Adaptive Pulse Oximeter

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What is a Pulse Oximeter? (B)

- Medical device that can read your heart rate and blood oxygen saturation.
- First steps in diagnosis and checkups
- Used to monitor oxygen saturation for administering external oxygen supply
- Minimally invasive method

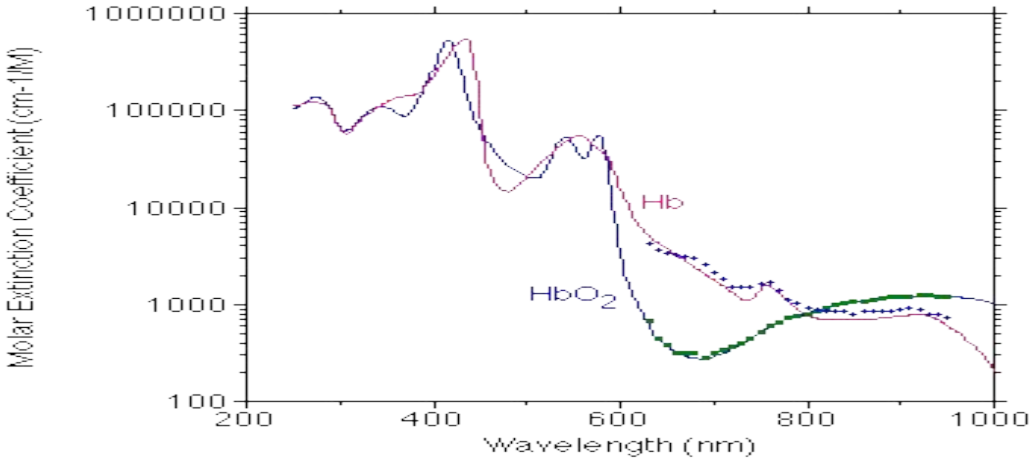
Consumer Grade Pulse Oximeter

Why do we care? (B)

- Pulse oximeters are minimally invasive
  - Blood draws are the only alternative
- Relatively cheap
- Very basic to manufacture/ Basic parts
- Very simple to use with adequate precision (exceptions)

Key Flaw in the pulse ox (B)

- Calibrated for lighter skin tones
- People with darker skin pigmentation get imprecise readings
- Gives readings that get artificially higher the darker the pigmentation
- Differences at key wavelength of 680 nm

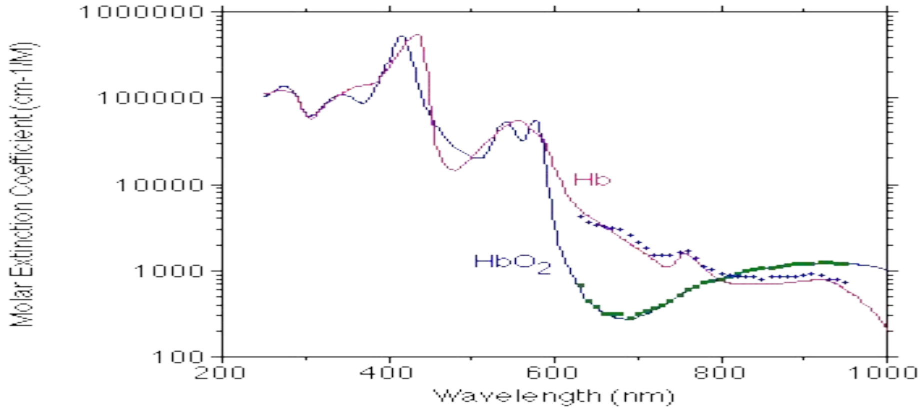


What does this mean? (B)

- Pulse Ox used to administer external oxygen
- Overestimate in Pulse Ox means under administering external oxygen in darker skinned patients
- Many other medical uses for pulse oximeters including diagnosis is disrupted by this
- Creates racial disparities in healthcare quality

Our Idea (B)

- Calibrate the standard Pulse Ox for every patient
- Includes a color sensor to detect skin pigmentation of subject
- Use some sort of regression method to extrapolate a calibration curve to 680nm
- Use a few wavelengths at points where Hb and HbO2 are close



Methods: Goal For Data Acquisition (B)

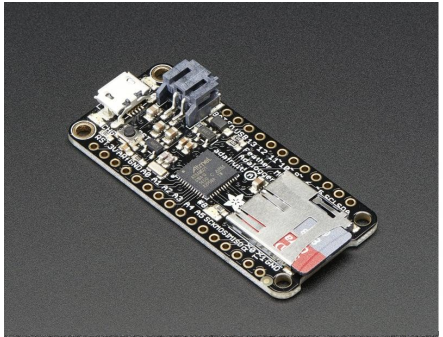
- Sample a diverse set of people (different skin tones)

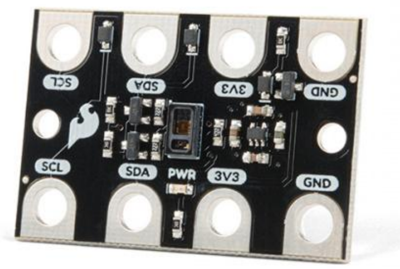
- Limitation: no reliable way to gather control data
  - Pulse oximeters are imprecise (as mentioned before)
  - Only alternative is to draw blood, we don't have that equipment

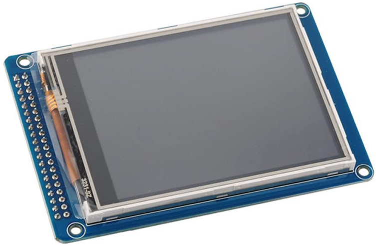
- Theoretical model of the spectra of patient solely from color data

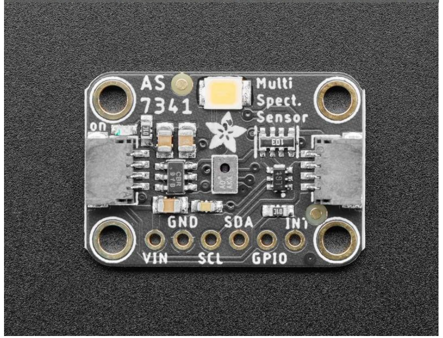
- Proceed to build a model regardless, with only color data.

