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Pulse Oximetry: The impact of the computer engineer

An analysis of the Computer Engineer and their influence on health-care disparities

Degree project report in Computer Engineering

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Pulse Oximetry: The impact of the computer engineer
An analysis on the intersection between Computer Engineer- ing and Society and its significance on social groups
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Abstract

In 1935 Karl Mattes a professor in physiology introduced the pulse oximeter which is a non invasive device that is used for measuring oxygen saturation level and pulse rate. Pulse oximeter is based on the principle that oxyhemoglobin and deoxyhemoglobin absorb light of different wavelength differently. The device has played a huge role in vital remote monitoring during the COVID-19 pandemic as patients were able to take readings at home which was a relieve to the pressure on the health centres. However the Center of Disease Control(CDC) reported in February 2021 about the possibility of the pulse oximeter having inaccurate reading on patients with dark skin.

The role of this report is to understand the functionality and the principles on which the pulse oximeter works and why its less effective on patients with dark skin. Further more the report presents possible solution to the existing problem. The group constructed a pulse oximeter and carried out measuring on different skin tones of the test subjects. The results from the reading didn't provide enough information for the group to conclude that indeed the pulse oximeter is ineffective on patients with dark skin tone since they were inconsistent and fluctuating. However from the research carried out by Takashi and Betsy, the group came to that the pulse oximeter is less effective on people with dark skin.

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1
Introduction

This chapter will present the history behind pulse oximetry, its functionality and purposes as it pertains to racial disparities in Health Care.

1.1 Background: Pulse Oximetry

The pulse oximeter is an electronic device that is placed on the body of a patient, usually with a reusable clip probe or a single-patient adhesive probe, to read the oxygen saturation level in the blood of the patient. The pulse oximeter is a frequently used and accessible device in the medical industry that also offers a non-invasive and continuous reading of other vital health signs such as pulse rate and blood pressure [1].

The technology for the pulse oximeter was first introduced in 1935 by professor in physiology Karl Matthes. Professor Matthes was the first to construct a pulse oximeter with two wave-lengths capable of continuous reading. Subsequently, Matthes was the first to recognize the potential of such a device which revolutionized the modus operandi of pulse oximetry [2].

Matthes work was integrated into society by Glen Millikan in 1939 where the technology behind the pulse oximeter was used to monitor and aid aircraft pilots during WW2. Millikan expanded on Matthes work by constructing an ear piece capable of on-board monitoring of the vital health signs in the pilots. The measurements along with the altitude of the aircraft provided data to the system responsible for the active supply of oxygen to the pilots. Although the device would prove to be faulty as it only responded to part of the infrared light omitted by the photocell in the ear piece, the integration of oximetry into society had been established and proved to serve a valuable functionality [2]. Efforts to expand the functionality of the device resumed in 1949. Robert Brinkman and William Zijlstra successfully demonstrated that light reflected from the forehead could be used to measure oxygen saturation of the blood [4].

Modern day advancements in oximetry rely on the findings of Dr. Takuo Aoyagi who in 1972 created the Pulse Oximeter device the medical industry takes use of. While developing techniques for measuring cardiac output, Dr Aoyagi recognized that the light absorbance in arterial blood fluctuated with pulsation. This discovery led to

the ability to measure the arterial oxygen saturation of any patient in an analogous manner. As of January 1 1990, the Pulse Oximeter became an American Society of Anesthesiologists (ASA) standard for intraoperative monitoring [3].

1.1.1 Global Market size

According to one market report done by Grand View Research: As of 2020, the global market size of the pulse oximeter was valued at $2.3 billion [6]. Additionally, the market value for the pulse oximeter is expanding due to the consistent demand for vital health monitoring world wide. Moreover, pulse oximetry has played a huge part in remote vital monitoring during the COVID-19 pandemic. Health organisations put efforts into informing medical practitioners and in-home patients with information regarding at-home treatment alternatives in efforts to relieve the pressure and overcrowding at public hospitals [5]. By 2028, the market size is expected to grow by 6.4% with a growth revenue of over $1 Billion [6].

The majority of the market revenue share is held in North America with 49.1% of the global market share in 2020. This is believed to be the cause of increased awareness amongst common population on the importance of vital health monitoring [6].

1.1.2 Racial Disparities in Health Care

In February 2021, the CDC reported on the risk of pulse oximeter having sub-optimal accuracy in dark skin patients [7]. The findings of the study published determined that the accuracy within pulse oximetry when measuring the arterial O2 saturation on individuals with dark skin had adverse effects on the ability to accurately diagnose and treat patients with dark skin. One of the diagnoses involve hypoxemia, a disorder that affects the oxygenation of the arterial blood. The findings are seen to affect persons with dark skin at a disproportional rate compared to persons with light skin.

According to David R. Williams [8], the existence of such records prove, and has proven the disparities between the quality of healthcare provided between different races for years. Additionally, the findings shows that the research to engineer revolutionary medical done equipment by individuals of similar ethnic phenotype also produce medical equipment best suited those of that same ethnic phenotype. The effect this oversight has on public health amongst persons of dark skin tone is often overlooked. According to Dr Williams, this oversight is often caused by a deep rooted issue within the healthcare system itself, rather than by the prejudice present at the individual level.

> *"Thus, understanding racial disparities in medical care requires an appreciation of the ways in which racism has operated and continues to operate in society. The term "racism" refers to an organized system, rooted in an ideology of inferiority that categorizes, ranks and differen-*

tially allocates societal resources to human population groups. It may or may not be accompanied by prejudice at the individual level.´´
[8]

1.2 Purpose

Unfortunately, the pulse oximeter has limitations. The readings from the pulse oximeter are directly dependent on the photo-detector and its ability to send and receive the wavelengths emitted by the device. This constraint causes shortcomings on patients with dark skin tones as some of the wavelengths passed through the skin of an individual with high melanin are absorbed more than on an individual with low melanin. The main purpose of this report is to examine this issue from a societal and ethical standpoint, all while emphasizing the role in which computer engineering plays in solving this issue through technical analysis. The goal of this report is to shed light on the importance of awareness and diversity among engineers and gain knowledge of pulse oximetry as a medical tool and evaluate its application and current societal impacts.

1.3 Research Questions

The following are questions that this report will evaluate:

- Why is the pulse oximeter less effective on darker skin?
- What role do computer engineering play in the existence of this problem?
- How has this affected the medical industry?
- How has this affected the ongoing COVID-19 pandemic?
- What would a solution look like?
- What effect would the solution have?

1.4 Limitations

This report will not research new methods of obtaining oxygen saturation values.

1.5 Sources

To ensure that the sources used in the research are reliable the group examined each documents purpose, origin, target audience and credibility. This method was combined with the CRAAP[38] test (acronym for Currency, Relevance, Authority, Accuracy and Purpose) for source-critical review of the documents. Furthermore, the group only reviewed documents from scientific publications and research institutions to avoid information that is not considered credible.

