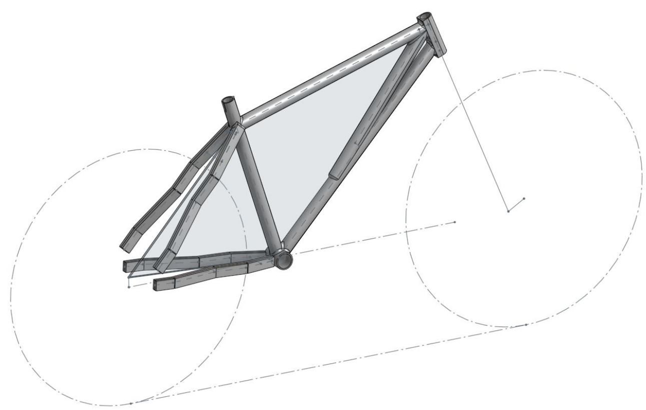
Building an Aluminum Mountain Bike Frame

By Kurt Foster, 2016



I decided to make a bike because I felt it encapsulated a large sum of my core interests. I like to design and engineer things from the ground up and mountain bike riding is a fun activity to do. To tell you the truth, I didn't have any idea of how successful this project was going to be, I just decided one day to work on it and not stop until it was done. Overall I was very pleased with the outcome. The following text was copied from my handwritten journal. I kept the flow throughout this "Typed Project Journal" version concurrent with how it was in the handwritten journal. This way you can see fluctuations in the project scope and what major changes occured.

April 16 (2 hours)
Today I got situated with my mentor and went over some basic trigonometric topics. Then later we discussed some goals and removed a major component from the design; rear suspension. Goals for the project: works, light, same material throughout, mountain bike preferred.

April 17 (3 hours)
As I start with the designing of the bike, I have quickly noticed how inconvenient it is to try and find calculators online about designing bikes and getting proper dimensions. This also creates the problem of whether or not I feel comfortable while riding it. Because of this, I will measure out an existing design, so I chose my father's mountain bike and went from there.

April 18 (2 hours)
Today I continued on computer aided design for the major frame components. I am noticing an increase in the amount of challenges that come with the design and including specific designs that I want. To counter this, I must learn to adapt quickly to new workflows and levels of design in the CAD process. A key finding in improving strength within the frame is to research some examples that experimented with off-road biking. The paper I found was, "Quantification of Structural Loading During Off-Road Cycling". This was basically a summary of data that was collected from testing the fundamental structural components that make up a mountain bike including the use of instruments for qualification and results.
Conclusions from that paper:

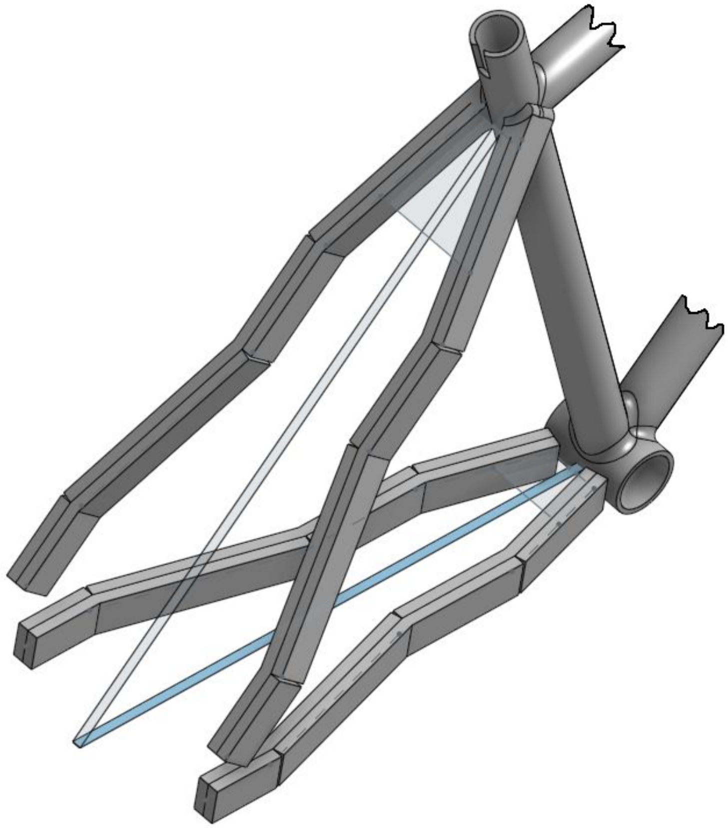
- High amplitude loading is around three (at the front wheel) to five (at rear wheel) times the weight of riding subjects
- Load ranges above 500 Newtons occured thirteen times in x-direction and only one time in the z-direction at the handlebars.
- Dynamic loads are inertial and would scale directly according to the rider's mass
- Points with greatest interest from a fatigue failure standpoint was the steering components (handlebars, stem, and fork), because structural failure of any of these would cause potential for a serious accident
- Full suspension (rear and front) would result in reducing dynamic loads.

