Name (Last, First): ___________________ ID Number: ________________________

Team Round: Solutions

1. **All about the brain**

a. *The brain is electrical, excitable*. All behavior, cognition, and emotion, a crush you might have, the apprehension you may be feeling reading this question, arise from the electrical activity of the neurons that make up the brain. How does this occur?

i. Separation of charges. A neuron's cell membrane separates its interior from its surroundings, creating an imbalance in ion concentration. Typical ion concentrations are given in the table below:

Species	Intracellular concentration (mM)	Extracellular concentration
Na^+	145	15
K^+	4	150

Recall the Nernst Equation: $E_A = \frac{RT}{zF}\ln\left(\frac{[A]_o}{[A]_i}\right)$. Calculate the equilibrium potential (in mV) to the nearest whole number of potassium ion inside the neuron (intracellular) relative to the outside (extracellular) at 37°C.

$$E_K = \frac{RT}{zF}\ln\left(\frac{[K^+]_o}{[K_i]}\right) = -97\text{mV}$$

Use of Nernst = 2pts;
correct use position of K out and in = 2pts;
correct answer = 1pt
Answer:______ -97mV _____________mV

ii. Resting potential.

a. At any given time, the potential across the membrane of the cell will not be equal to the equilibrium potential of either potassium or sodium. This results in a flow of ions (potassium from inside to outside and sodium from outside to inside) through many thousands of ion channels. Defining the current of positive ions flowing from inside to outside as positive current and using Ohm's Law, we note that

$$I_{ion} = (V_m - E_{ion}) * g_{ion}$$

(This question continues on the next page.)

Where I_{ion} is the ionic current, V_m is membrane potential, E_{ion} is the equilibrium potential of the ion, and g_{ion} is the membrane's conductance to the ion.
Since the total ionic current across the membrane is the sum of currents due to individual ionic species, we have

$$I = I_{Na} + I_K = g_K(V_m - E_K) + g_{Na}(V_m - E_{Na})$$

At steady state, I = 0. Derive an expression for V_m in terms of E_{Na}, E_K, g_{Na}, and g_K

b. A reasonable resting potential is -70mV. At this membrane voltage, calculate to the nearest whole number the relative magnitude of membrane conductance to sodium ion and potassium ion. For this problem, assume $E_K = -80$ mV. The equilibrium potential of sodium ion is 60mV.

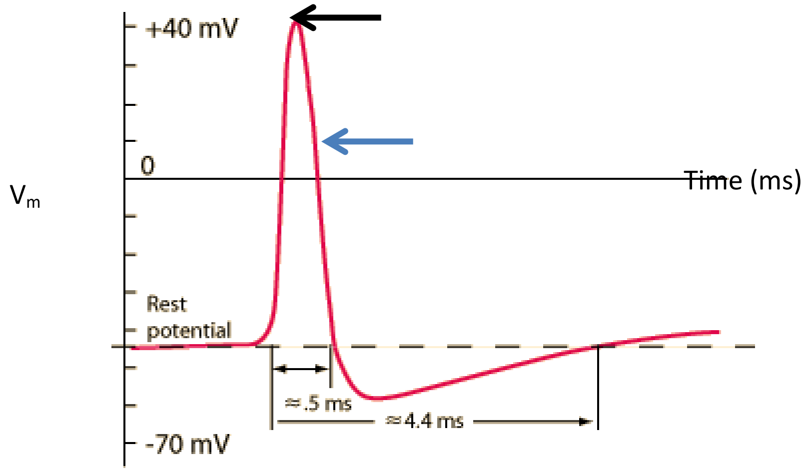
$$V_m = \frac{g_{Na}E_{Na} + g_K E_K}{g_{Na} + g_K}$$

