Consider the following two circuits:

1. Assuming $V_{in}$ is $+5$ V DC, sketch the time-dependence of $V_{out}$ for both circuits I. and II. after the switch is closed. Be sure to include tick marks with specific values along your axes [Note: the units of Farad are Coulombs/Volt, and the units of Ohm are $V/I = \text{Volt} / (\text{Coulomb/s})$].

2. How does the situation change for an AC input? Assuming the switch always remains closed, sketch Bode plots (i.e., $\log(V_{out}/V_{in})_p$ vs. AC frequency) for circuits I. and II. Again, be sure to include tick marks with specific values along your axes.

3. Propose specific applications for both circuits I. and II.

   (Many possible answers)

4.a. Assuming $V_{in}$ is a perfect square wave with a repetition rate of 1 MHz, make sketches of $V_{out}$ vs. time for both circuits I. and II. Again, be sure to include tick marks with specific values along your axes.
4.b. What is the relationship between your sketches in 4.a. and the Fourier transform of a square wave function?

The waveform in I is the square wave function with the high frequency components removed, and the waveform in II is just the high frequency terms.

5. If we wished to measure $V_{out}$ using an oscilloscope, we may choose to use the following circuit (shown for circuit II).

5.a. What is the role of the op-amp?

Isolate the signal without introducing load error.

5.b. What is the role of the 50 Ω output resistor?

Optimize power transfer through BNC transmission lines with 50 Ω impedances / minimize reflections.

5.c. Oscilloscopes are often designed for use with either 50 Ω or 1 MΩ input impedances. Which would you choose in this application and why?

- Since we are considering high frequency detection (>10 MHz), it is particularly important to impedance-match the scope to the BNC transmission line in order to minimize reflections. Furthermore, possible complications from load error introduced by use of a low resistance in the measurement device have been remedied by preamplification. Hence, 50 Ω is the way to go here!
1. Transcription is the mechanism through which genes are copied to produce RNA. RNA synthesis proceeds 5' -> 3' direction utilizing nucleotide triphosphates (NTP). Transcription is done by RNA polymerase. Hydrolysis of NTPs drives the reaction.

For transcribing genes, bacterial cells contain a signal polymerase to produce mRNAs, large ribosomal RNAs, small ribosomal RNAs, and tRNAs.

In bacterial cells, the σ factor directs the RNA polymerase to initiate transcription from a correct site. Initiation is controlled by two DNA control elements that precede the transcription initiation site (the Pribnow box at about -10 and the Schaller box at -35). For some sequences, RNA termination is facilitated by the ρ factor. For certain mRNAs, termination may be regulated by formation of a specific stem loop structure at the end of the mRNA.

Eukaryotic cells contain three different polymerases for transcriptions of protein coding genes, large rRNA genes, and small RNA genes.

In eukaryotic cells, the mechanism that control the initiation of mRNA synthesis is very complex and involves numerous proteins known as general transcription factors. The synthesized mRNAs are capped with a specific group of enzymes; their 3' ends may be trimmed and are often polyadenylated.

2. Translation is the mechanism through which the information in mRNA is decoded to synthesize the polypeptide chain of proteins. The translational machinery is very complex. It includes small RNA molecules (tRNAs), which bring the amino acids to the site of protein synthesis. Amino acids are attached to the ribose ring at the CCA end of tRNAs. This reaction is catalyzed by aminoacyl tRNA synthetases and is driven by ATP hydrolysis.

Translation is done by molecular machines known as ribosomes. Ribosomes contain two subunits, assembled from RNA and numerous proteins. Protein synthesis requires several auxiliary proteins including initiation, elongation, and release factors.

The genetic codes in the mRNAs are read three residues at a time (codons). Translation begins at a specific codon specifying the amino acid methionine. This methionine is brought to the site of protein by the initiator tRNA. Recruitment of this met-tRNA and assembly of the initiation complex requires the translation initiation factors, mRNA, and the ribosomal subunits. The subsequent amino acids, in the form of AA-tRNA are brought to the site of protein synthesis by specific transcription elongation factors. The AA-tRNAs are specified by the codons in the mRNA. Delivery of each AA-tRNA to the translational machinery is done by specific elongation factors, the reaction is driven by GTP hydrolysis. Formation of peptide bonds is catalyzed by a peptidyl transferase, which is a component of ribosomes. Movement of the ribosomes along the mRNA requires an additional elongation factor; again, the reaction is driven by GTP hydrolysis. Protein synthesis is terminated when the ribosome reaches a stop codon. Termination and the release of the polypeptide chain require release factors. The initiator met is removed from the amino terminus of the synthesized protein.

