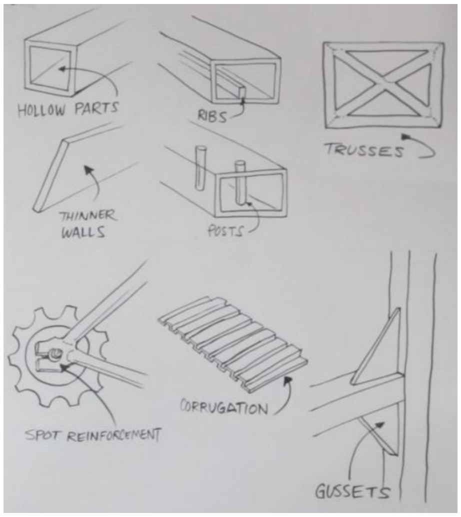
Lightweighting 1: Hollow Parts, Reinforcements, and Trusses

Companion to the video: Script and Illustrations

Why does a bicycle look like this… Rather than the way it used to look – like this?

The answer: it's been lightweighted. And you can do this too, beginning with a few simple strategies:

Hollow parts and thinner walls; spot reinforcement; reinforcing posts and ribs; gussets; trusses; and corrugation.



We're going to talk about all of these.

Let's dive in with hollow parts, a key strategy in modern bicycle design.

Imagine a rider on this 19th-century bike, basically acting like a load on a beam.

Here's how the beam is being stressed. The arrows show the amount of force at different points.

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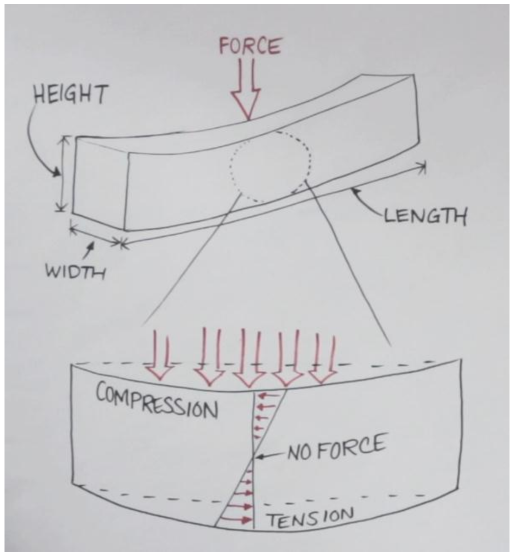
As you move toward the center, there's less and less force, until in the middle there's no force at all. So there's no need for material there.



But how much material can you remove without the beam bending too much under the load?

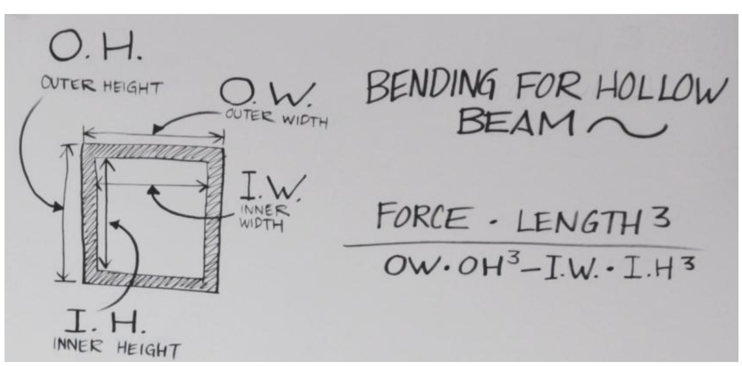
Here's a simplified form of the equation.

$$\text{BENDING} \sim \frac{\text{FORCE} \cdot \text{LENGTH}^3}{\text{WIDTH} \cdot \text{HEIGHT}^3}$$

Bending increases as the CUBE of the length between supports. It decreases linearly with the beam's width and the CUBE of the beam's height.

So the length between supports and the height of the beam make HUGE differences.

Now if you hollow out a solid beam it bends more, but you can play with the length and the height to avoid the extra bending. The math for a hollow beam is the same as a solid beam with the hollow space subtracted out.



Since the length and height variables are cubed, they make a much bigger difference than the hollowness, so you can get the same stiffness using much less material.

For example, if you make the beam 50% taller, you can make it 80% hollow, reducing materials use by 70% and still get a 20% stiffer beam! Higher performance with less material.

You can use tools like Autodesk Inventor to test the impacts of these types of design changes. They have the math built-in.

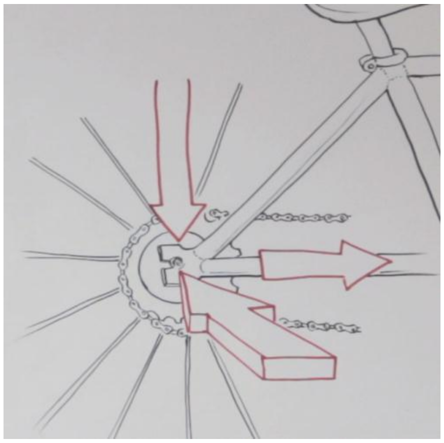
It's easy to make a thin-walled tube by extruding aluminum or plastic, or by welding cold-rolled sheet steel. But what if you're cutting wood or forging metal?