April 20 (2 hours)
Today I focused on just CAD prototyping. A major issue I should look out for is that within the standards of tube sizing for the bottom bracket cylinder (the cylinder that supports the pedals), I must makes sure that the inside diameter matches that of conventional sizing of pipes and fittings. The majority of today was refining the CAD model for the bike. So far I only have the top tube, down tube, and seat tube size and "assembled" together. There are no seat stays and chainstay members designed as of yet because I am still brainstorming different types of tubing

(i.e. rectangular or square tubing). For main dimensions, I do have the wheelbase, seat tube length, head tube and bottom bracket cylinder in the CAD model.

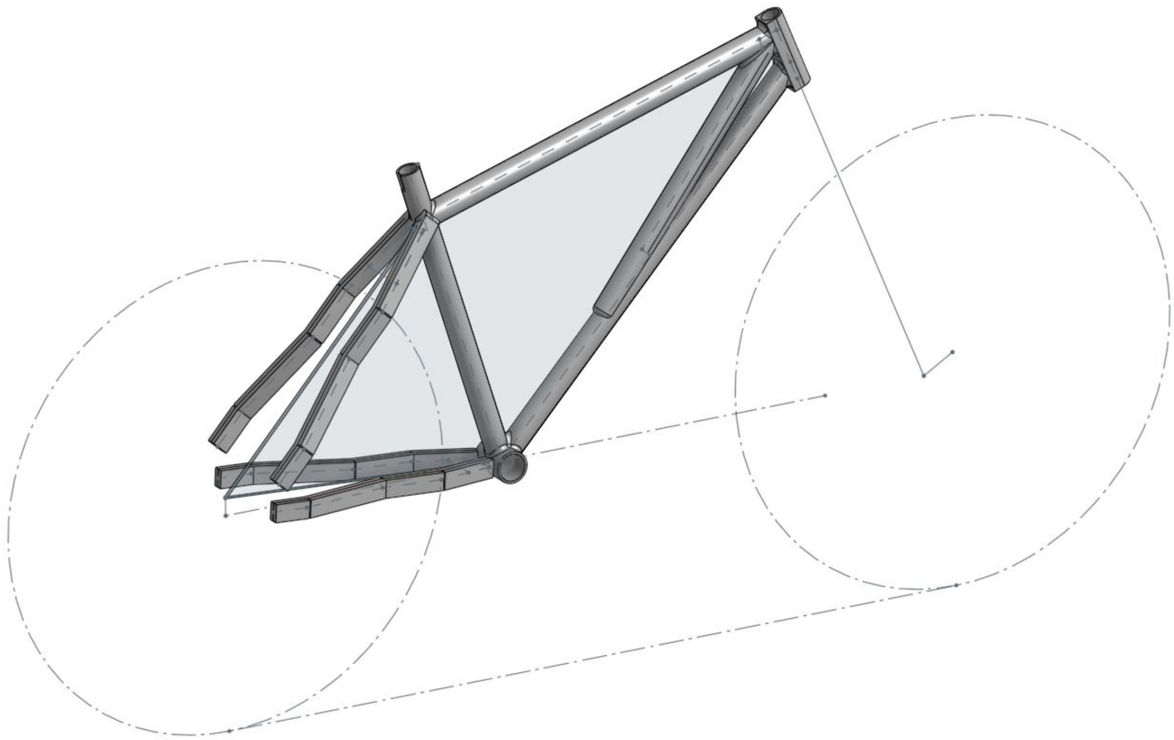
May 11 (1 hour)
Here is the (somewhat) designed frame I have planned out for the project. The only factors that have really been set in stone are the angles between pipes or bars and the points of intersection that they take up. The rear wheel section is obviously still in rough draft form. Factors that I have not solidified are material (should it be aluminum or steel), pipe dimensions (O.D., I.D., and wall thickness), and of course the rear components. Once I have fully designed the majority of the frame, I will have my mentor teach me how to isolate certain parts of the structure and test its stiffness. As well as calculating overall structure strength by incorporating the entire structure. In the end of the "strength estimation" process, I hope to find defects of the original design and update them accordingly.

May 13 (2 hours)
I learned an important tool for the software I am using for CAD (called OnShape). Below is the 3D design that I started with, and as you can see, it is quite "blocky" and inconsistent. The picture following this one is the total design I have as of writing this.



I was having trouble making the rear components more “legit-looking” and professional, so I found a quick “Getting started with OnShape” video. After viewing it, I noticed another feature which had to do with the extrude function. This will be elaborated further in the next post.

