Scale and Why It is Hard for Small to Win

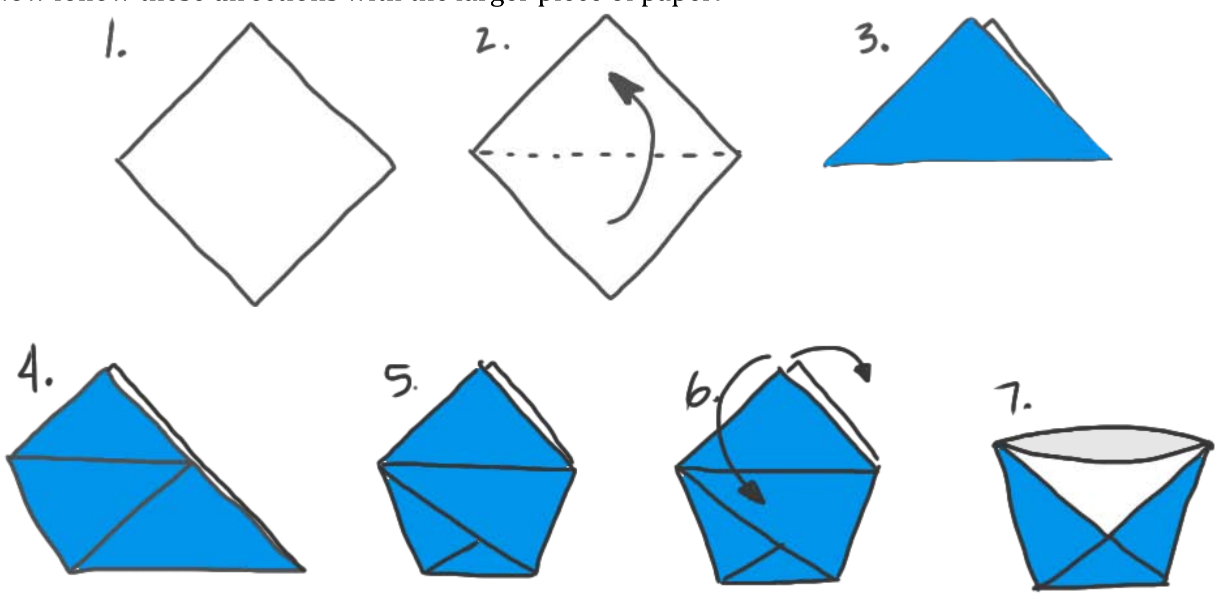
Origami teaches one of the fundamental tenets of chemical engineering.

It is now surprisingly common to hear arguments that biofuels and biomaterials plants can be made at small scale and remain competitive with larger, conventional chemical and fuels facilities. This flies in the face of experience, yet is commonly stated. A comparison is commonly made to Moore's law, misquoting it as "if you make lots of something they become very cheap". Moore's law is actually not so much about making lots, it is about making things small. Moore's law is about miniaturization.

Moore's law hasn't actually shown indications that it applies in the macro world. Car mileage hasn't followed a Moore's law improvement. Efficiency of gas turbines haven't followed Moore's law. Efficiency of distillation hasn't followed Moore's law. When we get into the world where we live, we have to move mass. We have to have food that can't be miniaturized. We have to have fuel that can't be miniaturized. For handling mass, scale is important. We are at a time when people want to rescind the strong suggestion (it really isn't a law of nature) that scale matters.

I have an exercise that will, if I am successful, drive home the point that scale matters. I will use some simple origami to make the point. Start with a sheet of normal eight and a half by eleven paper and make a square out of it. That will give you a square piece of paper that is eight and a half on each side. Take another sheet of paper and do the same thing. Now, split that piece of paper into four pieces that are four and a half on each side. Take one of those pieces and the larger eight and a half inch square.

Now follow these directions with the larger piece of paper:



By the time you get to step 7, you'll have a cup that has the volume of one cup. If you ever are in a cooking emergency and need to measure a cup of flour, you'll thank me.

Now do the same steps with the smaller piece of paper. You'll make a tiny little cup that has a volume of about one-eighth of a cup.

You've done the same amount of work making each cup. To make little cups that would hold as much as the big cup, you'll have to make seven more little cups. That's right, the little cups require twice as much material and you have to put in eight times the work to accomplish the same task. This might not seem like much, but suppose, just for the sake of argument, that you have a small fire to put out. You'd choose to make the bigger cup.