Name (Last, First): ___________________ ID Number: ________________________

$$\text{Let } g' = \frac{g_K}{g_{Na}}, \text{then at rest we have } -70\text{mV} = \frac{60\text{mV} + g' * -80\text{mV}}{1+g'} \rightarrow$$
$$-70 - 70g' = 60 - 80g' \rightarrow 10g' = 130 \rightarrow g' = 13 \rightarrow g_K \text{ is } 13 \text{ times larger than } g_{Na}$$
$$\rightarrow \text{neuron has greater conductance to potassium ion}$$

Correct derivation = 2 points, Correct answer with reasonable work = 4pts

i. <u>Excitability.</u> Neurons are excitable; in essence, they can be driven to generate action potentials. An action potential is shown below:



At the peak of the action potential (indicated by the black arrow), the membrane potential is +40mV). At the peak of the action potential, the membrane exists at a pseudo-steady state (I = 0). Calculate the relative magnitude of sodium and potassium conductance and comment on the difference between the calculated values in (i) and (iii). For this problem, assume $E_K = -80$ mV.

$$V_m = \frac{g_{Na}E_{Na} + g_K E_K}{g_{Na} + g_K}$$
$$\text{Let } g' = \frac{g_K}{g_{Na}}, \text{then at peak we have } 40\text{mV} = \frac{60\text{mV} + g' * -80\text{mV}}{1+g'} \rightarrow$$
$$40 + 40g' = 60 - 80g' \rightarrow 120g' = 20 \rightarrow g' = \frac{1}{6} \rightarrow g_{Na} \text{is } 6 \text{ times larger than } g_K$$
$$\rightarrow \text{neuron has greater conductance to sodium ion}$$

Correct answer with reasonable work = 3 points;
Correct comment on difference = 3 points

ii. Abhishek uses the equation from part ii to calculate the relative magnitude sodium and potassium conductance at the voltage indicated by the blue arrow. Is this valid? Why or why not?

No, the equation requires a steady state assumption for membrane voltage. Membrane voltage clearly not at a steady state.

1 point for no;
1 point for justification

Name (Last, First): __________________ ID Number: _______________________

c. *Studying the brain*. "New directions in science are launched by new tools much more often than by new concepts. The effect of a concept-driven revolution is to explain old things in new ways. The effect of a tool-driven revolution is to discover new things that have to be explained" – Freeman Dyson, theoretical physicist. For this problem, we explore three tools essential for the study of the brain.

i. The sharp electrode. To record the first action potential, researchers such as Joseph Erlanger and Herbert Gasser (at Wash U!) in the early 20th Century used incredibly sharp glass electrodes inserted into neurons. In order to penetrate a neuron, which has a diameter of around 20 micrometers, the tip of the electrode needs to be around 1 micrometer.

a) Because the tip is so thin, it is much easier to measure its diameter indirectly through measuring its resistance. Note that the tip cross-section of the electrode is a circle. The resistance of a resistor is inversely proportional to the cross-sectional area of the resistor. If the tip diameter is 16 micrometers at an electrode resistance of $1M\Omega$, what should the resistance (in Mohm) of the electrode is 1 micrometer, as desired?

$$1M\Omega * 256 = x * 1 \rightarrow x = 256M\Omega$$

1 point for setting up proportion; 1 point for correct answer

b) Why is it not desirable to make the tip of the electrode as fine as possible? (Hint: consider Ohm's Law and random fluctuations in ionic current)

Fine tip = very large resistance, so small random fluctuations in ionic current will be magnified into large fluctuations in recorded voltage. In essence, too noisy.