2
Theory

This chapter will present the relevant theory of which contributes to the inequalities of healthcare provided globally and the theoretical and technical framework behind pulse oximetry.

2.1 Understanding Disparities in Health Care

To begin to understand the racial disparities in health care it is important to understand what race is and how it is perceived. Scientists agree that race, as a concept, is recognized as a social construct rather than a biological construct, as there is no biological components that make up such qualities of belonging to a specific race [18]. The factors that determine the categorisation of an individuals belonging to a specific race strictly rely on the physical estimation based on a persons phenotype. The consistency of this estimation varies greatly across cultures throughout time. In this chapter, we will present when the concept of race first materialized and how its parameters have expanded through time.

2.1.1 The Conception of Race

The concept of race as we know it today is fairly young. Albeit bearing different meaning, the word first started being recorded in literature in the English, Spanish, French, Italian and Scottish languages as early as the 13th century to describe the trial of speed, often in the context of rivers and other bodies of water. Not until the late 1700s during the industrial revolution the word Race was used in conjunction with the term 'Ethnic Group' [11]. According to Britannica [13], up until the 18th century in the English language, the word had meaning similar to classifying terms such as 'like' or 'sort'. During the 18th century the definition had shifted to describe the peoples in the English colonies: Europeans: those who were free, Amerindians. those who had been conquered, Africans: those who had been enslaved.

Recalling how statisticians have recorded race historically, racial categories often times expand as a way to track new immigrant groups. In the first United States Census held in 1790, categorizations of individuals based on their race was originally categorized into 3 groups: Whites, Blacks and civilized Indians. By the late 19th century the constitution was extended to include Japanese, Chinese and Mexican as

distinct races [8]. The categorizations of race found in the US Constitution in 1790 can be further observed in the Naturalization Act of 1790 which, for the first time, established rules of granting citizenship by naturalization in the United States. This 1790 act, enacted by the American Senate and House of Representatives, limited access to citizenship of the United States of America to White persons from western Europe of good character, that had resided in the U.S for at least two years [19].

Contemporary definitions of the word 'race' are less concrete, but closely related to the previous definition popular in the English colonies highlighted by Britannica. The Cambridge article [12] describes the word as the categorisation of a group of people based on physical characteristics, such as skin color, eye color and hair texture, whilst also stating the meaning to a group of people who share the same language and history. Britannica states that the word can also apply to linguistic, religious or groups of nations, such as the Jewish, Arabic or the Asian race [13].

Although the parameters of what the definition is determined by varies greatly, what most definitions have in common is their attempt to describe the categorization of persons based on their physical attributes, sometimes even behavioural attributes, regardless of their individual cultural aspects. What can be observed is an intermixing use of four distinct words: race, ethnicity, nationality and culture, which may suggest synonymous or interchangeable use. To fully grasp the impact racial disparities has on the quality of health care provided globally, the definition of each word is provided below.

Culture: the general customs, beliefs, traditions, language and history of a particular group of persons at a particular time [15].
Ethnicity: a group of persons with a shared culture [14].
Race: a group of persons categorized into groups based on physical characteristics that they are perceived to share [12].
Nationality: being a citizen of a particular nation [16].

2.1.2 The Perpetuation of Race

An important question to be asked when acknowledging the existence of each category of race is: who decides the parameter of such categorizations? And then, the follow up question might be: who reinforces the definition of these parameters in each and current societies? When evaluating societies through history and across nations it is difficult to pinpoint a single individual or a single act that has contributed to the upholding of the concept of race in each place.

Dr. Ritchie Witzig describes in 1996 the legitimization of race as a concept solidified through its use in medical literature and practice and an acceptable descriptive label that was necessary for a proper diagnosis and treatment of disease in humans [21].

According to Dr Williams [8], the concept of race and its inequities in social insti-

tutions are perpetuated by institutional policies and unconscious bias amongst its participants. Further following observations made by Dr Williams explore the origins of the institutional policies regarding health care: the persons who fall under the classification of the White race consistently end up being the positive benefactors of such policies, whilst persons falling under the non-White category dis-proportionally receive its negative impacts.

> *Race was and is a social category that captures differential access to power and desirable resources in society. Throughout the history of the United States, non-dominant racial groups have, either by law or custom, received inferior treatment in major societal institutions. Medical care is no exception.* [8]

Additional sources from Stanford psychologist Steven O. Roberts and co-author Michael Rizzo describe the perpetuation of race in America as the perpetuation of a racist system that benefits from the oppression of marginalized non-White groups [23]:

> *"just as citizens of capitalistic societies reinforce capitalism, whether they identify as capitalist or not, and whether they want to or not, citizens of racist societies reinforce racism, whether they identify as racist or not, and whether they want to or not."*

Dr Williams further provides data on the racial attitudes of White persons in the United States years 1944–1996, showing that although the general attitude towards non-White individuals in America has improved and racial disparities has minimized, the issue is large enough to still affect the general health and well being of non-White persons in the United States. Ultimately, the concept of race is used as a systemic tool to divide and control populations, and perpetuate a system whose intentions consistently benefit those who are in power. The meaning of race has shifted over time to accommodate political goals through policies, including to assert biological inferiority of dark-skinned populations. Dr Williams concludes that persons belonging to the White race in the United States of America have received a better quality of service in healthcare.

It is important to note that the technical functionality of the pulse oximeter is not affected by any of the factors derived from the classifications of race, ethnicity, nationality or culture of any person. Rather, the project focuses on the factors affecting its technical functionality, such as skin tone. However, since the focus of this thesis highlights the social impacts that influence the engineer, who lays the groundwork of how the application of the device is executed, it is important to understand the principles directly affecting it.

2.1.3 Disparities in Healthcare

Medical anthropologist Jessica P. Cerdeña exemplifies the disparities in healthcare and its effects on non-White patients in the United States by highlighting how race is used in the rationale for race-based management in common health-care practices

and their harms [22]. The research shows the race-based medicinal practices negative impact on Black and Asian patients. Outcomes involve inappropriate dosing, delayed treatment, increased distrust for health care providers and adverse effects from recommended treatments. (see appendix table nr. 1)

A study released in May 2020 [24] report on the COVID-19 morality rate by race. The study concluded that Black people were 3.57 times more likely to die from COVID-19 than White people in the United States. Subsequently, the risk of death from COVID-19 among the Latinx population were 1.88 times more likely than White people.

Another study published in January 2022 [30] researched health-care access and coverage by race and found that non-White patients experienced an increased risk of negative health and economic impacts from the COVID-19 pandemic. Black and Hispanic persons were less likely to receive COVID-19 vaccines compared to White persons, this gap has over time closed for Hispanic people. Additionally, Black, Hispanic, American Indian or Alaskan Native identifying persons had higher rates of hospitalizations and death cases from COVID-19 compared to White and Asian identifying persons.

Examples of health care disparities can also be found in European countries. A study published in September 2000 [31] found that perinatal mortality was increased among women of foreign origin compared to women of Swedish origin. Black women with sub-Saharan background recorded having the highest risk of adverse outcomes related to childbirth.

