# Teaching Model for Ventilation-Perfusion Mismatching

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**Abstract:**

The ventilation-perfusion (V/Q) ratio is an important metric to evaluate the exchange of gas calculated from alveolar ventilation and capillary perfusion rates. V/Q mismatching occurs when the V/Q ratio differs from 0.8 and mismatching can be a difficult concept for medical students to grasp. A physical interactive model was created that utilizes LED lights to represent ventilation in an alveolus and blood flow through a surrounding capillary. Coordinated blinking of the lights creates the illusion of flow, and the rates of ventilation and perfusion are able to be manipulated by the user in order to display different V/Q ratios. Using a survey distributed across medical students and the general population, it was determined that the model is capable of improving upon a human subject's understanding of V/Q ratios. The survey did not test the subject's prior knowledge on the subject of V/Q ratios which is important for quantitatively measuring the effectiveness of the teaching model. Future work includes further testing and a modified circuit design.

## 1. Introduction

Maintaining normally oxygenated blood depends on gas exchange between the air in the alveoli of the lungs and the blood in the pulmonary capillaries. As seen in Figure 1, in order for air to reach alveoli, it must enter through the oral or nasal cavities and flow through the structures of the respiratory system to reach the alveoli, which are tiny air sacs with thin walls surrounded by capillaries for gas exchange [1]. This exchange of gas requires adequate ventilation, or airflow, of the lungs as well as appropriate perfusion, or blood flow, of the capillaries and is often evaluated by medical professionals through a metric known as the ventilation-perfusion (V/Q) ratio [2]. When ventilation and perfusion are functioning properly, the V/Q ratio is 0.8 which corresponds to 4 liters of air entering the lungs and 5 liters of blood going through the capillaries every minute [3]. Ventilation-perfusion (V/Q) mismatching occurs when the V/Q ratio is higher or lower than 0.8 and is a difficult concept for medical students to visualize, specifically, how it can lead to dead space ventilation and hypoxemia [4]. A model is needed to help the medical students conceptualize the different ventilation-perfusion ratios and their consequences.

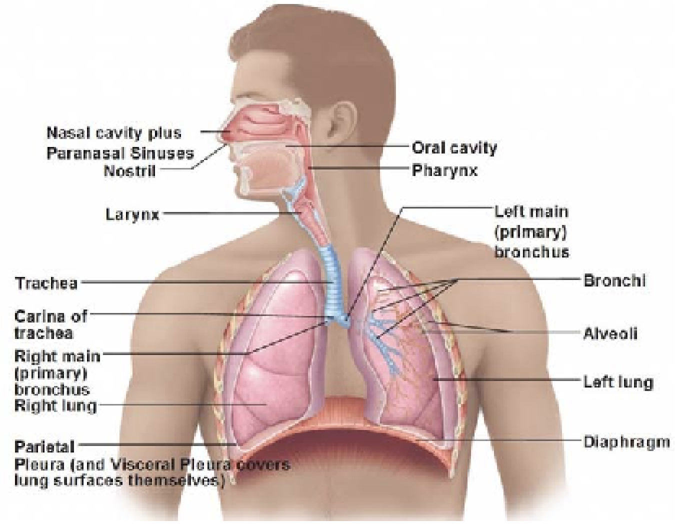

Figure 1. Anatomy of the respiratory system [5].

The V/Q ratio shows the matching of ventilation-perfusion rates and may vary between individual alveoli. In extreme cases of high V/Q rates, dead space ventilation can occur in which there is air movement in and out of the alveoli, but the ventilation is unable to participate in gas exchange because the alveolar capillaries in the area are not perfused [6]. Dead space can increase when there is a loss of alveolar function, decreased cardiac output, hypotension, pulmonary embolism, and vasoconstriction [6]. Inversely, a shunt occurs when there is perfusion, but no ventilation of the corresponding alveoli. Therefore, there is no contribution to blood oxygenation from this area. Hypoxemia results, leading to low oxygen concentrations in the blood [7]. The alveolar ventilation, the amount of air that reaches the alveoli for gas exchange, can be calculated using Equation 1, where tidal volume is defined as the amount of air that moves into or out of the lungs. In a normal healthy adult, normal tidal volume is about 500 ml and dead space is about 150 ml [6]. Equation 2 can be used to calculate the partial pressure of oxygen in the alveolus $(P_AO_2)$ where $P_IO_2$ is the partial pressure of inspired oxygen, $VO_2$ is $O_2$

consumption, $V_A$ is ventilation, and $P_B$ is barometric pressure [6]. Finally, the shunt fraction can be calculated with Equation 3, where $Q_s$ is the blood flow through the shunt, $Q_t$ is the blood flow through the lung, $Cc_{O_2}$ is the pulmonary end-capillary $O_2$ content, $Ca_{O_2}$ is the arterial $O_2$ content, and $Cv_{O_2}$ is the mixed venous $O_2$ content [6].

$$\text{Alveolar Ventilation} = \text{Respiratory Rate x (Tidal Volume - Dead Space)} \tag{1}$$

$$P_AO_2 = P_IO_2 - (VO_2/V_A) * (P_B - 47\, mmHG) \tag{2}$$

$$Q_s/Q_t = (Cc_{O_2} - Ca_{O_2})/(Cc_{O_2} - Cv_{O_2}) \tag{3}$$

## 2. Background

Medical students oftentimes have difficulty understanding that a high V/Q ratio leads to dead space or wasted ventilation and that a low V/Q can lead to hypoxemia [4]. Students also struggle to visualize or understand that an increase in a V/Q ratio can be attributed to either an increase in ventilation or a decrease in perfusion [4]. This holds significant clinical implications for physicians as it is important to understand the mechanisms resulting in V/Q mismatching in order to determine the correct treatment protocol. For example, hypoxemia from a shunt cannot be corrected by supplemental oxygen and inadequate knowledge about the causes of hypoxemia can lead to incorrect patient care [4].

Creating a reliable way to model the impact of changing ventilation and perfusion on V/Q ratios would help to improve medical education for future physicians. There are currently very limited options for educators to visually represent this concept, and this makes it a challenging concept both to teach and to learn. West (2016) presents a ventilation and perfusion model that utilizes water pumps to simulate the movement of air into the lungs and blood flow [8]. A dye is placed into the water to show the gas exchange between the lungs and the bloodstream as well as the resulting oxygenation of the blood. This model is not a physical model and the textbook uses this model as an analogy to describe V/Q ratios. Another model is a multi-scale computational model relying on the use of a series of ordinary and partial differential equations. It models the vascular network of the entire lung generated by a space-filling algorithm and tested by comparing it to existing literature [9]. A model like this [9] would require extensive programming and mathematical manipulation that would be very challenging to develop for a classroom model. The creation of a physical interactive model that could be easily manipulated by both instructors and students would be invaluable to education in this area.

A physical interactive model was created that utilizes LED lights to represent ventilation of an alveolus and blood flow through a corresponding capillary. Coordinated blinking of the lights creates the illusion of flow, and the rates of ventilation and perfusion are able to be manipulated by the user in order to display different V/Q ratios.

