DETECTOR BUILDING C – KEY

CAMAS SCIENCE OLYMPIAD INVITATIONAL TOURNAMENT 2021

TEAM ______________________ C - _______ *example: Science Olympiad High School – Team Blue*		
NAME(S) ______________ ______________		SCORE _______ / 132

INSTRUCTIONS

1	You have up to 50 minutes to complete as many questions as you can on this exam.
2	As specified in the event rules, you are permitted to use, for reference, resources within a single 2-inch or smaller three-ring binder. With the exception of datasheets linked within this test, you may not consult the internet or other people beyond your partner for information.
3	Your entire score for this event is this Written Test. For this tournament, there are not Design Log or device components to the Total Score.
4	Please limit short answer responses to 1-4 sentences per question. Full sentences are not required. You will not be penalized for writing a lot, but doing so may take time away from answering other questions.
5	All tiebreaker questions are included in the test score and in the event of a tie will be used individually in the order specified.
6	There are no penalties for incorrect answers. Partial credit will be awarded for fill-in-the-blank and multiple answer (i.e. "select all that apply") questions.
7	Some questions ask that you input your answer as a rounded number and without units. It is very important that you follow these instructions or the auto-grade function will mark your answer as incorrect! For example, if you are instructed to enter your answer 12.3456 V in millivolts (mV) to the nearest millivolt, input "12346" for your answer. Also, Scilympiad checks for exact matches (ignoring upper and lower case) so if rounded to the nearest integer, do not follow your answer with a decimal, i.e. enter "60" and not "60."

NOTES

1	This test was written for the Camas Invitational hosted on December 12, 2020, by Camas High School in Camas, Washington. This tournament was run in *mini SO* format with testing conducted via the Scilympiad platform. As such, many questions of this test were structured and/or worded for the online format.
2	This test was written by George Sun, a graduate of the University of Washington in Seattle.

QUESTIONS

<u>Questions 1-4</u>: At 25˚C, a 2.79 m long nichrome wire resistor with a diameter of 0.1 mm is connected in series with a single 5 mm red LED and a 9.0 V battery such that the red LED turns on. The manufacturer for this particular LED recommends its operation at 2.0 V with a maximum rating of 2.5 V. If needed, assume that the resistivity of nichrome is 1.00 × 10^-6 Ω m at 25˚C and the temperature coefficient of nichrome is 4.0 × 10^-4/°C.

1 **At 25˚C, what is the resistance of the nichrome wire? Answer in ohms (Ω) rounded to the nearest whole number and input your answer without units.** ____ / 3

The equation for resistance is given by R = ρL / A where ρ represents resistivity of the material, and L and A represent the length and cross-sectional area, respectively, of the resistor. The wire is assumed to be cylindrical so its cross-sectional area is given by A = π (d / 2)^2 = 7.85 × 10^-9 sq. meters. Using this with the values provided in the question, the resistance is R = (1.00 × 10^-6 Ω m) * (2.79 m) / (7.85 × 10^-9 m^2) or 355 Ω.

3 points – correct answer (355)

2	**At 25˚C, an ammeter measures the current through the resistor to be 20 mA. What is the voltage across the red LED? Answer in volts (V) rounded to the nearest 0.1 V and input your answer without units.** For a resistor, LED, and battery in a series circuit, the closed loop equation is V_battery – V_LED – V_R = 0. The voltage across the battery is given and the voltage across the resistor can be calculated as V_R = I R = 0.020 mA * 355 Ω = 7.1 V. Therefore, the voltage across the LED is V_LED = V_battery – V_R = 9.0 V – 7.1 V = 1.9 V. *3 points – correct answer (1.9)*	____ / 3
3	**Does the resistance of the nichrome wire resistor generally increase, decrease, or not change with increasing temperature?** **a. The resistance of the nichrome wire resistor should increase with increasing temperature.** **b. The resistance of the nichrome wire resistor should decrease with increasing temperature.** **c. The resistance of the nichrome wire resistor should not change with increasing temperature.** The positive temperature coefficient of nichrome indicates that with increasing temperature, its resistance should increase. *3 points – correct answer (a.)*	____ / 3
4	**Assuming that the LED and battery are unaffected by temperature changes (i.e. the forward current is temperature independent), what is the most extreme temperature at which the circuit can be operated without exceeding the maximum forward voltage rating of the LED? Answer in degrees Celsius (˚C) rounded to the nearest whole number and input your answer without units.** The maximum forward voltage rating of 2.5 V across the LED is achieved if the voltage across the resistor is 6.5 V. With 20 mA of current through the circuit, this is achieved if the resistance is changed to R = V_R / I = 6.5 V / 0.020 A = 325 Ω. The temperature-dependence of a resistor is given by R(T) = R(T_0) * (1 + α ΔT) where R(T) is the function for resistance, T_0 is the reference temperature, and α is the temperature coefficient for the resistive material. Using the values provided in the question and this new resistance, we can solve for ΔT to determine the final temperature: 325 Ω = (355 Ω) * (1 + 4.0 × 10^-4/°C * ΔT). The required change in temperature from 25°C is ΔT = -211.3°C, or a final temperature of -186°C. *5 points – correct answer (-186)*	____ / 5
<u>Questions 5-7</u>: The Steinhart-Hart equation models the resistance of a semiconductor at different temperatures and is given by 1 / T = A + B ln R + C (ln R)^3. For a particular thermistor, the coefficients A, B, and C are 2.22 × 10^-3 K^-1, 8.10 × 10^-5 (K ln Ω)^-1, and 0, respectively.		
5	**At what temperature is the resistance for this particular thermistor 10,000 Ω? Answer in degrees Celsius (˚C) rounded to the nearest whole number and input your answer without units.** Using the Steinhart-Hart equation and the coefficients provided, the temperature can be calculated: 1 / T = 2.22 × 10^-3 K^-1 + 8.10 × 10^-5 (K ln Ω)^-1 * ln (10,000 Ω) + 0 * (ln (10,000 Ω))^3 = 0.00297 K^-1. Therefore, T = 337.15 K or 64˚C. Note that the Steinhart-Hart equation as provided outputs temperature in Kelvin, not degrees Celsius, so a conversion is required. *3 points – correct answer (64)*	____ / 3
6	**Does this particular thermistor have a positive temperature coefficient (PTC), negative temperature coefficient (NTC), or can this not be determined from the information provided?** **a. The temperature coefficient is positive (PTC).** **b. The temperature coefficient is negative (NTC).** **c. The sign of the temperature coefficient cannot be determined from the information provided.** The Steinhart-Hart equation describes a semiconductor with decreasing resistance as temperature increases, so answer choice b. is correct. (This can be verified by graphing the Steinhart-Hart or by comparing temperature values from inputting into the equation two different resistance values.) *2 points – correct answer (b.)*	____ / 2

