CHEM 322   **Name**_____

Exam 1   **Fall 2014**

Complete these problems on separate paper and staple it to this sheet when you are finished. Please initial each sheet as well. Clearly mark your answers. YOU MUST SHOW YOUR WORK TO RECEIVE CREDIT.

Warm-up

1. The range of frequencies that a measurement is sensitive to is called the frequency

    ___bandwidth_____. (2 pts)

2. Application of large reverse-bias potentials to diodes can lead to __breakdown (or Zener breakdown____, resulting in a large current at essentially constant potential. (2 pts)

3. The __ion cyclotron resonance (ICR) mass spectrometer_____ does not use a detector such as an electron multiplier to count ions. Instead, and image charge is measured and converted to a signal. (2 pts)

4. The _____sensitivity_____ of a measurement can be described using the slope of the calibration curve for the measurement. (2 pts)

5. Clearly outline the steps you would take to determine the detection limit for an absorbance measurement based around Beer's Law (A = abc). Identify the data that you would need to collect and how you would use the data to calculate a LOD. (10 pts)

The detection limit is the concentration that corresponds to a signal that is three (or two) times the standard deviation of the background above the background. In order to determine the detection limit, you need multiple measurements of the blank to define the background and its standard deviation. With these values, you can calculate the signal at the detection limit as $Signal_{DL} = Signal_{blank} + 3s_{blank}$. You must then convert this signal into a concentration. This can be done by preparing a calibration curve by measuring the absorbance at several known concentrations and using the Beer's law relationship to convert the $Signal_{DL}$ (which is an absorbance) into its corresponding concentration.

Electronics: Complete *TWO* of the problems 6-8. Clearly indicate which problem is not to be graded. Show all work for calculations. (12 pts each)

6. You have a box that contains 50 op-amps and ten each of the following resistors: 1, 2, 5, 10, 20, 50 kΩ. Design a circuit to do the following calculation: $v_{out} = 30(v_1 + 2v_2) - 10v_3$ (You may not need all of the components in your box.). *You do not need to do calculations to prove your result;* it just needs to be correct.

There are several options that will do the trick. You need to be sure that your circuit performs the function $v_{out} = 30v_1 + 60v_2 - 10v_3$ and that the sign of the output is correct. The circuit below is an example:
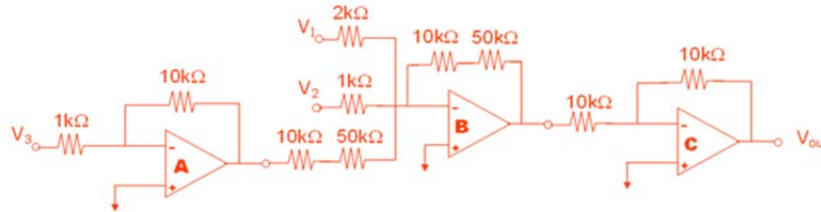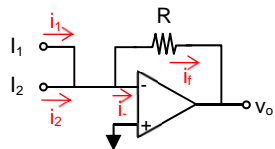

The opamp **A** in the circuit produces $v_A = -10v_3$. Opamp B produces $v_B = -(30v_1 + 60v_2 + v_A)$, and opamp C produces $v_{out} = v_c = -v_B = 30v_1 + 60v_2 - 10 v_3$.

7. *Derive* the relationship between the input and output signals for *two* of the following circuits. Show all work.
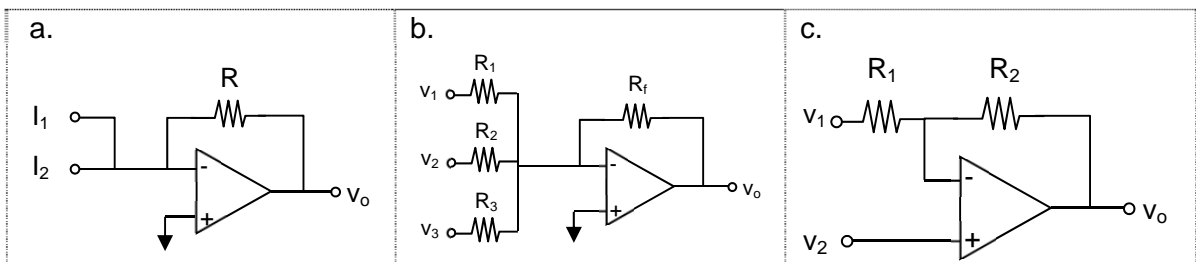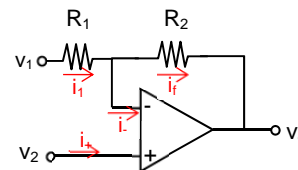

a.

