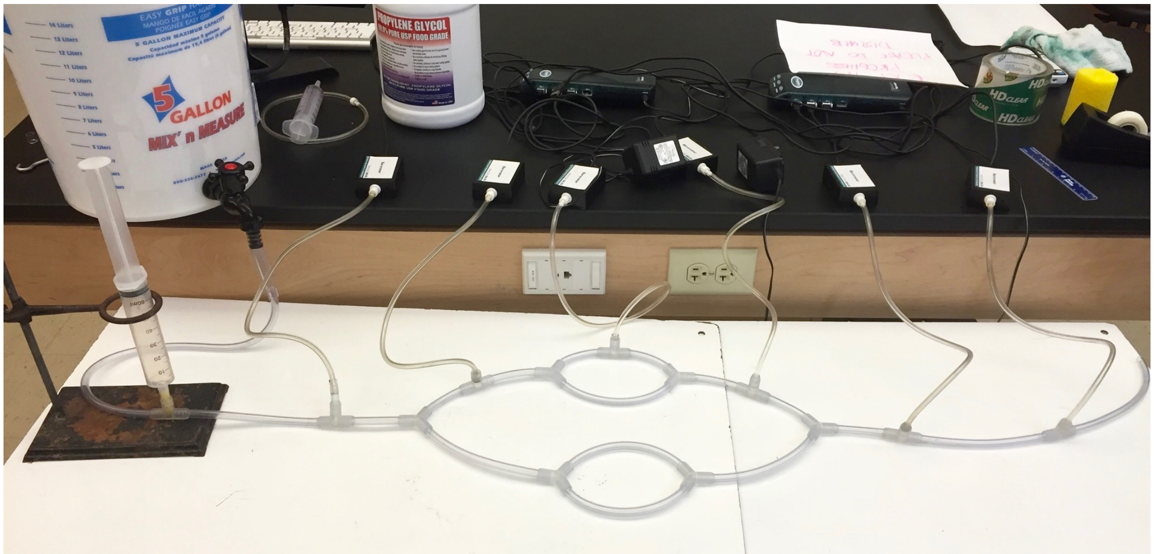
The Circulatory System Model

The model circulatory system shown below is a great demonstration to connect the physics of Poiseuille's Law with the functioning of the human circulatory system.



In this model, a 5-gallon bucket is filled with water (nominally with red food coloring for effect). When the spigot is opened the water is "pumped" by hydrostatic pressure. The water initially flows through one tube, representing the flow of blood in the aorta. Then the system branches multiple times, representing the progression to arteries, arterioles, and capillaries. In the model shown above, only two branchings are included before progressing back to a single tube (representing the vena cava) and the tube is the same radius throughout the model. The model can be built with variable radii, such that the first and last tubes have the largest radii (e.g. aorta and vena cava) and the central tubes have the smallest radii (e.g. capillaries). This increases the complexity for ordering parts, though has the added satisfaction of demonstrating the change in radius. A bucket should be placed on the floor to catch the water after it travels through the system. If a closed, continuously flowing system is desired, the exit tube could lead to a pump which lifts the water back up to the first bucket.

A key observation for students to see is that the water flows fastest through the single entrance and exit tubes, while the water flows slowest through the center branches. This demonstrates the principle of continuity and mimics the circulatory system, where the blood is moving very slowly in the capillaries to allow for gas and nutrient exchange. In the figure above, a plastic syringe (nested on a ring stand) is connected to the entrance tube by a plastic T-connector. By applying light pressure to the syringe, you can send air bubbles into the water, which allows you to watch bubbles travel from tube to tube, changing speed. Tubes smaller than ¼" diameter cause the bubbles to get trapped along the walls of the tube, so smaller sizes are not recommended. The introduction of bubbles provides the added benefit of video analysis. By measuring the radius and bubble velocity of each section of tubes, students can confirm the equation of continuity.

The model pictured above also includes 6 digital pressure sensors from Vernier (both the barometer and gas pressure sensors work for this experiment). Each sensor is connected to a plastic T-connector and monitors the pressure change as the water flows from branch to branch. The measurement shows that pressure is lower in each section as water progresses from left to right. This defies the prediction of Bernoulli's principle, which would suggest that the pressure increases as branches are added (and water slows), then decreases again as the branching returns to a single tube. Instead, the continual decrease in pressure is consistent with Poiseuille's law, which is an important concept in anatomy and physiology when discussing the circulatory system.

Parts to assemble the model

The original model, as described in the 2015 PERC paper by Whitmore, used three different tube radii, with the largest as the "aorta," the smallest as the "capillaries," and the other sections varied.

The parts listed below are a second model we constructed. This one utilizes a uniform tube diameter (1/4"). This simplifies the construction and the mathematics. One might argue that, since the aorta has a larger radius than a single capillary, our original model was "more realistic." However, the 3/8" to 2/8" ratio (1.5:1) does not truly represent the real aorta:capillary ratio (about 10,000:1). Also, we only constructed 16 capillaries, not 10 billion.

What you need:

- Water. Red food coloring is a nice touch.
- Two 5-gallon buckets
- One faucet/spigot for the elevated bucket
- One plastic syringe for bubble injection
- Clear PVC tubing, ¼" inner diameter
    - Order a lot; maybe 100 feet! We run 20 cm between each Y connection. But you can never have too much tubing. See link here, for instance.
- 30 Union Y Hose Connectors ¼"
    - We purchased the Y's and T's from Seelye Acquisitions, Inc; see link here.
    - 30 Y's will allow you to split from 1 : 2 : 4 : 8 : 16 : 8 : 4 : 2 : 1. You can purchase fewer if you wish to build the smaller system from 1 : 2 : 4 : 2 : 1

- 10 Union Tee Hose Connectors ¼”
    - See link here.
    - 9 T’s are inserted to allow a pressure measurement in each branch
    - Pressure is measured with Vernier barometers; gas pressure sensors should work equally well. The tube connecting the barometer and the T is the “18 inch [long] Tygon tubing with Luer Lock connectors” that was provided with the Vernier gas pressure sensor
    - The 10th T is inserted soon after the spigot to allow for the connection of the plastic syringe to inject bubbles. You can measure bubble velocity via video analysis.

This is the bare minimum, representing most of what you see in the two images. You will need a way to connect from the spigot to the ¼” tubes. You should probably order a spigot that directly connects to ¼” tubing. We worked with supplies that were on hand a used a few different diameter PVC tubes to step down. You could also find a connector that makes the jump directly; Seelye may have something. You are welcome/encouraged to order a handful of different diameter tubes in order to experiment with different versions of the setup. In those cases you may want T’s and Y’s that reduce or expand. Fortunately, the cost of these materials is not intimidating! (Note: The “4- capillary” model pictured second uses fancy 3D-printed Y’s and T’s in an attempt to reduce pressure losses. This isn’t necessary for standard use.)