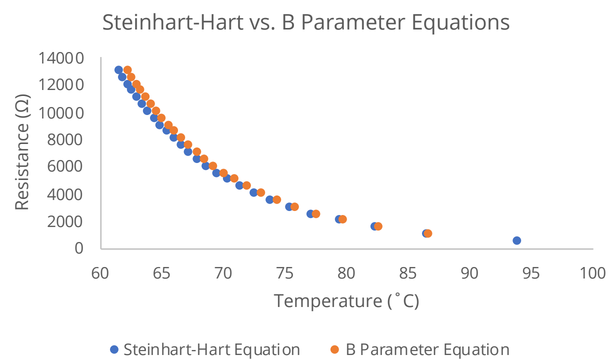
7 **<u>Tiebreaker 5</u>: What is the β parameter for this particular thermistor? Answer in Kelvin rounded to the nearest 10 K and input your answer without units.** ____ / 5

In this scenario, because the Steinhart-Hart coefficient C is zero, the Steinhart-Hart equation is essentially the B parameter equation.

The β parameter equation for thermistors is given by 1 / T = 1 / T_0 + (1 / B) ln (R / R_0), where T represents temperature, R represents resistance, and B represents the β parameter that is specific to each thermistor. The β parameter equation can be rearranged to solve for B: B = ln (R / R_0) / (1 / T – 1 / T_0).

Any two pairs of resistance and temperature values from the Steinhart-Hart equation can be used to solve for the β parameter. For example, from the Steinhart-Hart equation at 94.04˚C the resistance is 500 Ω, and at 70.51˚C the resistance is 5000 Ω. Substituting these values into the rearranged β parameter equation yields
B = ln (5000 Ω / 500 Ω) / (1 / 343.66 K – 1 / 367.19 K) = 12348 K, which rounds to 12350 K.

The graph below shows the similarity between calculations from the Steinhart-Hart provided in the question and the B parameter equation using the calculated β parameter.



5 points – correct answer (12350)

8 **<u>Tiebreaker 6</u>: Which of the following phenomena enables light emission by LEDs? Select all that apply.** ____ / 5

a. Recombination of electron carriers and electron holes
b. A growing depletion region releasing electrons as light
c. A forward voltage causing protons to displace electrons
d. Electron migration from the P-type region to the N-type region
e. None of the above.

a. Recombination of electron carriers with holes in the P-type region causes emission of photons at a wavelength that corresponds to the energy difference across the band gap.
b. In a forward bias LED, the depletion region narrows as carriers enter the depletion region. A widening of the depletion region occurs in LEDs connected in reverse bias and light is not emitted.
c. Light emission by LEDs does not involve protons displacing electrons.
d. In a forward bias LED, electron carriers migrate from the N-type region to the P-type region. This answer choice has the two regions reversed.
e. Answer choice a. is correct.

1 point – for each answer choice correctly selected (a.) or not selected (b., c., d., e.)

9 **Event rules for Detector Building require that your temperature-sensing device have three LEDs in the colors red, green, and blue. Rank the band gap energies of these three colors of LEDs from greatest to least.** ____ / 3

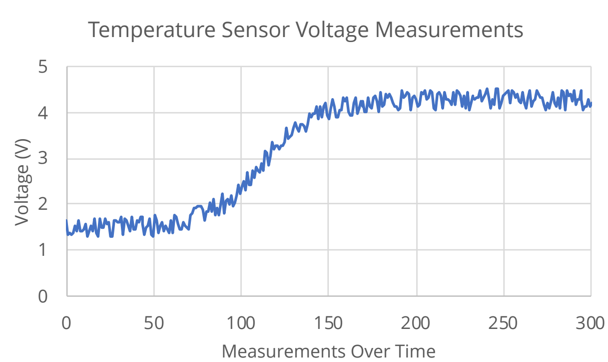
The band gap energy is inversely related to the wavelength of light emitted, as demonstrated by the Planck equation, $E = hc / \lambda$ (where E is the energy of a photon, h is Planck's constant, c is the speed of light in a vacuum, and λ is the wavelength of the photon). Blue light has the shortest wavelength, followed by green light, then red. A helpful mnemonic for remembering the order of visible colors in the electromagnetic spectrum is ROYGBV.