$i_1 + i_2 = i_f + i_-$, but $i_- = 0$, so;
$$i_1 + i_2 = \frac{v_- - v_o}{R_2}$$
But, $v_- = v_+ = 0$
$$i_1 + i_2 = \frac{-v_o}{R_2}$$
$$\mathbf{v_o = -R_2(i_1 + i_2)}$$

b.

$i_1 + i_2 + i_3 = i_f + i_-$, but $i_- = 0$, so;
$$\frac{v_1 - v_-}{R_1} + \frac{v_2 - v_-}{R_2} + \frac{v_3 - v_-}{R_3} = \frac{v_- - v_o}{R_f}$$
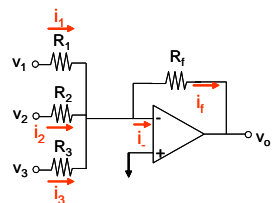
But, $v_- = v_+ = 0$
$$\frac{v_1}{R_1} + \frac{v_2}{R_2} + \frac{v_3}{R_3} = \frac{-v_o}{R_f}$$
and
$$\frac{v_1 R_f}{R_1} + \frac{v_2 R_f}{R_2} + \frac{v_3 R_f}{R_3} = -v_o$$

c.

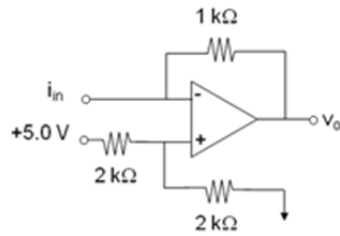$i_1 = i_2 + i_-$, but $i_- = 0$, so;
$$\frac{v_1 - v_-}{R_1} = \frac{v_- - v_o}{R_2}$$
But, $v_- = v_+ = v_2$
$$\frac{v_1 - v_2}{R_1} = \frac{v_2 - v_o}{R_2}$$
$$v_2 - \frac{R_2(v_1 - v_2)}{R_1} = v_o$$
or
$$v_o = v_2(1 + (R_1/R_2)) - (R_1/R_2)v_1$$

8. Given the circuit below, what output would you expect for a 1.25 mA input current? Derive the relationship between v_o and i_{in}. How would you redesign this circuit to make it suitable for measurement of low current signals (micro- to nano-amp signals)?

$$\frac{5-v_+}{2\ k\Omega} = \frac{v_+-0}{2\ k\Omega}$$

$$v_+ = v_- = 2.5\ V$$

$$i_{in} = i_o + i_- = i_o$$

$$i_{in} = \frac{v_--v_o}{1\ k\Omega} = \frac{2.5\ V-v_o}{1\ k\Omega}$$

2.5V – (1 $k\Omega$)i_{in} = v_o = 1.25V

Sensitivity can be increased by increasing the gain by increasing the value of the feedback resistor and by decreasing the +5.0 V reference voltage (remember lab?).

A/D Conversion, Signals and Noise: Complete *TWO* of the problems 9-11. Clearly indicate which problem is not to be graded. Show all work for calculations. (12 pts each)

9. Ensemble averaging (also known as *coadding*) and boxcar averaging are two common software-based approaches to improving signal to noise ratios (S/N). Concisely describe each approach and a scenario where boxcar averaging would be preferred over ensemble averaging for S/N improvement. What pitfalls need to be considered for each method?

   You should discuss how each method works and its limitations. Here are some items I'd expect to see.

   Ensemble Averaging: Several datasets are collected and "averaged" so that the non-random analytical signal is reinforced while the random noise is allowed to cancel. You would expect the S/N ratio to increase as the square root of the number of scans averaged increases.
   Challenges: as # of scans increases, the benefit diminishes so there is a point where the return is not worth the investment in time required to do more scans. Also, collecting more scans requires that the measurement (instrument and sample) be stable for a long period of time.

   Boxcar Averaging: Adjacent data points (typically 3, 5, or 7) within a single dataset are averaged to and replaced by a single data point. This averaging should serve to emphasize the lower frequency characteristics of the signal while de-emphasizing the high frequency noise. Boxcar averaging works on a single dataset, but you need to be careful so that you have enough data that when the boxcar is run, the result is still representative of the real data.

   In order for ensemble averaging to occur, you must be able to collect several sets of data, where noise is the only component that is varying. Any scenario that prevents this will prevent the use of ensemble averaging. Boxcar averaging is useful when you only have a single datset to work with. Such scenarios would include:
   - Destructive measurements and limited amounts of sample
   - Time consuming analysis
   - Instrument instability and drift
   - Transient signals

10. Considering the four types of noise we discussed, what characteristics should a measurement have to minimize the contribution of all four noise sources simultaneously?

