Winter 2025 **Chemistry 2000 Final Exam** ____/ 120 marks

Confidentiality Agreement:
I agree not to discuss (or in any other way divulge) the contents of this exam with (or in the presence of) any CHEM 2000 student who has yet to write it. I understand that breaking this agreement would constitute academic misconduct. The minimum penalty would be a mark of 0/120 on this exam.

Signature: _____ Date: _____

1) Please read the test carefully before starting. It has 13 pages of questions (seven pages double-sided).
2) You have also been given a data sheet. It does not have a QR code, so nothing written on it will be graded.
3) **DO NOT WRITE ON ANY QR CODE!!!** Work on pages without a QR code will not be graded.
4) You may use a calculator but only for calculation. No other electronic devices are allowed. Any non-trivial use of a calculator must be described. For example, if you use a calculator to solve a nonlinear equation, you need to make it clear what equation was solved and provide any other inputs you used to the calculation.
5) If your work is not legible, it will be given a mark of zero.
6) Show your work. Answers without supporting reasoning or calculations will not get full credit
7) Marks will be deducted for incorrect information added to an otherwise correct answer.
8) Marks will be deducted for improper use of significant figures and for missing or incorrect units. Show units in every step of all calculations. Significant figures will only be checked in final answers. If a question has subparts (a, b, c, etc.), the answer to each subpart is considered a "final answer".
9) You have 3 hours to complete this test.

Question Breakdown

Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12						Total
/ 10	/ 12	/ 6	/ 10	/ 8	/ 5	/ 19	/ 14	/ 13	/ 18	/ 4	/ 1						/ 120

1. Fill in each blank with the word or phrase that best completes the sentence. **[10 marks]**
Where options are provided in brackets after a blank, choose one of those options to fill in the blank.

(a) The conjugate acid of H_2S is _____.

(b) The conjugate base of H_2S is _____.

(c) When a nonvolatile substance is dissolved in a liquid, the boiling point of the liquid _____ *(increases or decreases or stays the same)*.

(d) When comparing the same substance at the same temperature in different phases, the entropy will be highest for the substance in the _____ *(solid or liquid or gas)* phase.

(e) When comparing the same substance in the same phase at different temperatures, the entropy will be highest for the substance at the _____ *(higher or lower)* temperature.

(f) When a reaction has $\Delta H > 0$ and $\Delta S > 0$, it will be thermodynamically favoured in the forward direction at _____ *(high or low or all or no)* temperatures.

(g) When a reaction has $\Delta H > 0$ and $\Delta S < 0$, it will be thermodynamically favoured in the forward direction at _____ *(high or low or all or no)* temperatures.

(h) When a reaction is thermodynamically favoured in the forward direction, _____ *(Q<K or Q=K or Q>K)*.

(i) When equilibrium has been reached, which of the following is true? *Circle the answer.*

$\Delta G = 0$ $\Delta G° = 0$ $\Delta H = 0$ $\Delta H° = 0$ $\Delta S = 0$ $\Delta S° = 0$

(j) If the pK_a of H_2CO_3 is 6.3 and the pK_a of HCO_3^- is 10.3, then the pH of an aqueous solution containing equal concentrations of H_2CO_3 and HCO_3^- will be _____.

2. This series of questions deals with molecules having the formula $\boldsymbol{C_3H_6O}$. Use your knowledge of organic chemistry principles to answer the following: **[12 marks]**

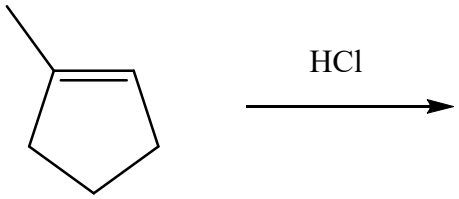
(a) Draw all the **structural** isomers of $\boldsymbol{C_3H_6O}$. Duplicate or incorrect structures will result in a deduction of marks. You may use any format for drawing your structures as long as you are consistent. *[9 marks]*

