enough to easily accommodate the polygons in the appropriate grain orientation. I cut the patterns into strips to print on label paper and adhere to the wood. All of the wood needs to be the same thickness – use a thickness planer or drum sander if you have one. The polyhedron I made for this demonstration has a finished diameter a little over 2.7", and I used wood that is 3/8" thick. Larger polyhedrons will of course need thicker wood if they are to be rounded into a sphere.

It is good to choose contrasting colors for the different shapes. If you make all the pieces from the same kind of wood, it will look very plain. I used maple for the pentagons, and walnut for the surrounding hexagons.

About the Polyhedron

The polyhedron is made up of 12 regular pentagons, and 20 regular hexagons. You can make the polyhedron whatever size you want, but the face shapes obviously have to be scaled together – this can be done in a drafting program such as Draft Sight. The inradius of a polyhedron is defined as the radius of a sphere concentric with the polyhedron that just touches the faces at one tangent point. The inradius is slightly different for the two different face shapes with the shorter radius tangent to the hexagons. This measurement is the largest sphere that can be made from the polyhedron. The polygon patterns included will produce a sphere with an inradius of 1.42, or almost 3" diameter.

The best way I know to check the angles is to make a gauge with a corner for each bevel angle in the polyhedron. This works the same as putting adjoining edges of a picture frame against a carpenters square to check the miter. Make this gauge by cutting it out the same way you will cut the polygons, except leave the blade square to the table. Attach the pattern for the gauge to plywood or some kind of material that is dimensionally stable. It is very important that all of the wood for the project is a constant thickness and very flat! This 32-sided polyhedron has 2 different bevel angles. You will make all the cuts for each bevel angle before adjusting your saw for the next.

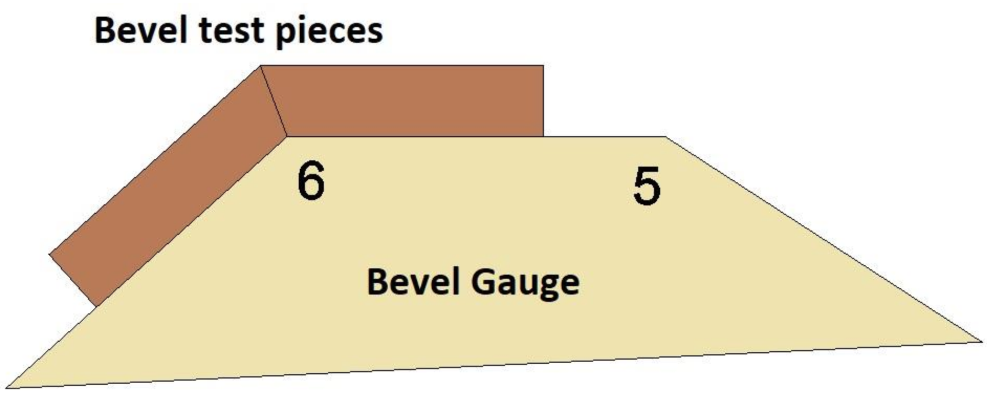

Photo 8. The bevel angle gauge both of the bevel angles used in this polyhedron labelled with 5 and 6 for pentagons and hexagons. The bevel angle for the pentagons is 16.4722°, and 20.9052° for the hexagons.

After making the gauge, do the following to make test cuts:

1. Cut two small pieces of wood around 1.5 to 2 inches long. The wood should be the same thickness as you plan to use for the polyhedron.
2. Set the bevel angle on your table saw as close as you can to the bevel angle for the hexagon using the gauge on your saw, tilt-box, protractor, or whatever device you normally use.
3. Clamp the first piece to the sled as if you were making a polygon. Move the sled along the fence to the blade and adjust the position of the wood so the blade will make a beveled cut intersecting the top surface. Make the cut.
4. Move the sled back towards you and without unclamping the test piece, align the glass reticle with the cut and clamp the reticle holder to the table. This sets up the rough alignment.
5. Move the sled forward and move the microscope so the test piece is now visible on the screen of the microscope camera. Tap the baseplate of the microscope with a small wrench or other object to put the microscope reticle directly on top of the saw cut and clamp the microscope to the saw table using a T-bolt in the miter groove and the hold-down board and spacer. The

spacer should prevent the hold-down board from contacting the edge of the microscope base, and put the pressure over the center of the base. Adjust the microscope to a height where the toggle clamp can pass underneath without touching using the rack and pinion knob and the column. Focus the microscope with the fine adjustment knob on the front of the scope. Adjust the magnification to the highest level that gives a clear image of the top surface using the adjustment on the side of the scope. Re-check that the reticle is still centered on the edge of the cut after focusing, the focus mechanism inside could possibly change the position.