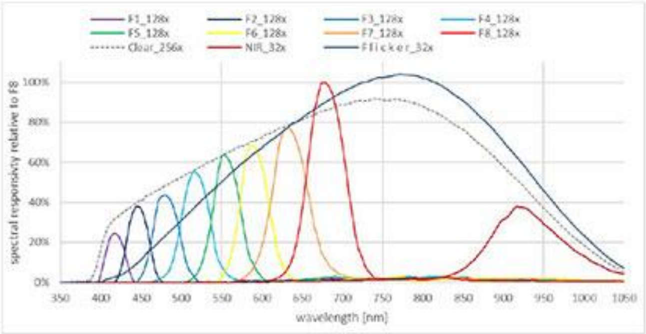
Breakdown of Sensor and Modules Used (B)



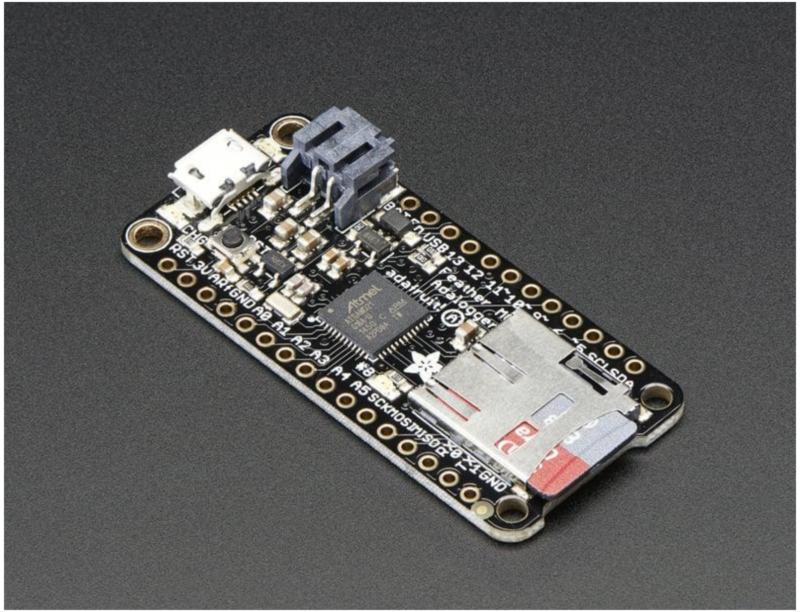








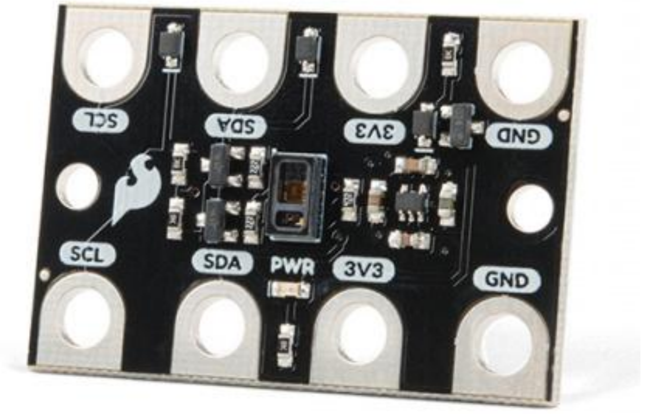
Feather M0 Microcontroller (B)



- As data logger and microcontroller
- Why we made the swap
    - Integrated SD card slot saved space
    - Small form factor compared to mega 2560
    - Support for an external lithium battery
- Difficulties
    - Not always straightforward to adapt code
    - Took time getting used to reset button
    - Required different board firmware (took us a while to figure out)
- Once difficulties were fleshed out the feather was great!

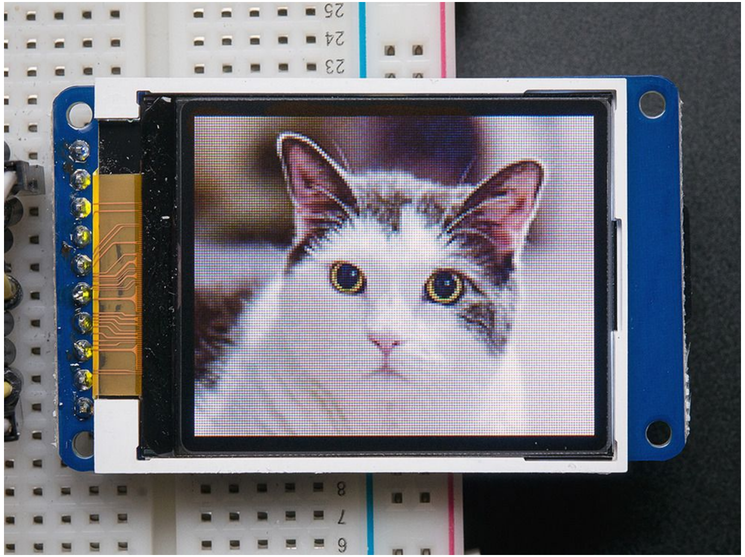
MAX30102 Pulse Oximeter (SparkFun) (B)

- Large, but similar in size to the Color Sensor
- Pulse sensor, SpO2 detection (blood oxygen)
- NOTE: this pulse ox uses reflectance
  - Clamp pulse oxes use transmittance through finger.
- BUT: our method is adaptable
  - Reflectance is inverse of transmittance
- We can apply calibration parameter to this



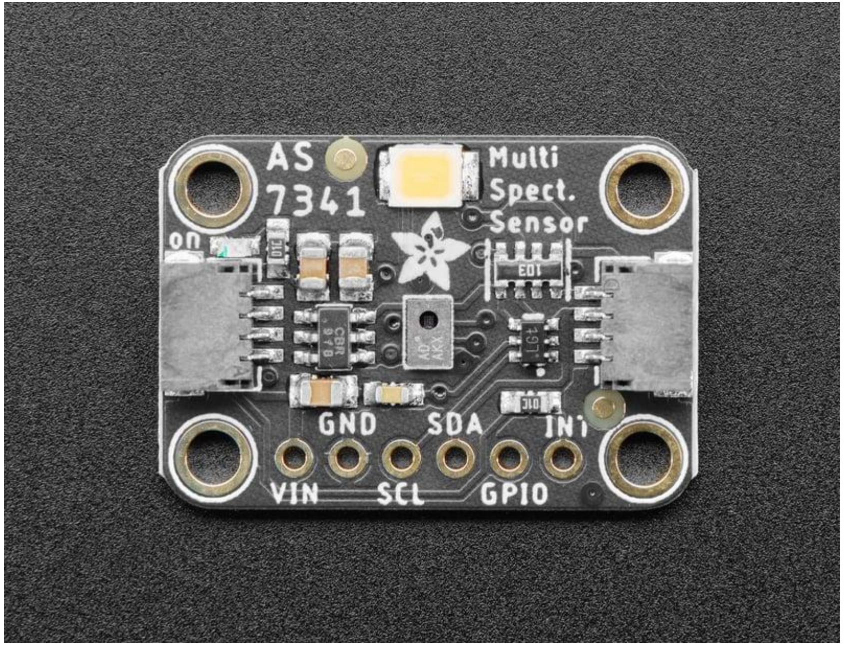
TFT Display (B)

- Provide a simple way to display data
- Large enough to display all sorts of things
- Colorful so it’s easy on the eyes
- Not much else. We thought it’d be interesting.

