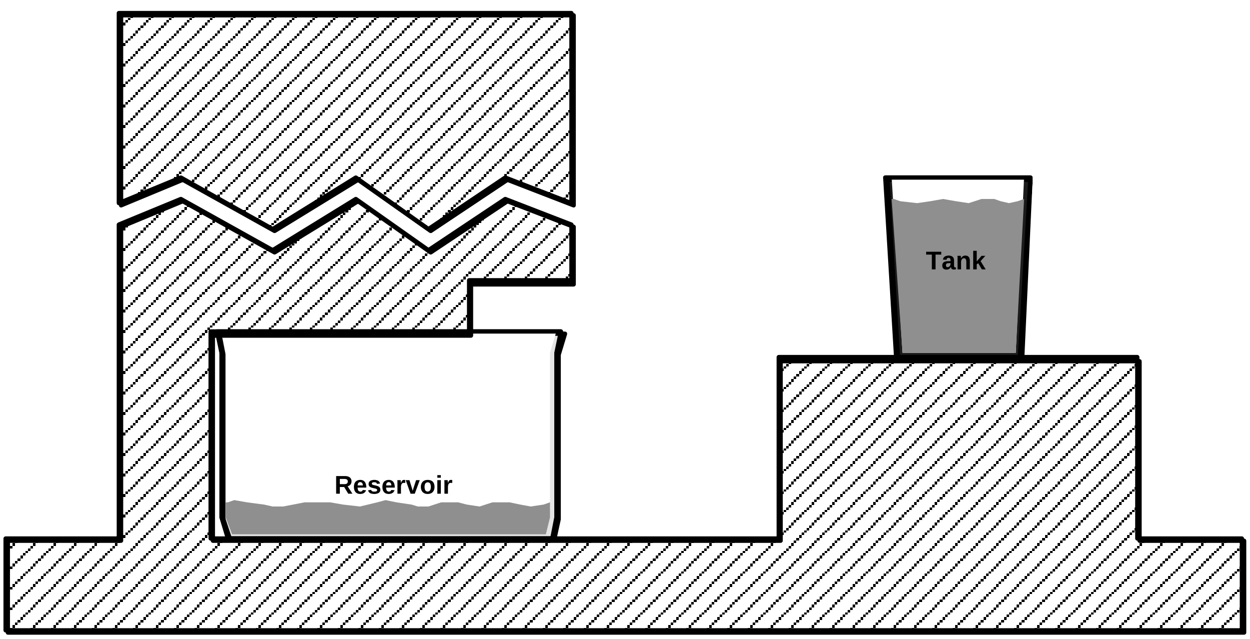
MEEM 3501
Product Realization I
HO1: A Product Development Example — Part 1

Water (200 ml) is to be transferred from an intermediate storage tank to the reservoir (can) on the left. The tank must be attached in some way to the existing structure. As shown, the reservoir has some physical constraints around it. This need can be satisfied by designing and manufacturing a product whose function is to transfer the water. There would typically be requirements on how or to what level the product must function. These requirements are actually part of the need. In other words, the need includes transferring water from the cup to the reservoir at the required speed, for the required number of times, etc. Let us consider the following customer requirements:

1. The product must withstand rain as it is located outdoor.
2. For mixing purposes, the water must enter the reservoir at a 45° angle with an output flow velocity of at least 2 m/s and a volume flow rate of at least $5 \cdot 10^{-5}$ m^3/s.
3. The flow of water must be controlled to be on or off.
4. The tank should be supplied as part of the product and must, of course, hold at least 200 ml.
5. Human involvement in the process (other than filling the tank) should be minimized.
6. The product must contact the existing structure only, but can occupy an unlimited space envelope around the existing structure.



We are engineers. Therefore, our objective should be to satisfy the need, including meeting the requirements, in the simplest economical way, **all things** — both product design and product manufacture — **considered**. The focus here will be on developing a product concept, breaking the product into a series of interacting components, then deciding for each product component whether to design it or select it. If the component is to be designed, then a plan for its manufacture should be simultaneously considered. The objective is to design for easy manufacture from common office supplies and with minimal machine tools and tooling found within an office.