A study collecting data from 36 European countries conducted in 2015 concluded that Foreign-born patients were less likely to receive appropriate care relating to heart failures. Additionally, Foreign-born patients were receiving lower rates of beta blockers than medically recommended compared to native born patients [32]. The same study showed that Black and Asian patients were less likely than White patients to receive a kidney transplant.

2.2 Pulse Oximetry

The human body receives oxygen through the lungs and is carried to other parts of the body through blood by means of hemoglobin. Pulse oximetry is a method used for measuring oxygen saturation i.e. the fraction of oxygen-saturated hemoglobin relative to the total hemoglobin(unsaturated and saturated) in the blood [26].

$$SpO2 = HbO2/(HbO2+Hb)$$

The HbO2 is oxygenated hemoglobin(oxyhemoglobin) and Hb is deoxygenated hemoglobin.

Normal oxygen saturation values are considered to be between 95 percent and 100 percent. Oxygen saturation level less that 90 percent is considered as hypoxemia and this can result into cardiopulmonary complications and sleep apnea. People with

chronic conditions that affect the blood, lungs or circulation need regular tracking of the oxygen saturation.

2.2.1 Pulse Oximeter

The oximeter is a non invasive instrument used for measuring oxygen saturation and it is designed based on Beer-Lambert's law which states that there is a logarithmic dependency between the transmission of light through a substance and the product of the absorption coefficient of the substances and the distance the light travels through the material [28]. The presence of hemoglobin in the blood causes the variation in the absorption of photons travelling through a blood specimen at different wavelength.

Pulse oximeters design is based on two physical properties. First, pulse oximeter takes advantage of the property that deoxyhemoglobin and oxyhemoglobin absorb light of different wavelength in a different way as shown in the figure below. The sensor on the oximeter consists of two LEDs emitting light, i.e. one is a red light having wavelength of approximately 650nm and the the other is infrared light of approximately 950nm wavelength[28].

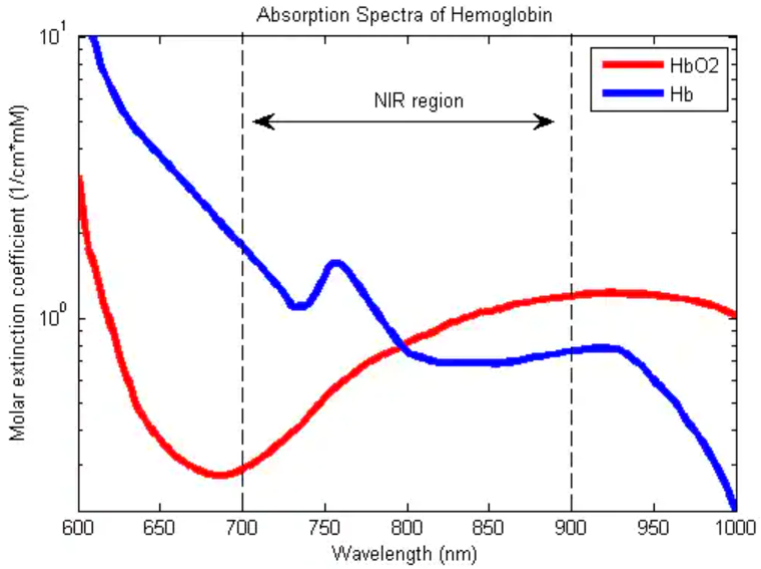

Figure 2.1: Graph of hemoglobin extinction [27]

Second, the absorbance at both wavelength has pulsatile (AC) component as a result of fluctuating volume of arterial blood during diastole and systole between the source and the detector. Measuring of oxygen saturation is made by the oximeter by sending out wavelengths of red and infrared light through the test subjects body and measuring the amount of light reflected through that body on a photo detector. Some light will be absorbed by the skin, bones and tissue and its is passed through without being scattered and is referred to as DC component. The two components are shown on the figure 2.2 below.

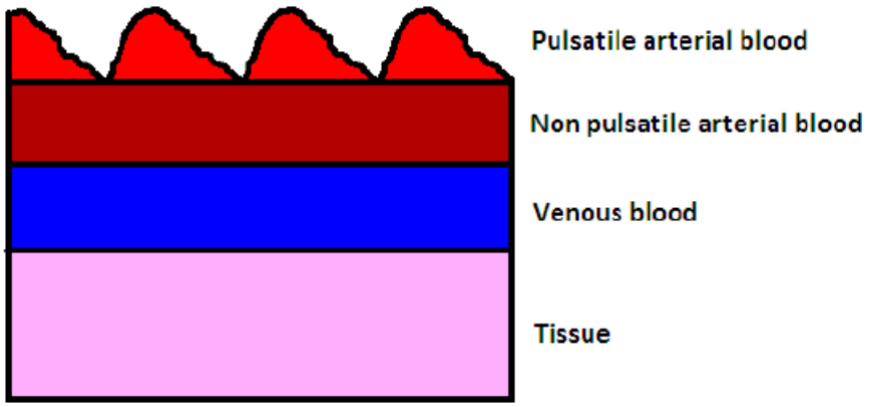

Figure 2.2: Figure showing the AC and DC component [27]

The light transmitted through the test object is obtained by calculating the ratio of ratios(R) from each of the LEDs [17] as defined by the equation below

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

where AC and DC are peak to peak amplitudes of the pulse shown in figure 2.2. After calculating the ratio R, oxygen saturation is calculated from the following equation

$$SpO2 = \frac{ED1 - R(ED2)}{R(EO2 - ED2) + (ED1 - EO1)}$$

where EO and ED represent extinction coefficients of HbO2 and Hb respectively and 1 and 2 represent red and infrared wavelength respectively.

2.2.2 Skin and light absorption

Light absorption leads to a reduction in the light energy and in the skin the dominant light absorption substances are hemoglobin and melanin[37]. Hemoglobin is found in the dermis layer where the blood vessels are found while melanin is found in the epidermis layer. Melanin attenuates the incident light wavelength since it is highly absorbent to light.

According to Takashi [36] there was study carried out on four different wavelength "470nm, 520nm, 630nm, 880nm" in which it was discovered that 520 displayed greater modulation (AC/DC) during resting while 470nm and 520nm displayed greater modulation during exercise regardless of skin types compared to other wavelength. The study also showed that dark brown skin has a significantly low modulation (AC/DC) compared to other skin types.

2.2.3 Limitations of the pulse oximeter

Even if the pulse oximeter has its advantages, for example, it is non invasive, quick and easy to use, there are circumstances where the device does not produce correct readings.

Pulse oximeters are sensitive to movement since the signal analysed is very small. If the device is placed incorrectly on the test location of the patient or displaced due to movements [20], it can affect the ability of the device to give correct readings. The device works well if all the light goes through the test specimen which is not the case if it is placed incorrectly leading to errors in the reading. It is not advisable to use pulse oximeter on patients that are shivering, have tremor or have excessive movement of the finger. Accuracy is also affected by finger nail polish which can absorb or reflect the light from the device.

