Pulse Oximeter with Digital Readout of SpO_2 and Heart Rate

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Blood Oxygen Saturation

- Healthy level of O_2 saturation > 95%
- Hypoxemia - low oxygen level in blood
    - Danger to organs
    - Can result in hypoxia (low oxygen levels in body tissues)
    - Hard to visually detect unless O2 saturation below 80% [Jubran 1999]
- Respiratory problems related to low blood oxygen levels
    - Asthma
    - Obstructive Sleep Apnea
    - Covid-19

Example of Disorders that Cause Hypoxemia

- Asthma
  - Airways blocked - difficulty breathing
  - Hypoxemia correlates with increased severity of attack [Solé et al. 1999]
- Obstructive Sleep Apnea (OSA)
  - Loud snoring, gasping, or choking during sleep
  - Difficult to diagnose - often requires sleep study
  - Can lead to heart failure
  - Early confirmation and treatment helps prevent complications [Chiang et al. 2018]
- Covid -19
  - Respiratory virus
  - Oxygen saturation lower than 90% indicates severe case

Bioinstrument - Pulse Oximeter (Transmission)

- Digital readout of SpO_2 (arterial blood oxygen saturation) and heart rate
- Benefits
  - Non-invasive
  - Accuracy within 2-3% [Jubran 1999]
- Function
  - Light-emitting diodes (LEDs) - red and infrared (IR)
  - Photodiode receives light transmitted
  - SpO_2 from ratio of absorbances at above wavelengths
    - oxyhemoglobin (HbO_2)
    - reduced hemoglobin (Hb)
  - Finds heart rate using IR signal

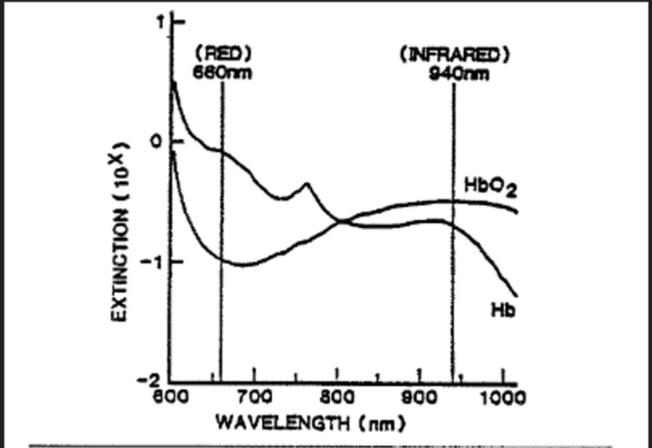
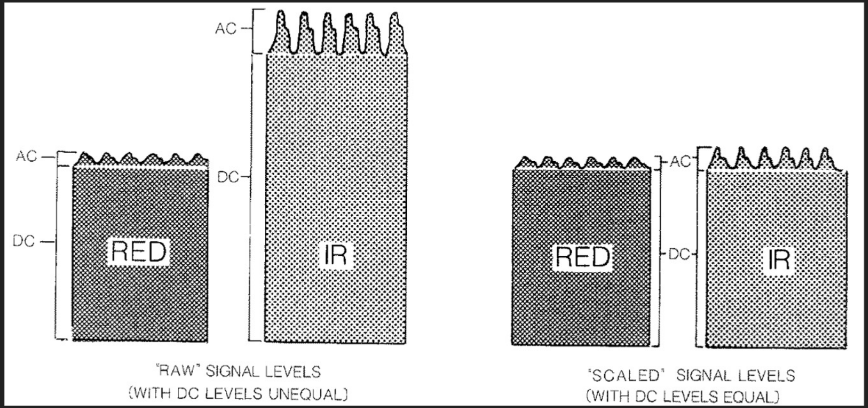


Fig 1. Oxyhemoglobin (HbO_2) and reduced hemoglobin (Hb) exhibit markedly different absorption (extinction) characteristics relative to red light at 660 nm and infrared light at 940 nm. (Courtesy of Ohmeda)