The amount of paper and labor are the capital requirement. The capital requirement divided by the volume gives you the capital efficiency. Dollars per gallon, dollars per cup, dollars per something. The origami cups show that the capital efficiency goes up as the size goes up. It turns out, to make an origami cup twice as big, you will require paper with an area that is the area of the original sheet raise to the two-thirds power.

I have just introduced you to the chemical engineering two-thirds scaling rule. Chemical plants are all about holding stuff. They are about containing and moving around volumes of material. People continue to try, but it is hard to beat going bigger whether it be high-tech or low tech.

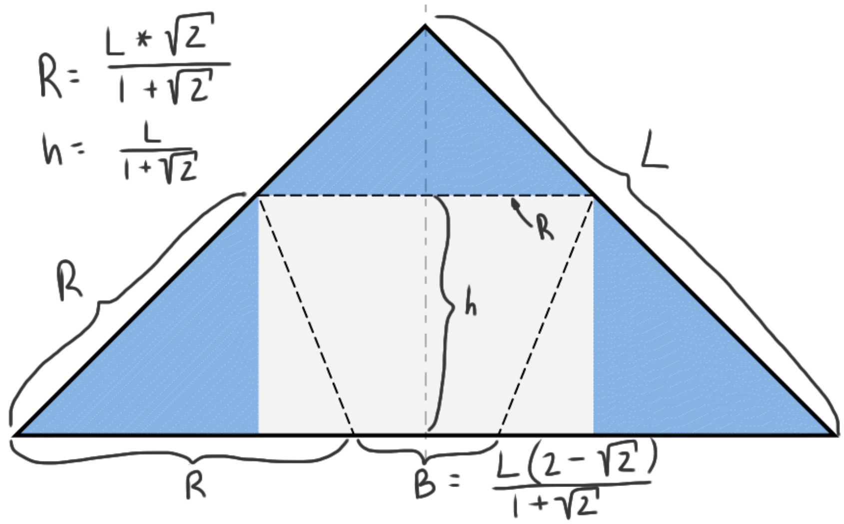
Some of you are thinking, what about improvements to manufacturing as you make more. Efficiencies do come from mass production, as Henry Ford and others clearly have demonstrated. The logic somewhat follows that if you simultaneously produce three things, the labor cost would roughly cost you what it would have cost to build two sequentially. You would gain efficiency through experience. This is actually called an experience curve and it is almost the sole hope of distributed manufacturing. This comes close to meeting the two-thirds scaling that the origami cups hopefully illustrated, if the materials become negligible. What happens, however, is that you more rapidly reach a point of diminishing return since no individual has the capacity to simultaneously fabricate but a relatively few items. To make more, you hire a second person and the economies now number up but on the basis of the increment an individual can produce. You also have the added issue that making the thing your making, whether it be a tank or a distillation column or a truck, even just infinitesimally bigger would still improve the capital efficiency.

Automobile manufacturing is one of the best examples of riding the experience curve. The following picture shows that even in the lowest tech business, scale wins over experience curve. Pictured is the CAT 797F truck, one of the world's largest. Next to it is a pick-up truck.

The CAT will haul 400 tons or 350 cubic yards. The pickup, two tons and about two and three-quarter yards. That means that it would take somewhere between 125 and 200 pickups to do the same job. Clearly the mine operators would do this if the economics worked out. Even with a price tag in the millions, the big truck is more capital efficient and more labor efficient.

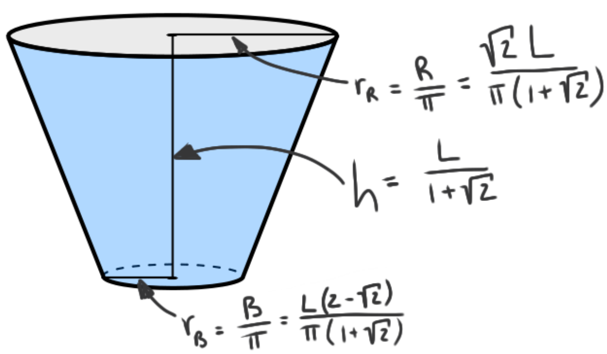
Summary is that scale wins when material is being handled.

Background math on the origami:



The origami cup approximates a truncated cone once you open the cavity fully:

$$V = \frac{\pi h \left(r_R^2 + r_B^2 + r_R r_B\right)}{3}$$



Applying the calculations allows the area of the starting paper to be correlated with the volume the cup contains. The area represents the amount of material used. This is proportional to the capital. The volume is the size. Plotting area as a function of capacity (volume), gives the following plot and fit. The fit is shows the two-thirds power dependence that is the common engineering scale factor.