3 points for correct answer

(This question continues on the next page.)

ii. The patch clamp. The patch clamp was developed by Neher and Sakmann in the 1970s and 1980s, an accomplishment for which they were awarded the Nobel Prize in 1991. Through patch clamping, one can study the current through individual ion channels, something not possible in sharp electrode recording. In patch clamp, the electrode does not penetrate the cell membrane but instead sucks onto the membrane; thus, the tip diameter should be much larger than a sharp electrode. Using the value you obtained in part i., what should the resistance (in Mohm to the nearest hundredth) of your electrode be when the tip diameter is 10 micrometers?

$$\mathrm{R} = \frac{256}{100} = 2.56\mathrm{M\Omega}$$

1 point for proportion

1 point for correct answer

iii. Extracellular recording. Both sharp electrode recording and patching clamping are techniques for single unit recordings (recordings from a single neuron). However, there are many instances when one wants to record from multiple neurons at a time (that is, conduct multiunit recordings). For example, I use multiunit recordings from the locust olfactory system to study the neurons involved in the sense of smell. Multiunit recording electrodes are much, much larger than intracellular electrodes (about as wide as a human hair, around 50 micrometers) and are metal wires inserted into the brain. We tune the resistance of our electrodes by plating it with gold nanoparticles. Assume that the only conducting portion of the electrode is a single layer of atoms with a circular cross section of diameter 50 micrometers. Initially, there are only tungsten atoms and no gold atoms in this layer, and the electrode has a resistance of 200kΩ. When plating, a 0.03 μA current is applied while the tip is immersed in a solution containing gold ions. The following half-reaction occurs:

$$Au^{+} + e^{-} \rightarrow Au_{(s)}$$

Name (Last, First): __________________ ID Number: _______________________

The gold atom replaces a tungsten atom originally on the tip. Assume that if the tip were composed entirely of gold, resistance would be $5k\Omega$. How long should the electrode be plated to reach a resistance of $50k\Omega$? The radius of a gold atom is 1.66 $*10^{-10}$ m. Assume (unrealistically) that all of the area of the electrode tip can be occupied by gold atoms.

$$x * (5000) + (1 - x) * 200000 = 50000 \rightarrow 200000 - 195000x = 50000 \rightarrow x = \frac{150000}{195000} = 76.9\% \text{ gold}$$

$$\text{maximum number of gold atoms} = \frac{(25 * 10^{-6})^2}{(166 * 10^{-12}\text{m})^2} = 2.27 * 10^{10}\text{atoms}$$

$$\text{we need } 0.769 * 2.27 * 10^{10}\text{atoms} = 1.74 * 10^{10}\text{atoms}$$

$$1\text{A} = 6.25 * \frac{10^{18}\text{e}^-}{\text{s}}, \text{so } 0.03\mu\text{A} = 3 * 10^{-8} * 6.25 * 10^{18} = 1.875 * \frac{10^{11}\text{ e}^-}{\text{s}}$$

$$\text{so we need } \frac{2.27 * 10^{10}}{1.875 * 10^{14}} = 0.121\text{s} = 121\text{ ms}$$

2 point for first equation
1 point for correct percent gold
1 point for maximum number of gold atoms
1 point for number of atoms needed
1 point for current
2 points for correct final answer

d. *The ionic basis of the action potential*.

i. Using information from part a (you will not need any of the answers of part a), explain which current (sodium or potassium) causes the increase in membrane potential during an action potential (known as depolarization) and which current contributes to the subsequent decrease in membrane potential (repolarization)?

At rest, V < ENa, so the electrostatic force is greater than the diffusive force. The inside of the cell is more negative than the outside, so sodium current flows into cell, making it more positive so it is responsible for depolarization. On the other hand, at the peak of the AP V > EK so potassium flows out of cell making it less positive/more negative → repolarization

3 points for correct rest explanation
3 points for correct peak explanation

ii. Below is a plot of the time course of sodium and potassium current during an action potential (as shown in plot A). Sakmann and Neher studied ionic current through single channels, and observed the following all or none responses in single ion channels-(as shown in plot B). In (B) red rectangles correspond to application of an excitatory electrical stimulus (i.e. one that opens ion channels). I_m denotes ionic current flowing across the membrane through the channel.