(Wukitsch 1988)

Finding SpO_2

- SIgnal from light transmitted through tissue
- At single wavelength:
  - Tissue absorbance proportional to (AC signal)/(DC signal)
  - Using ratios means the numbers will scale to each other



Demonstration of scaling [Wukitsch et al. 1988]

$$R = \frac{\frac{AC(\lambda_{Red})}{DC(\lambda_{Red})}}{\frac{AC(\lambda_{IR})}{DC(\lambda_{IR})}}$$

R: ratio of tissue absorbances

$$SpO_2 = 110 - (25 \times R)$$

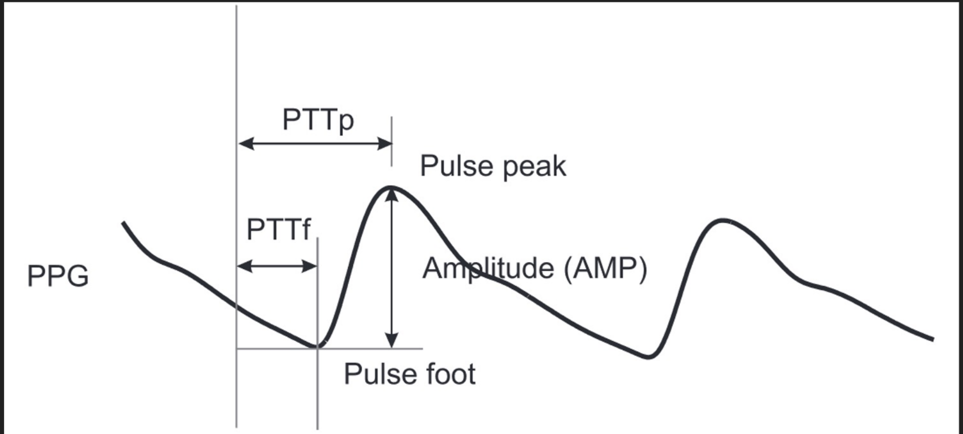
Equation for SpO_2

Finding Heart Rate

- Uses photoplethysmography (PPG)
  - Transmitted signal of IR light through tissue
  - Proportional to blood volume variations [Castaneda et al. 2018]
- Heart rate
  - contractions per minute
  - Found from peaks in PPG signal

