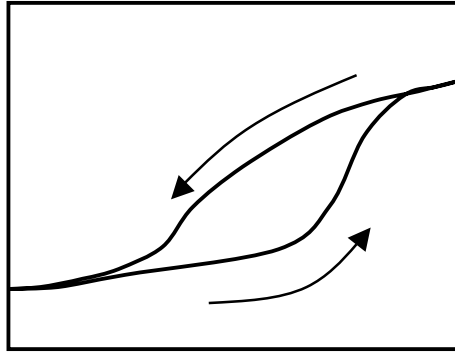


## Soil Water Potential (III)

We now encounter the interesting topic of hysteresis. First, an observation: when a soil is dried and then rewetted, the drying and wetting soil water characteristic curves are not identical. The wetting curve is drier than the drying curve over a wide range of soil water potentials. This general phenomenon is known as hysteresis: a hysteretic relationship between two variables depends not only on the value of the independent variable, but also on whether that value is increasing or decreasing. So the two curves form a closed loop with sharp ends:



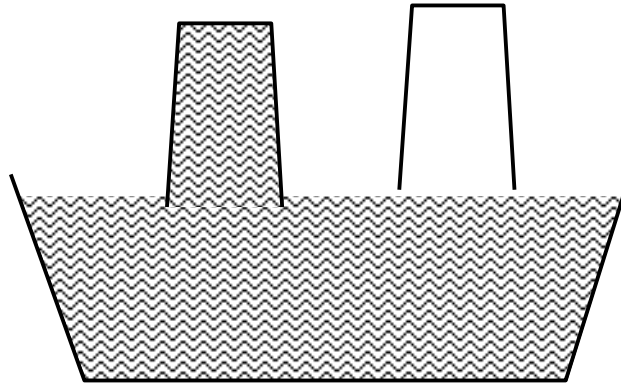
Such relationships show up in elasto-plastic deformation (see my notes in the soil mechanics section: I didn't use the term "hysteresis", but the sketch is there), magnetic induction, some kinds of phase change, and various other physical phenomena.

Causes:

Hillel gives 4 causes of hysteresis. I'll give a slightly different presentation here.

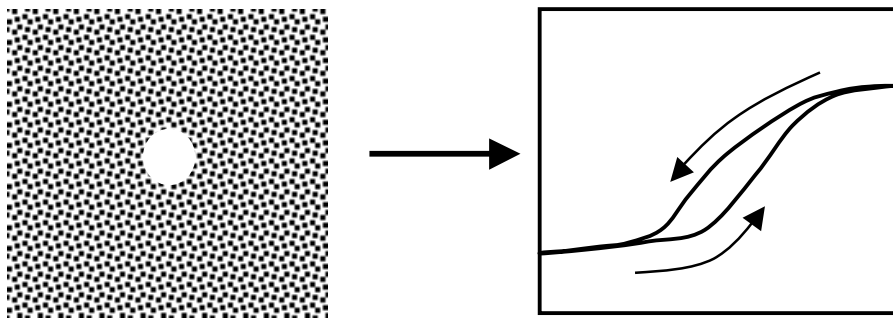
- 1) the "Ink Bottle" effect. We saw this in class as a sinusoidal capillary tube. The basic idea is that, if pores have a large "pore body" which then connects to neighboring pores through constricted pore throats, there is some hysteresis already at the pore scale. The drainage of an individual pore is controlled by the smallest radius (the "pore throat" radius), because when the meniscus retreats down the pore under increasing tension, its radius is decreasing (think of the capillary equation: a smaller  $R$  is needed if  $h$  is growing). If the radius now increases because the pore gets bigger, the interface can't support the weight of the water column anymore, and it collapses, draining the pore. But the rewetting (imbibition) of a pore is controlled by the pore's largest radius (the "pore body" radius), by similar reasoning.
- 2) Contact angle hysteresis. This is a well-recognized phenomenon, but it is only significant at relatively high flow rates. The slower the process, the less contact angle hysteresis. Because drainage and rewetting curves are generally measured at slow ("quasi-equilibrium") rates, this isn't likely to be an important contributor.
- 3) Aging effects. During imbibition, air can become trapped inside the larger soil pores (see below under "accessibility" for an explanation). Given sufficient time, the entrapped air bubbles will slowly dissolve in the water and diffuse to the edge of the sample, where they'll return to the atmosphere. The air bubble trapping is indeed a cause of hysteresis, but the aging (wherein the entrapping dissipates) is not strictly hysteresis at all.

- 4) Accessibility, or network effects. This is rarely covered in soils textbooks, but it's a well-known effect in the engineering and physics literature. Consider a system with large pores, such as a child's toy cups in a bathtub:



The two cups have large radii, and therefore almost no capillary force, so they ought to drain readily. But the water can't leave unless air moves in. So there are really two conditions needed for drainage, and so far we've studied the first but ignored or assumed the second. So: the second condition is that, in order for a pore to drain, there must be a continuous air-filled pathway from the outside to the pore. This is called the accessibility criterion.