6. Cut the other test piece. Use the glass reticle to adjust the position of the test piece on the sled so the cut removes just enough of the end to make a beveled cut across the entire thickness. Make the cut and verify the microscope reticle is again centered on the edge of the cut afterwards. Note that if the test pieces are not the same thickness, then the line will be shifted on the microscope screen. And if the wood is not planed to a consistent thickness, then the top of the cut edge will not be parallel to the fence even though the bevel surface is.
7. Place the test pieces on the angled edge of the gauge for the hexagon (6) and put the beveled surfaces together while the pieces are also flat on the gauge. Do the beveled edges touch from the inside to the outside, or is there a gap? If there is a gap is it on the inside or outside of the joint?
8. If there is a gap on the outside of the joint, then increase the bevel angle setting of the saw. If the gap is on the inside it means that the bevel angle setting should be reduced.
9. Make necessary adjustments and re-cut until the gap is eliminated. The same test pieces can be re-used by making a pencil mark on the bevel and shaving it all off with the next test cut. Note that thicker wood is more sensitive to errors in the bevel angle. Once the gap is eliminated you are ready to begin cutting hexagons.

Cutting Polygons

After some experimenting with different methods of making a polygon guide for each piece of wood, I concluded that the best method is to print the patterns on permanent labels, then stick them onto the wood. Precision is the name of the game here, and with the adhesive already on the paper there is no chance of the adhesive causing the paper to shrink or warp like what happened when I tried to save a few dollars by gluing the patterns on with white glue – it shrank enough to cause the parts to not fit right. I also tried making an aluminum template to use with a marking knife – that worked okay but the models I made still didn’t fit together as nice as the ones I made with permanent labels. So I’ll continue with what I know works best for me, but being able to make the lines as accurately with a marking knife and template would be nice - especially if I need many of the same shape polygon. I arranged the polygons in my drafting program so they could be cut as strips a little narrower than the strips of wood I would be sticking them to. Don’t pull tight on the paper strip as you are laying it down or it could stretch – pull just enough to keep it from wrinkling. Press the patterns down with your fingers, but don’t rub them hard.

Separate the pieces with a band saw or scroll saw and remove any burrs or splinters on the bottom side that can prevent the wood from lying flat on the sled.

There is an order that the bevel cuts should be made. Turn the piece clockwise for the next cut so any chipping that occurs as the blade exits the cut is on the waste instead of the polygon. The last cut on each piece should be along the grain of the wood to minimize the chance of chipping.

Make a "shoe" with a heel that is a little taller than the thickness of the wood for the toggle clamp to press down on. The rubber tip of the clamp would mash and possibly cause the label to slide or tear. The toggle clamp should press against the middle of the shoe, and the force is transferred through the toe end of the shoe to hold the wood against the sandpaper lined area of the metal plate. Make sure the toe of the shoe is centered over the middle of the polygon and does not extend over the edge of the metal base. Adjust the toggle clamp to apply enough pressure so the wood doesn't move. The cutting forces shouldn't be enough to cause the wood to move if using a sharp blade. Use a blade that is recommended for compound miters.

Align the first edge with the glass reticle and clamp it down. Move the sled under the microscope and watch the pattern line as the sled moves forward. Does it move left or right as the sled moves forward? If it moves left, then loosen the adjustment screw on the trailing end of the sled and tighten the front screw enough to put the video reticle on the center of the pattern line. Move the sled back and forth again and adjust accordingly. It will take a little practice to become fast. The adjustment screws rotate the entire sled the same angle as the error from the positioning under the glass reticle. After each cut is made, adjust the screws to re-center the adjustment. I like to keep the gap between the fence and the base of the sled around ¼" to 3/8". Also watch the other edge to make sure the metal plate doesn't get too close or far away from the blade. When the line is perfectly adjusted under the center of the video reticle, the blade will split the pattern line down the middle from one end to the other – a line that is only a few thousandths of an inch wide! Make the cut and verify that the video reticle is still centered on the edge. Be aware and consistent with how much pressure you press the sled against the fence, it can flex a little bit and you can see it under magnification. I like to back up the other side of my fence with a strong magnet to help resist flexing. I like to use large plastic peanut jars to put the parts in after being cut, and I use a different container for each of the different shapes. It is a lot of parts to cut, but this helps keep it organized (even in my shop)

That's all there is to it. Work your way through cutting all the bevels and check them now and then with the bevel gauge. After all the pieces are cut you can put them together with tape. I have tried a few brands of tape and prefer to use Scotch Super Hold, it holds better than others I have tried.