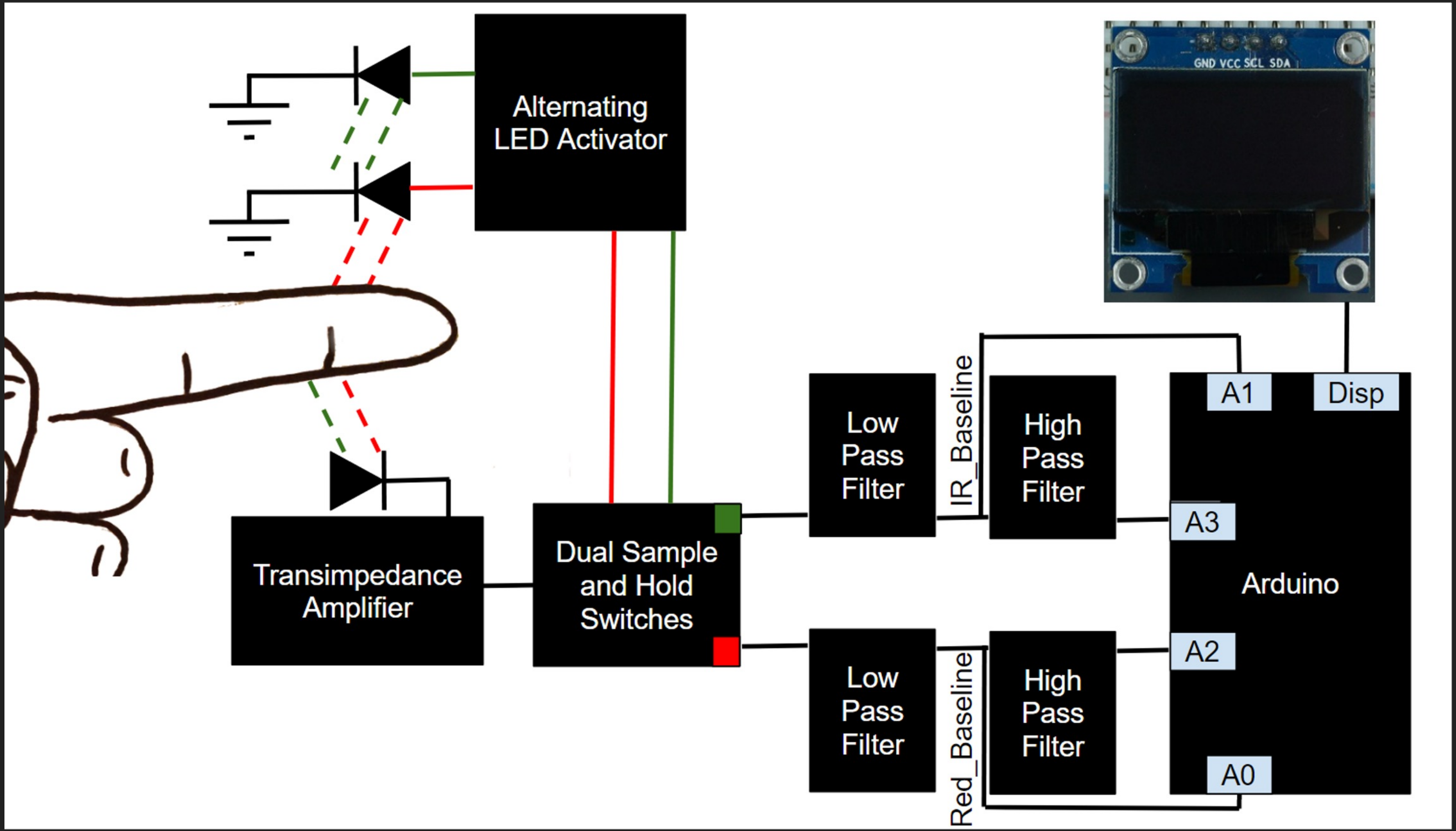
$$HR = \frac{60}{T_{pp}}$$

T_{pp} = time between peaks



[Allen 2007]

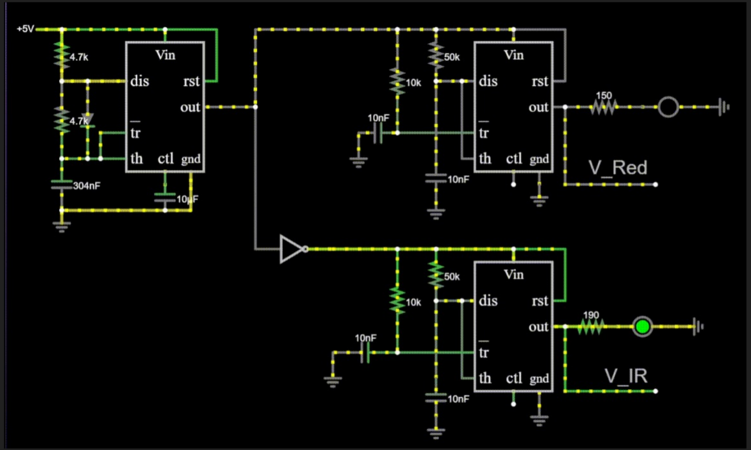
Big Picture

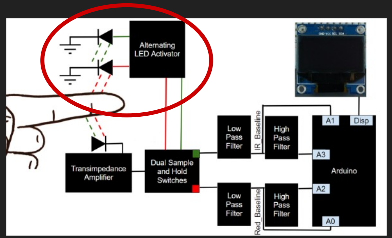


Alternating LED Activator
Transimpedance Amplifier
Dual Sample and Hold Switches
Low Pass Filter
IR_Baseline
High Pass Filter
Low Pass Filter
Red_Baseline
High Pass Filter
GND VCC SCL SDA
A1
Disp
A3
Arduino
A2
A0