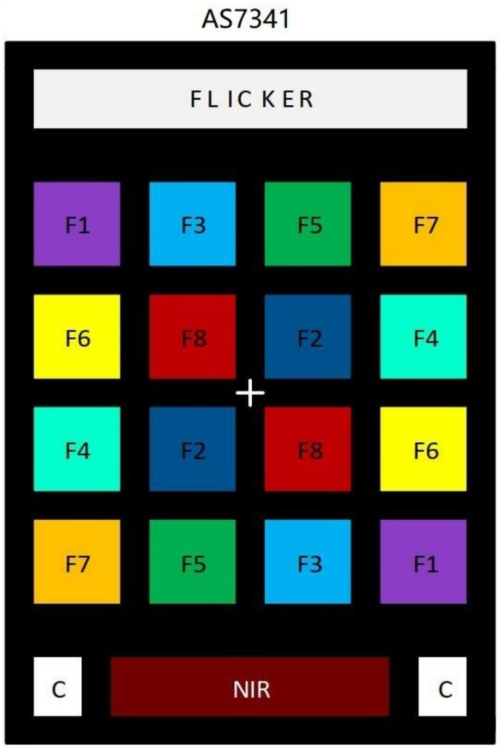


AS7341 Color Sensor (B)

- By far, most important.
- We use only 3 wavelengths
- Chose this one for its flexibility
- Small form factor
- Integrated white LED (pretty good)
- Caveat: glaring green LED onboard
  - Disrupts color readings (baffling inclusion)
- We removed the green LED

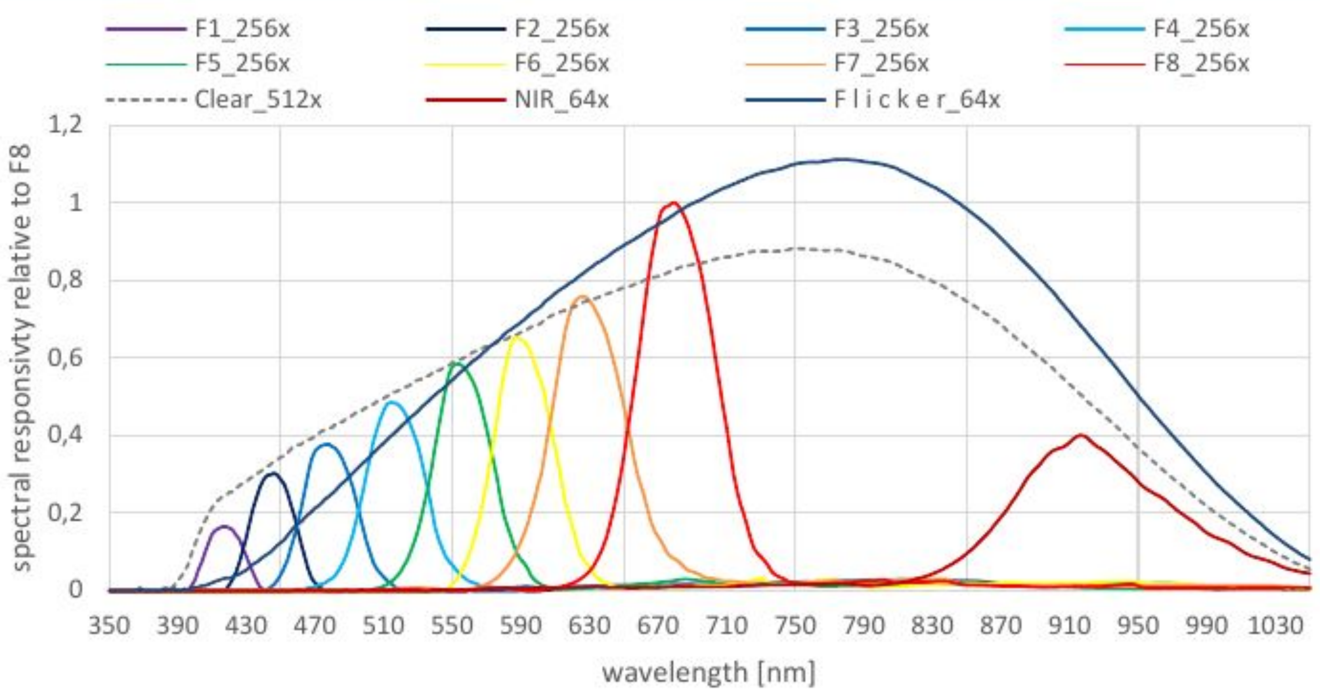


Sensor on AS7341 (B)