Clearly, the current observed in plot (A) differs greatly with respect to that recorded in plot (B). Rationalize this difference (hint: a neuron contains many, many ion channels).
There are many ion channels on the membrane of a neuron, so the population current observed by H and H represent more the probability distribution of individual channel opening. Notice that in (B), a channel has variable opening time after stimulus onset. This gives population opening a smooth appearance (Poisson distributed).
6 points for reasonable explanation (no need to mention poisson). Reasonable explanation must include variability of opening time after stimulus onset

Name (Last, First): ___________________ ID Number: ________________________

2. The kinetic theory of gases has two assumptions that cause problems in low temperature and high pressure conditions. Gases in these conditions behave as *real* gases, as opposed to *ideal* gases. Kinetic theory assumes that individual gas particles have no volume, and that these particles have no forces acting between them.

   a. Identify the features of a water molecule (H_2O) lead to its deviation from ideal behavior. Explain your answer using no more than three or four complete sentences. You may use drawings in conjunction with your written response if you deem them helpful.

-Water molecules have permanent molecular dipole moments (2 points)

-water molecules can form hydrogen bonds to other water molecules (2 points)

-water molecules have a non-zero volume (1 point)

These features violate the conditions of kinetic theory stated above. Since water molecules have a non-zero volume, the assumption that the volume of a container is the volume the gas occupies is wrong. At low temperatures, water molecules will be passing by each other more slowly, and the effects of hydrogen bonding will emerge—violating the condition that says there are no forces acting between the particles.

   b. Johannes Diderik van der Waals, who won the Nobel Prize in 1910, derived an equation to describe real gases: $\left[P + a\left(\frac{n}{V}\right)^2\right]\left(\frac{V}{n} - b\right) = RT$. This equation takes into account how a gas will deviate from ideal behavior. In the equation, a and b are constants specific to each gas. Give the units for each constant a and b.

   a = $L^2 atm/mol^2$, b = L/mol.

   1 point for a,

   1 point for b

   c. Ammonia (NH_3), Hydrogen (H_2), and Hydrogen Chloride (HCl) gases deviate from the ideal gas law.

      i. Draw the most preferred Lewis structure of each gas.
      ii. Rank the three gases in terms of their deviation from ideal gas behavior (the gas that deviates the most from ideal gas behavior should be ranked highest).

   Lewis structures accepted on following criteria. For NH_3, H's connected to N by either lines or dotted pairs of electrons, lone pair shown. For H_2, H:H or H—H accepted. For HCl, H:Cl and H—Cl accepted. Lone pair need to be shown on chlorine.

   i. 2 points per Lewis structure (6 total)

   NH_3 can form hydrogen bonds. H2 has volume. HCl has a permanent molecular dipole moment.

   NH_3 has intermolecular forces like dipole-dipole and hydrogen bonding, whereas hydrogen gas does not. We expect NH3 to have a larger deviation from ideal behavior at lower temperatures.

   H_2 is expected to most closely resemble ideal gas behavior, NH3 the least. The stronger the intermolecular forces ideal behavior at low temperatures. H-Bonds+dipole-dipole > dipole-dipole > instantaneous-dipole – induced dipole (ldf).

   4 points for correct ranking

Name (Last, First): ___________________ ID Number: ________________________

d. Acetic acid (CH3COOH) is known to form a cyclic dimer in the gas phase due to intermolecular interactions.

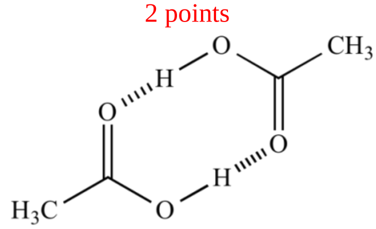
i. In a closed container with fixed volume, as the partial pressure of monomer (CH3COOH (g)) increases, how will the concentration of the dimer change? Write a balanced chemical reaction equation representing this dimerization. Terms "monomer" and "dimer" can be used instead of chemical formulae.

$$2CH_3COOH\ (\text{monomer}) \leftrightarrows CH_3COOH - -CH_3COOH(\text{dimer})$$
$$\text{Dimer concentration will increase (Le Chatalier's Principle)}$$

2 points for equation
2 points for saying conc. Will increase and invoking Le Chatalier

ii. Considering the Lewis structure of acetic acid, propose the structure of the dimer.