Alternating LED Activator

- Astable Oscillator (555 Timer)
  - Diode from Discharge to Trigger for 50% duty cycle
  - T = 0.7RC = 0.001 Sec (50% Duty) -> 500 Hz pulse rate
- Two Monostable Oscillators
  - Connected together with an inverter to create alternating pattern
  - T_ on = 1.1 x R(50k) x C(10n) = 0.0005 Sec (25% Duty)
  - Lower duty cycle = less heat, less power consumption
- LED
  - Red -> forward 2V, 20mA
    - LED Resistor = (5V-2V) / 0.02 = 150 Ω
  - Infrared -> forward 1.2V, 20mA
    - LED Resistor = (5V-1.2V) / 0.02 = 190 Ω
- Output: V_Red and V_IR for later



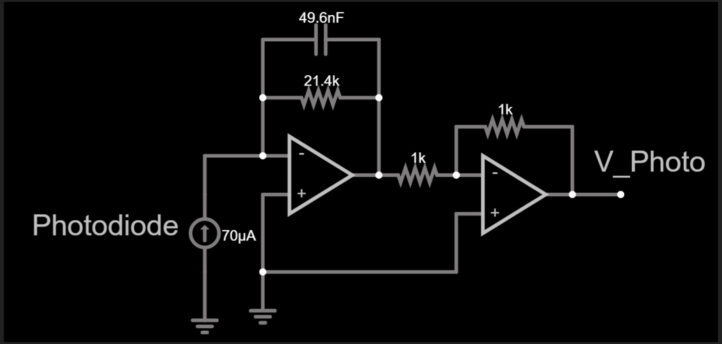


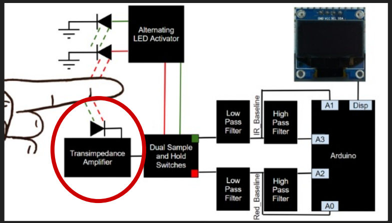
Transimpedance Amplifier (TIA)

$$\frac{V_{photo}}{I_{photo}} = -Z_{top}$$

$$Z_{top} = Z_C || Z_R = \frac{R}{jwRC+1}$$

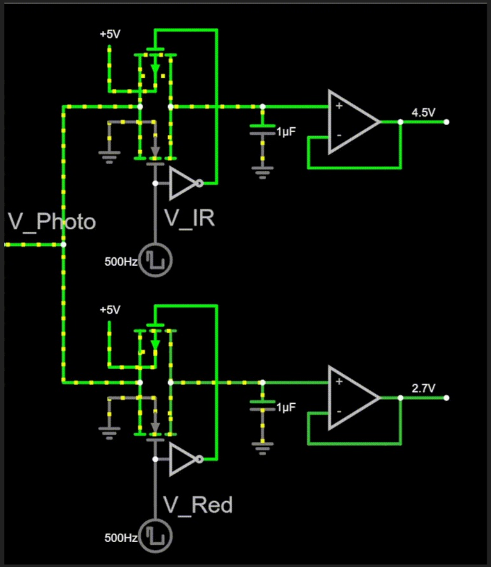
- Goal: Convert current output from photodiode to voltage
- Photodiode outputs current from ~ 0 - 70 uA [Duun 2007]
- Want V_Photo between 0 - 1.5V
  - R is set to 21400 ohm
- A capacitor is added in parallel to the resistor
  - Act as a low pass filter to filter out noise (fc = 150Hz)
  - Cutoff frequency (2pi*fc) = 1/RC
    - Capacitor set to 49.6 nF
- Inverting amplifier
  - Gain of -1 to ensure voltage remain positive for sample and switch stage

