Lightweighting 2: Lines of Force and Stress Concentrations

Companion to the video: Script and Illustrations

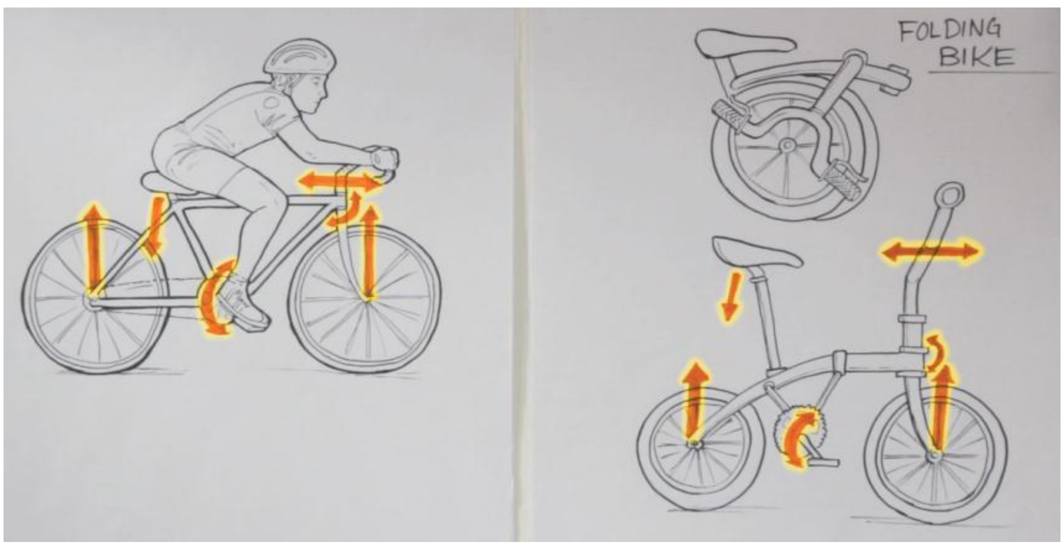
To keep your products strong, even as they get lighter, you'll need to learn how to follow lines of force and avoid stress concentrations.

Following lines of force is a nice non-mathematical way of finding where you can remove material. You can even just do it on paper before you get into your detailed design.

To start, think about how external forces will be acting on your design, draw them as lines, and then create designs that remove material in a way that matches these lines. That's all there is to it. Let me explain how.

Have you ever noticed that folding bicycles often weigh as much or more than normal bicycles, even though they're smaller?

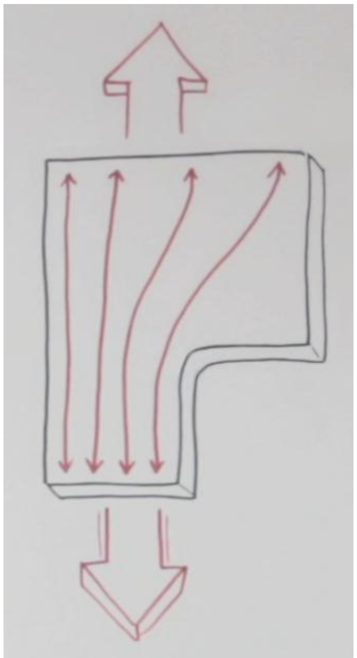
They often have wider and thicker tubes than a diamond frame bike because their frame geometries are less optimized to where the forces are being exerted. If you draw the force lines, you can see this.



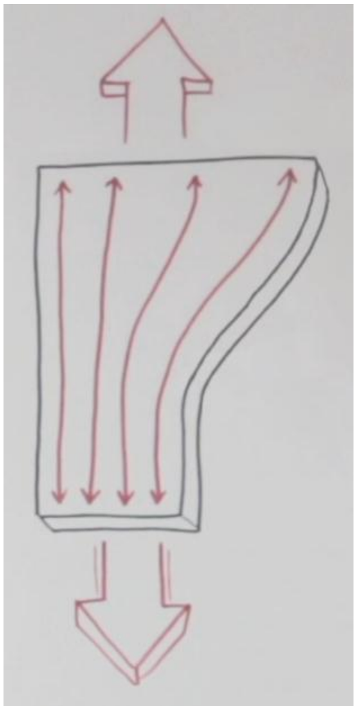
It doesn't matter what manufacturing method or material you're using. Drawing these lines of force helps you see simple ways to strengthen your product.