1 point – blue is the highest
1 point – green is in the middle
1 point – red is the lowest

10	**While building your temperature-sensing device, your partner realizes that they only have two-leaded 5 mm round red LEDs. Which of the following can be done to the red LEDs to produce light that is blue or green? Select all that apply.** **a. Use a potentiometer with the LED and change its resistance until the LED displays the correct color.** **b. Change the voltage of the power source for the LED until the LED displays the correct color.** **c. Apply a blue or green color filter to the red LED to change the observed color.** **d. Use a power supply that outputs a sinusoidal waveform with frequency corresponding to the wavelength for the color of interest.** **e. None of the above.** a. Changing the resistance of a potentiometer will change the voltage through an LED, which does not change the color of the light it emits. b. Changing the voltage of an LED does not change the color of the light it emits. c. Applying a color filter blocks light of all wavelengths except those permitted by the color filter. The wavelength-intensity spectrum of red LEDs (and many other colored LEDs) is narrow with practically all light emitted near red wavelengths (~625 nm), so there would be practically no blue or green wavelength light to pass through the color filter. d. Using a periodic waveform, such as a sinusoidal waveform, is in effect like pulse-width modulation, which at high enough frequencies produces the appearance of a dimmed LED. This does not change the color of light emitted by the LED. e. This is the correct answer. Changing the color of light emitted by an LED generally involves altering its components at the semiconductor-level. Remember, wavelength of light emitted is related to the band gap energy. *1 point – for each answer choice correctly selected (e.) or not selected (a., b., c., d.)*	____ / 5
11	**Which of the following statements about LEDs and conventional lighting sources is/are true? Select all that apply.** **a. Both LED lighting and conventional lighting sources are inherently directional.** **b. LED thermal path is accomplished by conduction, whereas in incandescent lighting it is not effectively managed.** **c. While compact fluorescent light (CFL) bulbs generally have lifespans longer than LED bulbs, they are less favored because they contain mercury vapors.** **d. Compared to conventional lighting, LEDs generate less waste on the consumer end.** a. LED lighting is considered directional because the light emitted by an LED is mostly in the direction the LED is facing. Conventional lighting sources such as incandescent or fluorescent lighting is not considered directional; these forms of lighting generally require reflectors to direct light in an intended direction. b. In this context, thermal path refers to how heat is dissipated from a light source. In LEDs, heat from the electronics of the LED is managed by conducting it to devices such as heat sinks for heat dissipation. This is important to prevent thermal-related degradation or failure. Thermal energy is not effectively managed in incandescent lighting, and most thermal energy is released in all directions—an incandescent bulb that has been on for a while is hot all around. c. Compact fluorescent light (CFL) bulbs generally do not have lifespans longer than LED bulbs. The statement about mercury vapors in CFLs is true. d. Because the lifespan of LED bulbs is longer, they generate less waste on the consumer end because replacement is less frequent. *1 point – for each answer choice correctly selected (b., d.) or not selected (a., c.)*	____ / 4

12	**Which of the following answer choice(s) describe difficulties of engineering LEDs? Select all that apply.** **a. Designing electronics of lights so they match the color characteristics of natural lighting** **b. Compact thermal management for larger lights** **c. Preventing color change over the lifespan of a device** **d. Engineering lights so they are responsive and can response within fractions of seconds to changes** **e. None of the above.** a. The human eye is remarkably sensitive to slight color differences. The color of light from LEDs is modified at the semiconductor-level, and it can be challenging to produce light with a wavelength-intensity spectrum mimicking that of incandescent light, which produces a continuous spectrum and is considered an optimal artificial light source. b. Thermal management is a significant consideration for larger and brighter LED lamps, and its optimization can be a challenge—overdo thermal management and the device may be larger and more expensive or underdo it and the device may prematurely fail. c. The color of light from an LED can change over its lifespan, and this is sometimes noticed when new bulbs are placed alongside old bulbs. d. The responsiveness of LEDs is an advantage of LEDs compared to conventional light sources. e. Answer choices a., b., and c. are correct. *1 point – for each answer choice correctly selected (a., b., c.) or not selected (d., e.)*	____ / 5
13	**Which of the following comparisons of through-hole and surface-mount LEDs is/are correct? Select all that apply.** **a. Surface-mount LEDs are better suited for breadboard prototyping of circuit designs.** **b. Surface-mount technology allows using LEDs that are both brighter and more energy efficient.** **c. Surface-mount technology produces circuits that are more reliable and physically robust.** **d. Surface-mount technology allows circuit designs that are more space efficient.** **e. Surface-mount and through-hole components are incompatible together.** a. Surface-mount components do not have wire leads that are required for use with breadboards. b. Surface-mount vs. through-hole describes how an electrical component can be integrated into a larger circuit, and it does not necessarily have an effect on the brightness or energy efficiency of the component. c. Surface-mount components are often considered less physical robust because their generally smaller size means less solder is used to adhere them to circuit boards, meaning they can be (accidentally) unmounted more easily. d. Surface-mount components are generally smaller because they do not contain wire leads that can take up a significant amount of space on circuit boards. e. Surface-mount and through-hole components are not necessarily incompatible with one another, though for simplicity of the manufacturing process it may make sense to use primarily one form. *1 point – for each answer choice correctly selected (d.) or not selected (a., b., c., e.)*	____ / 5
14	**Which of the following answer choice(s) correctly pairs a property and a possible metric used for its measurement? Select all that apply.** **a. Electrical characteristics, measured by input voltage or current** **b. Light output, measured by luminous flux** **c. Thermal efficiency, measured by maximum rate of temperature change without failure** **d. Lighting efficiency, measured by wattage** **e. Product lifespan, measured by hours of continuous operation until failure** **f. Color accuracy, measured by correlated color temperature** a. Voltage and current are electrical characteristics of a device. b. Luminous flux measures the light output by a device. c. Thermal efficiency describes the relative amount of energy that is dissipated as heat without doing work. The maximum rate of temperature change without failure describes a device's ability to withstand thermal shock. d. Lighting efficiency describes the relative amount of energy used compared to the light output. One way to calculate this is to take the ratio of luminous flux to wattage, but wattage alone is not enough. e. Product lifespan can be measured in many ways; one way is to measure hours of continuous operation until failure. Failure for an LED can be defined in many ways, from the LED not producing any light to the LED producing light that does not exceed a standard number of lumens. f. Color accuracy could describe the accuracy of the light emitted by a bulb which would be evaluated by a wavelength spectrum or correlated color temperature (CCT). Color accuracy could also describe the ability of a light source to reveal colors of objects compared to natural light—the metric for this would be its color rendering index (CRI). *1 point – for each answer choice correctly selected (a., b., e., f.) or not selected (c., d.)*	____ / 6

