<u>**Kinesthetic Circulatory System Model**</u>

Purpose: To demonstrate basic concepts of fluid dynamics not readily observed in traditional fluids demonstrations; primarily the equation of continuity and Poiseuille's law. Importantly, this model does NOT demonstrate the Bernoulli principle, although students are expected to predict that it will.

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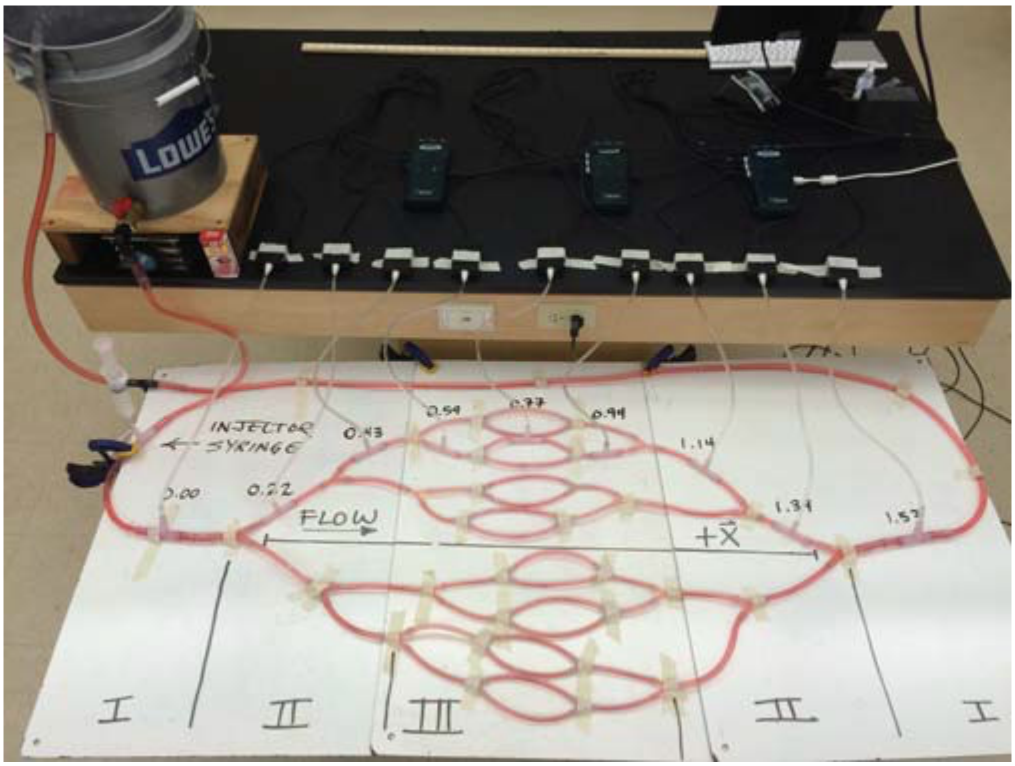


Figure 1. Model circulatory system consisting of transparent tubing, liquid reservoir, pressure sensors, and bubble injector. Scale: +x axis is 1.00 m in length.

To build: This model can be assembled for less than $100! The construction is fairly simple: you need two buckets, one spigot, flexible transparent tubing, y-adaptors for the splits, and T-adaptors to connect the pressure sensors. Assembly includes measuring proper lengths, cutting the tubes, and connecting (total of 2-3 hours). Once assembled, we recommend keeping it together permanently. A parts list is provided separately.

If you wish to measure pressure, you will need either the barometer or gas pressure sensor from Vernier or Pasco, or an equivalent measurement tool.

When to use: In a traditional curriculum, this model can be used at the end of the unit/chapter on fluids, where you cover hydrostatic pressure, the continuity equation, and Bernoulli's principle. If Poiseuille's law has not been taught, this model serves as a great introduction to pressure drop due to real (viscous) fluids.

We are currently testing a new curricular order that will cover Poiseuille's law prior to Bernoulli, and in fact, deemphasizing (possibly removing) Bernoulli. It is not yet certain where this model is best deployed in this curriculum; possibly after both Poiseuille's law and continuity have been covered. This model extends those ideas.

Pre-health students *really* get into the discussion of this model. They love seeing the ideas they've discussed in anatomy and physiology classes played out in a tube and water demo. In fact, this is one of the demonstrations that makes the greatest impact on them throughout the semester.

How to use: We used this model primarily as an interactive lecture demonstration, including predictions via clicker questions or whiteboarding in small groups.

To begin, we briefly discuss how this activity models the human circulatory system. We use anatomy and physiology (A&P) images such as the ones shown from the OpenStax A&P free online textbook.