## 3. Materials and Methods

Adafruit NeoPixel LEDs were utilized to represent both the air in the alveolus and the blood flowing through the capillary. A NeoPixel LED flex strip was used to represent the capillary, with the colors blue and red depicting deoxygenated and oxygenated blood respectively [10]. Three separate NeoPixel LED rings were nested concentrically to cover the alveolar area and depict the alveolus. The rates at which the alveolar LEDs illuminate, or blink, indicate minute ventilation. Additionally, the flexible LED strip mimic the direction of blood flow through the capillary and the rate of movement represents the speed of blood flow. Currently, the design also consists of four LED momentary contact buttons for the user to increase or decrease the rates of both ventilation and perfusion individually, which in turn changes the V/Q ratio. The buttons are user-friendly as their size makes them easy to push, and the different colors allow for easy identification as to each of their functions [11]. An Arduino Nano is used to control the input from the buttons and the output for the LED rates [12]. An LCD display is incorporated into the design to display the values of ventilation, perfusion, and the overall V/Q ratio [13]. Example of the software used to program the microcontroller is seen in Figure 2 and the hardware diagram is shown in Figure 3. A 3D-printed PLA base design was used as housing for the LEDs as well as the housing for the circuitry and can be seen in Figure 4. Figure 4 shows the respective locations of the alveolus LEDs and the capillary LEDs in the base design. The interactive model models two of the main extremes, shunt and dead space ventilation and the representation of these extremes can be seen in Figure 5 compared to the desired 1:1 ratio.

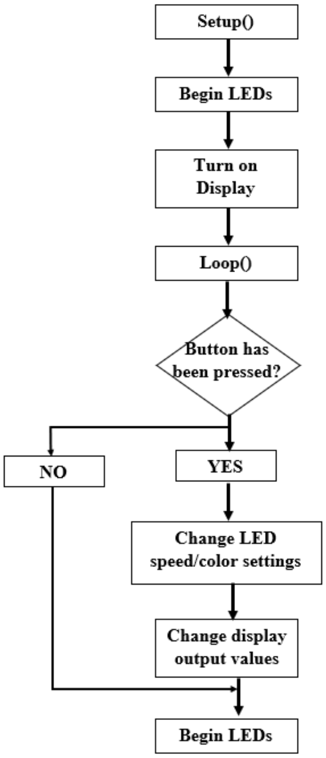

Figure 2. Software Flow Diagram

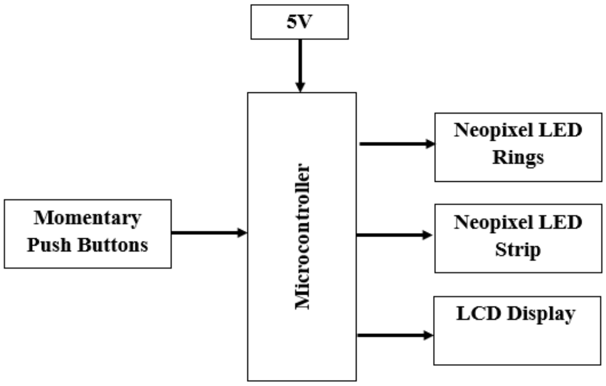

Figure 3. Hardware Block Diagram

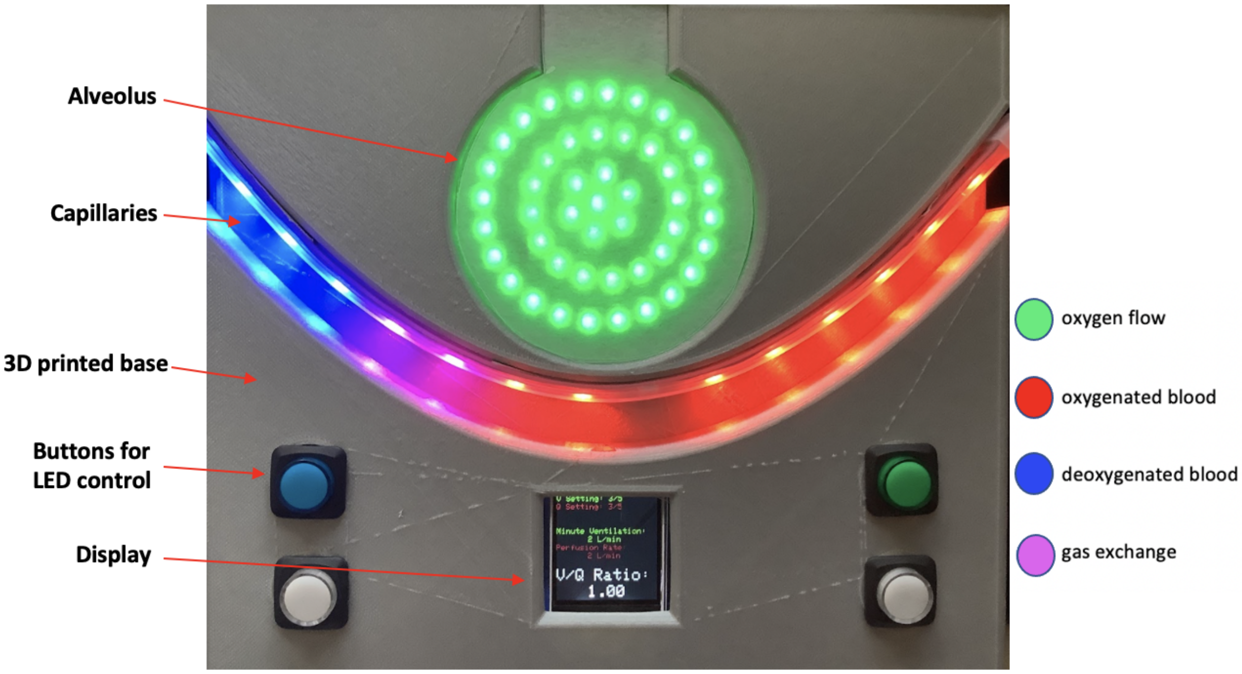

Figure 4. 3D printed base modeling the alveoli and bloodstream along with the ring and flexible LED strip to show the oxygen gradient for the V/Q ratios.

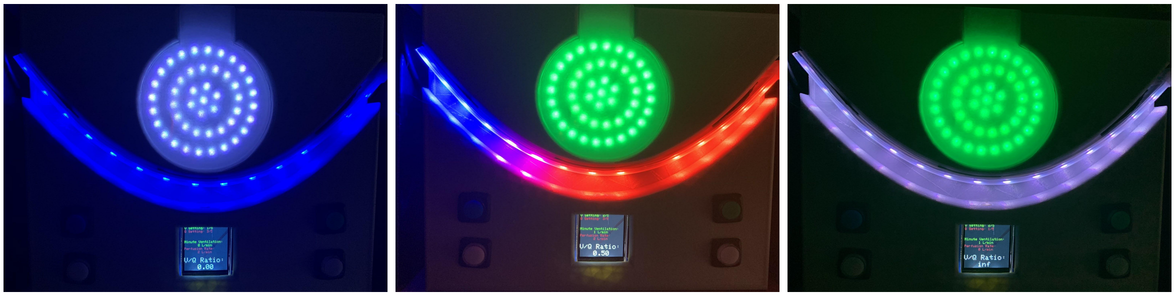

Figure 5. Representations of a shunt, 1:1 ratio, and dead space ventilation

Methods for testing will include an analysis of the model's capability to improve upon a human subject's understanding of ventilation or perfusion ratios by graphically displaying what occurs when the rates are modulated. A Google Form was created with pre-recorded videos of the teaching model displaying varying ratios and accompanying multiple-choice questions, meant to gauge understanding of the model. This Google Form was then distributed to two populations; one included participants without previous exposure to or knowledge of respiratory and pulmonary physiology and V/P mismatching and the other included medical students with prior knowledge of both subject areas.

For the first population, we assume that without the aid of the teaching model, they would receive a baseline score of 33.33% corresponding to selecting answers at random. Similarly, we would anticipate that if the model improved their understanding, we would expect that the mean score would increase above the baseline. To analyze the results, we elected to perform a T-Test on the data with the following hypothesis:

$$H_o:\ \mu = \overline{0.333}$$

$$H_a:\ \mu > \overline{0.333}$$

The null hypothesis was that the population mean would be equal to the baseline score of 33.33% corresponding to answers selected at random. The alternative hypothesis was that the mean was greater than the baseline meaning that our model improved upon the understanding of the subjects.