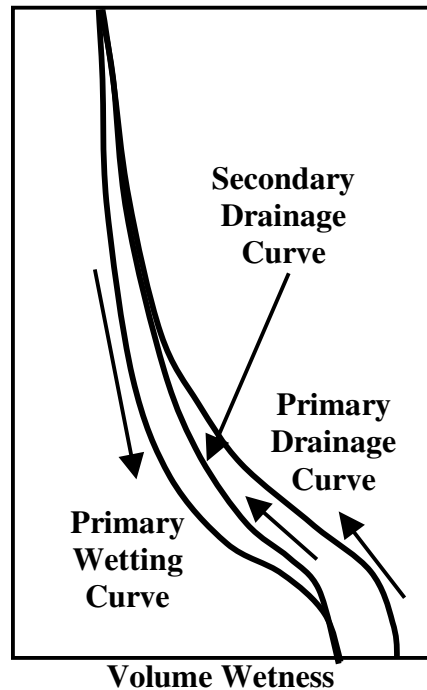
If we extend this accessibility reasoning, we end up with hysteresis. Consider: during drainage, a large pore that should drain by the first condition (radius) but can't by the second (access to air) will shift the drainage curve slightly, making it wetter at a given potential than it "should be" by the first condition alone. But during wetting, that same large pore might be surrounded by water, trapping the air inside and shifting the curve to slightly drier than it "should be" by the first condition alone. So accessibility is a cause of hysteresis.



In addition to hysteresis itself, there is the interesting issue that soils are just plain hard to saturate completely. If you wet a soil sample up from the bottom (the dense fluid in at the bottom, the less dense one escapes at the top), there will be some air trapped inside, and you might only get to about 85% saturation. In order to completely saturate the sample, you have to first displace the air with a water-soluble gas such as CO<sub>2</sub>, then seal the sample, introduce water at the bottom while pulling a vacuum at the top, and finally

flush the sample with de-aired water, weighing it intermittently, until its weight stabilizes. Needless to say, this rarely happens in the field!

So a soil actually has 3 water characteristic curves: the primary drainage curve (starting from saturation), the primary wetting curve (starting from air- or oven-dry), and the secondary drainage curve, which drains from the ending point of the primary wetting curve. The first is what we generally measure in the laboratory; the second and third are the ones that occur naturally.



Notice that the primary drainage and primary wetting curves are the two normally-occurring extremes, and all points in between are possible. A point in the middle of the loop can be reached by (for example) draining only part-way, then beginning to rewet. Funny thing: this is just what happens outside! Rain of varying amounts falls at irregular intervals, so that all intermediate points are scanned. The points on the graph that occur commonly in nature are therefore the points on and between the primary wetting and the secondary drying curves.

There are several equations in use to describe the wetting and drying curves, of which the most common are the Brook and Corey, and the van Genuchten. Both use the expression

$$\Theta = \frac{\theta - \theta_r}{\theta_s - \theta_r}$$

, where the subscript *s* is saturation and the subscript *r* is residual, to define the normalized water content. This is similar to Hillel's "S", except that here we're allowing the curve to go asymptotically to some non-zero residual water content. Brooks and Corey then describe the water retention curve as

$\Theta = \left( \frac{\psi_e}{\psi} \right)^\lambda$  if  $\phi < \phi_e$ , otherwise  $\Theta = 1$ . This equation gives an abrupt corner to the curve at  $\phi_e$ , the so-called “air entry pressure (in mathematical terms, it is not continuously differentiable). The van Genuchten equation says

$\Theta = \left( \frac{1}{1 + (a|\psi|)^n} \right)^m$  where  $a (= 1/\phi_e)$ ,  $n$ , and  $m$  are fitting parameters. This second equation has no physical meaning, but gives a smooth (continuously differentiable) and very flexible S-shaped curve. Because this curve is differentiable, van Genuchten was able to use Mualem’s previously published relationship between pore size distribution and unsaturated hydraulic conductivity, and so predict unsaturated hydraulic conductivity from the water retention curve. That equation,

$K(\theta) = K_s \sqrt{\Theta} \left[ 1 - (1 - \Theta^{1/m})^m \right]^2$ , is probably the most common  $K(\theta)$  relationship used in current computer models.

Measuring water potential:

The most commonly used direct way to measure soil water potential is with a tensiometer, which is a body of pure water hydraulically connected to the soil water via a permeable ceramic cup. If the soil water is under tension, then some tiny fraction of water in the tensiometer will be pulled out, lowering the pressure inside. This negative pressure can then be measured with a gage, a pressure transducer, or a water or mercury manometer. See Homework 2 and Exam 2 for some example tensiometer problems.

Another way to measure soil water potential is to put a substance with a known soil water characteristic into the soil, allow it to come to equilibrium, and measure its water content. This is a fairly new method which doesn’t show up in Hillel, but Or and Wraith, and Ren and Noborio, have worked with this method.

You can also control the potential by imposing it yourself, via a hanging water column, a pneumatic potential, or exposure to a concentrated salt solution inside a sealed container.