Pulse oximeter works on the principle that absorption of wavelength have both AC and DC components as a result of diastole and systole. In cases where the patient has a heart condition or has a weak pulse due to critical illness, the readings of the oximeter may be incorrect or the it may not be able to generate any readings at all [29].

In cases of carbon monoxide poisoning the oximeter may give normal readings when actually there is inadequate oxygen in the body. Carbon monoxide combines with hemoglobin and forms carboxyhemoglobin and the pulse oximeter cannot differentiate it from oxyhemoglobin leading to false readings [20].

There are number of studies that suggest that the device is unable to detect low oxygen saturation on patients with dark skin pigment. According to Millar [20] the US Food and Drug Administration mentioned the above points as limitations of the pulse oximeter and included skin pigmentation as a potential limiting factor but did not not further explain this factor. According to Todd [10] there was a research carried out at the University of Michigan Hospital from January through July 2020 and at ICU patients in 178 hospitals from 2014 to 2015 on adult patients on supplemental oxygen. The aim of the research was to compare pulse oximetry reading with arterial blood gas readings taken at a 10 minutes interval. He further explains that 11,000 pairs of measurements were carried at the university of Michigan of which 1,333 were White patients and 267 Black patients and more than 37,000 pairs in multicenter ICUs of which 7,342 were White patients and 1,050 were Black patients. Among both groups,there was undetected hypoxemia by the pulse oximeter but it was three times common in the Black patients compared to the White patients. At the University of Michigan, occult hypoxemia was evident in 11.7% of Black patients compared to 3.65% of White patients while at multicenter ICUs occult hypoxemia was evident in 17% of the Black patients and 6.2% of White patents.

3

Methods

This chapter will describe the methods of research that will be conducted and the planned process of building a fully functioning pulse oximeter device.

3.1 Project research and execution

The workload for the project was divided into 4 phases over the span of 6 months starting in 2022-01-13 to 2022-06-06.

1. **Phase 1: Research** consist of scientific analysis of the pulse oximeter from an engineering perspective, and a deep dive into academic topics relating to racial disparities in health-care. The research phase will be complemented with a reconstruction of a pulse oximeter device with the intention of gaining a fundamental understanding of the application of its theoretical framework, as well as its practical framework. The execution of phase 1 is planned to take at least 3 months due to the broad field of research and to accommodate for possible complications while constructing the device.
2. **Phase 2: Research findings & Application** concludes the application of the information gathered from phase 1. The research will be further evaluated and applied to the issue of inaccurate readings on persons with dark skin.
3. **Phase 3: Result** will serve as the groundwork for discovering possible solutions to the ineffective readings of the pulse oximeter. The application of these discoveries will be applied to the same societal, ethical and ecological standpoints while also emphasizing the responsibilities the engineer has in reaching possible solutions. Phase 2 and 3 are both planned to take 1 month each.
4. **Phase 4: Report** containing the findings of our research will be started on month 4 together with the start of phase 2.

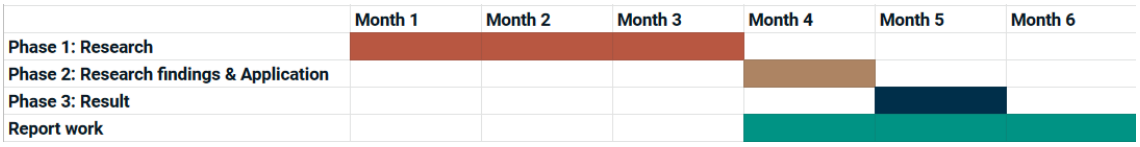

Figure 3.1: Planned time distribution of project research and execution

3.2 Procedure

In order to fully understand the technical framework behind the pulse oximeter and its functionality the group has decided to construct a pulse oximeter. This will be done by ordering a component capable of continuous reading of the spO2 values and connecting it to a micro-controller. The group will experiment on different test subjects to understand the consistency of the device. This will be done by placing the device on lighter body part and then compare the reading with those obtained after placing the device on a darker body part of the same person. The code for the program will be written in C programming language to fully understand the process of retrieving and displaying the values.

Once fully understanding the building process of the device, the group will reflect on where in the process the engineer had the most chance of impact in the application of the device and how it could be improved to minimize the disparities related to its field. Additionally it will give insight to a possible solution to the issue. The components for the project are to be provided for by Chalmers University of Technology, as well as the equipment and space handling such components such as multi-meter, wires and more.

3.3 Statistical procedures

To ensure that the readings are reliable and consistent, measurements will be carried out on three people at an interval of 90 seconds. On each person measurements will be carried out on a light body part and on a dark body part in order to determine the efficiency of the pulse oximeter on varying skin tones. This process will be repeated three times to compare the consistency of the readings on the same part of the body.

3.4 Components

The following subsections describes the components that will be used to build the pulse oximeter device and their functionality.

3.4.1 MAX30102

The MAX30102 is an integrated heart-rate and pulse oximetry module whose purpose is to provide continuous readings of blood oxygenation [33]. The module communicates via i2c protocol and a 3.3V supply, and its functionality fully adjustable via software solutions. The MAX30102 relies on the light being reflected to measure the oxygen saturation and it has the light emitters and detector on the same side. The pulse oximeter can be used on diverse measurement body parts such as feet, finger, forehead, wrists and arm.

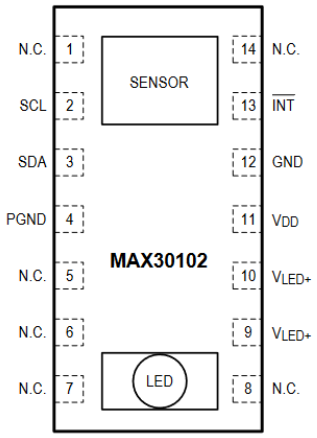

Figure 3.2: Pin mappings of the MAX30102 components.

PIN	NAME	FUNCTION
1, 5, 6, 7, 8, 14	N.C.	No Connection. Connect to PCB pad for mechanical stability.
2	SCL	I2C Clock Input
3	SDA	I2C Data, Bidirectional (Open-Drain)
4	PGND	Power Ground of the LED Driver Blocks
9	V_{LED+}	LED Power Supply (anode connection). Use a bypass capacitor to PGND for best performance.
10	V_{LED+}	
11	V_{DD}	Analog Power Supply Input. Use a bypass capacitor to GND for best performance.
12	GND	Analog Ground
13	$\overline{INT}$	Active-Low Interrupt (Open-Drain). Connect to an external voltage with a pullup resistor.

Figure 3.3: Description of the MAX30102 pins.

3.4.2 Arduino UNO

In order to connect and control the components together an Arduino UNO microcontroller in figure 3.4 was used [34]. The board was powered via a A/B Standard USB 2.0 cable from the USB B Connector to a laptop. To interact with the board and upload the program code the Arduino Software (IDE) was used.