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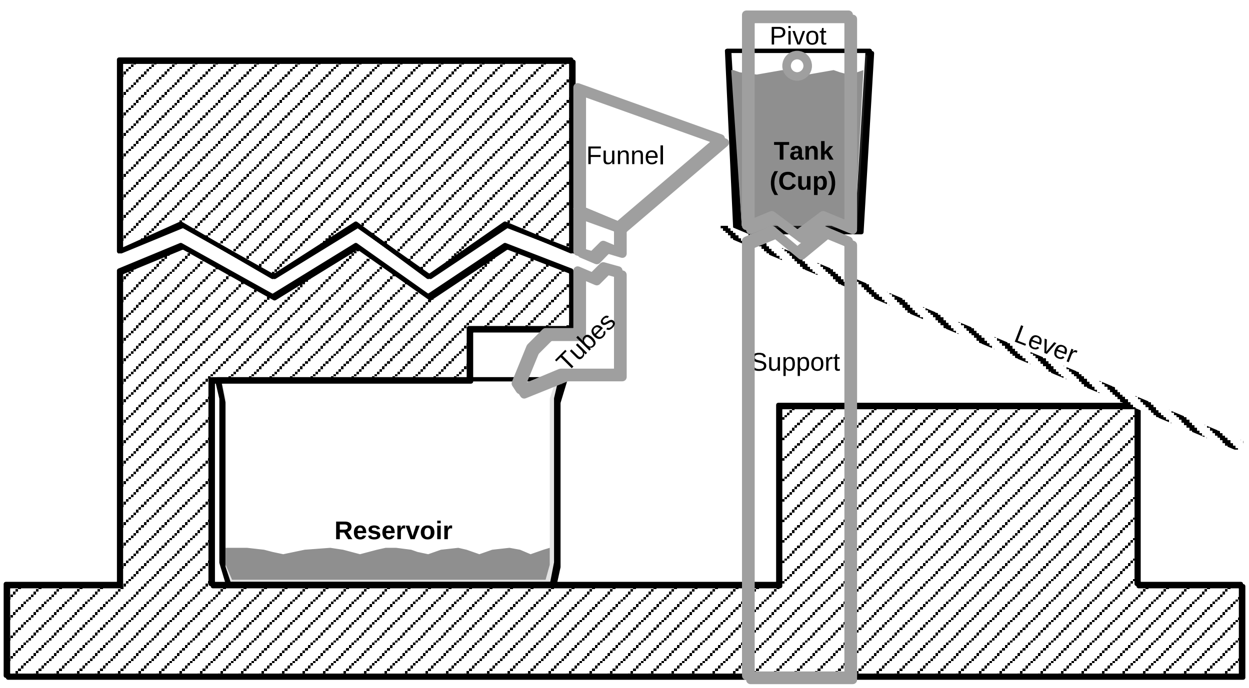
Considering office supplies obviously puts the following at our disposal:

- paper
- tape
- thumb tacks
- paper clips
- rubber bands
- rubber cement
- white glue
- Post-it™ Notes, of course!

Office tools include:

- scissors
- razor knife
- pen/pencil

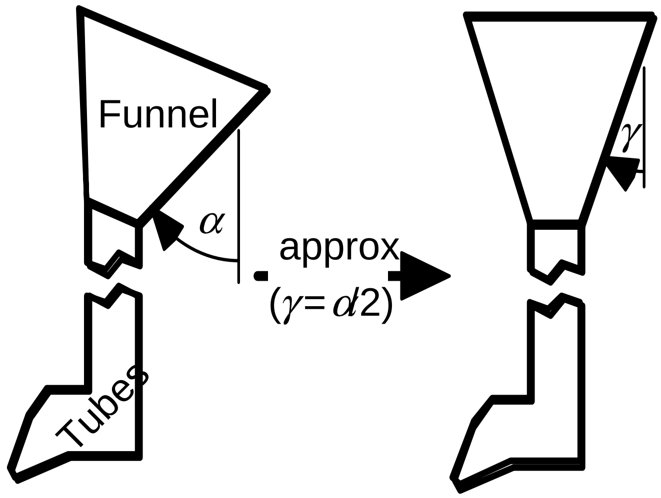
What is our product concept? Use a lever to tip the cup hence pouring the water into a funnel, after which the water flows through a vertical tube, to a horizontal tube, and finally to a 45° angled output tube/nozzle into the reservoir. By tipping the cup back, the water flow can be shut off.