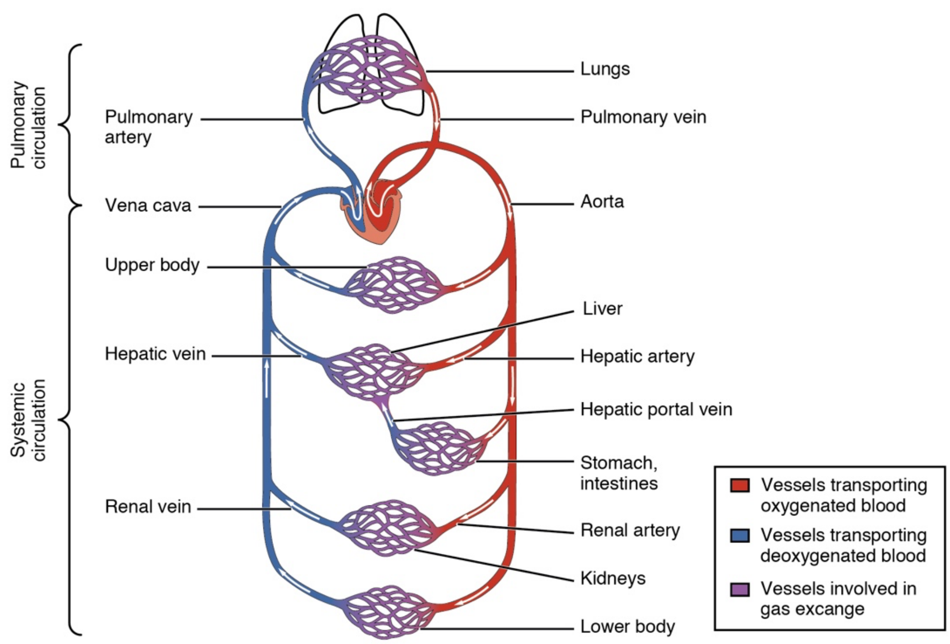


Figure 2. Cardiovascular Circulation

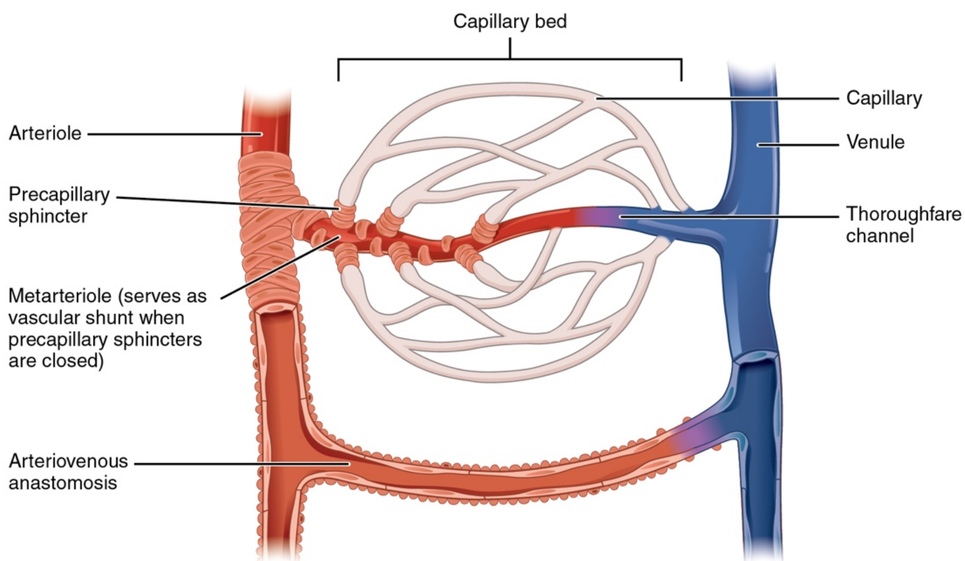


Figure 3. Capillary bed

Our first question for the students, before they even see the fluid flowing, is shown on the slide below.

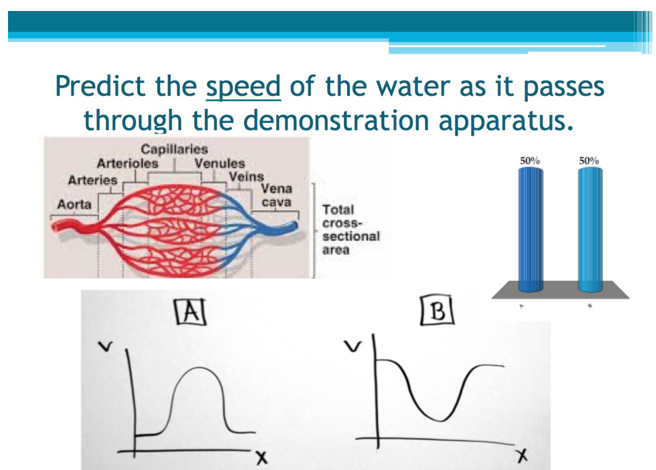


Figure 4. First question to ask the class: Predict the speed of the water.