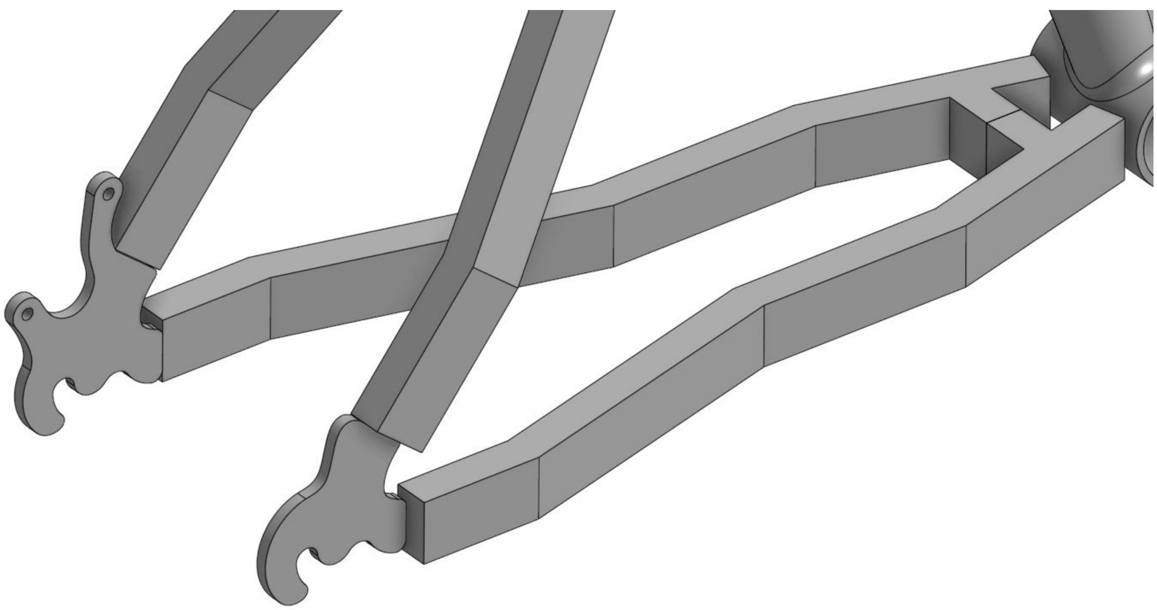
Here is the bike in all of its dimensions before the rear section was updated.



The two large circles represent the outside diameter of the wheels (dimensioned to 26 inches in diameter). As you can see, there is a major addition to the main triangle components. The center mounted bar towards the front of the frame is a placeholder for what a front-structural joint could look like. The overarching reason as to why I am updating the rear section is in order to get the exact dimensions of a series of square tubing attached together that “crunch” towards the rear wheel and still maintain structural integrity. Another reason why the rear section is zig-zaggy, is also to make way for proper rotation of the pedals for the user.

May 15 (8 hours)
The majority of the eight hours spent include cleaning up my overall design for the rear section. Making sure there is proper spacing fit for the wheels and brake-caliper system, as well as figuring out what should be done next. On top of this, I designed two metal plates that will be welded on the very rear of the frame. These two pieces will act as the slot holder for the rear wheel axle. The pieces will act as an attachment component to “pull together” the large (chain stay and seat stay) pieces of the rear. One of the two pieces has two extra holes drilled through them, this is to mount the brake caliper system for a rear disc brake system. As of this moment, the plan is to build the frame out of steel. Steel has high rigidity, strength, availability, and

simplicity to weld. If I choose steel, the material thickness will be smaller due to steel's inherent abilities. For a general side note, I seriously cannot believe the amount of time I put into the CAD of this bike this weekend. All for two pieces and "updated" measurements that more accurately depict a theoretical real world object. This just goes to show how long it takes to design and build something. The image below doesn't really look like much, but you're actually looking at over eight hours of drawing and design, making sure the axles are lined up, making sure they are close enough without too much play. Right now it's down to about 1/16" to 1/8" room of play total for the axles of the rear wheel. I am currently using my father's bicycle as a frame of reference to see what major components I could be missing, so that has been of considerable help.



Next, I will redesign the parts of the bike that have the greatest likelihood of failure, for example the current downtube design.

May 18 (1 hour)

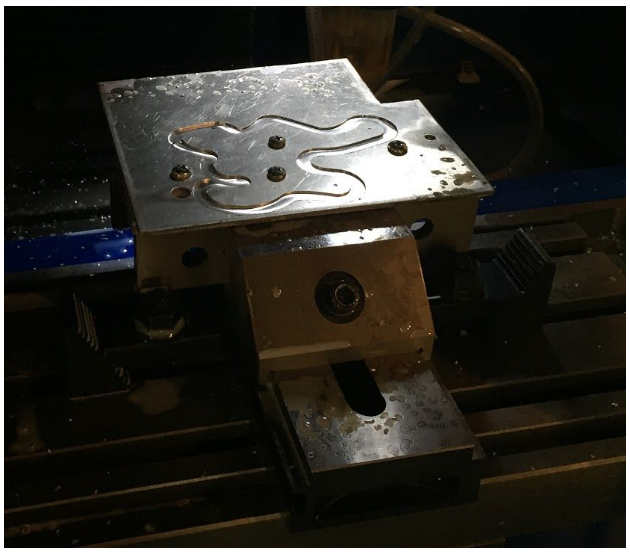
Before I redesign some of the front parts of the bike, I must get the two rear wheel attachments as shown above manufactured on a CNC machine or comparable system to get the exact shape and dimensions I want. Oddly enough, my high school has two ProMill 8000 CNC 3-axis milling machines. These machines are perfectly capable of doing my jobs. However, even though the two machines have sat in our school for about two years, no one has cut material out of the machines that is more tough than machinable wax. It is because of this one occurrence that caused me to change the whole material of the bicycle to aluminum. I am not kidding, the reason of this was because I wanted to weld the two components to the frame, not bolt them or rivet them. On top of this, the shop teacher aid that ran the machines didn't want to jump to cutting steel on the machine without cutting aluminum, and we only had about one and a half weeks left of school at this point. So the short term goal is to have these two pieces cut out before the end of the month or earlier. As for long term, I should think about if any custom jigs would need to be made so that the rear pieces are exact lengths. I should also make a jig for cutting holes on the ends of the pipes in order to assemble the main tubes together, which require specific angles to cut the pipes to. Another key factor in making a solid bike is the welds must be good enough to have large forces act on them. I will need to update out in-house (in our garage) welding situation to prepare for practice pieces. This could include making a breathable box to weld in and have the qualifying steps in order to achieve a good enough weld. I have never welded aluminum before, or done TIG for that matter, so this will be interesting.