(b) Geometric isomers are also called *cis- trans-* isomers. Identify **one** structure you listed from part (a) that can exhibit geometric isomerism. Draw the two isomers below and label which is ***cis*** and which is ***trans***. [*3 marks]*

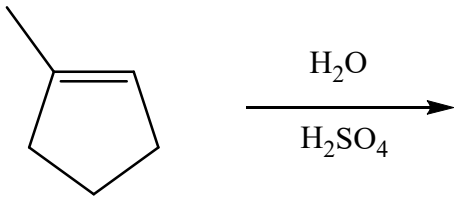
3. Draw the major organic product for each of the following reactions. **[6 marks]**

In cases where the reaction produces a specific stereoisomer of product, clearly show the stereochemistry of the product.

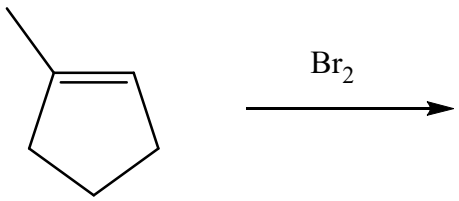
(a)



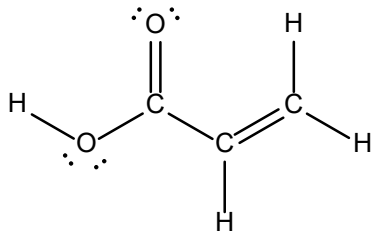
(b)



(c)



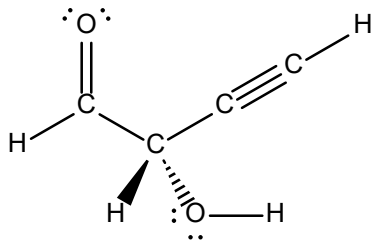
4. Consider the following molecule: **[10 marks]**



(a) This molecule is an acid. Circle the acidic hydrogen atom on the diagram above and explain your choice. Your explanation must include a drawing of the conjugate base and any other relevant drawings. *[4 marks]*

(b) The pK_a of this acid is 4.25. Calculate the pH of a 0.25 M aqueous solution of this acid at $25°C$. *[6 marks]*

5. Consider the following molecule: **[8 marks]**



(a) Beside each carbon atom, label its hybridization. *[4 marks]*

(b) Circle and name each functional group in the molecule. *[3 marks]*

(c) Draw the enantiomer of this molecule in the space below. *[1 mark]*

6. A material contains 99% germanium (Ge) atoms with 1% arsenic (As) atoms distributed throughout the lattice. **[5 marks]**

(a) Classify this material as a conductor, an insulator, an inherent semiconductor, an n-type semiconductor or a p-type semiconductor. *[1 mark]*

(b) Draw a band diagram for this material. Clearly label the valence band, conduction band, any other relevant bands and the band gap. Use shading to make it clear whether each band is fully occupied, partially occupied or unoccupied. *[4 marks]*

7. **[19 marks]**

(a) Draw a Lewis diagram for NO^+. Your diagram must show any non-zero formal charges on the appropriate atoms. *[1 mark]*

(b) With which homonuclear diatomic molecule is NO^+ isoelectronic? *[1 mark]*

(c) Draw a valence molecular orbital energy level diagram (MO diagram) for NO^+. *[13 marks]*