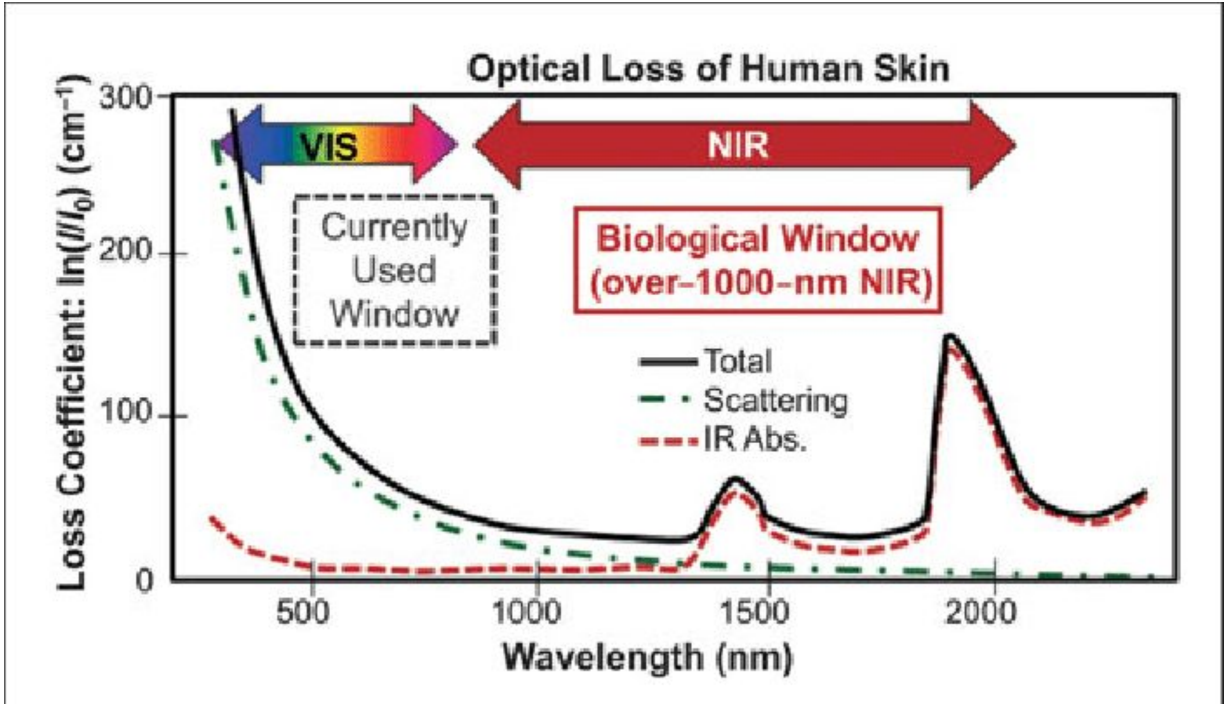


F1(405-425nm)
F2(435-455nm)
F3(470-490nm)
F4(505-525nm)
F5(545-565nm)
F6(580-600nm)
F7(620-640nm)
F8(670-690nm)

Spectral Range of AS7341 (B)



Typical Light Absorption of Skin (B)



(as a function of wavelength)

Prototype Pulse Ox

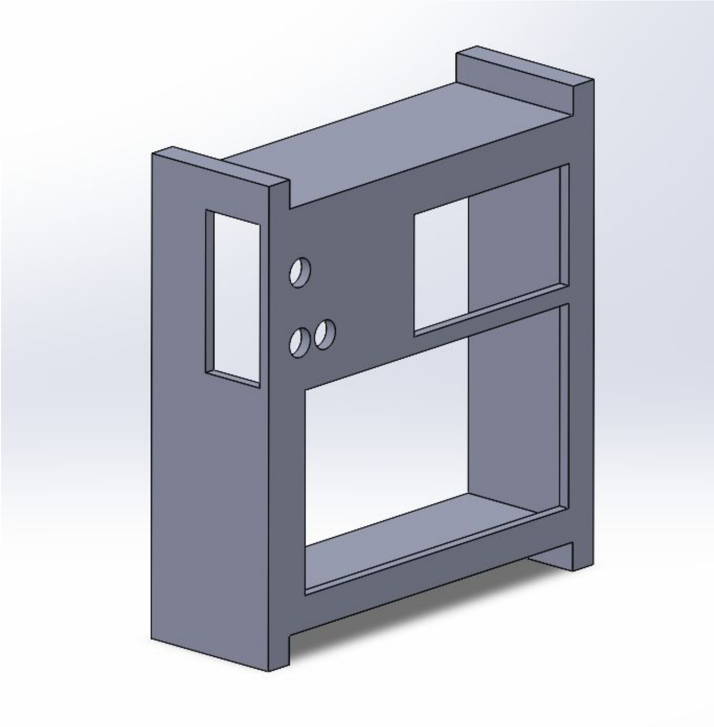
Device Design

- Two separate units
- Feather M0 and TFT in display case
- Spo2 and colorimeter in ergonomic finger holder