Now let's visualize how lines of force will travel within a specific part.

Here's a picture of a corner in a flat plate under tension, gripped at the top and bottom. Drawing the lines of force shows that the corner of the part isn't experiencing any stress.



So you could cut it off in a nice smooth curve following the force lines, saving weight without reducing strength.

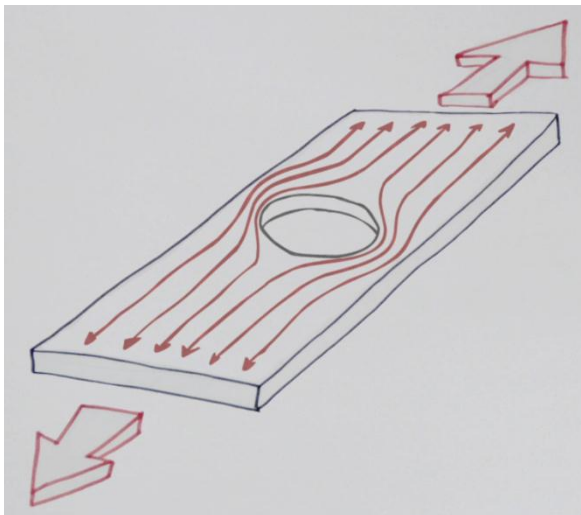


Drawing lines of force will also show you where stress concentrates. And that's good because avoiding stress concentrations is our next key strategy.

Stress concentrations are locations where forces go from being well-distributed to being focused. These are usually the first places to break, so avoiding them or reinforcing them will let you use less material in your parts.

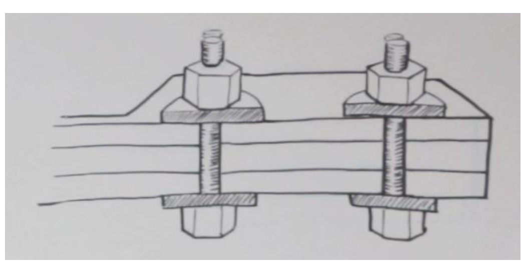
Here's a drawing of a solid beam that's being pulled on, with arrows going through it to show the force lines -- they're evenly distributed, so the force is nice and low everywhere.

Now let’s get fancy and see what happens when we cut out a hole. The area in the middle can't support any forces anymore, so they have to go around. The force lines are denser in the material around the hole, and the stresses there are higher. This will certainly be where the part breaks, so those regions need to be reinforced, while you can make the part thinner elsewhere.



Here's the same part with the same stresses, shown in Inventor’s stress analysis environment. The stress concentrations are color-coded, showing the same results as when we drew force lines, but quantified so that you can see if it's too much.

Stress concentrations around holes are why you should be careful when you connect flat parts together with bolts or rivets. Ever wondered why you use washers with bolts? Part of the reason is to help distribute stress and add reinforcing material, so the rest of the material can be thinner.