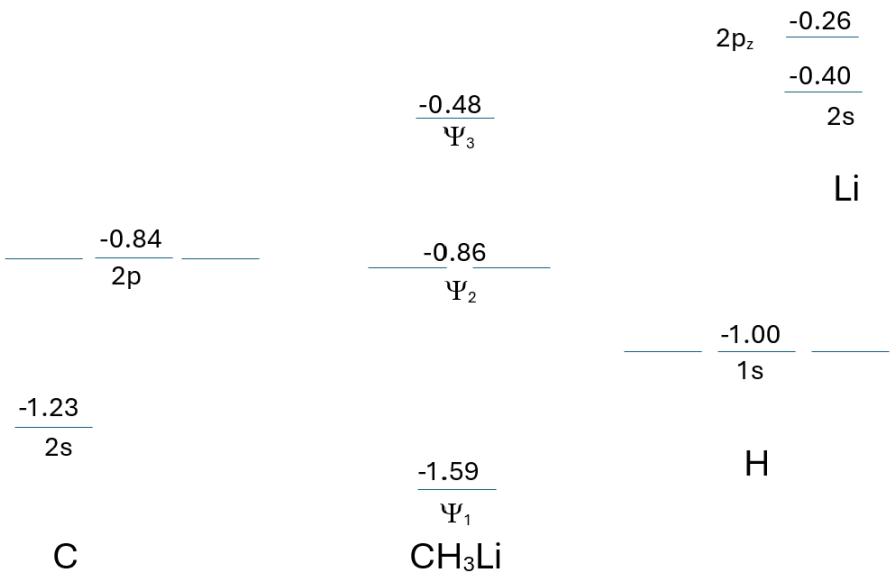
Your diagram must include:

- molecular orbital energy levels labeled using the convention taught in CHEM 2000 that communicates symmetry (σ or π) as well as bonding character (bonding, nonbonding or antibonding)
- electrons in the appropriate molecular orbitals
- a drawing of each molecular orbital, showing its shape, orientation and relative phases

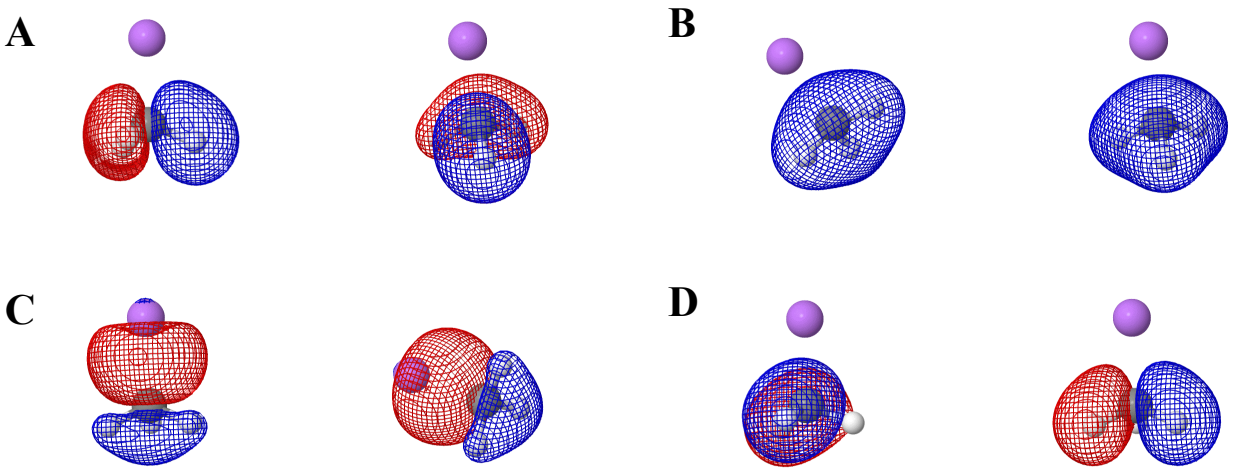
(d) Calculate the bond order for NO^+ based on your MO diagram. How does it compare to the bond order shown by your Lewis diagram? *[2 marks]*

(e) Energy levels of the molecular orbitals in a cation are lower than those for the corresponding molecular orbitals in the corresponding neutral compound. As such, all valence molecular orbitals in NO^+ have negative energy values. Knowing this, explain why it is the case that NO can form from NO^+ but NO^- will not readily form from NO. *[2 marks]*

8. The partial MO diagram below shows the four lowest energy valence molecular orbitals of CH_3Li. **[14 marks]**



The diagrams below show drawings of Ψ_1, Ψ_2 and Ψ_3. Each molecular orbital is shown from two different angles (front view and side view).