Display

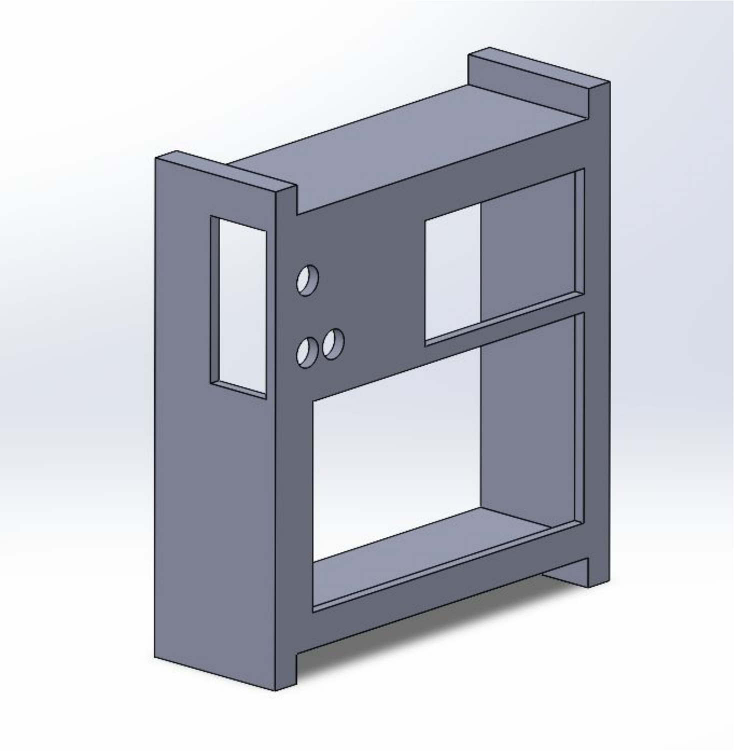
- Contains Feather M0 and TFT Display

- Access to SD card, micro usb port, and reset button



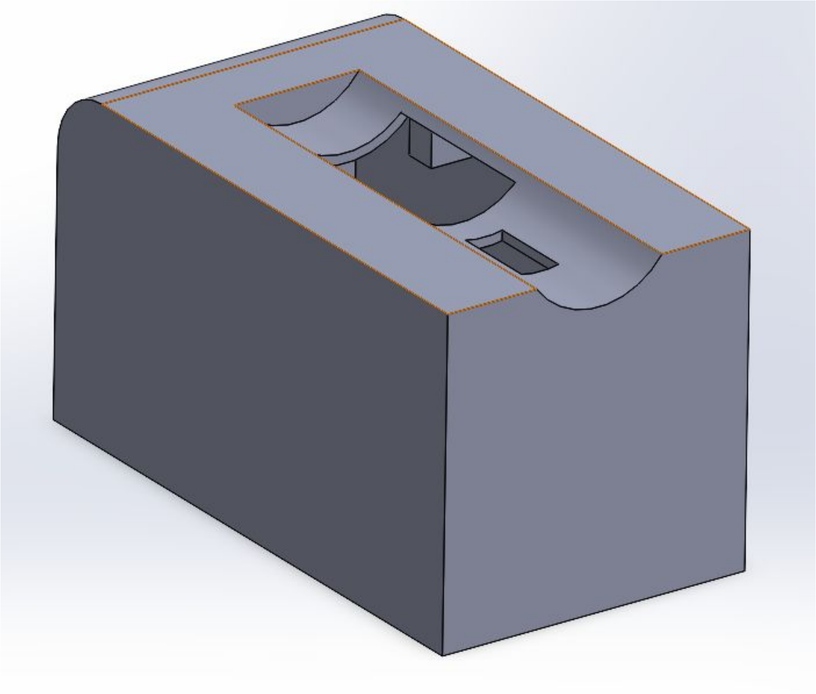
Challenges

- Opening for usb port slightly out of place
- Opening for SD card too small to access



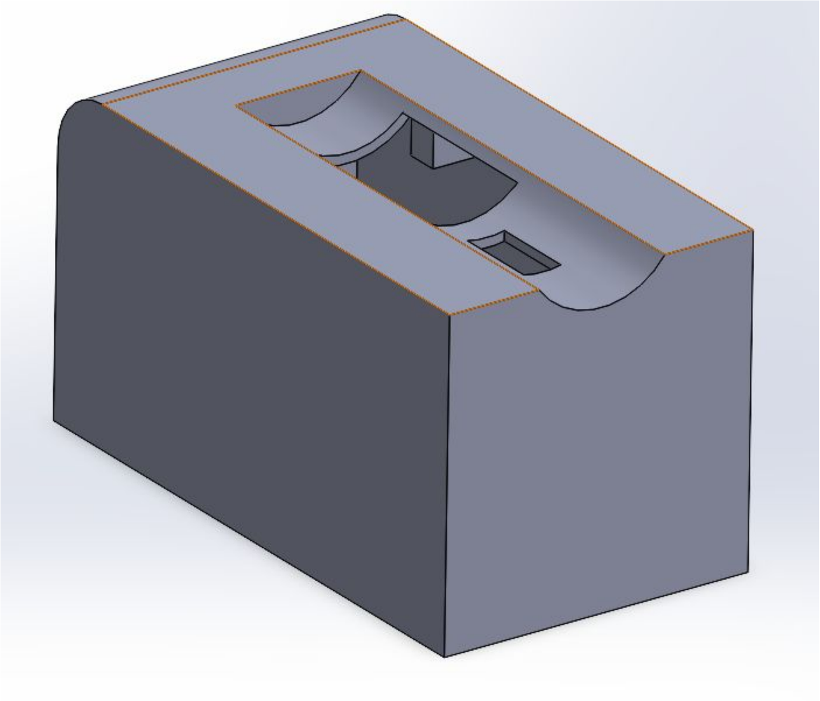
Finger Holder

- Based on existing pulse oximeters
- Maintains constant pressure on spo2 sensor
- Colorimeter at a distance from finger to avoid saturation



Challenges

- Opening for spo2 sensor was too small and would not sense the finger
- Colorimeter LED too bright, saturated the sensor
- Posts used to fasten pcb boards were too brittle



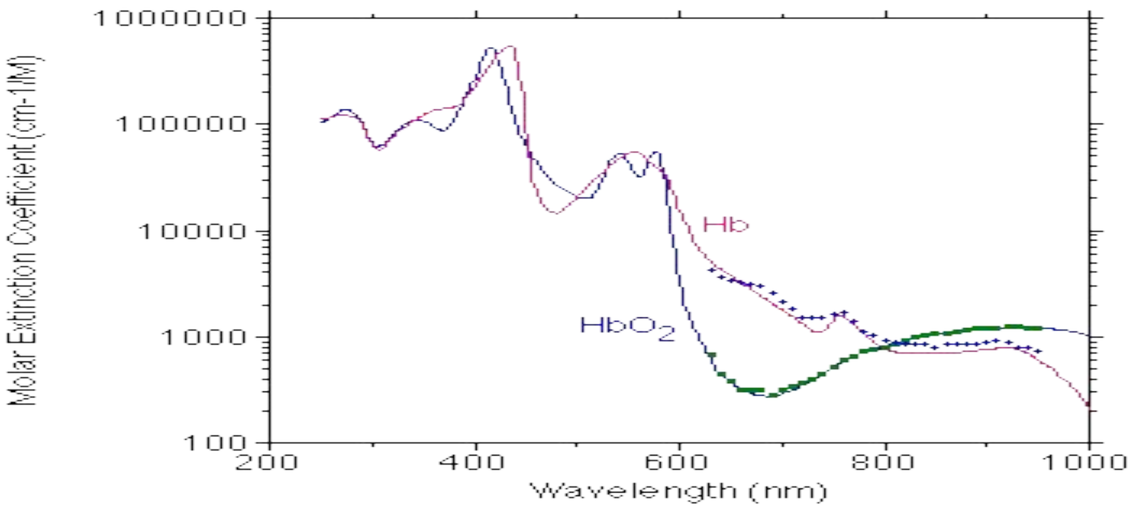
Data Collection

- Attempted to test front and back of finger to determine correlation between skin pigmentation and spo2 readings

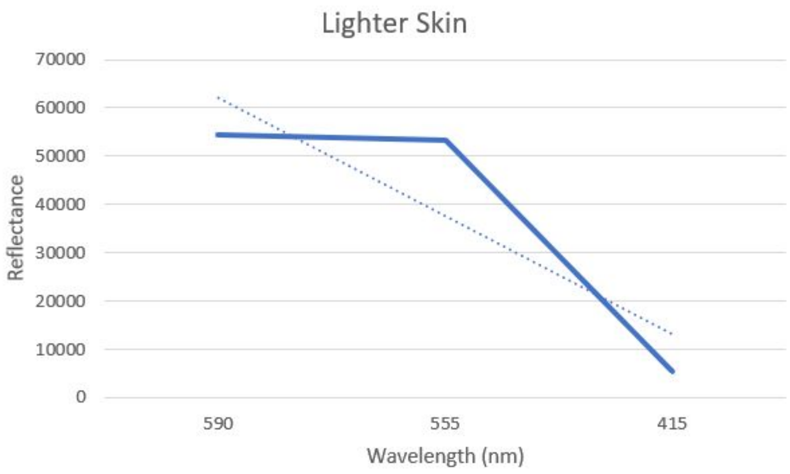
- Inaccurate spo2 when testing back of finger