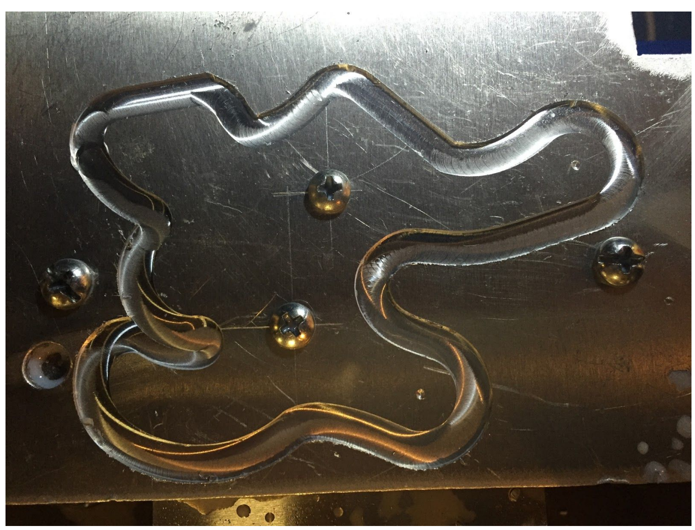
June 6 (4 hours)

The time since my last post has been spent on getting the two mounting plates milled out in order to free that up. This is because I cannot cut those two pieces by hand without being extremely careful. That is the reason I am using our CNC technology at school to do so. This post will talk about the things I have done so far on that particular job. On the May 15th post I showed a picture of the two components that I am cutting. I will cut them out of 0.25" 6061 aluminum. To do this, I have gotten help from one of the teachers that is a small jobs machinist who knew his way around the software and tooling for the CNC machine. We attached 0.25" flat stock on another piece of aluminum (which will act as the mounting plate which are clamped down to the vice). I drilled and tapped these two and we will do a dry run on the mill. The dry run will be done on 0.125" material and will go about half way down so we can see if its dimensioned correctly for the real deal. I am surprised for how long this has taken me just to finally cut the pieces out. The plan is to cut them both out before school ends. I cleaned out the ProMill CNC machine that we will use to cut my pieces. Also, I got experience with a $14,000 vertical milling machine with digital readout. If for some odd reason this small job doesn't work out in the end, I have a plan B, and that is just to contact some CNC shops around town and see which one has the lowest quote and just have them cut it.

June 9 (8 hours)

These past four days have only been spent milling out the two rear wheel attachment frame pieces. One thing that amazed me with this entire ordeal, was the fact that me and my teacher spent nearly 10 hours or more programming, laying out, drilling mounting holes and tapping holes all to endure about 10 minutes of terror as the computer controlled 800 rpm ¼" end mill came within a 1/16" from the head of a mounting screw going about 0.75"/second feed rate. The reason I am so hyped about this is because those two rear pieces needed around four hours of design work so I make sure it was correctly dimensioned. Then on top of that I spent four hours each day for about four days of trial pieces and mounting methods. So it actually took about twenty hours to complete just these two parts. Creating mechanically functional parts is a long and tedious process. Out of this experience, I would say the most rewarding part is being the first student with a project that required a mill to cut a shape out of aluminum. The machine-shop teacher was ecstatic too as the experience helped him out a lot.





⅛” thickness test run fresh from the mill

June 17 (3 hours)

I started my first aluminum welds with a Syncrowave 200 Miller TIG welding machine. Things went smooth and nothing broke. Below is the station I set up and the quality of the beads I welded. There's certain techniques for welding TIG, of which I will try and improve upon in the following weeks to get ready to weld some bike parts correctly. Here are my first welds, I did try vertical welding which didn't go to bad.