2 points



Name (Last, First): __________________ ID Number: _______________________

3. Everybody loves soda, right? You decide to use your chemistry knowledge and skills to make your own soda! The first step of making any soda is carbonation. Carbonated water has carbon dioxide dissolved in it, creating carbonic acid, $H_2O_{(l)} + CO_{2(g)} \rightleftarrows H_2CO_{3(aq)}$. To figure out what conditions are required for carbonation, explain the following observations:
   a. When you first open a soda can, the soda starts fizzing.

Before the can is opened, the gas pressure inside the can is much higher than atmospheric pressure and the solution is supersaturated with carbon dioxide. After the bottle is opened, this pressure is released and the dissolved carbon dioxide gas escapes from solution by fizzing out as bubbles.
1 point for saying high pressure before opening
1 point for saying that opening can decreases pressure
1 point for linking to fizzing

   b. An opened can of soda loses its carbonation more quickly at warmer temperatures than at colder temperatures.

The kinetic energy of the carbon dioxide gas molecules increases as temperature increases and the hydrogen bonds between the water molecules are easier to break. Thus, the carbon dioxide can escape the liquid more.

2 points for correct explanation

   c. From the above observations, list the temperature and pressure that conducive to the effective carbonation of water.

Higher gas pressure and lower temperature cause more gas to dissolve in the liquid

1 point for temperature

1 point for pressure

   d. Henry's Law
      i. The amount of carbon dioxide dissolved in soda is around 8g per liter. Use Henry's Law to estimate how the partial pressure (in atm to the nearest hundredth) of CO2 above the solution in order to carbonate 2 liters of water. The Henry's solubility constant (H_{cp})of CO_2 is $3.4\times10^{-2}\ \frac{\text{mol}}{\text{L}*\text{atm}}$ at 25°C. Henry's law is $H_{cp} = \frac{c_{aq}}{P_{gas}}$, where c_{aq} is the concentration of dissolved carbon dioxide and P_{gas} is the partial pressure of carbon dioxide gas.

$$P = \frac{c_{aq}}{H_{cp}} = \frac{8/44.01}{3.4*10^{-2}} = 5.35\text{atm}$$

2 points for using equation
2 points for correct answer

      ii. Your friend opens the 2 L of soda and leaves it sitting out for a few hours. What is the concentration (in g/L to three significant figures) of carbon dioxide dissolved in the soda now, given that the partial pressure of carbon dioxide in the atmosphere is 0.053 atm.?

$$c = P*H_{cp} = 0.053*3.4*10^{-2} = \frac{0.0793\text{g}}{\text{L}}$$

3 points for manipulating equation

Name (Last, First): __________________ ID Number: _______________________

2 points for correct answer

e. Explain why shaking a can of soda is a dangerous idea and can lead to an explosion(!).

Shaking acan inputs energy, giving the gas molecules more energy to break free from the hydrogen bonds in the liquid and form bubbles more easily.

2 points for correct explanation

f. You decide to do the infamous soda and Mentos experiment with your soda. Mentos, regular mints, and marbles are dropped separately into three different bottles of soda. The corresponding height of each responding explosion is shown in the plot below:

Given that the relative roughness of the three objects is mentos > mints > marbles, with mentos being the roughest.

Rationalize these results. Explain your conclusions with physical/chemical scientific knowledge.
Answer: The rougher the surface, the more surface area there is for carbon dioxide bubble formation on the Mentos. The activation energy at these bubble formation sites is lower, thus the Mentos can act like a catalyst in producing the many, many carbon dioxide bubbles that can cause the soda-mentos explosions.
2 points for talking about surface area (rougher = more surface area)
2 points for talking about mentos/mints/marbles as a catalyst
2 points for talking about bubble-formation/nucleation sites

Name (Last, First): ___________________ ID Number: ________________________

4. Scientists have discovered intelligent alien life on the planet sleon 05R. They have found what appears to be an unbalanced chemical reaction equation carved on an ancient rock.