(a) For each pair of drawings, identify the corresponding molecular orbital (Ψ_1, Ψ_2 or Ψ_3). *[4 marks]*

A is _____ **B** is _____ **C** is _____ **D** is _____

(b) Populate the partial MO diagram with the appropriate number of electrons in the molecular orbitals. *[1 mark]*

continued on next page…

8. *…continued from previous page*

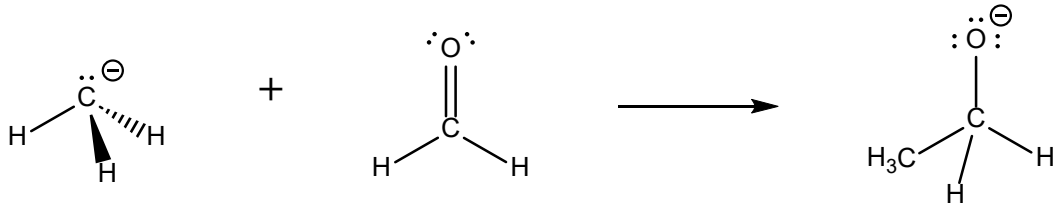
(c) Which molecular orbital is most relevant to the behavior of CH_3Li as a nucleophile? Your answer should indicate **both** whether it is the HOMO or the LUMO **and** the specific molecular orbital (Ψ_1, Ψ_2 or Ψ_3).

[2 marks]

(d) Organic chemists often consider CH_3Li to behave as the nucleophilic carbanion CH_3^-. How is the shape of the orbital identified in your answer to part (c) consistent with viewing CH_3Li this way? *[2 marks]*

Hint: You will need to consider which atomic orbital(s) formed this molecular orbital.

(e) Complete the diagram below showing the reaction between CH_3Li and CH_2O by adding curved arrows to show the movement of electrons. *[2 marks]*



(f) For the reaction shown above, into which molecular orbital must CH_2O accept the electron pair – into its HOMO or into its LUMO? Based on the reactants and products shown above, what must the symmetry and bonding character be for that molecular orbital? How do you know? *[3 marks]*

9. Typical rock minerals are composed of silicates of iron, calcium, potassium and aluminum. Consider the mineral Koalinite $\left(Al_2SiO_{5(s)}\right)$ which reacts with CO_2 in the atmosphere as follows: **[13 marks]**

$$Al_2SiO_{5(s)} + 3\ CO_{2(g)} \rightleftharpoons Al_2(CO_3)_{3(s)} + SiO_{2(s)} \qquad \textbf{(I)}$$

$Al_2(CO_3)_{3(s)}$ is extremely unstable and therefore reacts quickly with atmospheric water vapor as follows:

$$Al_2(CO_3)_{3(s)} + 3\ H_2O_{(g)} \rightleftharpoons 2\ Al(OH)_{3(s)} + 3\ CO_{2(g)} \qquad \textbf{(II)}$$

Finally, the $Al(OH)_{3(s)}$ dehydrates to form $Al_2O_{3(s)}$:

$$2\ Al(OH)_{3(s)} \rightleftharpoons Al_2O_{3(s)} + 3\ H_2O_{(g)} \qquad \textbf{(III)}$$

(a) Write a balanced chemical equation for the combined reactions **I** and **II**. *[1 mark]*

(b) Calculate the standard free energy change for the combined reactions **I** and **II**. *[2 marks]*

(c) Calculate the equilibrium constant for reaction **III** at $25℃$. *[4 marks]*

(d) Write a balanced chemical equation for the combined reactions **I**, **II** and **III**. *[1 mark]*

(e) Write the equilibrium constant expression for the combined reactions **I**, **II** and **III**. What must the equilibrium constant always be? Why? *[3 marks]*

(f) Keeping in mind answers to previous parts of this question, why would it take 5000 years for 50% of this mineral to erode? *[1 mark]*

(g) What is the term describing the role of the carbon dioxide in the overall reaction (i.e. combined reactions **I**, **II** and **III**)? *[1 mark]*

more space on next page…

9. *…continued from previous page*

10. Consider the unbalanced reaction equations below and answer the following questions to help you evaluate whether hearing aid batteries are better than lithium ion batteries: **[18 marks]**

$$___ Li_{(s)} + ___ O_{2(g)} + ___ H_2O_{(l)} \rightarrow ___ LiOH_{(aq)} \quad \textbf{(I)}$$

$$___ Li_{(s)} + ___ O_{2(g)} + ___ H_2O_{(g)} \rightarrow ___ LiOH_{(s)} \quad \textbf{(II)}$$

(a) Balance reaction **I** using the method of half reactions. *[5 marks]*
For full credit, you must show both balanced half reactions and label which occurs at the cathode and which occurs at the anode.