15	**Which of the following change(s) to your temperature-sensing device would require recalibration of your device? Select all that apply.** **a. Replacing the material used to waterproof your sensor (i.e. resealing your sensor)** **b. Changing the thermistor used for your sensor** **c. Changing the length of your temperature-sensing probe** **d. Changing the sampling frequency of your microcontroller** **e. Changing the resistance of a resistor used to keep input current of your temperature sensor within operating limits** **f. None of the above.** Frequently recalibrating measurement devices is generally recommended, but the changes that would require recalibration involve changes to the model used to calculate temperature measurements and its inputs (e.g. voltage or resistance of a thermistor). a. While changing the waterproofing material may change the thermal conductivity of the temperature sensor (which affects how quickly it detects temperature changes), it should not change any electrical measurements. b. Changing the thermistor used (even replacing it with one of the same type) can change electrical measurements (because no components are perfect), so recalibration is required. c. Changing the length of the probe (which possibly involves increasing the length of wires) should have negligible effect on electrical function of the device. While recalibration is not a bad idea, it is not required. d. Sampling frequency is the frequency of data collection, which should not affect the values of electrical measurements. e. Changing the circuitry of the sensor can change electrical measurements, so recalibration is required. f. Answer choices b. and e. are correct. *1 point – for each answer choice correctly selected (b., e.) or not selected (a., c., d., f.)*	____ / 6
<u>Questions 16-20</u>: The following questions reference the datasheet for the Everlight "Opto Interrupter" (https://www.endrich.com/fm/2/ITR-8105.pdf).		
16	**Which of the following statements about the Everlight "Opto Interrupter" is/are correct? Select all that apply.** **a. Forward current and forward voltage exhibit a linear relationship.** **b. The smallest possible dimension for the gap between the light emitter and detector is 2.4 mm.** **c. The sensor can be used either indoors or outdoors without additional considerations.** **d. The sensor has been tested for its ability to withstand sudden and drastic changes in ambient temperature.** **e. The sensor can be operated by making only two connections.** **f. The sensor produces a different response to partial interruptions vs. full interruptions.** a. Figure 4 on page 4 shows a graph of forward current and forward voltage. While the plot appears linear, forward current is plotted on a logarithmic scale, so the relationship is actually exponential. b. The device schematic on page 2 shows a gap width of 2.6 mm with a note stating that tolerances are ±0.20 mm. This means the smallest possible dimension as described by the manufacturer would be 2.4 mm. c. The photo transistor is sensitive to infrared (IR) light, so it could be affected by infrared radiation from the sun. When used outdoors, it is best to encase it in an opaque housing. d. The table on page 6 shows that reliability testing has tested the sensor's ability to withstand thermal shock. e. The device schematic on page 2 shows a total of four connections, two for the infrared emitting diode and two for the photo transistor. All four connections need to be made for the sensor's intended function. f. Figures 1 and 2 under "Typical Electro-Optical Characteristics Curves" on page 5 show that the collector current is dependent on the degree to which the gap is interrupted. *1 point – for each answer choice correctly selected (b., d., f.) or not selected (a., c., e.)*	____ / 6
17	**<u>Tiebreaker 2</u>: The manufacturer lists copiers, printers, and ticket vending machines as possible applications for the "Opto Interrupter" sensor. Describe in detail how the sensor could be used in one of these three applications and how the sensor serves its purpose in your described function.** Explanations need to explain the application for the sensor (3 points) and how the sensor functions in the suggested application (3 points). Some examples include: Detecting whether ink is loaded in the printer; the ink cartridge could have a fin that when loaded properly interrupts the sensor. Detecting whether a ticket has been dispensed by a ticket vending machine; the printed ticket could be dispensed such that it interrupts the sensor, and if no ticket is printed the customer could receive an automatic refund. *3 points – describing an application for the sensor in copiers, printers, or ticket vending machines* *3 points – explaining how the sensor serves its purpose in the described application*	____ / 6