    The measurement should have narrow bandwidth to minimize shot and thermal noise, operate at high frequency to minimize flicker noise, and operate at a frequency away from environmental noise sources. You may also mention a desire to have a low resistance system and low temperature.

11. The plots below show the digital representation of two Gaussian analog signals, as acquired by an eight bit analog to digital converter (ADC) with an input range of ±5.0 V. In neither case is the conversion ideal. For each case, explain what has lead to the non-ideal conversion and suggest a solution to each problem that does not involve buying a new ADC.

a.
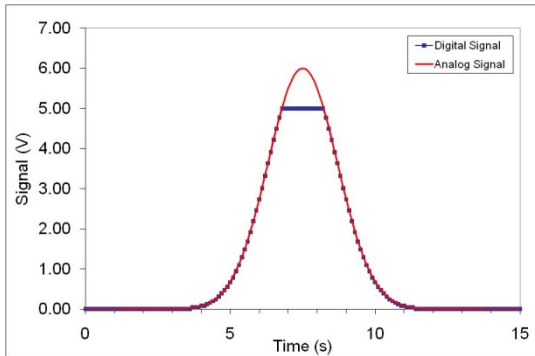
b.
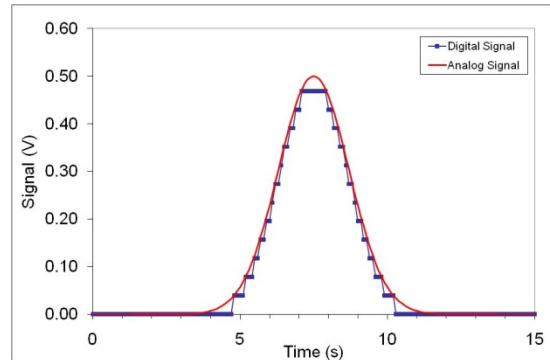
For dataset A, the magnitude of the analog signal (6V) is outside the input range of the ADC. Therefore any signal above 5V is recorded as 5V, causing the peak to be "clipped". To resolve this problem, the analytical signal must be attenuated (de-amplified) so that it no longer overloads the ADC. Solutions to both of these situations could be accomplished using a simple operational amplifier circuit.

For dataset B the "jagged" nature of the data is an indication that the acquisition resolution is being limited by the size of the least significant bit. This is called "bit noise" or a "bit limited" situation. This arises because the size of the analytical signal is small relative to the size of the least significant bit for the acquisition system (in this case $10V/2^8$ or 39 mV). One possible solution would be to amplify the analog signal to allow it to fill up more of the input range of the ADC, thus making the impact of the size of the LSB minimal.

Mass Spectrometry: Complete *THREE* of the problems 12-15. Clearly indicate which problem is not to be graded. Show all work for calculations. (12 pts each)

12. Mass spectra from electron impact (EI) sources are typically much more complicated than those from chemical ionization (CI), explain why this is the case. Why do typical MS instruments designed for organic mass spectrometry often have both EI and CI capabilities?

EI sources are hard ionization sources, with ions formed after collision with high energy electrons, producing excited state ions that are typically susceptible to extensive fragmentation. As a result, the molecular ion peak (M^+) is typically very small or nonexistent in a mass spectrum collected using an EI source.

CI sources are soft ionization sources, with ions produced by collisions with lower energy reagent gas ions, that tend to produce spectra with much less fragmentation. As a result of reactions with the ionizing gas in the source, the molecular ion peak, which is typically strong, occurs at $(M+1)^+$ or $(M-1)^+$.

The combination of EI and CI capabilities is fairly trivial in terms of hardware and provide the opportunity to get both molecular ion and fragmentation information.

13. The overall resolving power of a mass spectrometer is the result of limitations from all components of the MS. Describe how each of the following serves to limit resolution in a MS experiment.
    a. The ionization source (such as an ICP source)
    Most mass analyzers separation ions on the basis of their kinetic energy, velocity, or momentum. Each of these parameters depends on the extraction of a packet of ions from the ionization source that has a very narrow spread in the parameter being filtered. Depending on the design of the source and extraction ion optics, ions of a single m/z may exit the source with a spread in kinetic energy (or velocity or momentum). The larger the spread, the less effective the mass separation will be.

    b. The mass analyzer (such as a quadropole)
    In their filtering mechanism, most mass analyzers utilize controlled electric or magnetic fields to manipulate ions. Therefore, the ability to precisely control these fields plays a major role in differentiating ions of similar mass to charge.

    c. The detector (such as an electron multiplier)
    Since the role of the detector is to basically count ions, it has very little impact on the resolution of the MS experiment. I suppose in a TOF experiment, the response time of the detector would be very important, so that ions with slightly different flight times could be resolved.