July 3 (2 hours)
Met with my mentor and talked about how we could go about designing or seeing weaknesses in the frame system. We searched for free FEA (Finite Element Analysis) software but we decided that this was too complex and the learning curve was higher than what I was ready for. FEA requires a lot of learning to make the software do what you want it to do, which is time intensive. So in the end, we decided it would be best to take a more "do it yourself" project mentality with a low amount of resources and skill to getting the job done correctly and most importantly, getting the job done on schedule. This means higher chance for over-engineering, and lower chance of obtaining the best weight to strength ratio. Incorporating aluminum into the base material did well in this regard. From the standpoint of a DIY-project, our greatest concern is failure with the structure of the frame under normal wear-n-tear situations. In most of the failures I see with other bike frames is the failure point were the top tube connects to the downtube and head tube.

July 6 (1 hour)
Obtained 1 ¼" and 1 ½" bi-metal hole saw for cutting the aluminum pipe. I will use this device for prototyping the pipe welds together. Until then, I will try to find weak spots in the design or previous designs that other people have made and work from there.

July 10 (2 hours)
Welded a test cylinder on another cylinder to make a "T" joint. The welds are absolutely terrible and do not possess any real beard or overlap shape. I think what happened is the electrode was not focused on the exact point of the two metals touching to form the 90° corner. The TIG welding process is tough to go from making regular lines to cylindrical paths that must be uniform.

The original plan was to weld everything, but I don't see that happening from now on. I don't feel bad about hiring someone else to weld it. I am more worried about finishing it on time with strength, then finishing it late with terrible welds.

July 26 (2 hours)
There is still a major issue at hand, which I have yet to show within this journal. That is, how will I get all the components in order to actually create a fully functioning bicycle? In fact, for a bicycle to indeed be usable, the frame must fit certain measurements of current products (the bottom bracket cylinder and head tube inside diameter dimensions). However, when I go out and price each individual component and put it together, the total price of the bike easily reaches beyond $1,000 USD. This is well over my budget for the project so I must do something creative. Luckily, there is a solution. Individual components for bicycles are not competitive in pricing, so they will be generally more expensive per part then a group of components sold together. Entire bikes on the other hand are always very competitive in pricing, which means that buying a full bike could set you back $200 to $400, less than half the cost of pricing high quality components together. I ended up purchasing a bicycle for $150. All I need to do now is take everything off, cut the major frame sections out and replace it my frame, easy as that. For $150, I have two wheels, front disc brake, front suspension, handlebars, gear derailleurs, entire crankshaft assembly, friction wheel brake assembly, crankset, pedals, 18-speed toothed parts and head tube assembly.

July 29 (1 hour)
An overall design element may have to be eliminated. This is the "rectangular" designed chain stays and seat stays for the rear of the bike. The reason I am removing this is because I literally cannot find this small of rectangular tubing within a two-hundred mile radius of my house. The important aspect to learn from this is to not only design to reliability and manufacturability, but to design with actual sourceable material. I assumed this size of tubing would be available, yet I did not take the extra moment to research in this area. As of now, the plan is to use a larger size of rectangular tubing.

August 1 (2 hours)
If I do choose to make the rear members out of rectangular tubing, I must make an ease of manufacturability jig in order to weld the parts together the exact same. This would be useful in reducing the risk of error when cutting the tubes to certain lengths. It would also be useful in gauging the change in length after heating up the parts due to the welding process. All I got was the rough design of the jig frame, which is ending up to be a lengthy process. I will most likely make the jig out of wood, since it is the easiest to source material. The plan would be to make the outside length and shape, then cut the wood to that shape, much like a mold.

August 4 (4 hours)

This post goes off the July 26th post about getting the bicycle components. I took apart the bike and removed components that I required. The four hours listed was the absolute minimum amount of time that I put into completely dismantling the bike down to its major and minor components. The pictures below refer to to how far those four hours got me. I never took apart a bicycle to this level before, so it was a small learning curve. I still require tools to disassemble it even more. This includes; a lock ring spanner and crank puller for dismantling the crankshaft. The goal of taking an existing frame down to its bare metal will be very helpful in giving me parts to which would otherwise be unobtainable. For example, the bottom bracket cylinder is a custom piece for certain types of cranks. Long story short, I would rather buy a complete set that fits everything together, instead of buying everything separate.

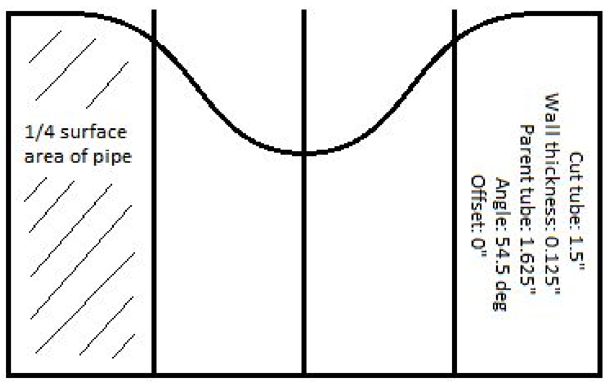
This is the bike untouched from the store, except for the fifty or so feet of road it had to endure, this bike isn't going to last long.