This can be presented as a clicker question in a large class, but in a small class we recommend asking student to work in groups to make a sketch of their prediction, without showing them any options. The options A and B shown in the figure are the most common drawings.

In the original model we built, we mention that the tubes in section I have a larger radius than those in II, which have a larger radius than those in III. Students who are considering that fluid speed increases when flowing from a larger radius to a smaller radius will predict 'A'. Students who are thinking about their knowledge of physiology will realize that the blood moves slowly in the capillaries, so they will predict 'B'.

After all predictions are made, students gather around the model at the front of the class. The spigot is turned on and they see the water flow. To see the speed, inject bubbles into the tubes and it is very easy to see that bubbles in region I move very quickly and bubbles in region II move very slowly. This leads to a discussion about using total cross-sectional area with the continuity equation. To extend the example, give a group calculation where students are given realistic values of blood velocity in the aorta and capillaries as well as the radius of each. From that, they can estimate the total number of capillaries in the body (around 10 billion).

The second question we ask is the following:

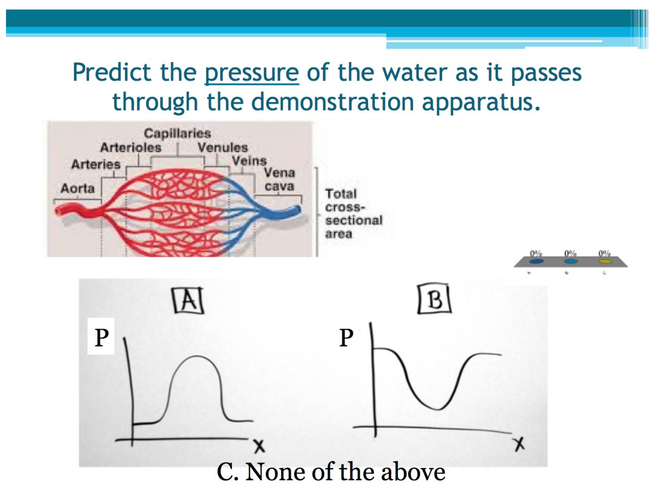


Figure 5. Second question to ask the class: Predict the pressure of the water.

Effectively, students have been setup to make an incorrect prediction. If students have recently learned the Bernoulli principle, they will apply that here. Since the flow speed is slowest in region III, they predict that this region will have the highest pressure, selecting A. Other groups will select B without correct reasoning. The students who have an A&P background are a little flummoxed at this point. Some will draw a horizontal pressure line. Some, though very few, will draw the correct picture.

We hook up pressure sensors to each split, monitor these pressures as the fluid flows, and then make a rough sketch on the board of what pressure vs. position looks like. The result below summarizes both pressure and velocity measurements.

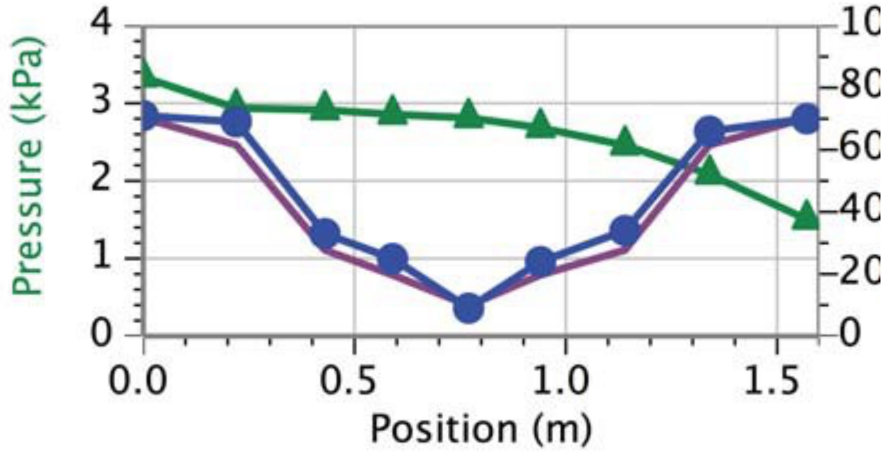


Figure 6. Measured results from the Whitmore paper. The green line is the pressure measured at each connector. The blue line is the velocity of the water through each branch measured from video analysis. The purple line is the expected velocity predicted from the equation of continuity.

Students quickly see that the Bernoulli principle has failed to make a correct prediction. You should follow this up by showing a classic graph from A&P, and begin a class discussion of what factors have not been taken into account. Usually a few students mention the idea of friction and resistance to flow. If you haven't done so yet, this is a great time to teach some principles of Poiseuille's law or do a Poiseuille lab activity. ΔP=Q*R is often discussed in A&P; bring this up now.