14. Electrospray ionization (ESI), matrix-assisted laser desorption ionization (MALDI) and atmospheric pressure chemical ionization (APCI) are relatively new approaches to ionizing large molecules. Compare how ions are formed in each process and discuss the similarities and differences in the spectra observed from the sources.

The two main big molecule ionization sources we discussed were MALDI and Electrospray ionization.
MALDI: The analyte is dispersed in a MALDI matrix (a molecule that readily sublimes when it absorbs energetic photons) and deposited onto a target. The target is irradiated with a laser pulse, resulting in absorption and sublimation of the matrix (including the analyte) and ionization. The result is the formation of intact molecular ions, most are singly charged. Benefits: Soft ionization source. Good for molar mass determination.

Challenges: Pulsed source, need mass analyzer that can handle pulsed introduction. Need appropriate matrix.

Electrospray: The sample solution flows through a needle which is subject to a large electric field. As solution leaves the needle, it obtains a charge. Electrostatic repulsion causes the charged stream to break into smaller charged droplet, which continue to "explode" until solvent is essentially evaporated and ionized analyte remains. This is a more energetic ionization source, capable of producing multiply charged ions and fragments. Benefits: Continuous source. No additional sample handling steps. Challenges: May lead to complex spectra. Need to remove some sample to produce lower pressure for mass analyzer.

APCI: Sample is introduced through a nebulizer in a heated block. The heater serves to desolvate the sample and produce a mixture of sample compounds and hot gas. This mixture is directed across a corona discharge electrode where ionization occurs. Since nebulizer gas is most prevalent, it is ionized preferentially to analyte. Analyte ions are then produced via chemical ionization processes. Ions are then directed into the mass spectrometer via skimmer cones and differential pumping phases.

15. Currently, two of the most popular mass analyzers are the quadrupole mass filter and the time of flight mass analyzer. These two devices have very different principles of operation. Clearly describe how each device serves to separate ions and the key benefits and limitations of each device.

Quad: As they move through the mass filter, ions are subject to both AC and DC potentials. Depending on their size, ions may be influenced differently by the RF and DC components. For example, heavy ions are least influenced by the RF component, while light ions are most influenced by the RF. The balance between DC and RF determines whether an ion will have a stable path. Spectra can be scanned by systematically adjusting either the RF or DC voltages. Benefits: Small, able to handle higher pressures, able to scan spectra rapidly. Challenges: relatively low resolving power.

Figure 11-4 A quadrupole mass spectrometer.

TOF: The TOF mass analyzer relies on the fact that ions that have different mass but the same kinetic energy will be moving at different velocities ($KE = mv^2/2$). Therefore, ions are formed in a pulse and the time that takes the ions to move through the field free region of the flight tube is measured. Once calibrated, these times can be used to determine the mass to charge of individual ions. Benefits: potential for high resolution and very fast analysis. Challenges: depending on the length of the drift tube, vacuum requirements might be demanding. Need to coordinate ionization and detection timing.
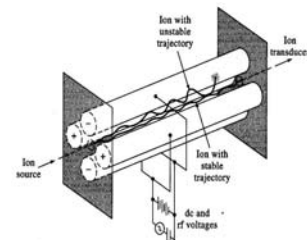

Figure 11-8 Principle of a time-of-flight mass spectrometer. A bunch of ions
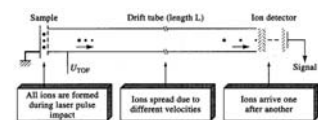
Possibly Useful Information

$\dfrac{dQ}{dt} = I = C\dfrac{dV}{dt}$	$P = IV = I^2R$
$V = IR$	$v_o = A(v_+ - v_-)$
$v_{rms} = \sqrt{4kTR\Delta f}$	$001 + 001 = 010$
$\Delta f = \dfrac{1}{3t_r}$	$i_{rms} = \sqrt{2ie\Delta f}$
$S_m = \overline{S}_{bl} + ks_{bl}$	$c_m = \dfrac{S_m - \overline{S}_{bl}}{m}$
$\lambda = \dfrac{RT}{\sqrt{2}\pi d^2 N_A P} \approx \dfrac{5\,cm}{mtorr}$	$\dfrac{m}{z} = \dfrac{B^2 r^2 e}{2V} = F_c$
$F_M = Bzev = \dfrac{mv^2}{r} = F_c$	$k = 1.38 \times 10^{-23}\ JK^{-1}$