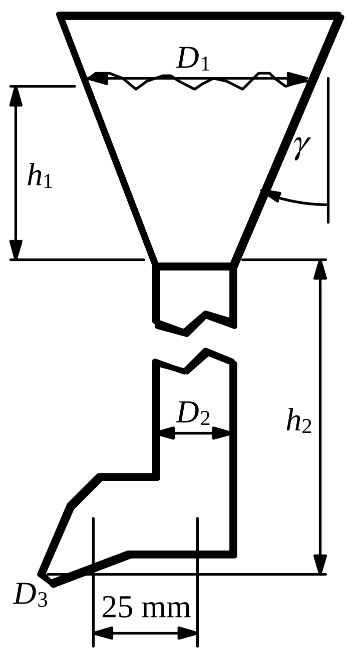


Is this a good plan that will work? Yes, it looks like it will work.

This *system* can be broken down into the following *components*: a 45° tube/nozzle, a horizontal tube, a vertical tube, a funnel, pivot joints for the cup, a supporting structure for the pivoting cup, a lever arm, attachments for the tubes and funnel to the existing structure, attachments for the cup pivot supporting structure to the existing structure, and a pivoting connection for the lever arm.

Begin the design at the output of the system. A real problem such as this requires that the load-driving capability be determined since it is not given, unlike a typical textbook problem. In this case, the load is specified as a water exit energy as dictated by a velocity and flow rate required for proper mixing in the reservoir (the mixing action is the load — someone else has done some of the work for us by determining the velocity, flow rate and angle needed for proper mixing). This load is driven by some power/energy input device, typically a power/energy conversion component. In this case, gravitational potential energy is converted into fluid kinetic energy. Therefore, sizing the required energy/power input involves determining the required potential energy of the water in the funnel, hence the height of the funnel relative to the water exit point.





Conservation of mass states that

$$V_1A_1 = V_2A_2 = V_3A_3 = Q.$$

Bernoulli's Equation is

$$\frac{p_1}{\rho}+\frac{1}{2}V_1^2+g\,z_1=\frac{p_3}{\rho}+\frac{1}{2}V_3^2+g\,z_3.$$

The inlet and outlet pressures are equal (i.e., $p_1 = p_3 = p_{atm}$). From conservation of mass

$$V_1=\frac{Q}{A_1}=\frac{4Q}{\pi D_1^2}$$

and the change in height is

$$z_1-z_3=h_1+h_2,$$

where the height of water in the funnel, h_1, is related to diameters D_1 and D_2 as

$$h_1=\frac{D_1-D_2}{2\tan\gamma}.$$

Therefore, Bernoulli's Equation can be rewritten as

$$\frac{1}{2}\left(V_3^2-\frac{16Q^2}{\pi^2 D_1^4}\right)=g\left(\frac{D_1-D_2}{2\tan\gamma}+h_2\right).$$

Solving for h_2 yields

$$h_2=\frac{V_3^2}{2g}+\frac{D_2}{2\tan\gamma}-\left(\frac{8Q^2}{\pi^2 D_1^4 g}+\frac{D_1}{2\tan\gamma}\right)$$

where the unknowns are D_1 and D_2. The D_1 term has a minimum found by

$$\frac{d}{dD_1}\left(\frac{8Q^2}{\pi^2 D_1^4 g}+\frac{D_1}{2\tan\gamma}\right)=-\frac{32Q^2}{\pi^2 D_1^5 g}+\frac{1}{2\tan\gamma}=0 \qquad \Rightarrow \qquad D_1=\left(\frac{64Q^2\tan\gamma}{\pi^2 g}\right)^{1/5}=15.6\text{ mm}$$

for a choice of $\gamma = 30°$. The flow rate constraint requires, from conservation of mass, that

$$A_3=\frac{\pi D_3^2}{4}=\frac{Q}{V_3} \qquad \Rightarrow \qquad D_3\geq\left(\frac{4(5\cdot 10^{-5})}{2\pi}\right)^{1/2}=5.642\text{ mm},$$

for V_3 set at 2 m/s. Also, it makes sense that D_2 be greater than or equal to D_3, so say $D_2 = 6$ mm.