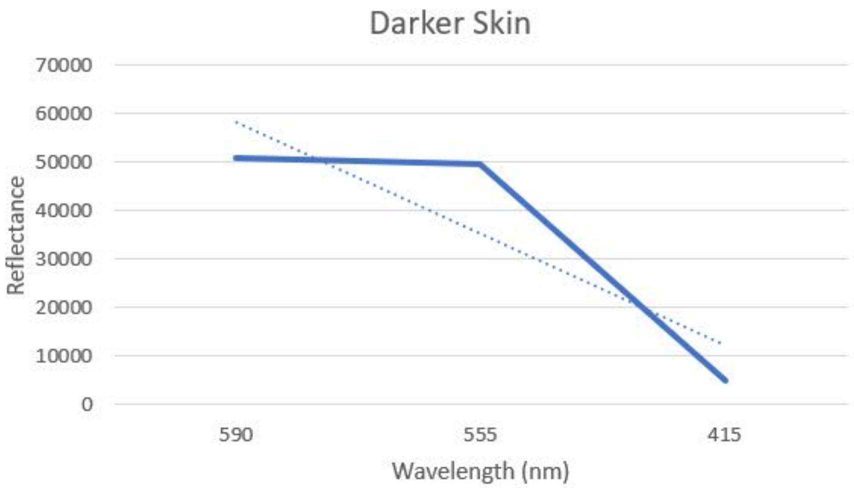
- Instead used select wavelengths to plot skin color absorption and compared the plots in an attempt to find a way to calibrate the pulse oximeter

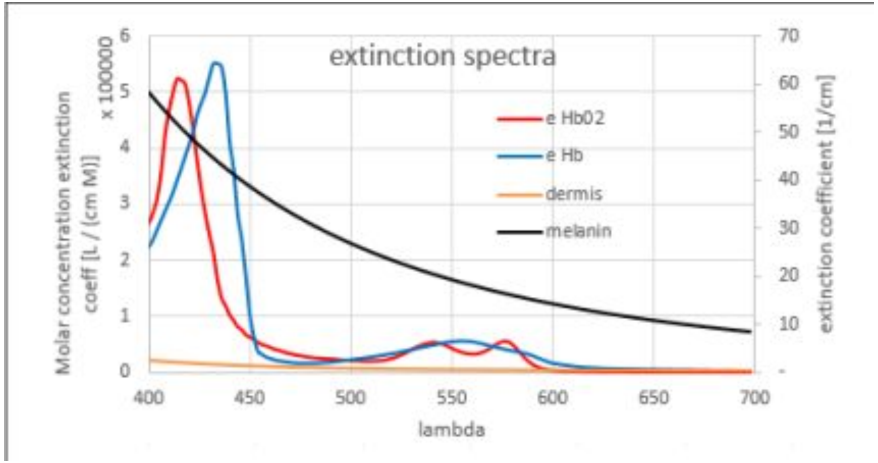
- Used 590, 555, and 415 nm wavelengths to plot melanin absorption

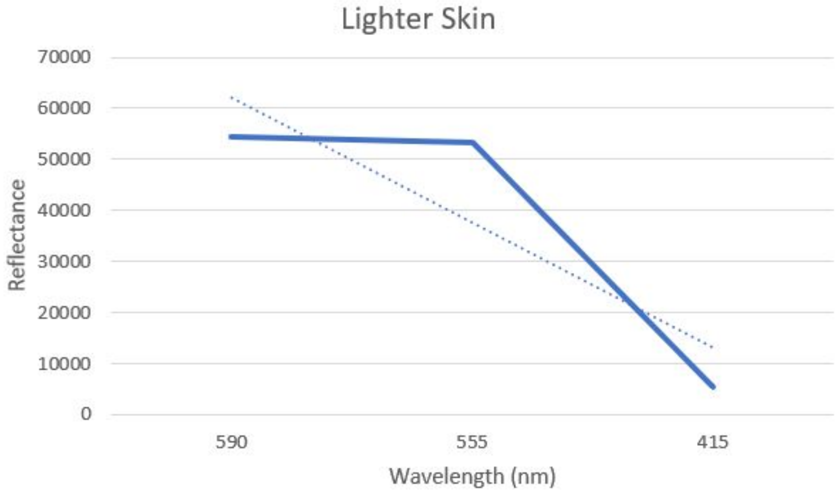


- 590 nm and 555 nm wavelengths were the best indicators of different skin colors
- Found line of best fit for the data points
- Compared slope in an attempt to calibrate the pulse oximeter






extinction spectra
e Hb02
e Hb
dermis
melanin
Molar concentration extinction coeff [L / (cm M)]
x 1000000
extinction coefficient [1/cm]
lambda
0
1
2
3
4
5
6
10
20
30
40
50
60
70
400
450
500
550
600
650
700


Lighter Skin
Reflectance
Wavelength (nm)
0
10000
20000
30000
40000
50000
60000
70000
590
555
415

Discussion: Calculation Method Limitations (B)

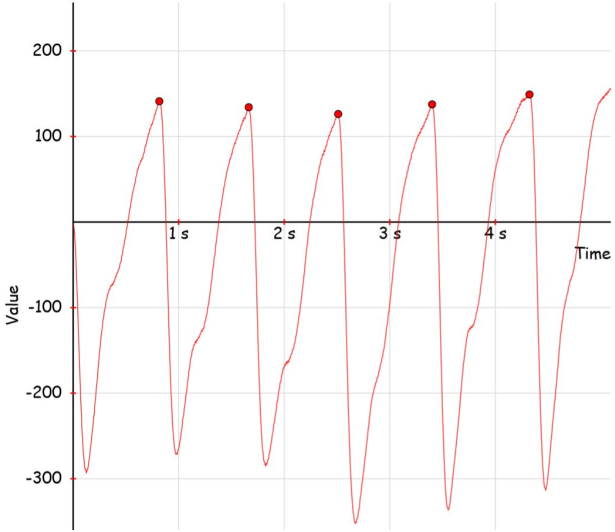
- Regression relies on extrapolation.
- Lack of control data means we can’t be sure how exactly absorption of skin changes with pigmentation at different wavelengths
- Dark skin may have details we can’t see or predict at lower wavelengths
- Without control (blood draws), we can’t know for sure.