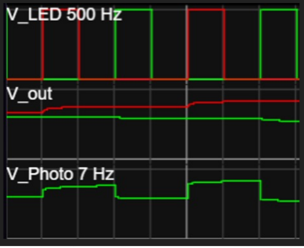


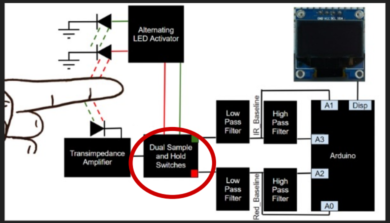


Dual Sample and Hold Switches

- Switch - Transmission gate
  - n-channel MOSFET and p-channel MOSFET connected in parallel with drain and source connected
  - Gate of each mosfet connected with an inverter
  - Current can flow both ways depending on the voltage difference between source and drain
- Sample and Hold
  - When the switch turn on from V_IR or V_Red, the capacitor charges or discharges to match V_Photo
  - Capacitor (1uF) - low to enable faster charging but large enough to prevent leak







Low Pass Filter

Poles	Butterworth (DC Gain H_0)	Chebyshev (0.5dB) λ_n	Chebyshev (0.5dB) Gain	Chebyshev (2.0dB) λ_n	Chebyshev (2.0dB) Gain
2	1.586	1.231	1.842	0.907	2.114
4	1.152	0.597	1.582	0.471	1.924
	2.235	1.031	2.660	0.964	2.782
6	1.068	0.396	1.537	0.316	1.891
	1.586	0.768	2.448	0.730	2.648
	2.483	1.011	2.846	0.983	2.904
8	1.038	0.297	1.522	0.238	1.879
	1.337	0.599	2.379	0.572	2.605
	1.889	0.861	2.711	0.842	2.821
	2.610	1.006	2.913	0.990	2.946

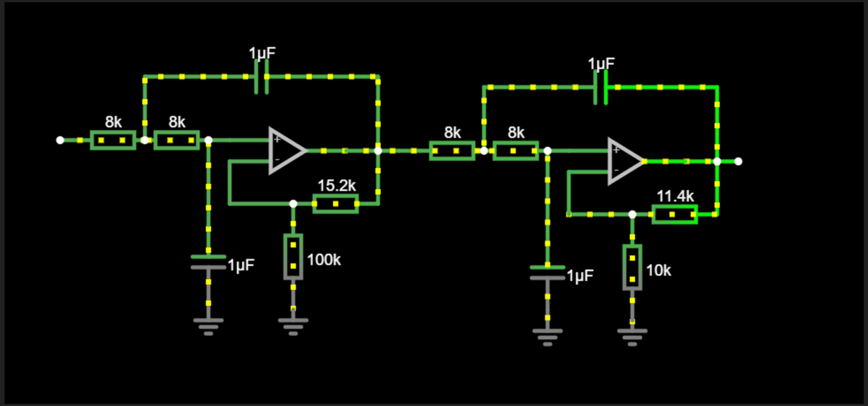
Table I Design Table for Butterworth and Chebyshev filters

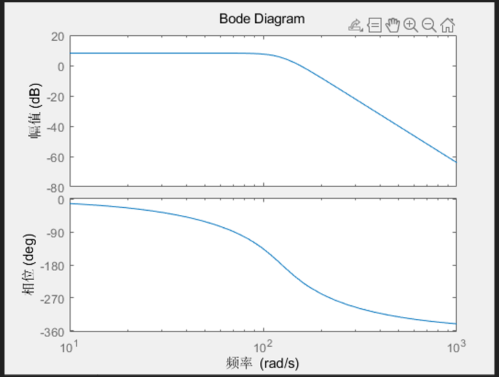
$$fc = \frac{1}{2\pi RC} = 19.89Hz$$

$$H(s) = H1(s) * H2(s)$$
$$= \frac{1.152}{(sCR)^2+1.848sCR+1} * \frac{2.235}{(sCR)^2+0.765sCR+1}$$
$$= \frac{2.5747}{(sCR)^4+2.6131(sCR)^3+3.4142(sCR)^2+2.6131(sCR)+1}$$