Given the second population's prior knowledge, we expected that they would be able to answer all questions correctly and achieve 100% given the aid from the teaching model. To analyze the results, we elected to perform a T-Test on the data with the following hypothesis:

$$H_o:\ \mu = 1$$

$$H_a:\ \mu < 1$$

The null hypothesis was that the mean score would be 1 corresponding to a score of 100% on the Google Form multiple-choice test given the aid from the teaching model. The alternative hypothesis was that the mean score was less than the expected outcome corresponding to the result that the teaching model did not do a sufficient job of improving the understanding of the medical students.

We performed a Two-Sample T-Test on the mean score from both the first and second populations to determine if there is a significant difference in the shift in understanding given prior knowledge. The hypothesis was as follows:

$$H_o:\ \mu_1 = \mu_2$$

$$H_a:\ \mu_1 < \mu_2$$

The null hypothesis was that the mean from population 1, or that of subjects without prior knowledge of respiratory and pulmonary physiology and V/P mismatching, would be equal to that of the medical students, or population 2. The alternative hypothesis was that the mean of population 1 would be less than that of population 2.

## 4. Results

The first population included 46 subjects without previous exposure or knowledge of respiratory and pulmonary physiology and V/P mismatching, in particular. Our population yielded an average score of 0.7935 or 79.35% on the Google Form, with a standard deviation of 0.073 or 7.3%. When analyzed with the T-Test, the data produced a p-value of $4.479*10^{-9}$ meaning that we can accept the alternative hypothesis at a significance level of 0.05 as alpha.

The second population included 5 medical students with prior knowledge of both respiratory and pulmonary physiology as well as V/P mismatching. The data had an average score of 0.98 with a standard deviation of 0.06 and the corresponding T-Test yielded a p-value of 0.17. At a significance level of 0.05, we can reject the alternative hypothesis meaning that the average score for this population was close to the expected value of 100%.

Lastly, when a two-sample T-Test was performed, the resulting p-value was equal to $7.25*10^{-4}$ meaning that we should accept the alternative hypothesis at a significance level of 0.05.

## 5. Discussion

The T-Test of the first population including 46 subjects without previous exposure to respiratory and pulmonary physiology and V/P mismatching yielded statistically significant results. In this case, we are able to conclude that the mean score for the population is above the expected result of randomly selecting answers. In the case of the teaching model, this result suggests that our device is capable of improving upon the subjects' understanding of different V/Q ratios as well as what each scenario entails.

The T-Test of the second population including 5 medical students with prior knowledge of both respiratory and pulmonary physiology as well as V/Q mismatching yielded statistically insignificant results leading us to conclude that the mean score for this data was approximately 100%. Applied to our teaching model, this result means that our device improves upon the existing knowledge of medical students significantly leading them to fully understand V/Q ratios as well as the implications in different related scenarios.

Lastly, the Two-Sample T-Test between the mean from populations 1 and 2 compares how the two different populations' collective scores compare. It was found that the mean score of the medical students was significantly different from the mean score of the general population without previous V/Q knowledge. We can conclude that prior knowledge of ventilation-perfusion and V/Q ratios is important for the effectiveness of the teaching model.

## 6. Conclusion

Ventilation and perfusion mismatching results from varying rates of ventilation, or airflow, and perfusion, or blood flow within the lungs. Mismatching can be corrected, but in order to correct mismatching, it is important to understand how and where mismatching occurs. There are currently no physical models to help teach ventilation and perfusion mismatching to medical students, therefore, this teaching model used in a classroom setting will help improve the knowledge of medical students.

A prototype was created that used colored LEDs to represent ventilation and perfusion through an alveolus and surrounding capillary. A dynamic model was designed so that students can further understand how alterations in ventilation or perfusion change the resulting V/Q ratio. Testing the design with the general public as well as medical students, it was determined that the design successfully demonstrates ventilation and perfusion mismatching and therefore, can be concluded that it will be an effective teaching model.

Due to the circumstances this semester, the design was unable to be tested by having hands-on interactions with the medical students resulting in decreased survey responses. Completing additional testing that can allow the users to alter the V/Q ratios can help to further verify the design. Also, due to an IRB application needing to be submitted early in the semester, the design in the survey did not accurately reflect all components of the design. For example, the display, as well as some of the speeds, were altered after the survey was completed which has the potential to alter the students' responses.

Future work for this design will include further testing of the design that will hopefully result in an increased number of medical student responses as well as a pre-and post-test for the medical students. A survey conducted in this manner will assess the knowledge of V/Q mismatching before using the prototype as well as after to see whether the design had an influence on one's learning. In addition, the circuit for the design will need to be modified so that it is more secure and can withstand the travel and handling by many users.

## 7. Acknowledgements

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## 9. Appendix

## Design Process

### A. Preliminary Designs

#### Flow Mechanism Design Models

LED Flow Model

The LED Flow Model consists of an alveolar duct leading into a single alveolus surrounded by a capillary tube. LEDs would line both the capillary tube and the alveolar duct to represent blood flow and gas flow respectively. Ideally, as the blood flows through the capillary tube from left to right (represented by the red arrow in Figure 6), the LEDs would change color to show that the blood has been oxygenated. The gas exchange would also be modeled using LEDs, where carbon dioxide would be modeled using one color flowing out of the duct and oxygen would be modeled by another color flowing into the duct and then into the bloodstream oxygenating the blood.

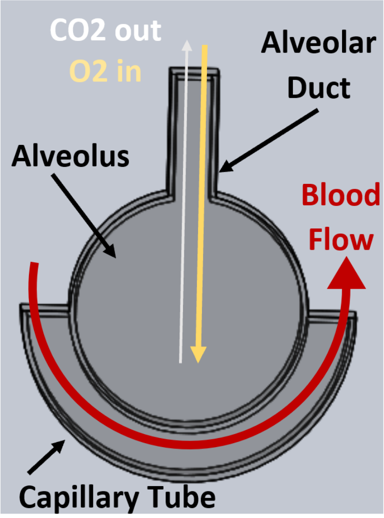

Figure 6. LED flow model with arrows to represent LED placement

Bead Flow Model

The Bead Flow Model consists of a tube representing a bronchiole that is connected to two alveoli that are surrounded by a single capillary tube which can be seen in Figure 5 [14]. This design would model flow using beads suspended in water. Pumps in the back of the design would control the amount of water and beads flowing through the system. The number of beads that are released into the alveoli represents the amount of ventilation, while the number of beads that mix with the water would represent the amount of perfusion. The release of the beads would be regulated through a pinched tube, with a smaller diameter corresponding to fewer beads flowing through the system. A complication with this design would be finding a way to separate the beads from the water with little effort from the user.

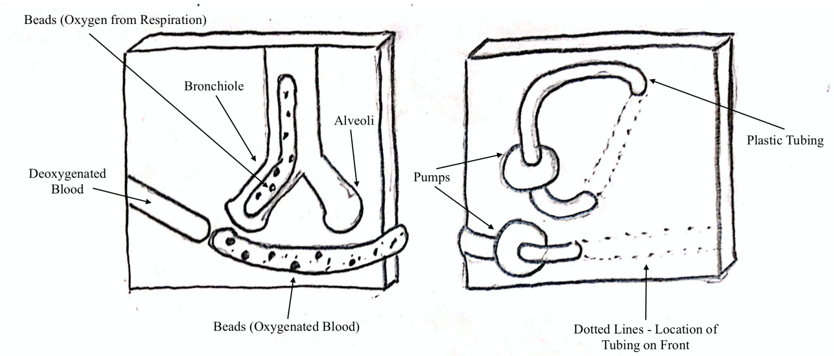

Figure 7. Bead Flow Model with black dots representing beads.