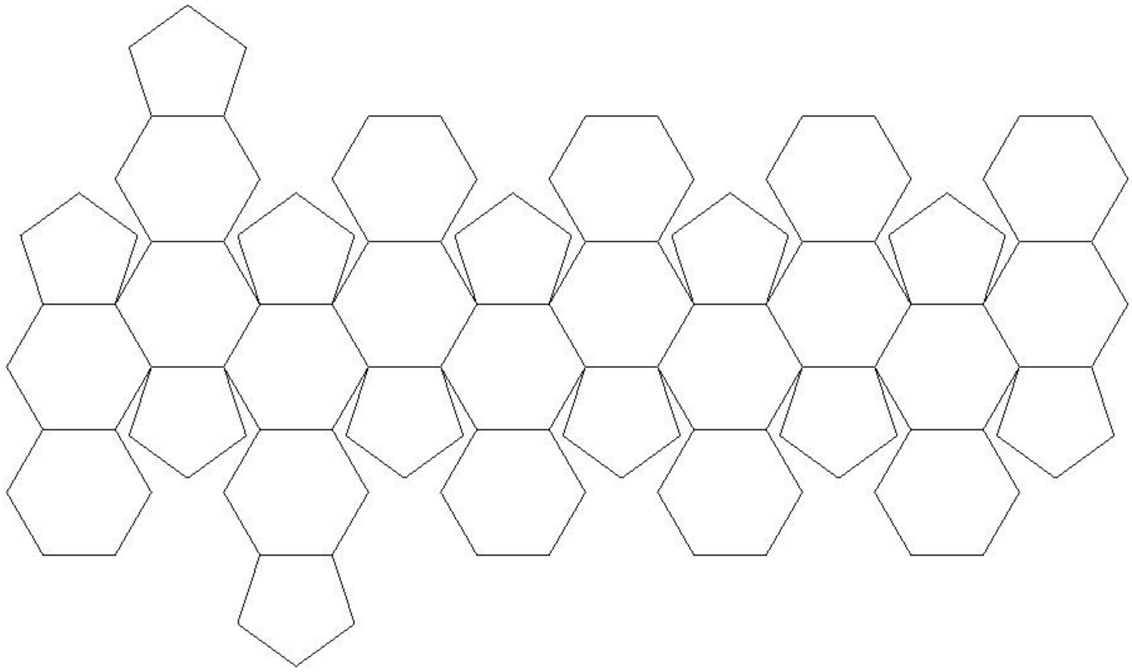

Photo 9. Assemble the pieces with tape into the net as shown here. It is important to dry-fit the polyhedron not only to make sure all the faces fit right, but also the more obvious check to see if you assembled the net correctly.

Gluing it together

Now for the fun part! For smaller polyhedrons I prefer to glue them all at once by applying glue to all the bevels and folding it into a ball. An extra pair of hands will help a lot! At that point you should have a few pieces of tape ready to keep it from un-folding when you reach for the stretch wrap. Be sure to free the end from the roll so you can get it wrapped quickly without fumbling around with it. Wrap the ball in several layers covering all areas equally. After the stretch wrap is on then it's time for the big rubber bands. I use one that I think was meant for securing large trash can liners. Use glue that has a long open time such as Tight Bond 3 in the green label bottle. Make sure the glue is fresh; it only has a shelf life of a year or so. More than once I have picked up a bottle of glue in a big box store and it was already expired and the glue had a layer on top where it was separating. Do a search online, and learn how to read the date code.

If you don't want the excitement of gluing the ball all at once you can use this other method. Dry fit the ball together and wrap it in a few layers of stretch wrap. Place tape on top of the stretch wrap to make an area around a few of the pieces. Cut through the stretch wrap over the parts inside the area, and remove a few of the polygons by cutting the taped joints with a sharp knife tip. Apply glue and put the pieces back in, the tape will stop the stretch wrap from coming undone around the rest of the ball. Mark the joints that are glued with a pencil or some way to tell the difference between glued and unglued joints. Wrap the ball back up covering the glued parts and let the glue take hold. Plan your next cut through the wrap to glue more joints together in a way so that all of the joints get glued. This method uses the adjoining polygons to push the glued parts in correct position while the glue is still slippery.

I don't recommend gluing the polygons together a few at a time when the ball is not assembled. This can get polygons a little out of alignment which only gets worse as more are added. The parts need adjacent parts all around to position them in perfect alignment – at least that's what works best for me.