⅂(∇ᑏ)$_3$ + ᒷ∇$_2^{2-}$ ----> ᒷ∇$_3^{2-}$ + ⅂

ᑏ, ∇, ⅂ and ᒷ are all symbols for different elements that exist on Earth. ∇ is the symbol for oxygen which has an oxidation number of -2 and ᑏ is an unnamed element with an oxidation number of 1.

Given that this reaction takes place in a basic solution. How many water molecules should be present in the chemical reaction equation?

Original equation: $Bi(OH)_3 + SnO_2^{2-}$ ----> SnO_3^{2-} + Bi

3ᒷ∇$_2^{2-}$ + 2⅂(∇ᑏ)$_3$ ----> 2⅂ + 3ᒷ∇$_3^{2-}$ + $3H_2O$

3 H20

15 points for correct solution with any work

If solution incorrect:

2 points for determining correct initial oxidation state of ⅂

1 point for determining correct final oxidation state of ⅂

2 points for determining correct initial oxidation state of ᒷ

2 points for determining correct final oxidation state of ᒷ

4 points for setting up half reactions involving electrons (2 points per correct half reaction)

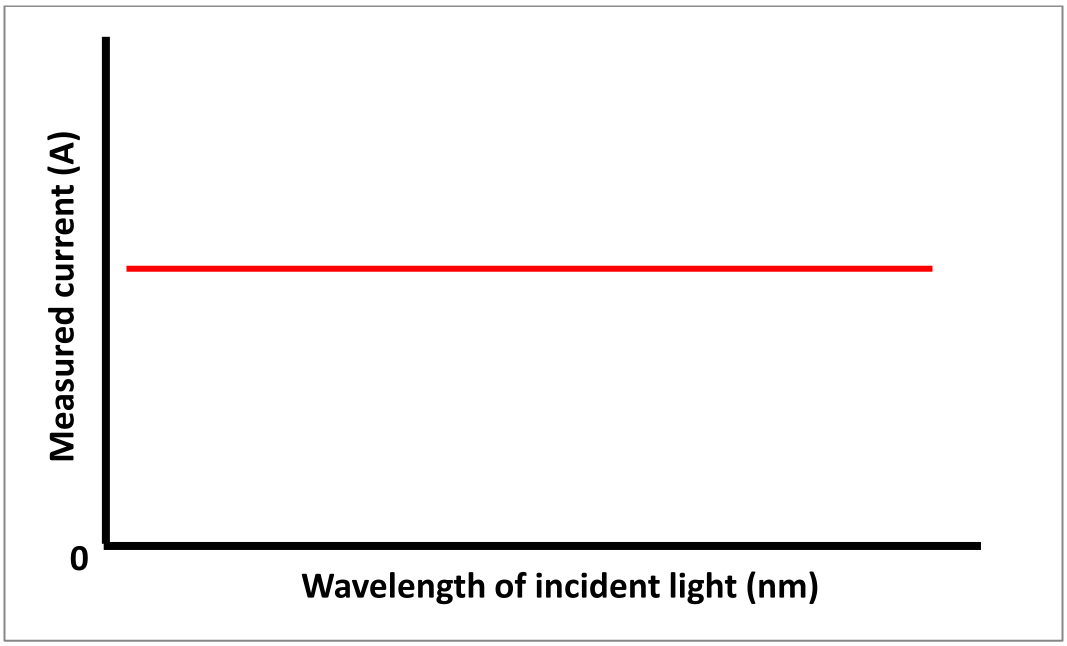
Name (Last, First): ___________________ ID Number: ________________________

One of the most important discoveries in physics in the 20th Century was that of **wave-particle duality**, or that light (and all matter, for that matter) possessed both wavelike and particle-like properties. This discovery led to the development of a new field of physics, quantum physics, which had far-reaching effects on how chemists viewed molecular structure and chemical reactions.