3. RNA polymerase I, RNA polymerase II, RNA polymerase III. POL I transcribes the large ribosomal RNA genes. POL II transcribes the protein coding genes. POL III transcribes the small RNA genes including the small ribosomal RNAs, tRNAs, and small nuclear RNAs.
Researchers have extensively focused on understanding the regulation of mRNA synthesis by RNA POL II because mRNA synthesis would specify the proteins that are produced in cells. The proteins would impart the cellular characteristics.

4. The coding sequences of genes (exons) may be interrupted by intervening sequences (introns). Introns are removed from the primary mRNA transcripts through a mechanism known as RNA splicing. During this process, differential exon utilization may occur. For a gene with three exons, splicing of an mRNA precursor may connect exon 1, 2, and 3. Splicing of another precursor mRNA may connect exon 1 and 3 (skipping exon 2). The two processed mRNAs would encode two different but related proteins. Differential splice site selection could also yield mRNAs encoding different but related proteins.


To date, two types of DNA microarrays have been developed: (1) cDNA microarrays, which require cloned DNA sequences corresponding to transcripts of genes; (2) oligonucleotide microarrays, which are made synthetically (based on reported DNA sequences).

In cDNA microarrays, individual DNA samples are applied to precise locations on a small solid matrix, usually glass. Each DNA sample corresponds to a specific DNA sequence from a collection of cDNAs (usually obtained using PCR). The spots defining the arrays are very small. The samples are applied using automated systems.

In experimental studies, the arrays are used to identify the genes are expressed in a given cell type. To do so, the arrays are challenged in hybridization experiments analyzing using sequences corresponding to RNAs transcribed in the selected cell type. Technically, before hybridization, the RNAs are often copied to DNA using reverse transcriptase. Fluorescent labels are incorporated into the copied DNA for preparing the probes. The probes are hybridized to the cDNA arrays on the glass matrix, under optimized conditions. A fluorescence detection system is used to measure the relative amounts of probes hybridized to the DNA spots in the arrays.

6. Transcription factors represent proteins that regulate the expression of genes. In eukaryotes, the general transcription factors control the initiation of mRNA synthesis. The nuclei of eukaryotic cells contain many transcription factors that function in upregulation and down-regulation of genes. Some factors are ubiquitous while others are cell-type specific. A relatively large number of transcription factors (about 1600) are involved in the regulation of human genes.

7. For bacterial systems acceptable answers include the σ factor and CAP; bacterial repressors would also be considered as an acceptable answer, even though they are usually referred to as repressors.

For higher eukaryotes, there are numerous examples including Sp1, CREB, MAX, SOX1, glucocorticoid receptor, vitamin D receptor, Ets1, Jun, fos, myc, max, etc.

8. There are many examples including CREB binding protein (CBP), GCN5, etc.

9. M P Q Q R M A V M K
1A. The combined mass of 82 neutrons and 57 protons is 140.178 amu. $^{139}$La has a mass of 138.91 because of the binding energy released when the nucleons come together to make the nucleus

$$\Delta E = \Delta m c^2$$

1B. $^{138}$Ba, $^{140}$Ce, $^{142}$Nd and $^{144}$Sm all have a magic number of neutrons, $N = 82$. 82 neutrons pair together to make a nice closed shell system compatible with binding various numbers of protons.

1C. The $s$ process is a type of nucleosynthesis associated with slow uptake of neutrons. If $^{147}$Nd or $^{147}$Pr were stable, it would be possible to make $^{148}$Nd by the $s$ process (since $^{148}$Pr would decay to $^{148}$Nd). They are not.
2A. Splitting by 2 equivalent $^3\!P$ nuclei gives rise to a $1:2:1$ triplet $(2nI+1)$ pattern. $^{103}\text{Rh}$ gives rise to a doublet splitting. For the minor isotope

$$J_{\text{PH}} J_{\text{RhH}} \quad \text{a triplet of doublets in each case. The } J_{\text{RhH}} \text{ splitting is small for the axial hydride.}$$