Water Flow Model

The Water Flow Model is based on the idea from John West's (2016) model presented in his textbook [8], this model is seen in Figure 9. This model would include a closed water system and a water pump to move the water from a reservoir through the design's capillary tubes. An example of a closed water system can be seen in Figure 8.

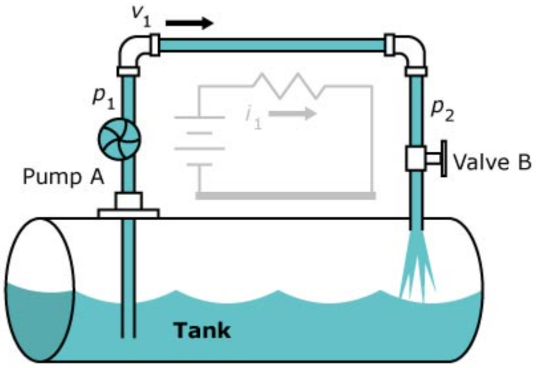

Figure 8. Closed water system with pump and reservoir [15]

Dye would be inserted through the alveolar duct portion of the design and then flow into the capillary tube where the water flows through. The amount of dye used represents the amount of ventilation and the concentration of the water and the dye would represent the V/Q ratios. The water flow model would require a water reservoir and a waste reservoir. The reservoir with clean water would allow clean and clear water to flow through the capillaries and the waste reservoir would hold the water that has already been mixed with the dye. This design can get messy involving the dye and can become heavy depending on the size of the reservoirs.

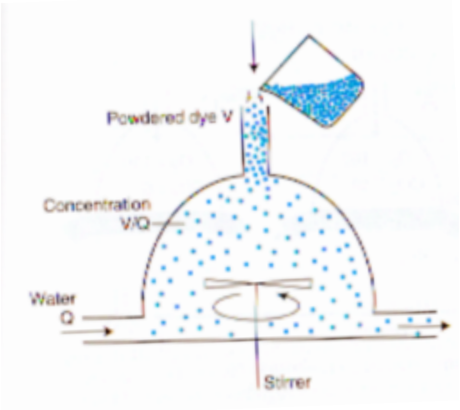

Figure 9. Water flow model using dye [8]

### LED Mechanism Design Models

Original LED Model

The Original LED Model consists of the LED Flow Model lined with singular LEDs of different colors. This design would feature each individual LED linked together into a system by some component that could alter the colors of the system as needed. While this design is simple, it does not allow for a gradient of colors to represent the difference in flow rates between each of the V/Q ratios.

Figure 10. Individual LEDs that would line the LED Flow Model [16]

## Diffused LED Model

The Diffused LED Model features an LED strip lining the LED Flow Model. The LED strip has functionality that would allow for each color gradient to be achieved, while also permitting different colors to be present on the same strip. This design is promising as it easily incorporates different color gradients in a synchronous fashion and could be modulated to model a large variety of different V/Q ratios. In addition, the diffused component of this model would greatly increase the light diffraction to intensify the colors from the LEDs.

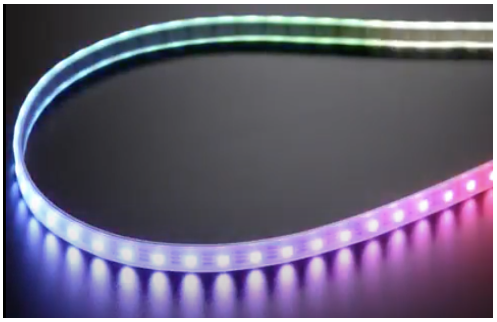

Figure 11. LED strip in diffused tubing representing a variety of color gradients [10]

## Water-Submerged LED Model

The Water-Submerged LED Model contains an LED strip lining the LED Flow Model. This design features similar benefits proposed in the above Diffused LED Model but attempts to increase the light intensity from the LEDs through light diffraction in water. The main drawback of this design is that it could potentially pose a challenge to incorporate water with an electronic system.

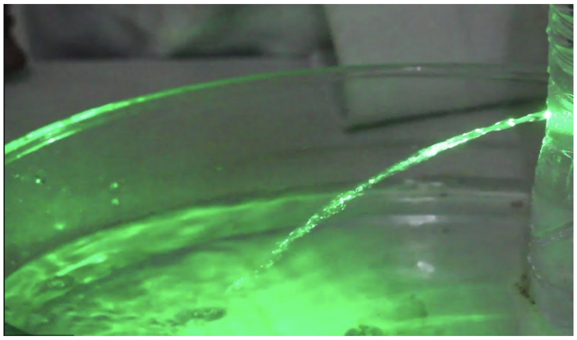

Figure 12. LED light diffraction in a stream of water [17]

## B. Design Matrices

### Flow Mechanism Design Matrix

Table 1. *The design matrix with categories on the left, their weights in parentheses, and each design labeled on the first row. The dark green cells represent the designs that won each category as well as the design that won overall.*

| **Designs**<br>**Categories** | LEDS | | BEADS | | DYE | |
|---|---|---|---|---|---|---|
| Effectiveness (35) (Competency) | 5/5 | **35** | 3/5 | **21** | 2/5 | **14** |
| Ease of Use (30) | 5/5 | **30** | 4/5 | **24** | 1/5 | **6** |
| Ease of Fabrication (15) | 4/5 | **12** | 3/5 | **9** | 2/5 | **6** |
| Viability (10) | 4/5 | **8** | 4/5 | **8** | 2/5 | **4** |
| Safety (5) | 3/5 | **3** | 4/5 | **4** | 4/5 | **4** |
| Cost (5) | 4/5 | **4** | 3/5 | **3** | 2/5 | **2** |
| **Total (100)** | 92 | | 69 | | 36 | |

## Flow Mechanism Design Evaluation

*Effectiveness:* Effectiveness was determined by the accuracy of the device to portray ventilation/perfusion mismatching. The design was considered more effective if it had a larger quantity of V/Q ratios it was able to present and if those ratios were represented in a precise way that would be observable to those using it. Effectiveness also took into consideration how well the device would appear in front of a lecture full of students. The LEDs scored perfectly in the effectiveness category as this design allows for a gradient of V/Q ratios, rather than set values in both the beads and dye design which lead to their lower scores in this category.

*Ease of Use:* Ease of use was considered as to how intuitive the device would be to operate for someone who may not have a technical background. This would include how easy it would be for the user to adjust the V/Q ratios as well as any action on their part to reset components of the device between different modeling sessions. It also considers the effort it would take to set up and store the device. As the users are professors or possibly students at the medical school, this device needs to be something that they can incorporate into the teaching of V/Q mismatch with very little effort as they have very busy schedules with lots of curriculum to go through. The LED design scored high in this category as it would be easily adjustable versus both of the other two designs that would require more effort to modify. The dye design scored the lowest in this category due to the complicated setup and reset of this model.

*Ease of Fabrication:* Ease of fabrication considers the ability of the team to produce the model. The fabrication process is a vital aspect of the design process, as it is important to be able to fabricate the device easily and effectively. Ease of fabrication takes into consideration the need for 3D printing, electronics, and outsourcing materials. The LED model was considered the simplest to fabricate due to the easy integration into an electronic system while both the beads and dye designs would need an intermediate component and would lead to a more complicated process.

*Viability:* Viability is characterized by the ability of the device to model ventilation/perfusion mismatching over a long period of time with little to no decrease in accuracy and precision. The time period will be determined by the client's needs but is anticipated to be at least 5 years. In addition, the device will be used multiple times throughout the year. The dye model was ranked lower than the other two designs because of the complications in storing and resetting the system.

*Safety:* Safety is an important criterion to consider for any product. Safety was ranked with low importance as the model does not have eminent safety concerns. Safety considered electrical concerns and other outstanding hazardous components. Both the beads and dye designs were scored higher than the LEDs in the safety category because they did not pose any serious electrical risks.