Yeah, that happened. The amount of parts that I have obtained is endless, or you could just call it priceless.

August 13 (7 hours)
Half of this time mark was bare minimum for obtaining the bottom bracket cylinder (and shape it into a cylinder) and head tube cylinder. The other half was used to remove the bottom cylinder from the parts it was attached to. In order to do that, I purchased a crank puller and crank wrench. The conclusion to purchase my own tools didn't occur to me until after I tried creating my own tool for the job. When you try to make your own tool that other engineers have already nearly perfected the design of, it usually doesn't work out. I tried to make my own style of wrench which mimicked the crank wrench. This required welding steel with a MIG welding machine. The problem was that it kept slipping off when I turned the tool. Now that I think about it, I think the material of steel wasn't strong enough to handle that torque.

August 14 (3 hours)
Spent today speaking with my mentor about how I could go about on my rear section design and manufacturing abilities. I realized my seat post from my frame would not be compatible with the seat from the bike I bought. This was because the inside diameters were not compatible. So I copied the design of that bike's seat post, and cut that same tube section out of the frame. I milled a slot with a hole in the side to accept the seat in order to tighten the seat to the frame.

August 15 (4 hours)
Cut out the three main pieces to my frame. The three pipes were all the same size with a 1.5” outside diameter with ⅛” wall thickness. To cut out the circular shapes so the pipes could fit together I used a 1.5” bi-metal hole saw. Unfortunately, there was only one link where the pipe touches another pipe whose both diameters were the 1.5”. The other connections had to be cut with custom dimensions. I shaped the final curve to the hole using a grinding file and a bench grinder with a sand wheel. My use of creativity has saved me from a couple extra dollars spent for the more hole saw tools I could have bought.



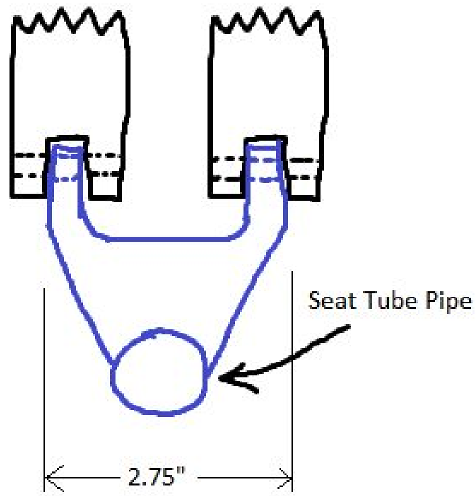
I used an online tool to get the angle attachments right, the picture above shows what the calculator determined. I taped this shaped to the end of the pipe and then cut around the line to make up for the 54.5° tube dimension.

August 16 (2 hours)
I did some design changes for the rear section. This proved to be a greater challenge then I had previously suspected because of material selection and complexity. Today was in fact a mentor meet up and we decided to tackle the rear section and come up with something that worked and was strong enough for the road. We decided to put the rear section of the bike I destroyed to hold the rear wheel. So instead of building my own rear section, I am using the old bike because of its simplicity. My current resources do not accept this level of sophistication because of the constraints that are involved, which include; pedal revolution, wheel thickness clearance, and brake attachment ability/positioning. The added benefit to taking advantage of the old bike is the added pivot point for precisely positioning the seat stay link to the seat tube.

August 18 (1 hour)
The following picture is the frame with the rear section un-adapted to the frame. There are specific details in the black section that make it far easier to just adapt to what I already have. Here are those specific details: slight indents near wheel hub on chain stay which increases strength and reduces need for extra components; exact lengths that already fit to the rear wheel dimensions; rear dropout drilled and threaded to accept rear derailleur.

In order for this adapted section to work properly with the seat tube and crankshaft tube I must incorporate some extra components. The next post should continue on this adaptation problem.

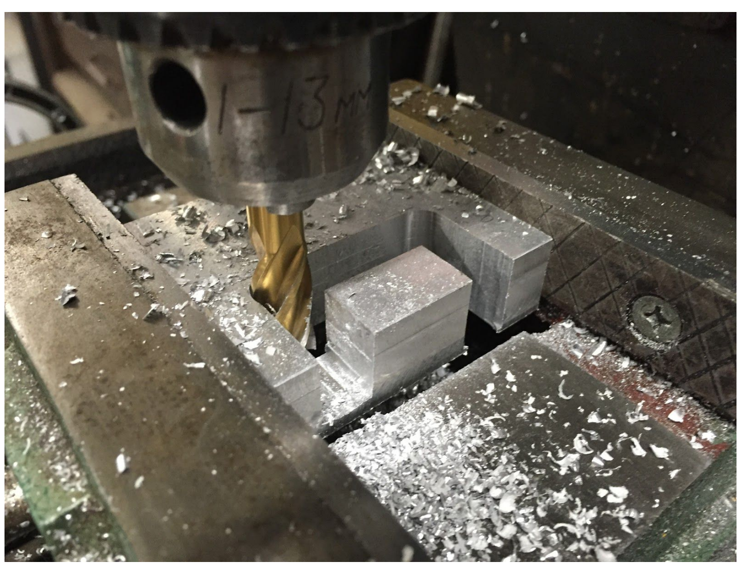
August 21 (1 hour)
Met with my mentor today to discuss a possible adapter for the head tube from the seat stay. The goal was to come up with a single piece design that attached these two components. The main idea is to get an attachment to the dual slots to sit up against the seat tube pipe at a 90° angle. The idea is to keep it simple and not complex. The part should be easily machinable based on what my skills and tools I have available. Material should be aluminum, since it is light and easier to machine than other metals. I also need to weld this part to the seat tube, so the material must be aluminum. The following page shows a sketch of that design.