Code

- Pulse Oximeter
- Spectrometer
- Data Collection
- Calibration

Pulse Ox

- Heart Rate - Zero Crossing



- SpO2

$$R = \frac{\frac{AC_{red}}{DC_{red}}}{\frac{AC_{ir}}{DC_{ir}}}$$

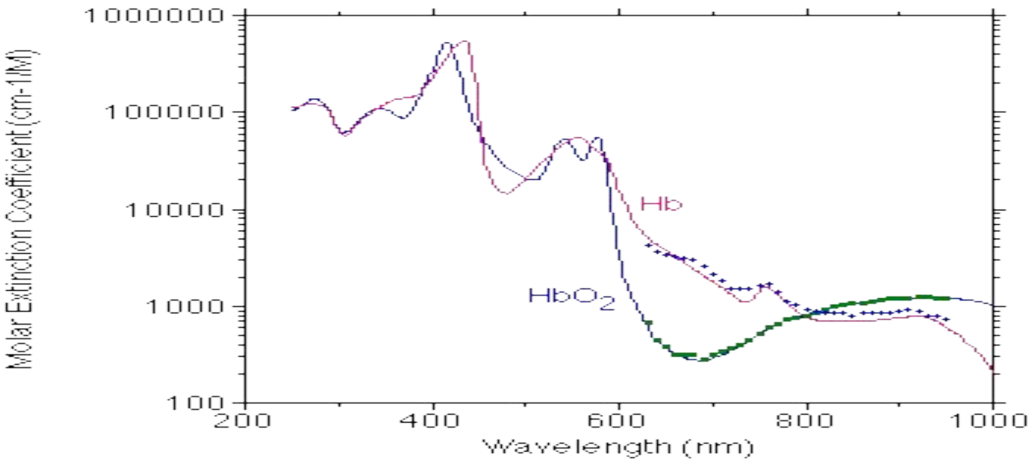
$$SpO_2 = a \cdot R^2 + b \cdot R + c$$

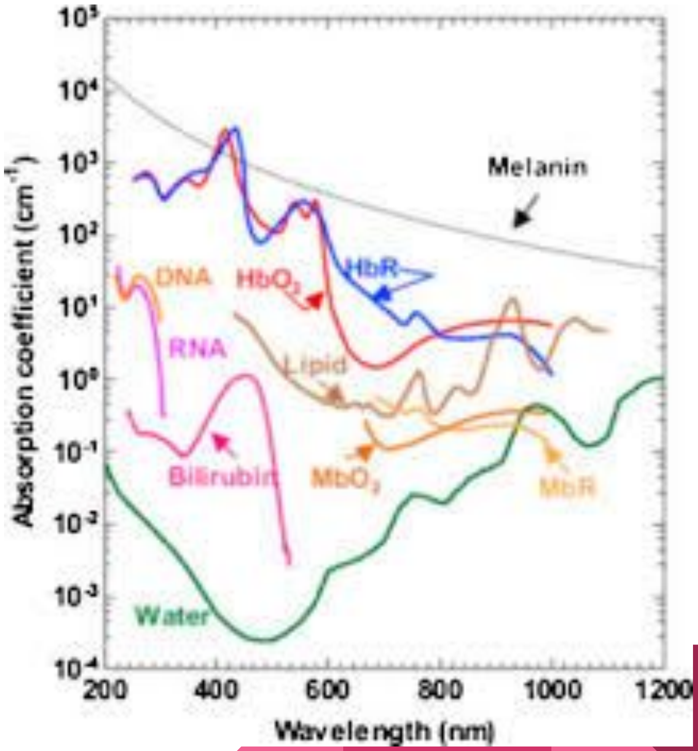
$$a = 1.5958422$$

$$b = -34.6596622$$

$$c = 112.6898759$$

Calibration Methods





CIELab colorspace and ITA

Table 2. Examples of Mean L*, a*, and b* Values for the Six Groups of Skin Color

Skin color type	ITA°	Mean values ± SEM L*	a*	b*
Very light	>55	74.5 ± 1.5	3.7 ± 0.5	14.5 ± 0.7
Light	55–41	68.8 ± 0.5	7.0 ± 0.6	17.4 ± 0.5
Intermediate	41–28	63.3 ± 0.4	7.4 ± 0.5	18.7 ± 0.5
Tan	28–10	57.5 ± 0.3	10.1 ± 6.0	20.2 ± 0.5
Brown	10 to −30	47.0 ± 0.9	10.4 ± 0.5	18.3 ± 0.6
Dark	< −30	35.5 ± 0.7	8.8 ± 0.4	11.6 ± 0.6

Abbreviations: CIE, Commission Internationale de l'Eclairage; ITA°, individual typology angle; SCI, specular component included; SEM, standard error of the mean.

CIE L*, a*, and b* values were measured for 135 photoprotected skin samples with variable pigmentation. The L*, a*, and b* values were classified into six skin color groups according to their ITA°. L*a*b* parameters were measured with a spectrophotometer (Datacolor Check) using D65, 10°, SCI, d/8° (Del Bino and Bernerd, 2013, and personal communication).