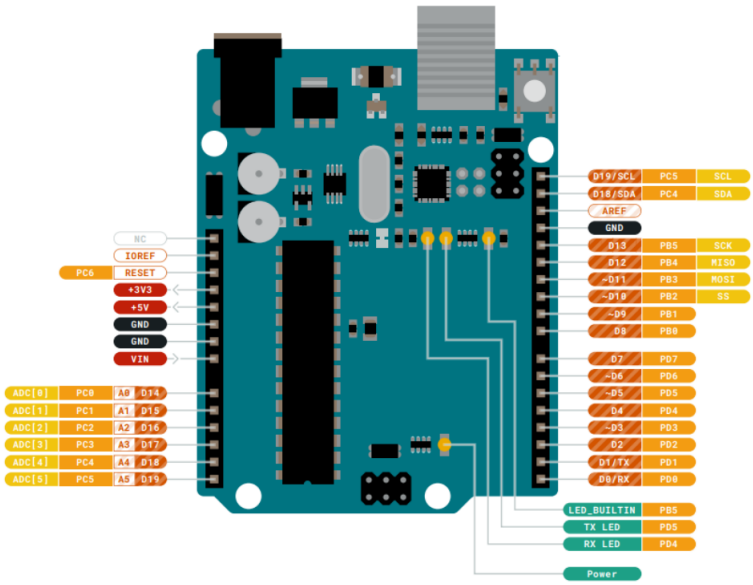

Figure 3.4: Pin mapping of the Arduino UNO.

Pin	Function	Type	Description
1	NC	NC	Not connected
2	IOREF	IOREF	Reference for digital logic V - connected to 5V
3	Reset	Reset	Reset
4	+3V3	Power	+3V3 Power Rail
5	+5V	Power	+5V Power Rail
6	GND	Power	Ground
7	GND	Power	Ground
8	VIN	Power	Voltage Input
9	A0	Analog/GPIO	Analog input 0 /GPIO
10	A1	Analog/GPIO	Analog input 1 /GPIO
11	A2	Analog/GPIO	Analog input 2 /GPIO
12	A3	Analog/GPIO	Analog input 3 /GPIO
13	A4/SDA	Analog input/I2C	Analog input 4/I2C Data line
14	A5/SCL	Analog input/I2C	Analog input 5/I2C Clock line

Figure 3.5: Description of the analogue Arduino UNO pins.

Pin	Function	Type	Description
1	D0	Digital/GPIO	Digital pin 0/GPIO
2	D1	Digital/GPIO	Digital pin 1/GPIO
3	D2	Digital/GPIO	Digital pin 2/GPIO
4	D3	Digital/GPIO	Digital pin 3/GPIO
5	D4	Digital/GPIO	Digital pin 4/GPIO
6	D5	Digital/GPIO	Digital pin 5/GPIO
7	D6	Digital/GPIO	Digital pin 6/GPIO
8	D7	Digital/GPIO	Digital pin 7/GPIO
9	D8	Digital/GPIO	Digital pin 8/GPIO
10	D9	Digital/GPIO	Digital pin 9/GPIO
11	SS	Digital	SPI Chip Select
12	MOSI	Digital	SPI1 Main Out Secondary In
13	MISO	Digital	SPI Main In Secondary Out
14	SCK	Digital	SPI serial clock output
15	GND	Power	Ground
16	AREF	Digital	Analog reference voltage
17	A4/SD4	Digital	Analog input 4/I2C Data line (duplicated)
18	A5/SD5	Digital	Analog input 5/I2C Clock line (duplicated)

Figure 3.6: Description of the digital Arduino UNO pins.

4

Results

The research process started at Chalmers Library and Google Scholar to gather relevant research papers and articles. Once a publication of interest was found it was put through the CRAAP test to ensure its credibility.

4.1 Building process

The total building process took approximately 5 weeks once the components had arrived and there were complications. The original component that was used to measure the oxygenation was the MA30100 component. Once the component was connected to the Arduino UNO board, an attempt to start a reading from the device failed. At the time this seemed to be because of the component itself so the group ordered a new component. However, the issue persisted and with no progress in resolving the matter the group decided to use the MAX30102 device instead. Once the new component was connected with the Arduino UNO board alongside with the program code the continuous reading of the oxygenation rate of the blood was successful.

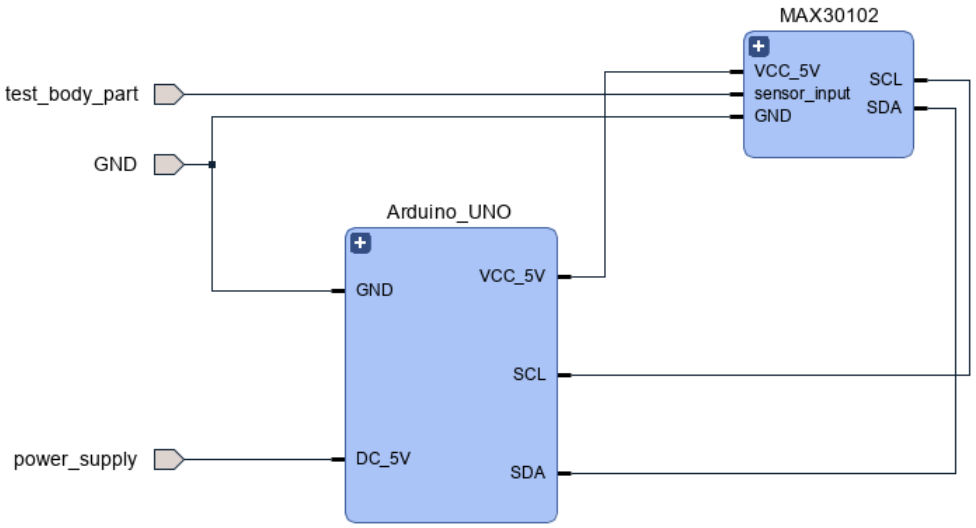

Figure 4.1: Port connection between the Arduino UNO & MAX30102

The group had planned on writing their own code for the program. Unfortunately, unexpected outcomes outside of the project resulted in stricter time restraints which

limited the amount of time that could be spent on construction. The code that was used for the program was provided for through an open-source library made by Nathan Seidle at SparkFun Electronics [35]. For further details the source code is listed in the appendix.