Prior to the discovery of wave-particle duality, physicists considered light to be an electromagnetic wave. This made sense; light had a wavelength and a frequency and could be reflected, refracted, and diffracted like waves of air or water.

However, around the turn of the 20th Century evidence emerged that fundamentally challenged this perception. Physicists had been studying the photoelectric effect, in which shining light onto a metal could induce a current in the metal if it exceeded a characteristic minimal energy, known as the work function (Φ) of the metal; they posited that the energy from the light removed electrons from metal atoms.

a. In an experiment, the experimenters varied the wavelength of light incident on a piece of metal with area $1m^2$. They varied the intensity of the incident light to keep the energy flux (energy input per unit area per unit time, units $\frac{J}{m^2 * s}$). If light had only wavelike properties, sketch on the axes below the expected relationship between the wavelength of incident light and the recorded current in the metal at constant energy flux. Assume that the energy flux used was sufficient to elicit some positive current in the metal.



3 points

Name (Last, First): ___________________ ID Number: ________________________

b. To the experimenters' surprise, the relationship between the wavelength of incident light and current in the metal was as shown below!

To rationalize this, Einstein, among others, postulated that light was behaving as a stream of particles and not as a continuous wave. The energy of light was packaged in discrete particles later dubbed 'photons.' The energy of a single photon is given by E = hf, where E is the energy, h is Planck's constant, and f is the frequency of the light. Furthermore, Einstein hypothesized that an electron could only interact with a single photon at a time. Briefly explain how this postulation helped explain the trend observed in Figure 1.

$$n * \frac{hc}{\lambda} = E_{tot} \rightarrow n = E_{tot} * \frac{\lambda}{hc}$$

2 points for equation or similar reasoning
Where the energy of the photon is greater than work function, number of photons increases linearly with wavelength; since there is a one-to-one correspondence between photon flux and current, at low wavelengths relationship is linear (4 points)
However, when wavelength is too high, energy is lower than work function and electrons cannot be emitted because the photons lack the energy to overcome the attraction between nucleus and electron. (3 points)

c. In the above diagram a beam of light of wavelength 360nm shines on a metal surface. Given in every second, 2000 photons hit the metal surface. The work function of the metal is $6*10^{-19}$ J. With justification, determine if electrons can be emitted from the metal.
Ep=hc/λ
Ep=5.5216*10^(-19)J
5.5216*10^-19J<6*10^-19J → no
2 points for equation
2 points for correct answer
2 points for conclusion consistent with their answer, regardless of whether or not it is correct

d. If your answer to (c) is yes, calculate the max kinetic energy of electrons that are emitted. If your answer to part (c) is no, calculate the minimum induced potential difference between the plates to make the emitted electrons hit the upper plate.
If c correct:
1 volt = 1 eV energy
convert energies to eV
Ep=3.45ev (3 points)
Φ=3.75ev
Difference=.3ev (3 points)
So voltage difference is .3 volts needed
Otherwise, calculate Ep (2 points), calculate difference (2 points), calculate energy (2 points)

e. After any necessary adjustments, at what rate will gold atoms plate onto the electrode (assume wire and electrode have no resistance).
2000 gold atoms a second (2 points)

f. What photon flux would be required to plate 5 grams of gold onto the electrode in 20s?

g gold = 0.0254 mol * 6.022 * 10^{23} = 1.53 * 10^{22} electrons

$$\frac{1.53 * 10^{22}}{20} = 7.64 * 10^{20} \frac{e^-}{s} \rightarrow 7.64 * 10^{20} \frac{photons}{s}$$

2 points for moles of gold, 2 points for number of electrons, 2 points for final calculation