So, as long as D_1 is less than 15.6 mm (for $Q = 5\cdot10^{-5}$ m^3/s), the total D_1 term decreases as D_1 increases. Therefore, as long as D_1 is less than 15.6 mm, h_2 increases as D_1 increases. The largest value of D_1, and hence the largest value of h_2, depend on the total water volume. For ease of analysis, the worst case (largest D_1) is when all the water is in the funnel. The corresponding value of D_1 is found from

$$\frac{\pi}{4}\left(\frac{D_1+D_2}{2}\right)^2 h_1=\frac{\pi}{4}\left(\frac{D_1+D_2}{2}\right)^2\left(\frac{D_1-D_2}{2\tan\gamma}\right)$$
$$=\frac{\pi}{32\tan\gamma}\left(D_1^3+D_2D_1^2-D_2^2D_1-D_2^3\right)=0.0002\text{ m}^3.$$

This yields the maximum D_1 as approximately 104 mm. Therefore, the worst case (maximum necessary h_2) occurs when D_1 is at 15.6 mm. Hence, making this substitution and that of D_2 = 6 mm, the minimum height h_2 for V_3 known to be 2 m/s is

$$h_2 \geq \frac{2^2}{2(10)} + \frac{(0.006)}{2\tan(30°)} - \left(\frac{8(5 \cdot 10^{-5})^2}{\pi^2 (0.0156)^4 (10)} + \frac{0.0156}{2\tan(30°)} \right) = 188.3 \text{ mm}$$

This assures that the minimum flow rate is maintained.

Letting D_3 equal D_2 simplifies the design by eliminating a nozzle component. Therefore, choose $D_2 = D_3$ = 6 mm resulting in

$$Q = V_3 A_3 = 2\frac{\pi(0.006)^2}{4} = 5.66 \cdot 10^{-5} \text{ m}^3/\text{s}$$

As a check, use this value of Q to re-determine h_2 as

$$h_2 \geq \frac{2^2}{2(10)} + \frac{(0.006)}{2\tan(30°)} - \left(\frac{8(5.66 \cdot 10^{-5})^2}{\pi^2 (0.0156)^4 (10)} + \frac{0.0156}{2\tan(30°)} \right) = 187.3 \text{ mm}$$

From the above analysis, the input energy source, as characterized by h_2, is now known. The resulting quantities, specifically, $D_2 = D_3$ = 6 mm and γ = 30°, represent the detail design parameters of the tubes and funnel. Though it may not be obvious, we have just sized the “motor” to drive the fluid mechanical system through conversion, to mechanical kinetic energy, of gravitational (natural) potential energy.

Now, we continue with the remainder of the component detail design. NO!!!!

- How do we manufacture the tubes and funnel?
- Are they easy to manufacture?
- Can they be designed differently so it is easier to manufacture them, but at the same time not costing more in materials, design effort, etc.?

First, consider that paper can be cut to size with the scissors; rolled into a tube shape; and taped to hold it in a tube shape. Scissors can then be used to cut two tubes at matching angles; then the two tubes can be glued together. What type of glue should be used?

- White glue? No, it may dissolve in the water.
- Rubber cement? This should work.

We have decided how to manufacture the funnel and tubes, and it does not appear that a design change will make things easier. But, have all supplies been considered? Upon looking around the office a bit more, your response might be: “Oh, there is a coffee machine and some other minor kitchen supplies. Perhaps we can use these straws.” Using straws instead of rolling and taping paper in a tube would be easier. The straw material needed may cost $0.11 while the paper and tape totaled $0.01. But, how long will it take to roll the paper tube and tape it? The cost of a worker is at least $30 per hour, or $0.50 per minute. Therefore, the straw is cheaper in the long run if it takes longer than twelve seconds to cut the paper, roll the tube, and tape it. Conclusion: the straw material is cheaper since it is **easier** to work with.