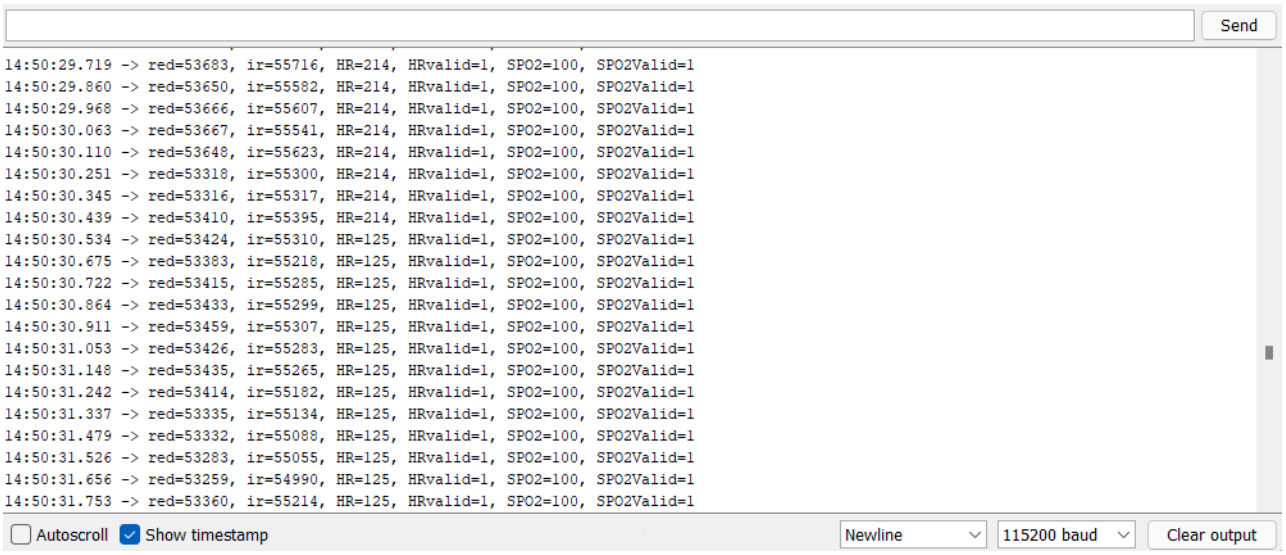

Figure 4.2: Example output from the MAX30102 component.

Once running, the program fetches the raw data measured by the infra-red and red sensors on the device. Variables "red" and "ir" are continuously updated every second to represent the infrared and red LED sensor data from the individual. The blood oxygenation value is then calculated and displayed in the output variable "SPO2" by measuring the systolic and diastolic peak of the individuals cardiac cycle, coupled with the infra-red and red sensor data. The validity of the data is determined by the consistency of the AC and DC parts of the reading. If the reading is considered to be valid the "SPO2Valid" variable output equaled to 1. On the occasion of invalid data, the output of SPO2 was shown as -999 and was noted as invalid in the statistical results.

4.2 Statistical results

As the skin tone changes depending on the individual and the location on the body, the body parts that were chosen for the testing was based on highest skin tone variation. This includes lighter body parts such as inner lower arm, chest and finger, in comparison to the darker body parts which were the elbow and on top of the foot. Other factors that could affect the effectiveness of the reading, such as excessive movement, have been taken into account when conducting the tests. To achieve the highest possible consistency between all readings, the test individual was asked to not move for the duration of the test. The tests consisted of placing the MAX30102 component on the body part and letting the device continuously read for 90 seconds. The readings were repeated 2 or 3 amount of times on each body part, this is denoted by the number preceding the percentage value in the test trials. The result

gathered from the readings minimum and maximum values are listed below.

	spO2 individual 1 (dark skin)	**spO2 individual 2 (light skin)**	**notes**
Inner lower arm	1. 98% 2. 99% 3. 99%	1. 97-100% 2. 66-99%	
Finger	1. 98-100% 2. 98-99% 3. 97-98%	1. 99% 2. 100% 3. 100%	Notable invalid readings for individual 1.
Chest	1. 96-98% 2. 61-98% 3. 19-88%	1. 3-97% 2. 99-100% 3. 98-100%	
Foot	1. 96% 2. 100% 3. 98-100%	N/A	Values not available for individual 2
Elbow	1. 99% 2. 17-100% 3. 96-99%	1. 75-100% 2. N/A 3. 45-100%	Notable invalid readings for individual 1 and 2.

Table 4.1: Test trials for pulse oximeter

The result of the tests were difficult to interpret. The values varied greatly within the stated ranges, several readings were invalid. The readings that were valid stayed within the expected range of normal SpO2 values in healthy adults but kept fluctuating throughout the 90 second test period regardless of which body part or test person who was at subject. As the fluctuating and invalid readings were not an accurate representation of the SPO2 value of the individual, the group opted for a min-max representation of the reading rather than an average.

The results were able to provide a general understanding of an approximate range of SpO2 of the test individuals body part. Due to the inconsistent readings across all test subjects and body parts the results were unreliable to determine the disproportional difference in measurement of spO2 values on darker and lighter body parts.

5

Discussion

5.1 Result data

There were differences and similarities between the actual results compared to the expected results of the tests. The met expectations consisted of the ranges the valid data fell within. Healthy adults experience spO2 values within 95% - 100%, as did the valid SpO2 data from the conducted tests. The unexpected outcomes consist of the amount of fluctuating and invalid readings from the pulse oximeter across all test individuals.

It was difficult to isolate the cause for the invalid readings. What could be observed was all test individuals experienced invalid and fluctuating readings of varying degree from the tests conducted on all body parts. Out of all tests conducted, individual 2 received the most invalid readings of SpO2 values. Analyzing the library associated with the code, the validity of the readings depend on the peak to peak value of the AC and DC component. If the AC and Dc compenent value is below 2 or above 184 the SpO2 value is invalid otherwise the reading is valid.

Coinciding with the lack of clarity regarding the cause of the invalid readings it was difficult to identify the cause of the fluctuating readings. Readings fluctuated from $\pm 1\%$ to $\pm 94\%$ across the respective test periods depending on the body part and individual. The most consistent data is observed on tests conducted on individual 1 for inner lower arm, finger and foot, although individual 1 received notable invalid readings for the finger. Individual 2 had the most consistent readings for tests conducted on the finger. We assume that the invalid readings from body parts such like the chest is due to the change in the thickness of the DC part of the reading. The skin on the chest and the forehead are thicker compared to the skin on the finger where the blood vessels are close to the light source. We also assume that invalid and fluctuating readings on the same body part where due to placement of the pulse oximeter, for example on the elbow and the top of the foot. We had to test on different parts of the body with different skin tone but it was challenging taking the measurements since it resulted in shaking or placing the device wrongly which may have caused the fluctuations in the readings. In some cases we placed the pulse oximeter a little to hard on the test surface which we assume could have blocked the blood circulation thus leading to the fluctuating results.

The testing process had a limitation of test subjects, since we would have wished to

test on more subjects to conclude which body parts represents the most fluctuating results. To reach a better understanding of the cause of the invalid and fluctuating readings, additional research outside the scope of this report has to be conducted.

In addition to the lack of test subjects, the ambiguity regarding the cause of the inconsistencies in readings does not provide enough certainty in demonstrating that the pulse oximeter is inconsistent in reading spO2 values on persons with dark skin.