18	**The infrared emitting diode of the Everlight "Opto Interrupter" uses gallium arsenide (GaAs) which has a band gap of 1.441 eV. What wavelength in nanometers does this correspond to? Answer in nanometers (nm) with two significant figures and input your answer without units.** Using the Planck equation, E = hc / λ (where E is the energy of a photon, h is Planck's constant, c is the speed of light in a vacuum, and λ is the wavelength of the photon), we can solve for wavelength. First, the band gap is converted to Joules: 1.441 eV * (1.6 × 10^-19 J / 1 eV) = 2.3 × 10^-19 J. With h = 6.6 × 10^-34 J s and c = 3.00 × 10^8 m/s, we have λ = (6.6 × 10^-34 J s) * (3.00 × 10^8 m/s) / (2.3 × 10^-19 J) = 8.58 × 10^-7 m or approximately 860 nm. *3 points – correct answer (860)*	____ / 3
19	**Two AA batteries with nominal voltage 1.5 V each are connected in series with a resistor to power the input of the Everlight "Opto Interrupter." What resistance in ohms should be used for the resistor such that the device is operating at its recommended specifications? Answer in ohms (Ω) rounded to the nearest ohm and input your answer without units.** The closed loop equation is V_battery – V_LED – V_R = 0 which can be rewritten as R = (V_battery – V_LED) / I_R. Page 3 of the datasheet lists the recommended forward voltage as 1.2 V at a current of 20 mA. By substituting the values provided by the question and datasheet, we can determine that the resistor needed must have a resistance of R = (3 V – 1.2 V) / (0.020 A) or 90 Ω. *3 points – correct answer (90)*	____ / 3
20	**<u>Tiebreaker 3</u>: Figures 1 and 2 on page 5 show device response for shielding/interruption in different dimensions. The trend observed is one common to sensors in general. Explain why such a response curve is expected in sensors in general, discussing each of the three parts of the curve.** All sensors exhibit this pattern of behavior in three ranges. Below the detection range, the measurement is around the measurement at the threshold of detection (2 points). Above the detection range, the detector is "saturated" and the measurement is the around the measurement at the maximum of its detection range (2 points). Within the detection range, measurements vary with input (2 points). One example of a sensor that follows this pattern is the sensor of your phone camera: in low light photos will appear black, in adequate lighting photos will display a range of colors, and in intense lighting photos will appear white or overexposed. *2 points – describing sensor behavior below detection threshold* *2 points – describing sensor behavior within detection range* *2 points – describing sensor behavior beyond detection range*	____ / 6
21	**<u>Tiebreaker 1</u>: Your partner has decided to modify your temperature-sensing device such that it displays a temperature measurement only after readings have stabilized. Write code that processes an array of real-time voltage measurements and prints the calculated temperature if voltage readings have stabilized or otherwise prints "UNSTABLE." (To help you understand the objective of this question, think about what happens when you place a thermometer in boiling water. The temperature reading does not immediately change from 25˚C to 100˚C; rather, it gradually increases from 25˚C to 100˚C, then stabilizes at 100˚C and may fluctuate within a few degrees.)** **You may write your code in any language of your choice. To calculate temperatures from voltages, you may use the mathematical model from your actual device, or you may make up one. Your code will be scored on implementation and clarity, so you are encouraged to comment your code and name variables appropriately. You will not be penalized for minor errors such as missing semicolons, etc.** 	____ / 12