You can hollow out from the outside rather than the inside. That's what an I-beam is: an easy way to make a hollow part out of hot-rolled steel part.

This is all part of what you're seeing with modern bicycle design. A typical steel bike tube is 90% hollow – and sometimes you'll even notice that the tubes are oblong, maximizing the height factor in the direction of the load.

Bending loads are only one type of load that a structure can see. Other loads act on structures in dramatically different ways.

On a modern bike, forces are concentrated at the places where the frame meets the axle. Hollow tubes here would crumple under the high loads from a combination of shear and other forces.



That's one of the reasons why, in spots like these, the tubes are welded to solid plates that are much stronger.

If the part were injection-molded or cast, it'd be easier to design it to be thicker in some places and thinner in others. Either way, reinforcing a few spots like this with thick material lets you use much less material elsewhere.

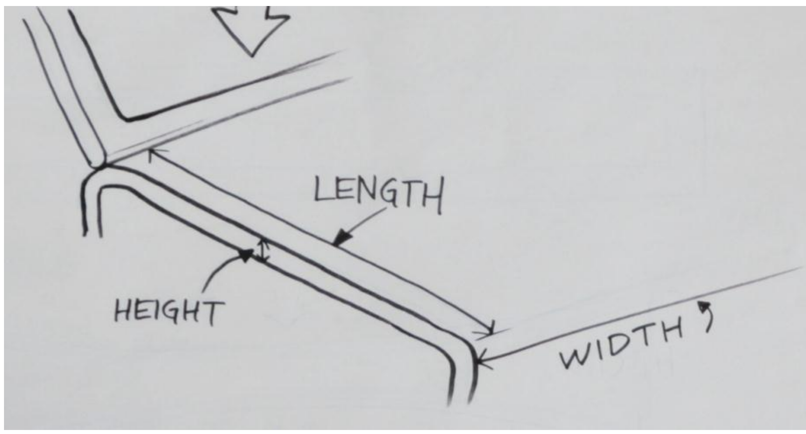
When designing a product, use your engineering intuition to find these points of stress and determine if they are tension, compression, torsion, shear, or a combination. Again, tools like Autodesk's Inventor and Algor can help.

But what if your product is already hollow, like a laptop or the body of a car?

Well, you can still lightweight it by making the walls thinner.

Of course, this will reduce its strength and stiffness. But remember that beam equation?

The top of your hollow part is like that beam we were talking about.

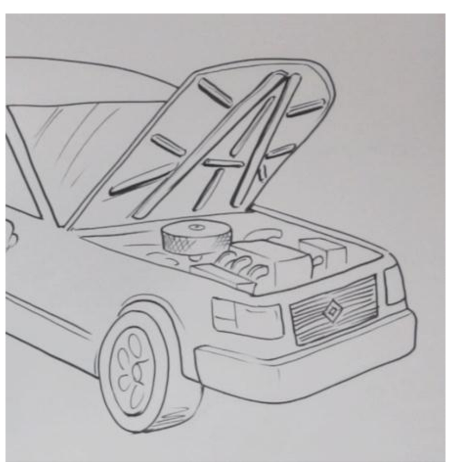


Bending increases as the cube of the reduction in the height, or thickness. But bending also decreases as cube of the unsupported span decreases.

So putting in a post for support allows you to reduce the wall thickness.

This works great for a hollow product that doesn't open and close. But with a car you can't weld a post from the hood to the engine block, 'cause how would you ever open it?

Instead, you can strategically place ribs, not connected to anything at all, to reinforce the surface. The thickness, or the height, of the rib makes the surface much stronger there.



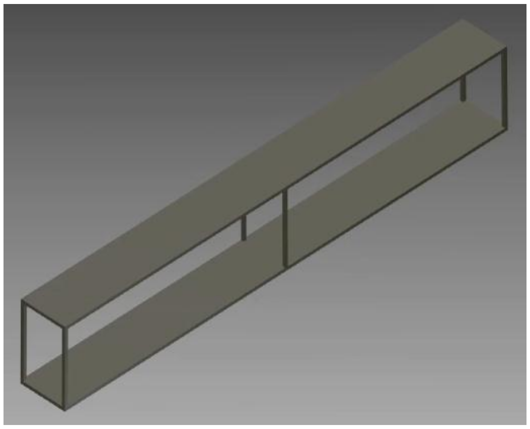
You can even lightweight the ribs, making them hollow!

Ribs are great, and pretty easy to add to injection molded or extruded parts. But if you're manufacturing from bent sheets of metal or plastic, extra wall thickness means extra parts with extra welds or fasteners.

There's another way to approximate solid ribs in a bent sheet: corrugation. By folding the material, you stiffen it just like with a rib or a post. That's what you see in lightweight soup cans and cardboard.