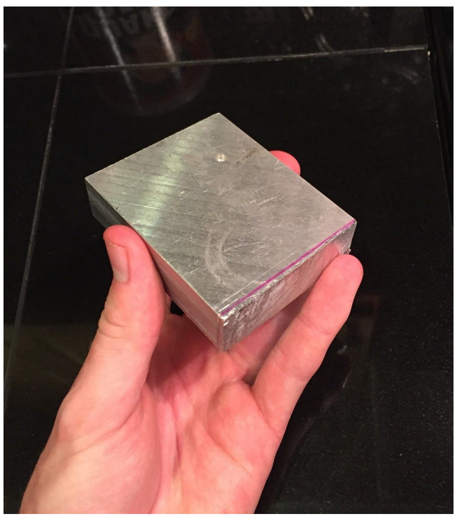
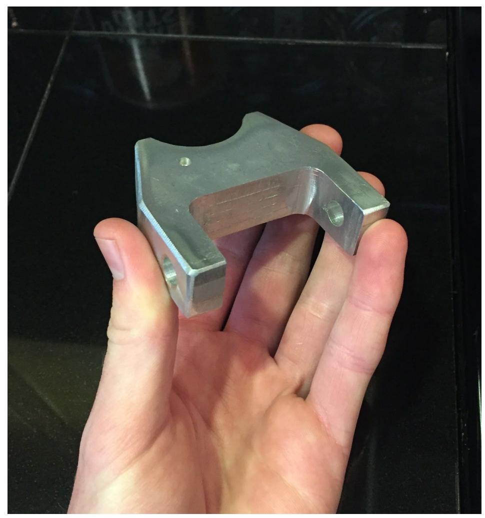
The only problem so far with this design is the width of connection from the pipe to the u-shaped section. There will be a weld going from ⅛” wall pipe to ½” thickness metal. If it works, it will probably work for me.

August 22 (3 hours)

Now for the fun part, let’s machine some stuff! In order to get the desired shape of the previous post, I will act like a CNC machine. I will detail everything that goes into cutting the part. This means I must be aware of my cutting speed, direction of cutting, how wide my cutting tool is, what kind of cutting tool, cutting speed rate (in terms of feet per minute), and making sure the outside diameter of the cutting tool is reaching the exact point of where I want to cut to. First off, I will cut the main rectangular shape out of the aluminum stock. The tool I am using will be a ⅝” flute end mill.