5.2 Improving the Pulse Oximeter

The main purpose of constructing and testing the pulse oximeter device was to gain a fundamental understanding of the construction process of the device. By recreating the construction process and running tests on the device we gained a better understanding of where in the process the computer engineer can interject and possibly improve the conditions of which the device is applied. The tests conducted did not prove nor disprove that the pulse oximeter provides faulty readings on persons with dark skin. After conducting the building and testing of the pulse oximeter device it was clear that the computer engineer had a lot of influence in the software and hardware components of the device. By demonstrating the role of the computer engineer at every stage of the production process, the possibilities to improve the application of the device can be highlighted.

The conception of the pulse oximeter began at the moment the technology of the device was established in 1935 by Karl Matthes and ended when Glen Millikan managed to successfully utilize and integrate the technology into society in 1938. From this moment on the technology was improved and adapted to different societal needs, such as on-board monitoring of vital signs in war pilots to being one of the most integral parts of health-care service globally. This progression would not have been a reality without the researchers and engineers who saw the potential of the already existing technology and dedicated their efforts in expanding it. Without individuals like Dr. Takuo Aoyagi the pulse oximeter could not be capable of becoming a staple in continuous measurements of arterial oxygen saturation in individuals, which has also proved to be an integral and necessary part of monitoring and the assessment of COVID-19 symptoms during the ongoing pandemic.

According to the working principle of the pulse oximeter, it measures oxygen by analysing the absorption of the pulsating blood and therefore its effectiveness should not be affected by the fact that melanin absorbs also light. However, according to Takashi [36], dark skin had significantly low modulation compared to other skin types which indicates that the presence of melanin affects the efficiency of the pulse oximeter. In addition, according to Betsy Todd [10] there was a study carried out at the University of Michigan hospital where they compared readings from patients using a pulse oximeter with those using arterial blood gas method. There were more cases of undetected hypoxemia in the dark skin patients compared to the light skin patients indicating that dark skin affects the efficiency of the device.

It has proved to be an extensive task to find a definitive answer as to why there is a trend of negative disparities targeting individuals with dark skin in health-care. Due to the invalid and fluctuating data from the conducted tests, we cannot ascertain that the pulse oximeter is inconsistent on persons with dark skin. But by using examples in current health-care systems located in Europe and America to showcase the disparities, it is not clear where the disparities come from and that the issue still persists to this day. The pulse oximeter is a technical device that by itself does not perpetuate any negative disparities in the quality of health-care. The negative disparities only surface once its developments and applications are limited by the lack of perspective and diversity in the developmental process. Any technical device has the potential to improve and the engineer has the power to do so. Specifically, the computer engineer is directly related to the hardware and software aspects and has the knowledge to influence both regarding this device. Dr. Takuo Aoyagi is a great example of demonstrating the improvement of the application of a device once the time and effort has been set to further its scope.

In addition to identifying how and where the engineer can make improvements to eliminate resulting disparities, we further analysed the research study of Takashi [36] where he discovered that the green light has modulation at rest while the green light and blue light have greater resolution during exercise regardless of skin type. This discovery seems to indicate that the pulse oximeter can be improved by using green light and the blue light instead of the red and infrared light.

6
Conclusion

Our conclusions from this project can be summarized as answers to the questions framed in the introduction:

- **Why is the pulse oximeter less effective on dark skin?**

  The pulse oximeter device works on the principle of wavelength absorption. Melanin is known for its ability to absorb light causing patients with high amount of melanin to absorb more of the wavelengths that are passed through the body part once the measurement has started. This causes the data returned by the device to be less accurate on patients with dark skin compared to patients with light skin.

- **What role do computer engineering play in the existence of this problem?**

  In the case of the pulse oximeter, its developments are not hindered by the lack of existing knowledge among scientists such as computer engineers and researchers. Rather, the lack of development is hindered by the absence of initiative, awareness and accountability around the conditions of which the patients suffer. The computer engineer has the knowledge to inspect and affect any hardware or software aspects of any technical device, including the pulse oximeter. It is the responsibility of the engineer to ensure that any technology being developed includes human safety for all and does not contribute to the oppression of it.

- **How has this affected the medical industry?**

  The effectiveness of the pulse oximeter has caused inconsistencies in the quality of service to patients who do not have light skin. A lack of action and acknowledgement from the medical industry regarding this issue is contributing to the continuation of systemic oppression. As a consequence of this, the medical industry has become untrustworthy and unsafe for non-white patients which can be seen to have a negative impact on the health of non-white patients globally.

- **How has this affected the ongoing COVID-19 pandemic?**

  The pulse oximeter has proved to be a necessary tool in diagnosing and assessing early symptoms of patients with COVID-19. Due to the previously mentioned limitations of the pulse oximeter, non-white patients were more likely to seek medical attention at the later stage of the disease or suffer death from COVID-19 compared to white patients. This is due to the presence of more melanin in the skin which absorbs more light thus resulting into higher SpO2 readings causing the patient to hesitate seeking medical help. The inefficiency of the device affected the general public at large not only patients with dark skin and this is due to the fluctuating readings that were observed due to various limitations of the device.

- **What would a solution look like?**

  A solution to the limitations of the pulse oximeter most likely lies within the findings of Takashi where changing the wavelength of the light omitted by the device can complement the properties of dark skin.

- **What effect would the solution have?**

  A solution to the limitations of the pulse oximeter could possibly contribute to the improvement of the quality of health-care provided to patients with dark skin. Consequently, it could possibly increase trust amongst non-white patients towards the medical industry.