*Cost:* Cost is ranked as one of the least important criteria for the design matrix determined by the flexible budget of $1000 provided by the client for designing and fabricating the device. An important aspect of the design will be in minimizing the cost of resetting the model after every use. LED design scored the highest in the cost category primarily due to the minimal cost of resetting the device compared to the other two models.

### LED Mechanism Design Matrix

Table 2. *The design matrix with categories on the left, their weights in parentheses, and each design labeled on the first row. The dark green cells represent the designs that won each category as well as the design that won overall.*

| **LED Designs**<br>**Categories** | Diffused LEDs | | LEDs + Water | | Original LEDs | |
|---|---|---|---|---|---|---|
| Effectiveness (50) (Competency) | 5/5 | **50** | 5/5 | **50** | 3/5 | **30** |
| Ease of Fabrication (35) | 4/5 | **28** | 3/5 | **21** | 5/5 | **35** |
| Safety (10) | 5/5 | **10** | 4/5 | **8** | 4/5 | **8** |

| | | | | | | |
|---|---|---|---|---|---|---|
| Cost (5) | 4/5 | **4** | 3/5 | **3** | 5/5 | **5** |
| **Total (100)** | 92 | | 82 | | 78 | |

### LED Mechanism Design Matrix Evaluation

*Effectiveness:* The effectiveness of LEDs was determined by how clearly they would demonstrate ventilation/perfusion ratios and whether those ratios would be clearly observable by a lecture of students. For this category, it was thought that the diffused LEDs and the water LEDs would clearly show the V/Q ratios while also demonstrating the flow of capillary blood and oxygen, whereas the original LEDs would be able to accurately show V/Q ratios, but would not clearly show the flow of movement.

*Ease of Fabrication:* Ease of fabrication considered how easy it would be to incorporate the LEDs into the design and how much fabrication easy design would require. The original LEDs would be the easiest to incorporate as they can simply be added into the design with simple circuitry, whereas the diffused and water LEDs would require additional components. The water LEDs would require the most fabrication to be able to house the water and waterproof the LEDs.

*Safety:* Safety is important to consider when dealing with any electrical components. The water LEDs and the Original LEDs were ranked the lowest. The water LEDs could cause issues with the water involved because it could cause issues if any open wires were exposed to the water. The original LEDs were also ranked lower because of their open wires and circuits compared to the diffused LEDs.

*Cost:* Cost was considered the lowest ranking category as this is likely not an issue with any of the LED designs chosen. It was determined that the original LEDs would be the most cost-efficient design as they would not require extra components to diffuse/refract the light.

### First Prototype

Based on the high score of the "Diffused LEDs" from the design matrix, the team chose this method of modeling for the final design. It scored highest in the two criteria of the highest importance, signifying that the design will effectively cover the client's requirements for the model. The design will include the base model representing the alveoli and bloodstream where ventilation-perfusion takes place, along with the visual oxygen flow representation using the diffused LEDs. In addition, a dial will be incorporated onto the base to choose between five different ventilation-perfusion ratios to be shown by the model.

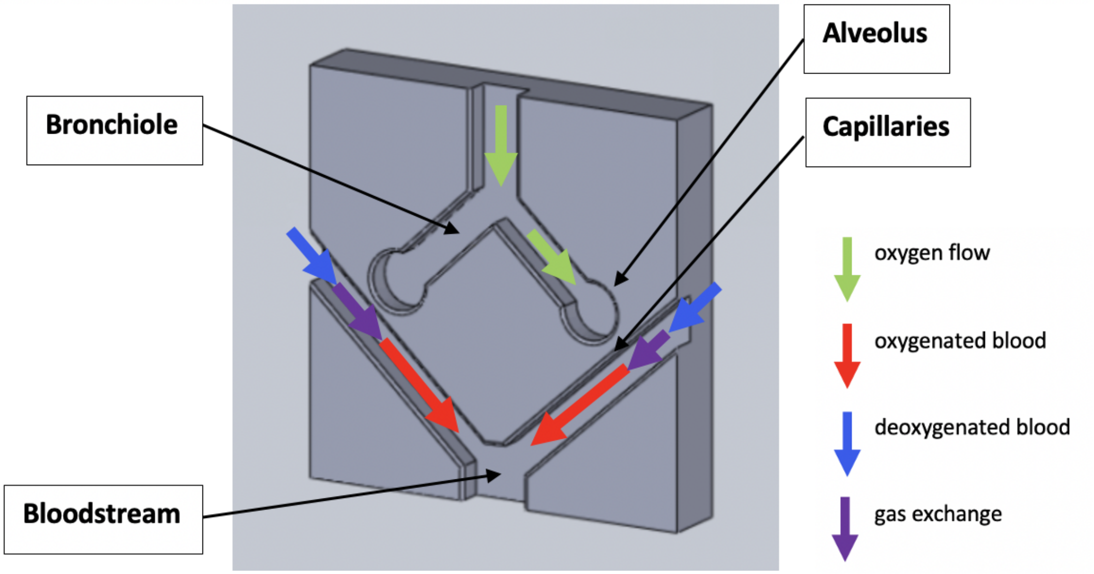

Figure 13. CAD drawing of the base modeling the alveoli and bloodstream along with arrows to show the oxygen gradient to be represented using diffused LEDs.

## B. Preliminary Design Specifications

**Teaching Model for Ventilation and Perfusion Mismatching Product Design Specification**

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**Date:** 2020/09/17

**Problem Statement:**

During medical school, students are taught about the importance of ventilation/perfusion mismatching and the effects it has on the body. Oftentimes, the students have a difficulty understanding that a high Ventilation/Perfusion (V/Q) ratio leads to dead space ventilation, or wasted ventilation, and that a low V/Q can lead to hypoxemia, which is a condition where there is low oxygen concentrations in the blood. A model representing the mechanisms underlying ventilation/perfusion mismatching would help students understand this concept.

**Client Requirements:**

- The device needs to accurately model ventilation and perfusion mismatching
- The device should include an interactive component that will allow the user to change the ratios of ventilation and perfusion
- The device should be large enough to be seen in a classroom full of 180 people with the use of a projector or camera, yet small enough for easy storage
- The device is able to be used multiple times per lecture
- The budget for the project is $1000

**Design Requirements:**

1. **Physical and Operational Characteristics**
    a. **Performance Requirements:**
        - The device will likely be used in a classroom setting
        - Must model a range of ventilation/perfusion ratios
            1. Minimum of five settings: dead space ventilation, high V/Q ratio, 1:1 ratio, low V/Q, and shunt

    b. **Safety:**
        - No open wires that could be harmful to the user
        - No sharp edges or corners that could be dangerous during transport of the device

    c. **Accuracy and Reliability:**
        - Students in the lecture hall need to be able to easily differentiate between the different settings
            1. When asked, users can correctly identify that the oxygenation of the blood has increased or decreased 19 out of 20 times when viewed on a screen as in a lecture

d. **Life in Service:**
  - At least five years

e. **Shelf Life:**
  - Electrical components must be of good quality so they will not degrade and need to be replaced

f. **Operating Environment:**
  - Will be used in a classroom setting
    1. Likely with use of document camera or projector
  - Portability of the device could mean there is a chance of damage between storage and classroom
  - Damage could occur if misused

g. **Ergonomics:**
  - People should be able to view the device on a screen from 14 meters away
  - People with visual impairments, such as color blindness, should be able to learn from the design

h. **Size:**
  - No more than 0.61 x 0.61 m (2ft x 2ft)
  - Maximum dimensions of 0.22 x 0.27 m (8.5 x 11 in)
    1. Must fit on a tabletop
    2. Must fit under a document camera

i. **Weight:**
  - Less than 6.8kg (15lbs)

j. **Materials:**
  - No Material Restrictions

k. **Aesthetics, Appearance, and Finish:**
  - No unfinished points, edges, or open wires