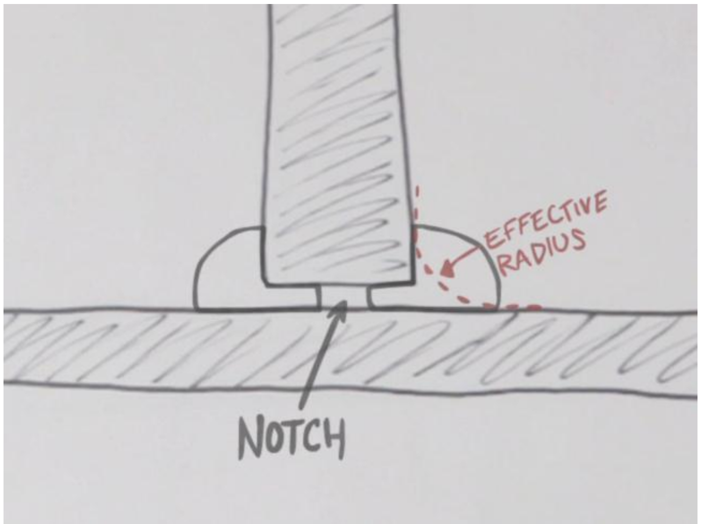
You can also distribute the load more evenly with a lot of small bolts or rivets rather than a few big ones. You can see this on airplanes and the Golden Gate Bridge.

If a hole that you've made is a flat notch, stresses become even higher. Stress concentrations are determined by both the size of the whole and the, so the sharper the curve, the more it concentrates stress.

The math for this is difficult, but using Finite Element Analysis in Autodesk Inventor or Algor can help you find the location and magnitude of these stress concentrations.

Some manufacturing methods actually cause notches in a part. Like welding plates.

A weld joint that doesn't go all the way through the material is like having a notch cut out of it.



A nice fat weld joint with deep penetration is better, because it both decreases the size of the notch, and it also increases the effective radius of the joint.

That's right, joints and corners also cause stress concentrations, not just holes.

You could deal with these stress concentrations in two ways: either by reinforcing, or by rounding the corners more.

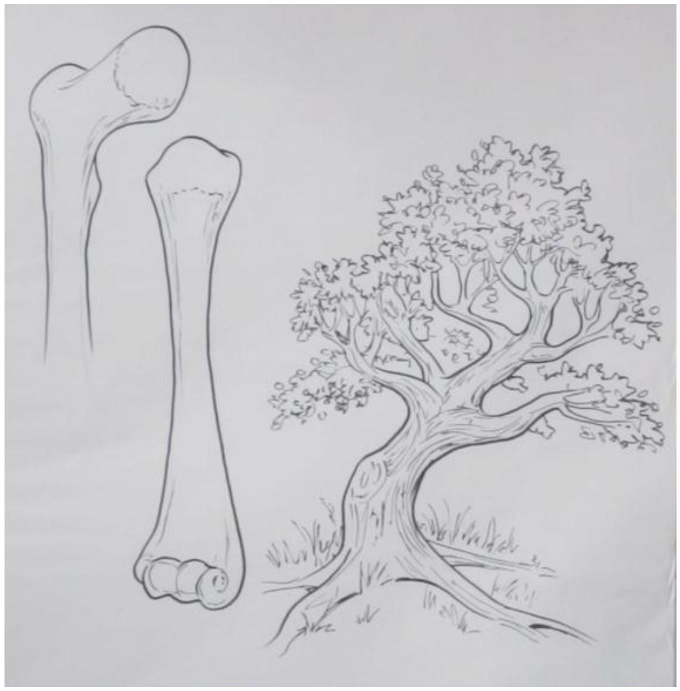
It again depends on your manufacturing method. With a steel tube frame, you can't round the corners much, so you should reinforce with lugs or thick weld beads.

Curves are easy to make with injection-molded or forged parts, or even extruded parts in 2 dimensions. They can even be done in sheet metal, through processes like hydroforming or deep-drawing.

This is actually an amazing feat of lightweighting that uses deep-drawing to turn a flat metal sheet into a highly optimized curved form.

With a carbon fiber bike, you have even more control over how the material is sculpted, so you can make the joints gentler curves. Remember, the bigger the radius the less the stress concentrates.

Nature avoids corners too. Look at bones or trees -- they usually have gradual corners and nice radiused curves.



Swoopy curves to make your products look more like nature, that’s nice aesthetics. But sweeping curves to avoid stress concentrations, so you can make your products both strong and lightweight, now that's hot!