2B. Rapid intramolecular ligand exchange (flip-flopping) produces an average spectrum when the rate of hydride exchange between axial and equatorial positions exceeds the chemical shift difference in $\text{H}_2$. The chemical shift and coupling constants become mole-fraction-weighted averages:

$$J_{\text{PH}} = \frac{9(15) + 45}{10} = 18.5$$

$$J_{\text{RhH}} = \frac{9(11) + 13}{10} = 2.2$$
I. (a) Provide the missing structures 2, 4, and 6. (15 pts)

\[ 2 \] \[ 4 \] \[ 6 \]

(b) What is the name for the reaction of \(2 + 3 \rightarrow 4\) (5 pts)

**Hetero Diels-Alder** Reaction

(c) Name the reaction/rearrangement for \(6 \rightarrow 7\) transformation (5 pts)

**Ferrier** rearrangement

II. (a) Provide the missing structures 2 and 3. (10 pts)

(b) Using curved arrows, write a mechanism for the transformation of 4 to 5. (10 pts)
(c) What is the generic name of this reaction (for the transformation of 4 to 5)? (5 pts)

**Allylboration**

(d) What is the common name of the reagent 1? (5 pts)

**Thexylborane**

(e) Provide an IUPAC name for 5. (5 pts)

1-phenyl- \( E \)-3-dodecen-1-ol

For answers to questions III and IV, refer to any undergraduate textbook.

III. (a) Give an example of Crossed Claisen condensation. (10 pts)

(b) Outline all of the possible combination of starting materials for the preparation of \( N \)-ethyl \( N \)-methylaniline using a reductive amination sequence. (15 pts)

IV. (a) Write the structures of A and B in the following scheme. (10 pts)

\[
\begin{align*}
\text{\( \text{COOEt} \)} & \quad + \text{NaCN} \quad \xrightarrow{\text{EtOH} \ \text{H}_2\text{O}, \text{H}^+} \quad \text{A} \quad \xrightarrow{\text{H}_2\text{O}^+ \ \text{heat}} \quad \text{B}
\end{align*}
\]

(b) Write the mechanism for ester hydrolysis under acidic conditions. (10 pts)
Consider a liquid at a specified pressure and temperature in equilibrium with its vapor.

\[ l = g \]

1. What is the thermodynamic condition for equilibrium at a specified \( p \) and \( T \)?

\[ \mu_l(T,p) = \mu_v(T,p) \]

2. Derive a relation that describes the pressure dependence of the chemical potential of the vapor. You may assume that this vapor behaves as an ideal gas.

For a specified temperature:

\[ d\mu_g(T) = \left( \frac{d\mu}{dp}(T) \right)_T dp = \frac{V}{n} dp = \frac{RT}{p} dp \]

Integrate from reference pressure (1 atm) to \( p_v \):

\[ \mu_g(T) = \mu_g^0(T) + RT \ln p_v \]

3. Use the results of parts 1 and 2 to derive an expression for \( p_v \), the vapor pressure of the liquid at equilibrium. You may assume that the chemical potential of the liquid is pressure independent.

\[ \mu_l(T,p) = \mu_l^0(T) \]

\[ \mu_g(T,p) - \mu_l(T,p) = \mu_g^0(T) - \mu_l^0(T) + RT \ln p_v = \Delta G_{vap} + RT \ln p_v = 0 \]

\[ \ln p_v = -\frac{1}{R} \frac{\Delta G_{vap}}{T} \]

4. How does this equilibrium pressure vary with \( T \)? Derive an equation for:

\[ \frac{d\ln p_v}{dT} \]

\[ \frac{d\ln p_v}{dT} = -\frac{1}{R} \frac{d}{dT} \left( \frac{\Delta G_{vap}}{T} \right) = -\frac{1}{R} \left[ \frac{1}{T} \left( \frac{\partial \Delta G_{vap}}{\partial T} \right)_p - \frac{\Delta G_{vap}}{T^2} \right] \]
5. Integrate this equation between the limits \( p_o \) and \( p \) to cast this equation in finite terms. (Recall that the chemical potential behaves as a Gibbs free energy. \( G \) is temperature dependent, but you may assume that \( H \) is not.)