This is great, but we can go even further by replacing solid walls altogether with trusses, which are arrays of thinner beams.

Look again at the beam we hollowed out earlier. What happens if we hollow out the walls too? We reduce material use enormously.

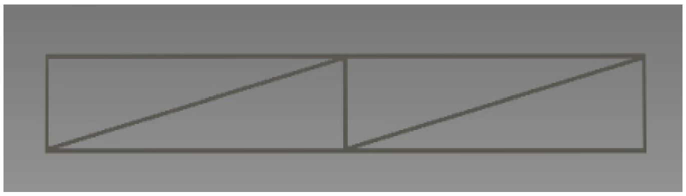


But right off, you can see we'll need to put in posts to avoid long unsupported spans.

Also, this hollowing has made the part much less able to resist shear forces--which push parallel to the face of the object.

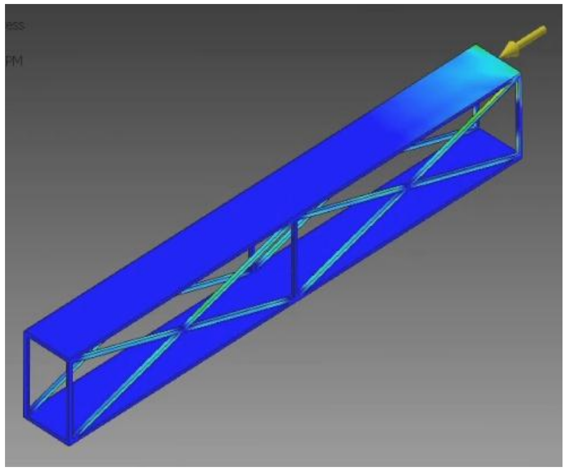
We can think of the edge that's resisting the shear force as a separate beam, with the top unsupported.

To support it, we can anchor a diagonal beam to the opposite corner. Similar to what we did with the post.



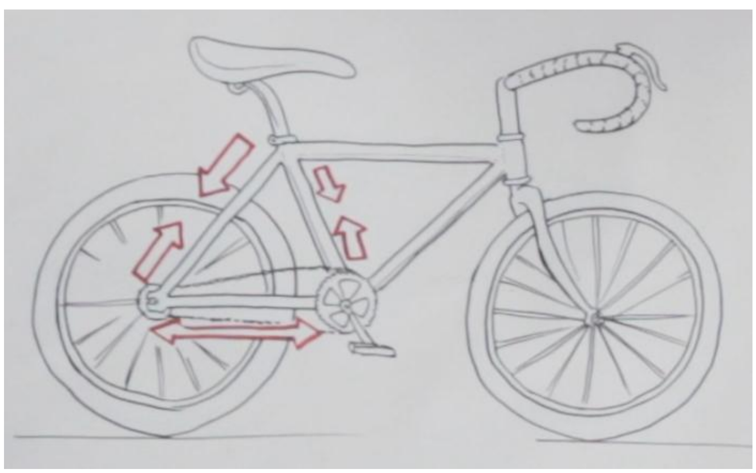
With this diagonal beam, the shear force effectively becomes a compressive force, directly fighting the strength of the material.

Adding another diagonal beam connecting the opposite corners also helps by resisting that shear force in pure tension and also by resisting shear forces from the other side.



A diamond-frame bike is a truss, where the tubes are resisting a number of forces from different directions.

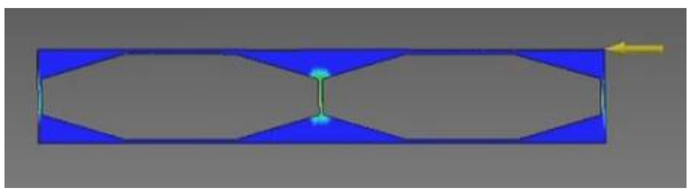
The individual components usually just experience stress from the rider's weight as compression or tension, rather than bending.



Trusses are usually made by welding or fastening smaller components together. But they can be made in other ways. Corrugated cardboard is actually a truss in two dimensions.

You'll see trusses in bridges, roofs, the Eifel Tower, any structures that need to be stiff but light.

You may not need a whole truss to lightweight. Sometimes you can just reinforce the corners well with gussets.



Gussets are ribs that reinforce corners by reducing the unsupported length of beams so they can better resist bending and shear.

Gussets won't add as much strength as full cross-members, but they'll use less material, and in hollow parts, they'll keep the insides free to hold more parts.

On this mountain bike, a gusset is welded into this joint for when impacts on the front wheel exert shear and bending on the frame.

The kinds of strategies we've just looked at: hollow parts, spot reinforcement, posts/ ribs and corrugation, trusses and gussets have allowed great leaps forward in lightweighting.

Combined with advancements in material science, these have allowed bicycle designers to reduce the weight of their products by more than half in the last century, at the same time making them much stronger.

Designing sustainably means doing this everywhere, reducing materials use and improving performance.