Now that the availability of straws has been established, we may wish to consider other types of straws, i.e., accordion pleated straws may also be available. Using this type of straw would eliminate the cutting and gluing. It is a more expensive material and even more expensive since it would be a special order item. It is estimated to cost at most $0.20 for this type of straw material. Therefore, if the entire paper structure takes more than about 24 seconds to manufacture, and the acts of cutting the angles and gluing the pieces together takes longer than 12 seconds, this design would be better, and is assumed to be so. It is likely to function better too.

Above is an example of considering both function and manufacturability in formulating product design <u>details</u> and selecting components (*buy vs. build*).

For the funnel, paper can be cut, rolled into a funnel shape, and taped to hold its shape. Can you think of an alternative? What about a Post-it Note with its self-adhesive strip? One would have to determine the cost difference versus the ease of manufacture. Also, will the Post-it Note adhesive stand the test of time? The 3-M company probably does not have this type of test data, and it is probably not worth the time and effort (cost) to conduct tests ourselves. Therefore, use the paper and tape. Can you think of another alternative?

The funnel must be attached to the tube and the entire funnel-tube subsystem must be attached to the structure. Where and how it is attached will dictate the load carrying requirement of the funnel-tube attachment. It is proposed that the tube subassembly and funnel each be attached so that the attachments carry their respective shares of the weight and the water-exit propulsion force. To support the tube-funnel subassembly weight and the propulsion load, the tube could be taped to the structure, but the tape may not adhere well to the wood. One could just try it and see what happens. But, if it does not work, what then? An on-the-spot design change will be needed. Engineers will have to travel to the site (money, money, money!). Also, the required materials may not be immediately available which introduces time delays (money, money, money!). What about a simple test? Or, maybe just plan to thumbtack the tape to the wood. Then, why not use paper for the strap? In this case, paper must be cut into a small strip versus tearing a piece of tape off the roll. And, the tape will stick to the straw while a paper strap would require friction via a normal clamping load to keep the straw from sliding out. The tape material probably costs more. Obviously, there are a number of things to consider. Additionally, how much load is there? Some analysis would help, but at a production volume of one, additional analysis time probably would not save money in the long run. You decide.

It is proposed that the tape be used with thumb tacks to better attach to the wood structure. Likewise, a thumbtack can hold the funnel to the structure assuming it is acceptable to deform the funnel slightly to do so.

Now, the cup must pour water into the funnel. Paper tubes could be used for the structural support. How large should their diameter be? Some analysis might help, but again, it is probably cheaper in materials to make them large and save on engineering analysis time/cost. The cup pivots could be thumbtacks, but they need to stick into something. Using pencils instead of paper tubes would certainly be easier than making the tubes, but maybe more expensive. However, (1) the paper tubes may not stand up in the rainy outdoor environment, and (2) thumbtacks will stick into the wood, but not to the paper tube — the paper tube would require something additional for the thumbtacks to stick into. STOP!!!

What mistakes were made at the very start of solving this product development problem?

1. A single concept was generated and implemented**. Multiple concepts should always be considered at the start** to allow creativity to surface. To illustrate: at this point, I have formulated a new/revised concept that would be much easier from the standpoints of both component design and developing a manufacturing plan. The new concept

appears as though it would be much less costly in the end. But, I have already spent much design and manufacturing planning effort, and hence, cost.

2. As already noted, the availability of materials (and selectable components) was not rigorously thought out. As a result, we were inadvertently channeled into considering only certain materials, which stifled our creativity.

Problems with this concept include two big ones: (1) where does the energy come from to tilt the cup — a human pushing down on the lever is actually manual mechanical energy which is converted into additional fluid potential energy, which is then converted to the fairly constant (funnel acts as a capacitor) kinetic fluid energy of the flow, and (2) it is difficult to build and analyze. This brings us to an important and concluding point:

***Simplicity and Economy* — a simple design concept will often function better and longer, and usually leads to easier analysis and manufacture, both of which save money.**