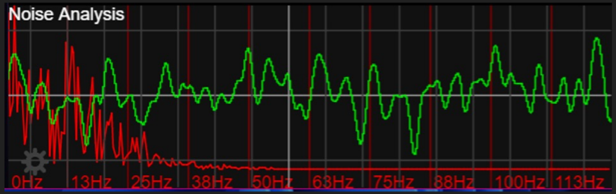
Gain of 2.5747

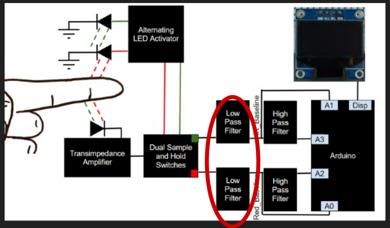
Signal range: 0 - 3.862 V





Goal: Filter out noise above 20 Hz (Shimizu, Hatano, & Shimoyama, 2012)



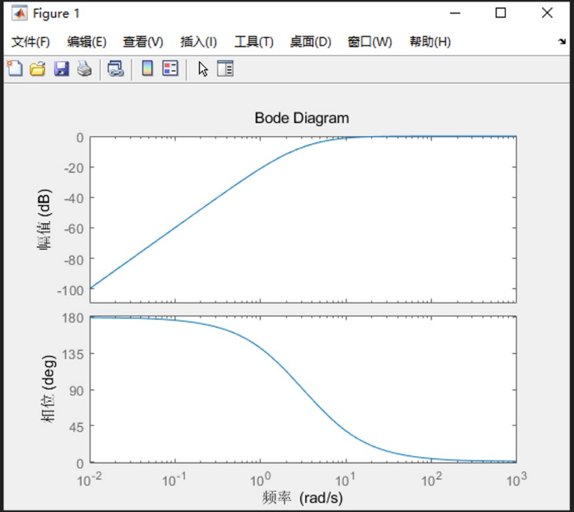


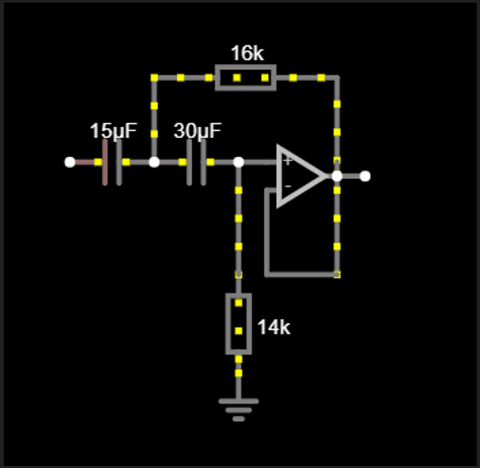
High Pass Filter

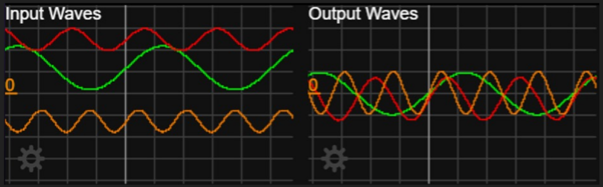
$$fc = \frac{1}{2\pi\sqrt{R1C1R2C2}} = 0.501Hz$$

(Shimizu, Hatano, & Shimoyama, 2012)

$$\frac{Vout(s)}{Vin(s)} = \frac{s^2}{s^2+s(\frac{1}{R2C1}+\frac{1}{R2C2})+\frac{1}{R1C1R2C2}} = \frac{s^2}{s^2+7.1429s+9.9206}$$

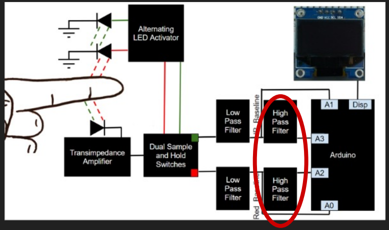






Goal: Obtain the AC component

Active high pass filter set to filter out frequencies below 0.5 Hz, which removes the DC offset as shown in the simulation plots