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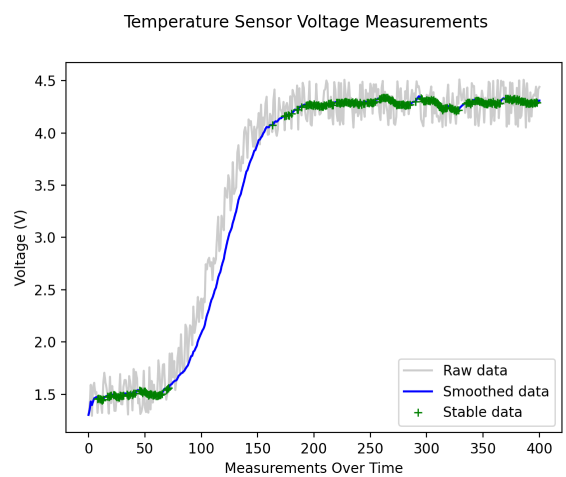
Code must implement a generalizable method for checking if readings have stabilized (2 points) that is not sensitive to small amounts of noise (2 points). Code must print “UNSTABLE” when readings are not stable (2 points), convert voltage values into temperature values (2 points), and print the temperature when stable (2 points). Code is clear and organized (2 points). An example of an acceptable solution, written in Python, is included below. This solution smooths data with a moving average filter, then identifies measurements as stable if they are within an acceptable tolerance from previous measurements.

```
# import packages for computing and plotting
import numpy as np
import matplotlib.pyplot as plt

# array of example voltage raw data
raw_data = [1.302, 1.399, 1.590, 1.293, 1.566, 1.609, 1.503, 1.520, 1.321, 1.473,
1.412, 1.426, 1.321, 1.594, 1.705, 1.613, 1.559, 1.453, 1.314, 1.667, 1.415, 1.578,
1.476, 1.341, 1.341, 1.491, 1.428, 1.430, 1.692, 1.405, 1.403, 1.570, 1.636, 1.635,
1.547, 1.306, 1.673, 1.615, 1.542, 1.345, 1.741, 1.549, 1.713, 1.651, 1.413, 1.456,
1.311, 1.335, 1.395, 1.724, 1.374, 1.329, 1.445, 1.323, 1.757, 1.354, 1.627, 1.420,
1.591, 1.456, 1.478, 1.512, 1.824, 1.700, 1.478, 1.601, 1.782, 1.788, 1.536, 1.448,
1.525, 1.523, 1.889, 1.561, 1.891, 1.661, 1.817, 1.540, 1.649, 1.851, 1.944, 1.706,
2.073, 1.808, 1.705, 1.774, 2.165, 2.131, 1.809, 1.997, 2.159, 2.141, 1.969, 2.338,
2.087, 2.154, 2.240, 2.430, 2.192, 2.374, 2.414, 2.226, 2.415, 2.380, 2.743, 2.694,
2.781, 2.805, 2.724, 2.762, 2.592, 2.803, 2.750, 2.792, 3.010, 3.198, 2.869, 2.896,
3.207, 3.133, 3.068, 3.473, 3.417, 3.380, 3.595, 3.543, 3.258, 3.348, 3.720, 3.416,
3.451, 3.479, 3.807, 3.882, 3.658, 3.635, 3.773, 3.710, 4.010, 4.054, 3.980, 3.762,
4.129, 4.074, 4.113, 4.001, 3.868, 4.059, 3.834, 4.032, 4.069, 4.190, 3.890, 4.270,
3.964, 4.147, 4.073, 4.281, 4.346, 3.982, 3.987, 4.182, 4.154, 4.008, 4.310, 4.415,
4.023, 3.972, 4.036, 4.334, 4.226, 4.213, 4.170, 4.296, 4.025, 4.252, 4.286, 4.219,
4.177, 4.350, 4.040, 4.411, 4.369, 4.340, 4.224, 4.453, 4.032, 4.427, 4.223, 4.168,
4.479, 4.431, 4.220, 4.134, 4.111, 4.254, 4.492, 4.083, 4.070, 4.281, 4.270, 4.168,
4.469, 4.256, 4.251, 4.175, 4.187, 4.287, 4.274, 4.405, 4.418, 4.501, 4.470, 4.138,
4.141, 4.346, 4.162, 4.081, 4.486, 4.408, 4.197, 4.114, 4.481, 4.078, 4.476, 4.116,
4.083, 4.508, 4.380, 4.293, 4.363, 4.482, 4.310, 4.334, 4.221, 4.051, 4.276, 4.195,
4.327, 4.160, 4.190, 4.462, 4.124, 4.489, 4.228, 4.154, 4.412, 4.332, 4.377, 4.257,
4.471, 4.431, 4.184, 4.465, 4.394, 4.465, 4.262, 4.420, 4.195, 4.123, 4.431, 4.497,
4.186, 4.393, 4.271, 4.205, 4.075, 4.285, 4.139, 4.352, 4.345, 4.090, 4.077, 4.154,
4.493, 4.383, 4.299, 4.427, 4.206, 4.240, 4.169, 4.399, 4.327, 4.497, 4.179, 4.257,
4.327, 4.411, 4.294, 4.378, 4.343, 4.493, 4.438, 4.446, 4.374, 4.129, 4.098, 4.064,
4.262, 4.158, 4.364, 4.332, 4.355, 4.371, 4.444, 4.096, 4.389, 4.186, 4.265, 4.155,
4.165, 4.108, 4.143, 4.256, 4.056, 4.336, 4.233, 4.070, 4.337, 4.462, 4.220, 4.096,
4.211, 4.379, 4.228, 4.183, 4.087, 4.345, 4.279, 4.511, 4.398, 4.311, 4.356, 4.421,
4.191, 4.246, 4.434, 4.145, 4.321, 4.146, 4.476, 4.443, 4.448, 4.075, 4.362, 4.170,
4.067, 4.189, 4.297, 4.404, 4.331, 4.099, 4.336, 4.304, 4.262, 4.489, 4.474, 4.082,
4.162, 4.497, 4.115, 4.337, 4.316, 4.505, 4.141, 4.333, 4.499, 4.453, 4.490, 4.279,
4.434, 4.060, 4.330, 4.085, 4.483, 4.190, 4.477, 4.264, 4.297, 4.079, 4.431, 4.060,
4.502, 4.142, 4.163, 4.301, 4.508, 4.423, 4.051, 4.475, 4.276, 4.109, 4.387, 4.157,
4.339, 4.367, 4.356, 4.442, 4.265, 4.418, 4.440]

# array for storing voltage data after smoothing
smoothed_data = []

# array for storing voltage data that is considered stable
stable_data = [[], []]

# number of data points to average for moving average smoothing
points_to_average = 20

# acceptable noise in smoothed voltage data for determining stability
voltage_noise_tolerance = 0.01

# loop to read through each point in voltage raw data
count = 0
for raw_point in raw_data:
    count += 1

    # smooth voltage data by taking the average of several previous points
    according to `points_to_average`
    if count >= points_to_average:
        smoothed_point = np.average(raw_data[(count - points_to_average):count])
    # if the number of previous points is not at least `points_to_average`, take
    the average of all existing points
    else:
        smoothed_point = np.average(raw_data[0:count])

    # add averaged data point to the array of smoothed voltage data
```