My Other Polyhedrons

Be sure to check out my other polyhedrons that I have designed http://www.spiralsbysteve.com/. Some will be spheres suitable for turning on a lathe, and I also plan on making some others that are not round that might make interesting jewelry boxes and such. If you have a favorite polyhedron that you'd like me to offer the dimensions for so you can build it, then email the information about it to me, and I'll let you know if it's something I can do or not. Here's my email address: Stevegarrison769@gmail.com

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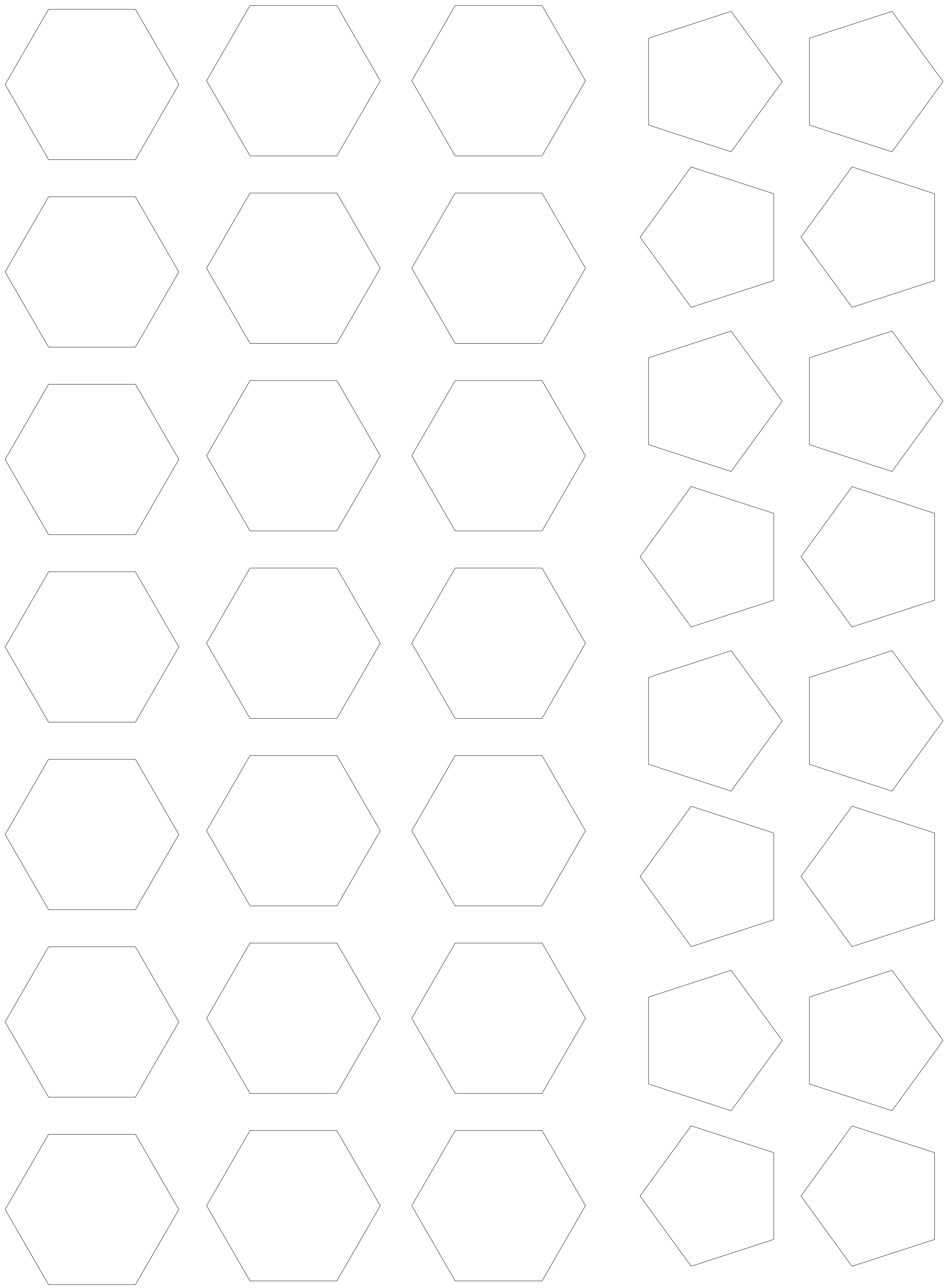
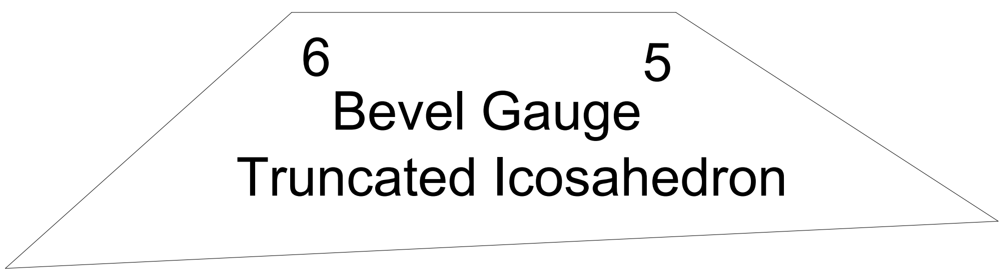
Patterns

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5
Bevel Gauge
Truncated Icosahedron