2. **Production Characteristics**

a. **Quantity:**
  - Only one Ventilation/Perfusion Model will be needed for client's classroom

b. **Target Product Cost:**
  - The product should remain under a total budget of $1,000

3. **Miscellaneous**

a. **Standards and Specifications:**
    - Not applicable at this time

b. **Customer:**
    - Easy to use for professors in medical school with no technical background
        1. Controller with different settings
    - Minimal set-up and reset time
        1. Maximum set-up time of two minutes
        2. Maximum reset time of one minute
    - Differentiation in color, brightness, or speed between blood coming to and leaving the lungs
    - Differentiation in color, brightness, or speed between air exerting and leaving the alveolus
    - Visible flow of blood

c. **Competition:**
    - West's model for V/Q matching [17]
        1. Uses pumps and dye to show the effect of V/Q ratios on blood oxygenation
    - E-learning Computer Model for Cardiovascular System [18]
        1. Incorporated a Lumped Parameter Model (LPM) into an e-learning environment to create a tool to help students, undergraduate medical students, in particular, understand cardiovascular physiology, map disease progression, and classify the severity of a disease.
    - Circ-Adapt [19]
        1. A computational model of the pulmonary and respiratory systems that is used to investigate clinical aspects by incorporating mechanical and hemodynamic interactions.
        2. Contains flexible parameters to mimic various physiological states.

## References

[1] J. B. West, "Chapter 5: Ventilation-Perfusion Relationships," in *Respiratory physiology: the essentials*, Baltimore: Williams & Wilkins, 1974, pp. 70–71.

[2a] Warriner Dr, Bayley M, Shi Y, Lawford PV, Narracott A, Fenner J (2017) Computer model for the cardiovascular system: development of an e-learning tool for teaching of medical students. BMC Med Educ 17: 017-1058.

[2b] W.Dassen et al., "The application of complex research simulation models in education; A generic approach," 2011 Computing in Cardiology, Hangzhou, pp.465-468.

## C. Expenses

Table 3. List of expenses for one unit

| **Item** | **Part Number** | **Link** | **Description** | **Vendor** | **Cost** | **Quantity** | **Subtotal** |
|---|---|---|---|---|---|---|---|
| Adafruit Neopixel 7x5050 RGB LED | 2226 | https://www.adafruit.com/product/2226 | Ring with 6 outer LEDs and 1 inner LED for alveolus | Adafruit | 5.95 | 1 | 5.95 |
| Adafruit Neopixel 16x5050 RGB LED | 1463 | https://www.adafruit.com/product/1463 | Ring with 16 LEDs for alveolus | Adafruit | 9.95 | 1 | 9.95 |
| Adafruit Neopixel 24x5050 RGB LED | 1586 | https://www.adafruit.com/product/1586 | Ring with 24 LEDs for alveolus | Adafruit | 16.96 | 1 | 16.96 |
| Adafruit Neopixel LED strip | 3919 | https://www.adafruit.com/product/3919?gclid=CjwKCAjww5r8BRB6EiwArcckCzEIg95MquQekbTMIV_LZ4VwndfflJ-GjxrnGvsVQTvlRloZGAF2jxoCVIoQAvD_BwE | A flexible strip with 30 LEDs powered with 5V | Adafruit | 12.50 | 1 | 12.50 |
| Adafruit 1.44" TFT LCD Display | 2008 | https://www.adafruit.com/product/2088?gclid=Cj0KCQiAgomBBhDXARIsAFNyUqNVz_2Y6bdeOxecKVJgMEzjOet_mG9W9xiGz0KYxVGgmN3bENCZ9kkaAjMEEALw_wcB | Small LCD display with color for output V/Q ratios | Adafruit | 14.95 | 1 | 14.95 |
| Adafruit 16 mm Blue Momentary Push Button | 1447 | https://www.adafruit.com/product/1477?gclid=Cj0KCQiApsiBBhCKARIsAN8o_4irRf_DqUKndbWPvUnLyjTu6oPf3cAu-MDltWIVq2bAMA7dpFhfuqgaAqf7EALw_wcB | Glowing blue button that reads HIGH when pressed | Adafruit | 1.95 | 1 | 1.95 |
| Adafruit 16 mm Green Momentary Push Button | 1440 | https://www.adafruit.com/product/1440 | Glowing green button that reads HIGH when pressed | Adafruit | 1.5 | 1 | 1.5 |
| Adafruit 16 mm White Momentary Push Button | 1479 | https://www.adafruit.com/product/1479 | Glowing white button that reads HIGH when pressed | Adafruit | 1.95 | 2 | 3.90 |
| Arduino Nano | A000005 | https://store.arduino.cc/usa/arduino-nano | Microcontroller with no pins | Arduino | 20.70 | 1 | 20.70 |
| Shrink Plastic Sheets | AS067 | https://www.amazon.com/gp/product/B08BLC8NSQ/ref=ppx_yo_dt_b_asin_title_o01_s00?ie=UTF8&psc=1 | 25Pcs Shrink Plastic Sheets for Crafts Heat Shrink Paper for Crafts Kids DIY Jewelry Making | Amazon | 10.54 | 1 | 10.54 |
| 3D-Printed PLA Base | - | - | 3D printed model if PLA consisting of cutouts for 4 buttons and LCD display. Circular alveolus component with surrounding capillary | Makerspace | 37.54 | 1 | 37.54 |

**Total Cost: $136.44**

## D. Hardware Designs

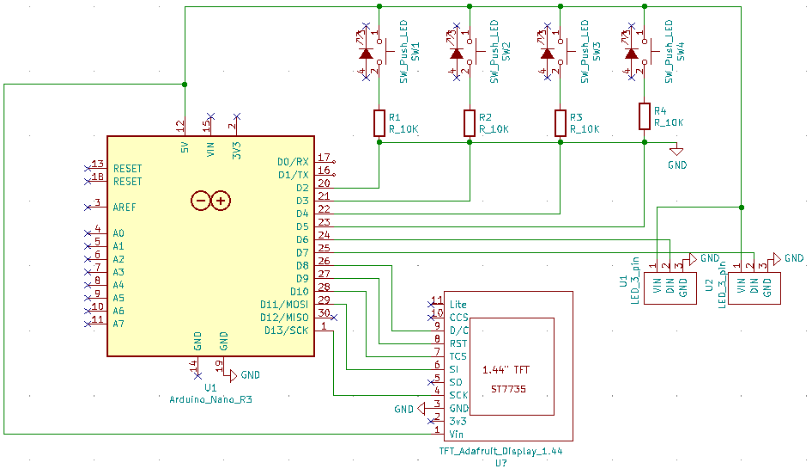

Figure 14. Circuit schematic with LCD display, ArduinoNano, Momentary Push buttons, and two sets of Neopixel LEDs