21

```
        smoothed_data.append(smoothed_point)

        # determine if the smoothed data point is stable
        if count >= 5:
            # take the average of the last five smoothed data points
            smoothed_data_comparison = np.average(smoothed_data[(count - 5):count])

            # if the difference between the average and the most recent smoothed point
            is within the noise tolerance
            if ((smoothed_point - smoothed_data_comparison) <=
            voltage_noise_tolerance):
                # for the purpose of plotting data, append the point to the array of
                stable data
                stable_data[0].append(count - 1)
                stable_data[1].append(smoothed_point)

                # use a mathematical model to convert voltage into temperature and
                round to two decimal places
                temperature = 21.47 * smoothed_point - 1.92
                temperature = round(temperature, 2)

                # print the temperature value
                print(str(temperature) + "˚C")
            # otherwise print "UNSTABLE"
            else:
                print("UNSTABLE")

    # plot the voltage raw data with smoothed data and identify points considered as
    stable
    fig = plt.figure()
    fig.suptitle('Temperature Sensor Voltage Measurements')
    plt.plot(raw_data, 'k-', label='Raw data', alpha=0.2)
    plt.plot(smoothed_data, 'b-', label='Smoothed data')
    plt.plot(stable_data[0], stable_data[1], 'g+', label='Stable data')
    plt.xlabel('Measurements Over Time')
    plt.ylabel('Voltage (V)')
    plt.legend(loc='lower right')
    plt.show()
```

The graph below shows the effect of smoothing data using the code above. Data points identified as stable by the code are plotted in green.



2 points – code implements a generalizable method for checking if readings have stabilized (e.g. checking for a pattern and not specific voltage values)
2 points – method for checking if readings have stabilized is not sensitive to small amounts of noise (as shown in the figure)
2 points – code prints "UNSTABLE" when readings are not stable
2 points – code prints temperature when readings are stable
2 points – code converts voltage values into temperature values
2 points – code is clear and organized

22 **In what programming language did you write your code for the previous question?** ____ / 0

23 ____ / 6

Which of the following is/are appropriate methods for minimizing noise in your detected signal? Select all that apply.

a. Passing your signal through a low-pass filter prior to analog-to-digital conversion.
b. Passing your signal through an exponential moving average filter.
c. Passing your signal through a proportional-integral-derivative (PID) controller.
d. Positionally stabilizing your temperature-sensor during data collection.
e. Recalibrating your temperature-sensing device against a trusted thermometer.
f. Increasing your sampling frequency to avoid aliasing.

a. Low-pass filters remove high frequencies (associated with noise). This step can be performed prior to analog-to-digital conversion with electrical components (operational amplifiers, resistors, capacitors) or afterwards within software.
b. An exponential moving average calculates averages from a series of multiple datapoints which minimizes noise in the processed signal.
c. PID controllers are used for maintaining values at set points (e.g. maintaining a water bath at a set temperature). They are not related to minimizing noise in measured signals.
d. A moving temperature-sensor can contribute to fluctuations in measurements, so positionally stabilizing the sensor may help minimize noise.
e. While recalibrating your device should ensure accuracy of its readings, it will not change noise in your signal, which is considered random.
f. While increasing sampling frequency can avoid aliasing, aliasing is not related to signal noise. Decreasing the sampling frequency can minimize the appearance of noise because they are fewer datapoints to contribute to the noise, but this isn't exactly considered a solution since noise can still be present in your fewer datapoints!

1 point – for each answer choice correctly selected (a., b., d.) or not selected (c., e., f.)

24 ____ / 2

Analog input for Arduino Uno microcontrollers reads voltages between 0 and 5 V as integer values between 0 and 1023, inclusive. How many bits does this correspond to? Round your answer to the nearest whole number.

Integral measurements between 0 and 1023 correspond to 1024 or 2^10 "bins" which correspond to 10 bits.

2 points – correct answer (10)

25 ____ / 3

The number of bits in the analog-to-digital converter (ADC) of the Arduino Uno is hypothetically increased by two bits. What is the analog input voltage resolution of this hypothetical device? Answer in millivolts (mV) rounded to the nearest 0.1 mV and input your answer without units.

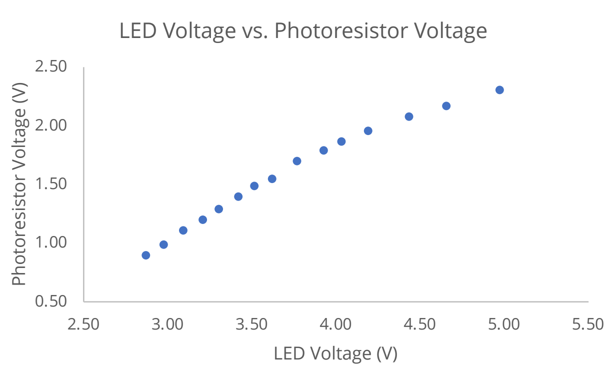
Increasing the ADC by two bits increases the number of bins to 2^12 or 4096 which for a range of 5 V allows for a voltage resolution of 5 V / 4096 or 1.2 mV.

3 points – correct answer (1.2)

<u>Questions 26-31</u>: In medicine, a device called a pulse oximeter measures oxygen saturation (the percentage of hemoglobin molecules that are oxygen-bound) using two LEDs of different wavelengths and a photodetector. A student creates a functioning low-cost battery-powered pulse oximeter using a single red LED and a photoresistor.

Realizing that the voltage supplied to the LED and therefore its brightness will vary as the battery powering the pulse oximeter is drained, the student decides to characterize the relationship between LED voltage and the voltage measured across the photodiode. The student positions the LED directly opposite to the photodiode in a dark room and measures the voltage across the photodiode as the voltage across the LED is adjusted.