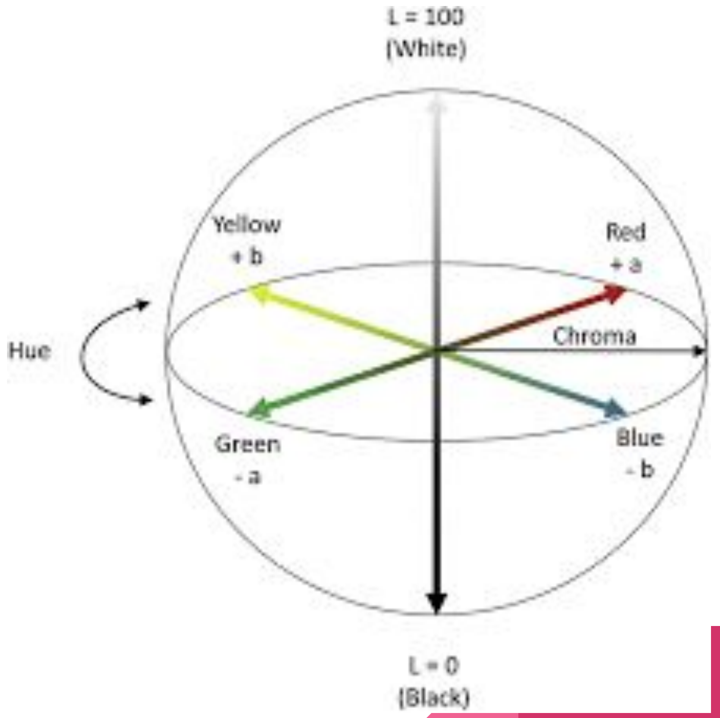


Table 4.2 Colour matching functions of Stiles

WL (nm)	Colour matching functions $\bar{r}(\lambda)$	$\bar{g}(\lambda)$	$\bar{b}(\lambda)$	WL (nm)	Colour matching functions $\bar{r}(\lambda)$	$\bar{g}(\lambda)$	$\bar{b}(\lambda)$
390	0.00184	–0.0004	0.01215	560	1.2283	0.93783	–0.01461
395	0.00462	–0.001	0.03111	565	1.4727	0.88039	–0.01378
400	0.00963	–0.002	0.06237	570	1.7476	0.82835	–0.01265
405	0.01898	–0.004	0.13161	575	2.0214	0.74686	–0.01136
410	0.0308	–0.007	0.2275	580	2.2724	0.6493	–0.00993
415	0.04246	–0.013	0.35897	585	2.4896	0.56317	–0.00841
420	0.05166	–0.017	0.52396	590	2.6725	0.47675	–0.00702
425	0.05284	–0.021	0.68586	595	2.8093	0.38484	–0.00574
430	0.04429	–0.02	0.79604	600	2.8717	0.30069	–0.00427
435	0.03222	–0.016	0.89459	605	2.8525	0.22853	–0.00291
440	0.01476	–0.007	0.96395	610	2.7601	0.16575	–0.00227
445	–0.00234	0.0014	0.99814	615	2.5989	0.11373	–0.002
450	–0.02913	0.0196	0.91875	620	2.3743	0.07468	–0.00151
455	–0.06068	0.0435	0.82487	625	2.1054	0.0465	–0.00094
460	–0.09622	0.071	0.78554	630	1.8145	0.02633	–0.00055
465	–0.13759	0.1102	0.66723	635	1.5247	0.01272	–0.00032
470	–0.17486	0.1509	0.61098	640	1.2543	0.0045	–0.00014
475	–0.2126	0.1979	0.48829	645	1.0076	0.00966	0
480	–0.2378	0.2404	0.36195	650	0.78642	–0.00196	0.00011
485	–0.25674	0.2799	0.26634	655	0.59659	–0.00263	0.00019
490	–0.27727	0.3335	0.19593	660	0.4432	–0.00263	0.00023
495	–0.29125	0.4052	0.1473	665	0.3241	–0.0023	0.00022
500	–0.295	0.4906	0.10749	670	0.23455	–0.00187	0.00016
505	–0.29706	0.5967	0.07671	675	0.16884	–0.00144	0.0001
510	–0.26759	0.7018	0.05025	680	0.12086	–0.00108	0.00005
515	–0.21725	0.8085	0.02878	685	0.08581	–0.00079	0.00004
520	–0.14768	0.9108	0.01331	690	0.06026	–0.00057	0.00003
525	–0.03518	0.9848	0.00212	695	0.04148	–0.00039	0.00002
530	0.10614	1.0339	0.00416	700	0.02811	–0.00026	0.00002
535	0.25981	1.0538	0.0083	705	0.01912	–0.00018	0.00001
540	0.41976	1.0512	–0.01219	710	0.01331	–0.00012	0.00001
545	0.59259	1.0498	–0.01404	715	0.00941	–0.00009	0.00001
550	0.79004	1.0368	–0.01468	720	0.00652	–0.00006	0.00001
555	1.0078	0.9983	–0.01495	725	0.00454	–0.00004	0.00001
560	1.2283	0.9378	–0.01461	730	0.00317	–0.00003	0

$$X = \frac{1}{N}\sum_i \bar{x}_i S_i I_i \Delta\lambda$$

$$Y = \frac{1}{N}\sum_i \bar{y}_i S_i I_i \Delta\lambda$$

$$Z = \frac{1}{N}\sum_i \bar{z}_i S_i I_i \Delta\lambda$$

$$N = \sum_i \bar{y}_i I_i \Delta\lambda$$

$$\bar{x}(\lambda) = 0.49\,\bar{r}(\lambda) + 0.31\,\bar{g}(\lambda) + 0.20\,\bar{b}(\lambda)$$
$$\bar{y}(\lambda) = 0.17697\,\bar{r}(\lambda) + 0.8124\,\bar{g}(\lambda) + 0.01063\,\bar{b}(\lambda)$$
$$\bar{z}(\lambda) = 0.00\,\bar{r}(\lambda) + 0.01\,\bar{g}(\lambda) + 0.99\,\bar{b}(\lambda)$$

$$f_x = \begin{cases} \sqrt[3]{x_r} & \text{if } x_r > \epsilon \\ \frac{\kappa x_r + 16}{116} & \text{otherwise} \end{cases}$$

$$f_y = \begin{cases} \sqrt[3]{y_r} & \text{if } y_r > \epsilon \\ \frac{\kappa y_r + 16}{116} & \text{otherwise} \end{cases}$$

$$f_z = \begin{cases} \sqrt[3]{z_r} & \text{if } z_r > \epsilon \\ \frac{\kappa z_r + 16}{116} & \text{otherwise} \end{cases}$$

$$x_r = \frac{X}{X_r}$$

$$y_r = \frac{Y}{Y_r}$$

$$z_r = \frac{Z}{Z_r}$$

$$L = 116 f_y - 16$$

$$a = 500(f_x - f_y)$$

$$b = 200(f_y - f_z)$$

$$\epsilon = \begin{cases} 0.008856 & \text{Actual CIE standard} \\ 216/24389 & \text{Intent of the CIE standard} \end{cases}$$

$$\kappa = \begin{cases} 903.3 & \text{Actual CIE standard} \\ 24389/27 & \text{Intent of the CIE standard} \end{cases}$$

$$S_A(\lambda) = 100\left(\frac{560}{\lambda}\right)^5 \times \frac{\exp\frac{1{,}435\times10^7}{2{,}848\times560} - 1}{\exp\frac{1{,}435\times10^7}{2{,}848\,\lambda} - 1}$$

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