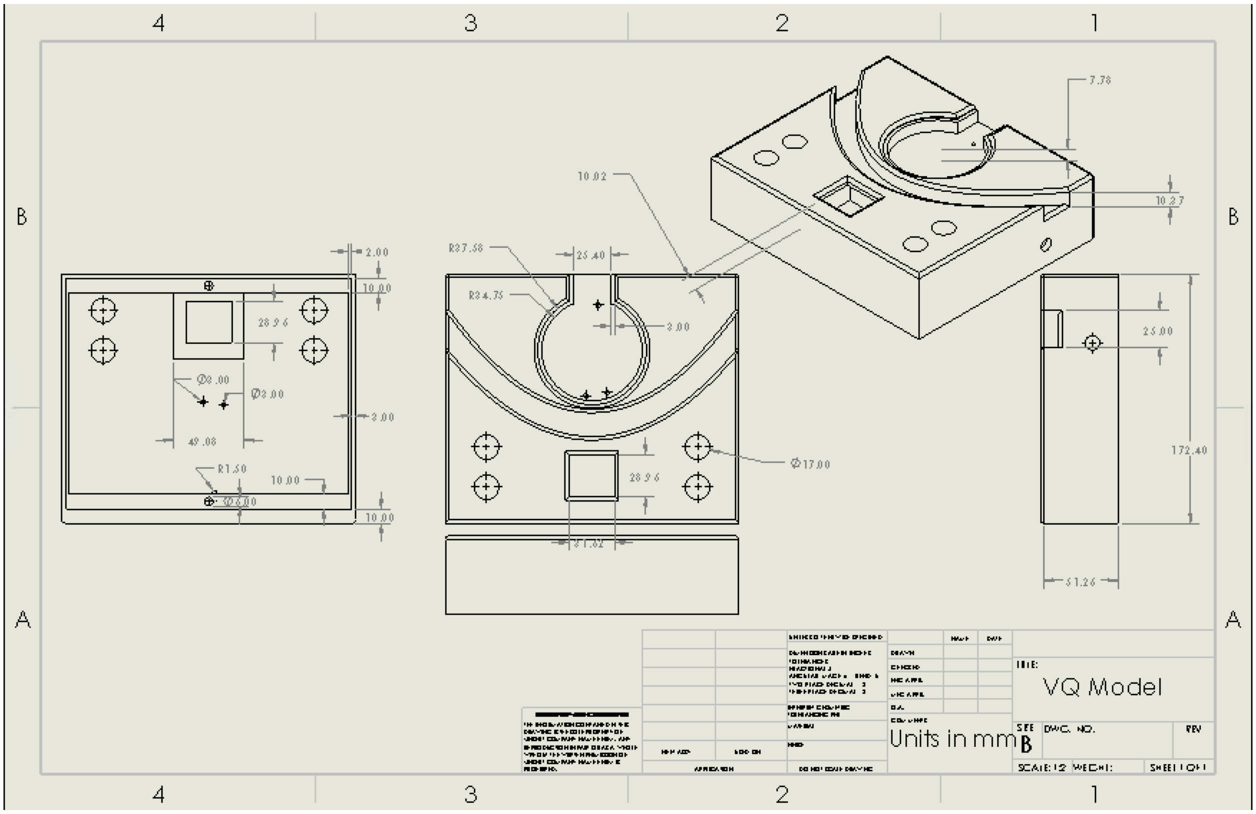

Figure 15: CAD drawing with dimensions in millimeters

## E. Arduino Program

```
#include <Adafruit_NeoPixel.h>
#include <elapsedMillis.h>
#include <Adafruit_GFX.h>    // Core graphics library
#include <Adafruit_ST7735.h> // Hardware-specific library for ST7735
#include <Adafruit_ST7789.h> // Hardware-specific library for ST7789
#include <SPI.h>

// These variables are set specifically for the display
#define TFT_CS        10
#define TFT_RST        9 // Or set to -1 and connect to Arduino RESET pin
#define TFT_DC         8

// Alveolus Variables
int ALV_LED_NUMBER = 64; // Number of LEDs connected in the ring LEDs
elapsedMillis minuteVent = 0; // THis counts the time between time the LED rings turn on and off
int alvSpeed = 2000; // Starting speed for the LEDs to turn on
int alvBrightness = 2; // Brightness used for the alveolus LEDs
bool ALV_ON = true; // When true, this turns on the LEDs, when false it will turn them all off to start over
bool SHUNT = false; // When true, all alveolus LEDs are white
String respirationRate = "2 L/min"; // String is updated as the settings change and it is the rates that are outputted to the display

// Capillary Variables
 int CAP_LED_NUMBER = 15; // Number of LEDs in the LED strip
 int blue = CAP_LED_NUMBER; // Used for the colors of the LED strip
 int red = (CAP_LED_NUMBER - 1) * 3; // Used for the colors of LED strip
 int pixelNumber = CAP_LED_NUMBER - 1; // PixelNumber is the LED that is off for each cycle
 bool capON = true; // when true, capillary LEDs are blue-red and flow, when false LEDs are turned to white
 int cap_4_5 = CAP_LED_NUMBER * 0.8; // Used to determine when the LEDs should change color
 elapsedMillis capillaryTime = 0; // Time between each off LED in the flow pattern
 int capSpeed = 400; // Initial capillary speed
 String perfusionRate = "2 L/min"; // String is updated as the settings change and it is the rates that are outputted to the display

 // Button values
 int alvSetting = 2; // Inital alveolus setting
 int capSetting = 2; // Initial capillary setting
 int alvIncreaseButton = 2; // digital pin for alveolus increase rate button
 int alvDecreaseButton = 3; // digital pin for alveolus decrease rate button
 int capIncreaseButton = 4; // digital pin for capillary increase rate button
```

```
 int capDecreaseButton = 5; // digital pin for capillary decrease rate button
 elapsedMillis buttonWait = 0; // used to create debouncing circuit


// Initializes neopixel LEDs and LCD dispaly
Adafruit_NeoPixel alveolusLED(ALV_LED_NUMBER, 7, NEO_GRB + NEO_KHZ800);
Adafruit_NeoPixel capillaryLED(CAP_LED_NUMBER, 6, NEO_GRB + NEO_KHZ800);
Adafruit_ST7735 tft = Adafruit_ST7735(TFT_CS, TFT_DC, TFT_RST);



void setup() {
  // Sets up serial and neopixel LEDs
  Serial.begin(9600);
  alveolusLED.begin();
  capillaryLED.begin();

  // pinMode for all 4 buttons
  pinMode(alvIncreaseButton, INPUT);
  pinMode(alvDecreaseButton, INPUT);
  pinMode(capIncreaseButton, INPUT);
  pinMode(capDecreaseButton, INPUT);
  // Initializes display
  tft.initR(INITR_144GREENTAB);
  // Setup display for initial start variables
  tftPrint();

}

void loop() {

// This section only counts how many times the button has been pressed
// The button wait is used to create a debouncing circuit - 300ms allows for it to count on 1 press each time
if(buttonWait > 300){
  // When the button is pressed, the digital pin will read 1 and it will increase or decrease settings and resets button timer
  if(digitalRead(alvIncreaseButton) == 1){
    alvSetting++;
    buttonWait = 0;
    // The max setting for this design is 4 for all variables
    if(alvSetting > 4){
      alvSetting = 4;
    }
    // Will redo the settings depending on how the buttons were pressed
    settingValues();
  }else if(digitalRead(alvDecreaseButton) == 1){
    alvSetting--;
    buttonWait = 0;
    if(alvSetting < 0){
      alvSetting = 0;
    }
    settingValues();
  }else if(digitalRead(capIncreaseButton) == 1){
    capSetting++;
    buttonWait = 0;
    if(capSetting > 4){
      capSetting = 4;
    }
    settingValues();
  }else if(digitalRead(capDecreaseButton) == 1){
    capSetting--;
    buttonWait = 0;
    if(capSetting < 0){
      capSetting = 0;
    }
    settingValues();
  }
}

  ////////////////////////////////////////////////////////////////////////////////////////////////////
  /////////////////////////////////////////////////////////////////////////////////////////////////////
  // ALV_ON will turn on the LEDS, if they are already on, they will then be turned off in the else statement
  // Turns LEDs on from inside out
  // alvSpeed is the total time it will take to turn on or off all the LEDs, but each ring will turn on every 1/4 of the alvSpeed
  // If a shunt occurs by user, no ventilation, the LEDs will turn white
  if(!SHUNT){
  if (ALV_ON) {

  // This will turn off LEDs from inside out
    // This turns on the inner most LED
    if (minuteVent > (alvSpeed / 4)) {
      for (int i = 40; i < 41; i++) {
        alveolusLED.setPixelColor(i, 0, alvBrightness, 0);
      }
      alveolusLED.show();
    }
    // This turns on the third LED ring
    if (minuteVent > (alvSpeed * 2 / 4)) {
      for (int i = 41; i < 47; i++) {
        alveolusLED.setPixelColor(i, 0, alvBrightness, 0);
      }
      alveolusLED.show();
    }
    // This turns on the second LED ring
```

```
    if (minuteVent > (alvSpeed * 3 / 4)) {
      for (int i = 24; i < 40; i++) {
        alveolusLED.setPixelColor(i, 0, alvBrightness, 0);
      }
      alveolusLED.show();
    }
    // This turns on the Outer most LED ring
    if (minuteVent > alvSpeed) {
      for (int i = 0; i < 24; i++) {
        alveolusLED.setPixelColor(i, 0, alvBrightness, 0);
      }
      alveolusLED.show();
      // This resets counter so only one counter needs to be running
      minuteVent = 0;
      // ALV_ON is changed to true so the LEDs turn back on in the other direction
      ALV_ON = false;
    }
  } else {
    // This allows the rings to stay on for a given period of time so they don't disappear right away
    if(minuteVent > alvSpeed /4){
      // After the LEDs wait for a given time, they will turn off and restart from the innermost ring
      alveolusLED.clear();