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A

Appendix 1

A.1 Table: Race-based medicine data

	How race is used	Rationale for race-based management	Potential harm	Race-conscious approach
eGFR	eGFR for Black patients is multiplied by $1 \cdot 16$–$1 \cdot 21$ the eGFR for White patients, depending on the equation used	Black patients are presumed to have higher muscle mass and creatinine generation rate than patients of other races	Black patients might experience delayed dialysis and transplant referral	Use eGFR equations that do not adjust for race (eg, CKD-EPI Cystatin C).
BMI risk for diabetes	Asian patients considered at risk for diabetes at BMI 23 vs 25 for patients of other races	Asian patients are presumed to develop more visceral than peripheral adiposity than patients of other races at similar BMI levels, increasing risk for insulin resistance	Asian patients screened for diabetes despite absence of other risk factors might experience increased stigma anddistrust of medical providers	Screen patients with lower BMIs on the basis of indications of increased body fat (eg, body roundness,12 body fat percentage), not based on race
FRAX	Probability of fracture is adjusted according to geography or minority status, or both	Different geographical and ethnic minority populations are presumed to have varied relative risks for fracture on the basis of epidemiological data	Some populations, including Black women,might be less likely to be screened for osteoporosis than other populations	Screen patients for osteoporosis on the basis of clinical risk criteria, rather than race; counteract existing biases that place Black patients at risk because of racial essentialist beliefs about variation in bone density
PFT	Reference values for pulmonary function are adjusted for race and ethnicity	Racial and ethnic minority groups are presumed to have varied lung function on the basis of epidemiological data	Black patients might experience increased difficulty obtaining disability support for pulmonary disease	Use unadjusted measures of lung function for all patients; counteract existing biases that harm Black patients because of racial essentialist beliefs about variation in lung capacity
JNC 8 Hypertension Guidelines	Treatment algorithm provides alternate pathways for Black and non-Black patients	ACE-inhibitor use associated with higher risk of stroke and poorer control of blood pressure in Black patients than in patients of other races	Black patients might be less likely to achieve hypertension control and require multiple antihypertensive agents	Consider all antihypertensive options for blood pressure control in Black patients; adjust as needed to achieve goals and manage adverse effects
Paediatric UTI diagnosis	White race in girls and non-Black race in boys are considered independent risk factors for UTI	Study of febrile children in the emergency department found highest prevalence of UTI among White girls and non-Black boys	Experimental data suggests that these guidelines could affect management of UTI by race	Treat UTI in children on the basis of clinical presentation, regardless of race
ASCVD risk estimation	Race-specific equations includedto estimate ASCVD risk	ASCVD events higher for Black patients than patients of other races with otherwise equivalent risk burden	Black patients might experience more adverse effects from recommended statin therapy, including persistent muscle damage	Recommend preventive therapy on the basis of clinical metrics and comorbidities; consider pathways by which structural racism might increase cardiovascular risk among Black patients and promote resources to reduce racial stress and trauma
Eltrombopag dosing	East Asian patients receive half the starting dose compared with non-east Asian patients	Limited pharmacokinetic studies suggest reduced metabolism of eltrombopag in patients of East Asian descent	Some East Asian patients might receive inappropriate dosing	Initiate same starting dose for all patients, regardless of race, and adjust as needed on the basis of platelet response

Table A.1: Examples of race-based medicine, the potential harm to patients, and race-conscious alternatives [22].

A.2 Source Code: Pulse oximeter reading

The following code is provided by Nathan Seidle at SparkFun Electronic [35]

```
#include <Wire.h>
#include "MAX30105.h"
#include "spo2_algorithm.h"

MAX30105 particleSensor;

#define MAX_BRIGHTNESS 255

#if defined(__AVR_ATmega328P__) || defined(__AVR_ATmega168__)
//Arduino Uno doesn't have enough SRAM to store 100 samples of IR led data and red led data in 32-bit format
//To solve this problem, 16-bit MSB of the sampled data will be truncated. Samples become 16-bit data.
uint16_t irBuffer[100]; //infrared LED sensor data
uint16_t redBuffer[100];  //red LED sensor data
#else
uint32_t irBuffer[100]; //infrared LED sensor data
uint32_t redBuffer[100];  //red LED sensor data
#endif

int32_t bufferLength; //data length
int32_t spo2; //SPO2 value
int8_t validSPO2; //indicator to show if the SPO2 calculation is valid
int32_t heartRate; //heart rate value
int8_t validHeartRate; //indicator to show if the heart rate calculation is valid

byte pulseLED = 11; //Must be on PWM pin
byte readLED = 13; //Blinks with each data read

void setup()

  Serial.begin(115200); // initialize serial communication at 115200 bits per second:

  pinMode(pulseLED, OUTPUT);
  pinMode(readLED, OUTPUT);

  // Initialize sensor
  if (!particleSensor.begin(Wire, I2C_SPEED_FAST)) //Use default I2C port, 400kHz speed

    Serial.println(F("MAX30105 was not found. Please check wiring/power."));
    while (1);


  Serial.println(F("Attach sensor to finger with rubber band. Press any key to start conversion"));
  while (Serial.available() == 0) ; //wait until user presses a key
  Serial.read();

  byte ledBrightness = 60; //Options: 0=Off to 255=50mA
  byte sampleAverage = 4; //Options: 1, 2, 4, 8, 16, 32
  byte ledMode = 2; //Options: 1 = Red only, 2 = Red + IR, 3 = Red + IR + Green
  byte sampleRate = 100; //Options: 50, 100, 200, 400, 800, 1000, 1600, 3200
  int pulseWidth = 411; //Options: 69, 118, 215, 411
  int adcRange = 4096; //Options: 2048, 4096, 8192, 16384

  particleSensor.setup(ledBrightness, sampleAverage, ledMode, sampleRate, pulseWidth, adcRange);
  //Configure sensor with these settings


void loop()

  bufferLength = 100; //buffer length of 100 stores 4 seconds of samples running at 25sps

  //read the first 100 samples, and determine the signal range
  for (byte i = 0 ; i < bufferLength ; i++)

    while (particleSensor.available() == false) //do we have new data?
```

```
    particleSensor.check(); //Check the sensor for new data

  redBuffer[i] = particleSensor.getRed();
  irBuffer[i] = particleSensor.getIR();
  particleSensor.nextSample(); //We're finished with this sample so move to next sample

  Serial.print(F("red="));
  Serial.print(redBuffer[i], DEC);
  Serial.print(F(", ir="));
  Serial.println(irBuffer[i], DEC);


//calculate heart rate and SpO2 after first 100 samples (first 4 seconds of samples)
maxim_heart_rate_and_oxygen_saturation(irBuffer, bufferLength, redBuffer, &spo2, &validSPO2, &heartRate,
&validHeartRate);

//Continuously taking samples from MAX30102.  Heart rate and SpO2 are calculated every 1 second
while (1)

  //dumping the first 25 sets of samples in the memory and shift the last 75 sets of samples to the top
  for (byte i = 25; i < 100; i++)

    redBuffer[i - 25] = redBuffer[i];
    irBuffer[i - 25] = irBuffer[i];


  //take 25 sets of samples before calculating the heart rate.
  for (byte i = 75; i < 100; i++)

    while (particleSensor.available() == false) //do we have new data?
      particleSensor.check(); //Check the sensor for new data

    digitalWrite(readLED, !digitalRead(readLED)); //Blink onboard LED with every data read

    redBuffer[i] = particleSensor.getRed();
    irBuffer[i] = particleSensor.getIR();
    particleSensor.nextSample(); //We're finished with this sample so move to next sample

    //send samples and calculation result to terminal program through UART
    Serial.print(F("red="));
    Serial.print(redBuffer[i], DEC);
    Serial.print(F(", ir="));
    Serial.print(irBuffer[i], DEC);

    Serial.print(F(", HR="));
    Serial.print(heartRate, DEC);

    Serial.print(F(", HRvalid="));
    Serial.print(validHeartRate, DEC);

    Serial.print(F(", SPO2="));
    Serial.print(spo2, DEC);

    Serial.print(F(", SPO2Valid="));
    Serial.println(validSPO2, DEC);


  //After gathering 25 new samples recalculate HR and SP02
  maxim_heart_rate_and_oxygen_saturation(irBuffer, bufferLength, redBuffer, &spo2, &validSPO2, &heartRate,
  &validHeartRate);
```

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