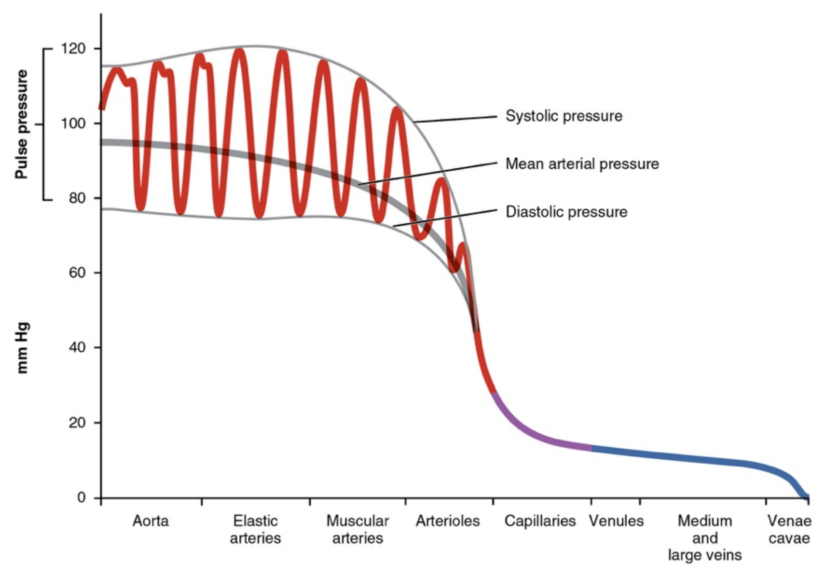
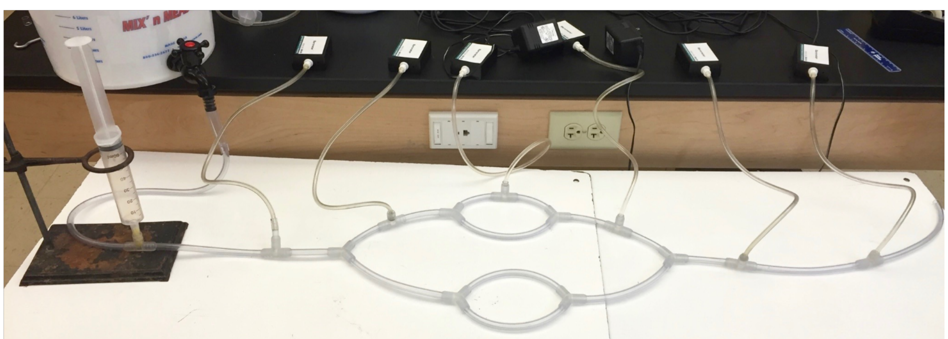


Figure 7. The graph shows the components of blood pressure throughout the blood vessels, including systolic, diastolic, mean arterial, and pulse pressures.

If you have an additional 30-45 minutes available for this activity, the following measurement can be done. Students collect velocity data, as shown in the image below. Each group of students will send a representative to the model and record bubbles passing through a single branch. The group performs video analysis and reports their value. The class data is assembled and students investigate whether or not the continuity equation is upheld (spoiler: it is!).

Smaller versions can also be assembled. A “4-split” (below) rather than “16-split” (as above) shows the same principles, is easier to assemble, and takes up less space in the classroom and storage room. Additionally, you could assemble multiple setups and potentially have on at each lab group table.



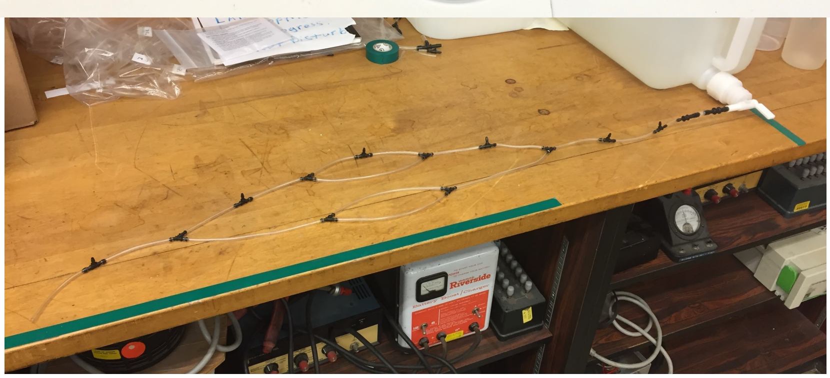


Figure 8. Top “4-split” assembled at UNE and the bottom one assembled at Portland State University. The top one uses ¼” tubing while the bottom one uses ⅛” tubing. Smaller tubing ensures laminar flow for better calculations, but watching bubbles is much more challenging (they get stuck!). The wider tube is recommended for purely demonstration purposes.