The student's measurements are shown in the table to the right below



LED Voltage (V)	Photoresistor Voltage (V)
2.88	0.87
2.99	0.97
3.10	1.09
3.22	1.18
3.32	1.27
3.43	1.37
3.53	1.47
3.63	1.53
3.78	1.67
3.94	1.77
4.05	1.84
4.20	1.93
4.45	2.06
4.67	2.15
4.99	2.28

26 **Which of the following circuit arrangements is most likely how the student wired their pulse oximetry device?** ____ / 2

a. The LED and photoresistor in series
b. The LED and photoresistor in parallel
c. The LED and photoresistor in separate circuits
d. The LED and photoresistor connected by a relay
e. The photoresistor connected to the base of an NPN transistor with the LED at the emitter

Of the answer choices, it makes most sense for the LED and photoresistor to be in separate circuits so that the LED is unaffected by changes in the photoresistor when the device is used.

2 points – correct answer (c.)

27 **What conclusion can be made from the student's data?** ____ / 2

The student's data shows that as LED voltage is increased (1 point), the voltage across the photoresistor increases (1 point).

1 point – relating LED voltage to photoresistor voltage
1 point – mentioning that the two measurements increase with each other

28 **How would the student's model change if it had been performed in a room that was not dark?** ____ / 3

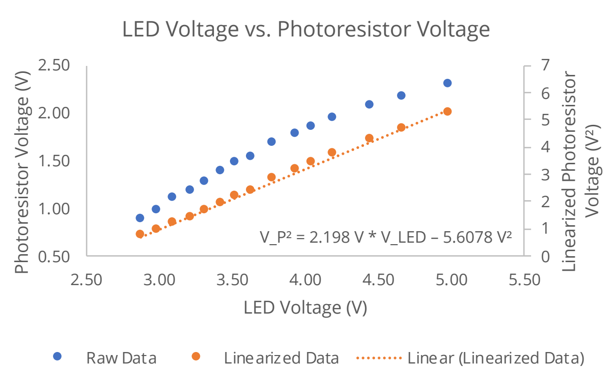
a. The photoresistor voltage values would all be higher.
b. The LED voltage values would all be lower.
c. There would be no change in the student's model.
d. LED voltage and photoresistor voltage would follow an exponential trend.

The student's data shows that as LED voltage is increased (causing a brighter LED), the voltage across the photoresistor increases. Therefore, if the room were not dark, we should expect all photoresistor voltage values to be higher due to ambient light contributing to the voltage of the photoresistor.

3 points – correct answer (a.)

29 **<u>Tiebreaker 4</u>: Linearize the student's voltage/voltage data. Clearly describe what operation(s) you performed and on which variable(s) to linearize the data.** ____ / 2

The student's data can be linearized by mathematically manipulating photoresistor voltage or LED voltage, but not both. Some operations that appear to linearize the data include squaring the photoresistor voltage (V^2) or applying a power function to the photoresistor voltage (2^V). Award 2 points for any valid attempt at linearizing the data. An example of the data linearized by squaring the photoresistor voltage is plotted below.



2 points – any valid attempt at linearizing the data

30 **<u>Tiebreaker 4</u>: Determine an equation that describes your linearized data. Include units and define any variables you use.** ____ / 3

A sample answer is $V_P^2 = 2.198\ V * V_{LED} – 5.6078\ V^2$ where V_P is photoresistor voltage and V_{LED} is LED voltage. Answers should provide an equation that is linear (1 point), matches linearization operations from the previous question (1 point), and includes variable definitions and units (1 point).

1 point – providing an equation that is linear
1 point – variables/parameters in equation match linearization operations (e.g. inverse temperature)
1 point – correct units used in equation/variable definitions

31	**The student is dissatisfied with the line of best fit and decides to take repeated measurements for a greater range of values. What will happen to the R-squared value?** **a. The R-squared value must increase.** **b. The R-squared value must decrease.** **c. The R-squared value must stay the same.** **d. The R-squared value must approach a limit.** **e. None of the above.** An R-squared value describes how well a regression fits a dataset. As more data is collected, it is not clear whether the new data will improve, worsen, or not change the fit of the regression. *3 points – correct answer (e.)*	____ / 3
32	**Tiebreaker 7: Which of the following statements about working with data is/are true? Select all that apply.** **a. Any dataset can be linearized to produce a linear trend.** **b. Adding a new datapoint to a dataset for which a regression has been performed will not change the regression if the new datapoint lies on the original regression curve.** **c. A negative correlation indicates that two variables are not related.** **d. A high R squared value indicates that two variables are strongly correlated.** **e. None of the above.** a. Not all data can be linearized—for example, a sinusoidal curve. b. A regression curve tries to minimize the collective error between each datapoint and the curve. If a new data point is already on the regression, it will have an error of zero, which requires no change of the regression to minimize error. c. A negative correlation indicates that one variable increases while the other decreases and vice versa. d. An R squared value does not describe the correlation between two variables, but the fit of a regression to a set of data. e. Answer choice b. is correct. *1 point – for each answer choice correctly selected (b.) or not selected (a., c., d., e.)*	____ / 5
33	**A student models the temperature-voltage relationship for their temperature-sensing device with the equation T = 63.56 [UNITS] * ln (V_Th) + 254.15 K, where T represents temperature in Kelvin and V_Th represents voltage in volts across the temperature sensor. What are the correct units for the slope?** **a. K V** **b. K V^-1** **c. K ln (V)** **d. K (ln V)^-1** **e. K e^-V** The slope when multiplied by ln (V_Th) must produce a value with units Kelvin. This is satisfied by answer choice d. *2 points – correct answer (d.)*	____ / 2