      alveolusLED.show();
      // Resets variables so it can continue to count to turn on at a certain pace
      ALV_ON = true;
      minuteVent = 0;
    }
  }
  }else{
    // When there is no ventilation, LEDs will turn on a dim white light
    for(int i = 0; i < ALV_LED_NUMBER; i++){
      // Should set capillary to a dim white instead of off
      alveolusLED.setPixelColor(i, alvBrightness / 2, alvBrightness / 2, alvBrightness / 2);
    }
    alveolusLED.show();
  }
//////////////////////////////////////////////////////////////////////////////////////////////////////////
////////////////////////////////////////////////////////////////////////////////////////////////////////
    // capON is used so that if no perfusion is occuring, it is set to false and the capillary LEDs turn white
    if(capON){
      // LEDs wait a given time before flowing, this speed is manipulated by the buttons
      if (capillaryTime > capSpeed){
        // pixelNumber ensures that the LEDs don't continue counting down for non-existant LEDs, if so it will restart at the top of the LEDs
        if(pixelNumber > -1){
          // if a shunt occurs in the alveolus, no diffusion occurs and capillary lights remain blue (done in else statement)
          if(!SHUNT){
            // This originally turns on all the leds to flow from blue to red to show deoxygenated to oxygenated
            for(int i = 0; i < CAP_LED_NUMBER; i++){
              // LEDs , "oxygen", diffuse early on so this makes sure that the color changes happens at a certain time
              if(i<CAP_LED_NUMBER/2 +1){
                capillaryLED.setPixelColor(i,red,0,blue);
                }
              else if(i<(CAP_LED_NUMBER)*0.8){
                  capillaryLED.setPixelColor(i,red,0,blue);
                  red = red - 14;
                  blue = blue + 14;

                }
             else{
                    capillaryLED.setPixelColor(i,0,0,blue);
                 }
            }
      }else{
        for(int i = 0; i < CAP_LED_NUMBER; i++){
          capillaryLED.setPixelColor(i,0,0,15);
        }
      }


    // This sets one LED off in the LED strip so they have a pattern of flow
    capillaryLED.setPixelColor(pixelNumber, 0, 0, 0);
    capillaryLED.show();
    // PixelNumber states which LED is off in a given time to create the illusion of flow
     pixelNumber--;
     // capillaryTime is reset so they rate is the same and lights don't flash through
     capillaryTime = 0;
     // Color variables need to be reset each time and LED is turned off so when they turn back on it creates flow
     red = (CAP_LED_NUMBER -1) *3;
     blue = 0;
     }
     else{
      pixelNumber = CAP_LED_NUMBER - 1;
     }
        }
  }else{
       for(int i = 0; i < CAP_LED_NUMBER; i++){
          // Should set capillary to a dim white instead of off
          capillaryLED.setPixelColor(i, 5, 5, 5);
        }
    capillaryLED.show();
        }
}
// Function for the display
```

```
void tftPrint(){

  // Sets up back ground color
  tft.setTextWrap(false);
  tft.fillScreen(ST77XX_BLACK);

  // Sets cursor position, size, and color for ventilation settings
  tft.setCursor(0, 0);
  tft.setTextColor(ST77XX_GREEN);
  tft.setTextSize(1);
  tft.print("V Setting: ");
  tft.print(alvSetting + 1);
  tft.println("/5");
  // Sets cursor position, size, and color for perfusion settings
  tft.setCursor(0, 10);
  tft.setTextColor(ST77XX_RED);
  tft.setTextSize(1.5);
  tft.print("Q Setting: ");
  tft.print(capSetting + 1);
  tft.println("/5");
  // Sets cursor position, size, and color for ventilation flow rates
  tft.setCursor(0,40);
  tft.setTextColor(ST77XX_GREEN);
  tft.println("Minute Ventilation: ");
  tft.setCursor(40,50);
  tft.println(respirationRate);
  //Sets cursor position, size, and color for perfusion flow rates
  tft.setCursor(0,60);
  tft.setTextColor(ST77XX_RED);
  tft.println("Perfusion Rate: ");
  tft.setCursor(40, 70);
  tft.println(perfusionRate);

  // Sets cursor position, size, and color to output overall V/Q ratio
  tft.setCursor(0, 90);
  tft.setTextColor(ST77XX_WHITE);
  tft.setTextSize(2);
  tft.println("V/Q Ratio: ");
  // This will calculate the V/Q ratio based off of the setting values which correspond to the ventialtion and perfusion rates
  tft.setCursor(40,110);
  tft.println((double)alvSetting/capSetting);
}
void settingValues(){
  // This is taking the value of the capillary/alveolus setting and assigning values
  // Cap settings are 0 through 4 and increases in perfusion rate with increase in cap setting values
  if(capSetting == 0){
    // capSpeed doesn't matter because LEDs will be solid white
    capON = false;
    // This changes the values of flow outputted to the display
    perfusionRate = "0 L/min";
    // This calls the display function to change the values on display corresponding to the new settings
    tftPrint();
  }else if(capSetting == 1){
    capON = true;
    // capSpeed changes for values 1-4 of settings and changes the rate the LEDs flash/flow
    capSpeed = 600;
    perfusionRate = "1 L/min";
    tftPrint();
  }else if(capSetting == 2){
    capON = true;
    capSpeed = 400;
    perfusionRate = "2 L/min";
    tftPrint();
  }else if(capSetting == 3){
    capON = true;
    capSpeed = 200;
    perfusionRate = "3 L/min";
    tftPrint();
  }else if(capSetting == 4){
    capON = true;
    perfusionRate = "4 L/min";
    tftPrint();
    capSpeed = 50;
}
// This is specific to the alveolus settings
  if(alvSetting == 0){
     SHUNT = true;
     // respirationRate sets the string value for flow rate for the display
     respirationRate = "0 L/min";
     // this calls the display function
     tftPrint();
  }else if(alvSetting == 1){
    // This changes the rate at which the LEDs turn on and changes for every setting manipulated by the user
    alvSpeed = 3000;
    SHUNT = false;
    respirationRate = "1 L/min";
    tftPrint();
  }else if(alvSetting == 2){
    alvSpeed = 2000;
    SHUNT = false;
    respirationRate = "2 L/min";
    tftPrint();
  }else if(alvSetting == 3){
```

```
    alvSpeed = 1400;
    SHUNT = false;
    respirationRate = "3 L/min";
    tftPrint();
  }else if(alvSetting == 4){
    alvSpeed = 900;
    SHUNT = false;
    respirationRate = "4 L/min";
    tftPrint();
  }
}
```