(b) Using the half-cell potentials provided, calculate the standard cell potential for reaction **I**. *[2 marks]*

(c) Using the standard free energies of formation provided, calculate the standard cell potential for reaction **II**. *[4 marks]*

(d) Calculate the cell potential of the solid-state battery (reaction **II**) at sea level where $p_{H_2O} = 0.032\ bar$ and $p_{O_2} = 0.21\ bar$ on a 30°C day. *[4 marks]*

(e) If a solid-state battery described in part (d) has an initial mass of 1 kg (i.e. contains 1 kg of lithium metal), what is the maximum amount of energy it can produce in kWh? *[2 marks]*

Note that energy can be calculated by multiplying the cell potential by the charge of the electrons consumed during the reaction and that Faraday's constant specifies the charge of one mole of electrons.

Also, note that $1kWh = 3.6MJ$ where kWh stands for "kilowatt hour" and MJ stands for "megajoule".

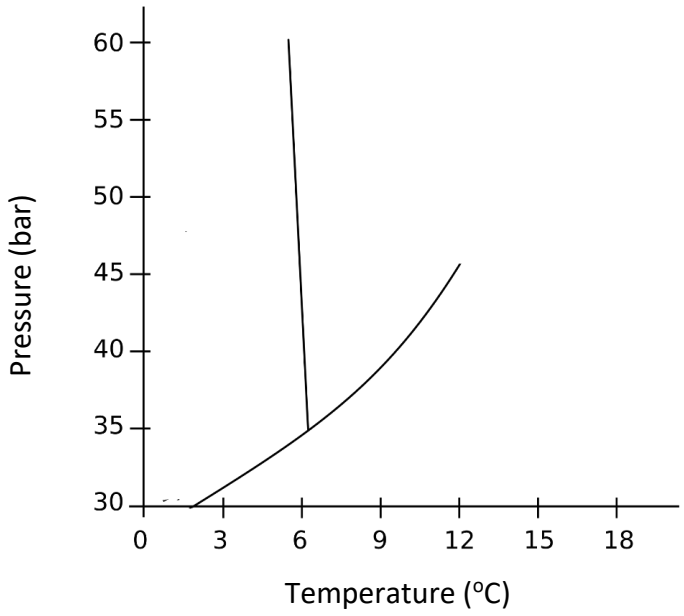
(f) A typical lithium-ion car battery that can produce 1 kWh weighs 6 kg. If you have two batteries (a lithium-ion battery and a solid-state lithium oxide battery (reaction **II**)) that both produce the same amount of energy, which one will weigh less? Why is this important if you want to use the battery to power a vehicle? *[1 mark]*

Hint: 15-25 kWh is needed to drive 100km.

more space on next page…

10. *…continued from previous page*

11. Circle the correct word in each bracket in accordance with the phase diagram below. **[4 marks]**



(a) The **(critical / triple)** point is at 35 bar and 6°C.

(b) Increasing the temperature from 1°C at a constant pressure of 32 bar will result in **(fusion / sublimation)**.

(c) The slight negative slope of the straight line in the phase diagram means you can induce freezing by **(compressing / decompressing)** the liquid form of the substance.

(d) At 35 bar and 18°C, the substance exists in the **(gaseous / supercritical)** state.

12. What was the most useful and/or interesting thing you learned in CHEM 2000? **[1 mark]**

…AND THAT'S ALL FOR CHEM 2000.
HAVE A GREAT SUMMER!