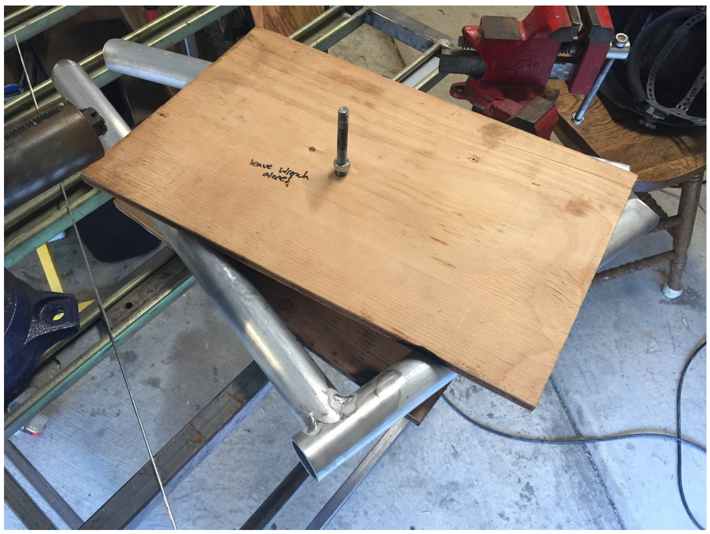


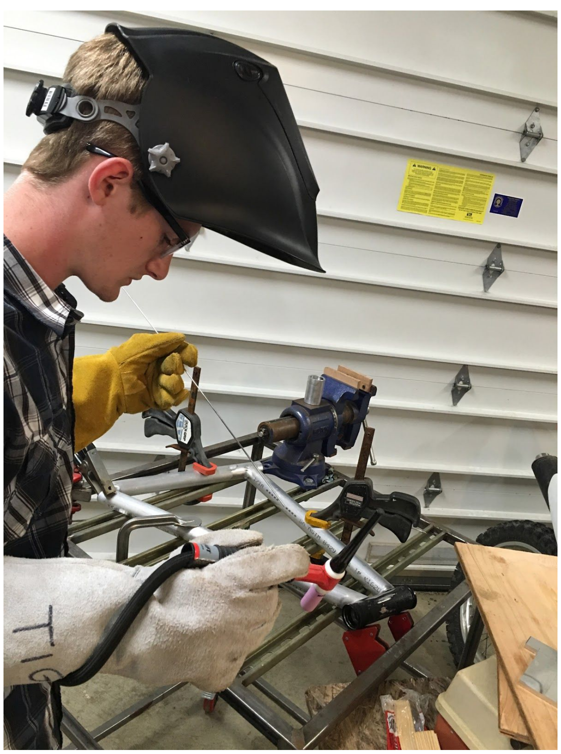
Here is the piece mounted to the vice I used for cutting. You can tell there is a gap under the workpiece. This is so once the bit goes under the aluminum, it won't hit the vice. Each pass I made I was going down about ⅛". This bit is for high speed steel so I wasn't too worried about going too fast. The following pictures show the finished "before" and "after". I cut the angles leading up the pipe cutout to reduce weight and increase appeal of design. Cutting off those corners actually increases safety, because a rider could cut his/her legs on this part when they get on the bicycle. The main half-hole was cut with the 1.5" bi-metal hole saw. Then the last step was to machine the two horizontal holes that mount with the old bicycle component.

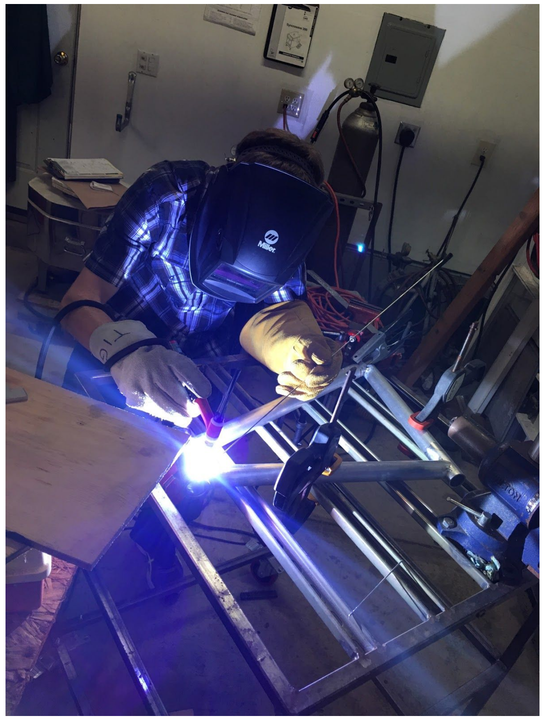



September 11 (2 hours)
Officially got to welding my main triangle frame components together. The idea is to get as much of the frame tac-welded together so I could take the frame to my welding shop at school and get some professional help from a knowledgeable teacher. I tac-welded together the head tube, seat tube, down tube, and top tube. Bicycle welding jigs can be expensive and hard to make, but not for me. All I did was place the main three long frame members in a sandwich orientation with a bolt going through the two plywood members that acted like the bread of the sandwich. This in theory created a complete planar surface where the aluminum pieces laid directly in a symmetrical plane.

First, I tac-welded to the top of the seat tube to the end of the top tube. This was the easiest connection because it was a direct 90° angle and the hole fit perfectly. I then welded the down tube to the bottom of the seat tube. I did this by welding the section that forms an angle with the two tubes. By this point it's 9:30 pm on a sunday night, whiffing up the TIG welding fumes. The most challenging part of tac-welding the bike together is making sure the head tube was positioned correctly. In fact I will come clean right now and say I just eyeballed it. But that's what it takes. No trial and error, no learning, that's the game of increasing your odds of success.







September 23 (12 hours)
Since the September 11th post, I spent about four more hours welding the rest of the welds together, and getting everything lined up. Then I spent about three hours putting bondo over the welds to make it aesthetically look more pleasing and so it looked like the frame was one big single piece of metal. Then I spent about an hour painting (one coat primer, two coats blue paint) and finishing. I chose to paint it with the same color as the wheel to make it more aesthetically pleasing. Then I spent four more hours putting on all the components back on the frame and making sure bearings were properly greased. Other than that, here are some last photos of the project. If you made it this far, I want to thank you for reading and spending the time looking through this. I also hope you found this documentation helpful!

Above: This was just moments after welding the frame together. If you look closely, you can tell I did the welds, since they aren't that great. Below: this is painting the frame with a primer.

Me on the left and my mentor, Jake Montgomery with MS in Civil Engineering on the right.

Project length:	5 ½ months
Total logged hours:	85
Average time/day:	>1 hour
Total project cost:	$225*

Logged hours broken up:

- Working with mentor:	10 hours	11%
- Designing the bike:	20 hours	24%
- Machining parts:	30 hours	35%
- Assembly/Welding:	20 hours	24%
- Other/Brainstorming	5 hours	6%

*includes $150 bicycle + material used + transportation expenses