Writing,

\[
-\frac{1}{R} \left[ \frac{1}{T} \left( \frac{\partial \Delta G_{vap}}{\partial T} \right)_p - \frac{\Delta G_{vap}}{T^2} \right] = -\frac{1}{R} \left[ \frac{-\Delta S_{vap}}{T} - \frac{\Delta H_{vap} - T \Delta S_{vap}}{T^2} \right] = \frac{\Delta H_{vap}}{RT^2}
\]

Then,

\[
\int_{p_o}^{p} d \ln p_v = \int_{T_o}^{T} \frac{\Delta H_{vap}}{RT^2} dT
\]

or

\[
\ln p - \ln p_o = -\frac{\Delta H_{vap}}{R} \left( \frac{1}{T} - \frac{1}{T_o} \right)
\]

6. Consider your expression for the case in which \( p_o \) is selected to be the vapor pressure at \( T_B \), the boiling point of the liquid. Use what you know about this reference point to simplify your expression. Write it in the form, \( p = C \exp(-\ldots\ldots) \)

\[
\ln p = -\frac{\Delta H_{vap}}{R} \left( \frac{1}{T} - \frac{1}{T_B} \right)
\]

\[
p = e^{\frac{\Delta H_{vap}}{RT}} e^{\frac{\Delta H_{vap}}{RT}}
\]

7. You can view the vapor pressure as a reflection of the probability for a molecule to escape free of the liquid. Comment on the state variables that govern this probability for any given system. Give a physical interpretation of your expression for vapor pressure in these terms.

\( \Delta H_{vap} \) represents the molar \( Q_p \) necessary to overcome the potential energy of attraction binding molecules to the liquid. It appears in a Boltzmann expression because the exponential describes the probability of taking that amount of heat from the reservoir and apportioning to the purpose of liberating molecules to the gas phase.
7. Trouton's Rule holds that, when brought to their various boiling points, all liquids have about the same entropy of vaporization, $\Delta S_{\text{Vap}} = 90 \text{ J/K mol}$. Compare the room temperature (20 °C) vapor pressures of ethyl bromide ($T_B = 38.3 ^\circ C$), benzene ($T_B = 80.2 ^\circ C$), and acetic acid ($T_B = 118.3 ^\circ C$).

<table>
<thead>
<tr>
<th>Sample</th>
<th>$\Delta S_{\text{Vap}}$ (J/K mol)</th>
<th>$T_B$ (K)</th>
<th>$\Delta H_{\text{Vap}} / R$ (K)</th>
<th>$P$ (atm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EtBr</td>
<td>90</td>
<td>311.3</td>
<td>3,369.9</td>
<td>0.508</td>
</tr>
<tr>
<td>Benzene</td>
<td>90</td>
<td>353.2</td>
<td>3,823.4</td>
<td>0.108</td>
</tr>
<tr>
<td>HOAc</td>
<td>90</td>
<td>391.3</td>
<td>4,235.9</td>
<td>0.026</td>
</tr>
</tbody>
</table>

8. Trouton's Rule fails for room temperature methane ($T_B = -162 ^\circ C$, critical temperature = -82.7 °C, critical pressure = 45.37 atm). Calculate a Trouton's Rule vapor pressure for methane at 20 °C, and say why this number is not very useful. How do you suppose liquid methane (LNG) is transported?

$P = 832 \text{ atm}$.

This number is not useful because above the critical temp and pressure, no liquid exists to be in equilibrium with vapor at $p_v$. Liquid methane can exist only at temperatures less than -82.7 °C. Normally, it is shipped at a temperature where its vapor pressure is near 1 atm (111 K).
pV = nRT

R = 8.314 J K\(^{-1}\) mol\(^{-1}\)
= 0.08206 dm\(^3\) atm K\(^{-1}\) mol\(^{-1}\) \(\text{(1 L = 1 dm}^3\))

First Law of Thermodynamics

\[ \Delta U = Q - W \]

Second Law of Thermodynamics

\[ \Delta S \geq \frac{Q}{T} \]

Composite State Variables

\[ H = U + PV, \text{ where } \Delta H = Q_p \]
\[ G = H - TS \]

Combined forms of the First and Second Laws

\[ dU = pdV - TdS \]
\[ dG = -SdT + Vdp \]

Exact differentials

\[ dU = \left( \frac{\partial U}{\partial T} \right)_V dT + \left( \frac{\partial U}{\partial V} \right)_T dV \]
\[ dG = \left( \frac{\partial G}{\partial T} \right)_p dT + \left( \frac{\partial G}{\partial p} \right)_T dp \]

For a one-component system

\[ \mu = \frac{G}{n}, \text{ where } \mu = \left( \frac{\partial G}{\partial n} \right)_{T,p} \]
\[ \Delta G_{\text{vap}} = \mu_s^a(T) - \mu_i^a(T) \]