Arduino

```
#include <Wire.h>
#include <Adafruit_SSD1306.h>

#define OLED_RESET 4
Adafruit_SSD1306 display(OLED_RESET);

const int redDCPin = A0; // Analog input pin for DC signal from red LED
const int irDCPin = A1; // Analog input pin for DC signal from IR LED
const int redACPin = A2; // Analog input pin for AC signal from red LED
const int irACPin = A3; // Analog input pin for AC signal from IR LED

const int numSamples = 1000; // Number of samples to average for each
reading

// Function to find the time between peaks in the given signal
float findPeakTime(int signalPin) {
  int threshold = 512; // Threshold for peak detection
  int peakCount = 0; // Count of peaks found
  float lastValue = analogRead(signalPin); // Last value of the signal
  float peakTime = 0.0; // Time of the last peak found
  float sampleRate = 1000.0 / numSamples; // Sample rate in Hz

  // Iterate over the samples in the signal
  for (int i = 0; i < numSamples; i++) {
    float value = analogRead(signalPin);
    if (lastValue < threshold && value >= threshold) {
      // A peak has been found
      if (peakCount == 0) {
        // This is the first peak found
        peakTime = i * (1.0 / sampleRate);
      } else if (peakCount == 1) {
        // This is the second peak found, return the time between them
        return i * (1.0 / sampleRate) - peakTime;
      }
      peakCount++;
    }
    lastValue = value;
  }

  // No peaks were found
  return 0.0;
}

void setup() {
  // Initialize the OLED display
  display.begin(SSD1306_SWITCHCAPVCC, 128, 32);

  // Print a message to the display
  display.clearDisplay();
  display.setTextSize(1);
  display.setTextColor(WHITE);
  display.setCursor(0, 0);
  display.println("SpO2 & Heart Rate");
  display.display();
  delay(1000);
}
```

Find peaks

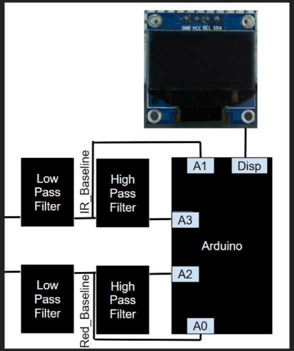
```
void loop() {
  // Read the DC signals from the analog inputs
  int redDC = analogRead(redDCPin);
  int irDC = analogRead(irDCPin)

  // Read the AC signals and average over numSamples
readings
  float redAC = 0.0;
  float irAC = 0.0;
  for (int i = 0; i < numSamples; i++) {
    redAC += analogRead(redACPin);
    irAC += analogRead(irACPin);
  }
  redAC /= numSamples;
  irAC /= numSamples;

  // Calculate the ratio of AC to DC signals for both
red and IR
  float redRatio = redAC / redDC;
  float irRatio = irAC / irDC;

  // Calculate SpO2 using the ratio of red and IR
signals
  float ratio = redRatio / irRatio;
  float SpO2 = 110 - 25 * ratio;

  // Calculate heart rate by finding the time between
peaks in the AC signals
  float redPeakTime = findPeakTime(redAC);
  float irPeakTime = findPeakTime(irAC);
  float heartRate = 60.0 / (0.5 * (redPeakTime +
irPeakTime));

  // Display the results on the OLED display
  display.clearDisplay();
  display.setCursor(0, 0);
  display.print("SpO2: ");
  display.println(SpO2);
  display.print("Heart Rate: ");
  display.println(heartRate);
  display.display();
  delay(1000);
}
```

DC recording

AC recording

SpO2

Heart rate



Limitations/Future Directions

- Accuracy: Various factors could affect the accuracy, such as motion artifacts, skin pigmentation, poor contact, and ambient light.
- Noise: Susceptible to noise, which can affect the accuracy of the measurements.
- Battery Life: Consume a lot of power, which reduces the longevity of pulse oximeter.
- Complexity: Difficult to manufacture and maintain due to the complexity.
- Simulation: While simulators are powerful, they may not always perfectly reflect the real-world performance.

References

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