Last Name:________________First Name_________________NetID_______________
Discussion Section:________Discussion TA Name:______________________________

Instructions—
This is a closed book exam. You have two hours (120) minutes to complete it.

1. Use a #2 pencil. Do not use a mechanical pencil or pen. Darken each circle completely, but stay within the boundary. If you decide to change an answer, erase vigorously; the scanner sometimes registers incompletely erased marks as intended answers; this can adversely affect your grade. Light marks or marks extending outside the circle may be read improperly by the scanner. Be especially careful that your mark covers the **center** of its circle.

2. **This Exam Booklet is Version A**. Mark the **A** circle in the **TEST FORM** box near the middle of your answer sheet. **DO THIS NOW!**

3. Print your **NETWORK ID** in the designated spaces at the *right* side of the answer sheet, starting in the left most column, then **mark the corresponding circle** below each character. If there is a letter "o" in your NetID, be sure to mark the "o" circle and not the circle for the digit zero. If and only if there is a hyphen "-" in your NetID, mark the hyphen circle at the bottom of the column. When you have finished marking the circles corresponding to your NetID, check particularly that you have not marked two circles in any one of the columns.

4. Print **YOUR LAST NAME** in the designated spaces at the *left* side of the answer sheet, then mark the corresponding circle below each letter. Do the same for your **FIRST NAME INITIAL**.

5. Do not write in or mark the circles in any of the other boxes (STUDENT NUMBER, DATE, SECTION, SCORES, SPECIAL CODE).

6. Sign your name **(DO NOT PRINT)** on the **STUDENT SIGNATURE** *line*.

7. On the **SECTION** *line*, print your **DISCUSSION SECTION**. You need not fill in the COURSE or INSTRUCTOR lines.

*Before starting work, check to make sure that your test booklet is complete. You should have **12 numbered pages** plus a Formula Sheet at the end.*

*Academic Integrity—***Giving assistance to or receiving assistance from another student or using unauthorized materials during a University Examination can be grounds for disciplinary action, up to and including expulsion.**

Exam Grading Policy—

The exam is worth a total of xxx points, composed of two types of questions.

MC5: *multiple-choice-five-answer questions, each worth 6 points*.
Partial credit will be granted as follows.

(a) If you mark only one answer and it is the correct answer,
you earn **6** points.
(b) If you mark *two* answers, one of which is the correct answer,
you earn **3** points.
(c) If you mark *three* answers, one of which is the correct answer,
you earn **2** points.
(d) If you mark no answers, or more than *three*, you earn 0 points.

MC3: *multiple-choice-three-answer questions, each worth 3 points*.
No partial credit.

(a) If you mark only one answer and it is the correct answer,
you earn **3** points.
(b) If you mark a wrong answer or no answers, you earn **0** points.

The next two questions pertain to the following situation:

Consider the following two systems:

A: three interacting harmonic oscillators with total energy 6ε.

B: two interacting harmonic oscillators, with total energy 4ε.

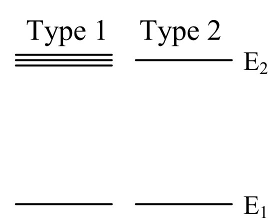
1. What is the ratio of entropies for the two systems?

a. $\sigma_A/\sigma_B = 0$
b. $\sigma_A/\sigma_B = 0.86$
c. $\sigma_A/\sigma_B = 1$
d. $\sigma_A/\sigma_B = 2.07$
e. $\sigma_A/\sigma_B = 3.5$

2. Now the systems are brought into contact and allowed to reach equilibrium. The increase in entropy due to the process is

a. 0
b. 1.97
c. 6.41

3. Two types of atoms have energy levels as shown in the figure. All of the excited states are at the same energy, E_2, but atoms of type 1 have three states at that energy, while atoms of type 2 have only one. A box of gas contains both types of atoms in equilibrium at temperature, T. Compare the probability that an atom of type 1 is in its ground state (*i.e.*, has energy E_1) with the probability that an atom of type 2 is in its ground state.



a. Atoms of type 1 are more likely to be in the ground state.
b. Atoms of type 2 are more likely to be in the ground state.
c. Atoms of the two types are equally likely to be in the ground state.

The next three questions are related:

Consider a large collection of spins with dipole moment $\mu = 1 \times 10^{-23}$ J/Tesla.

4. If B = 1 Tesla, for what temperature will twice as many spins be pointing up (along the field) as down?

a. T = 2.1 K
b. T = 5.2 K
c. T = 14.5 K
d. T = 23.7 K
e. T = 88.4 K

5. Assuming there are N spins, what is the heat capacity in the limit of high temperature?
Hint: What happens to the energy at high temperature?

a. $C_V = \frac{\mu^2 B^2}{kT^2}$

b. $C_V = \frac{Nk^2T^2}{\mu B}$

c. $C_V = \frac{N\mu B}{kT^2}$

d. $C_V = \frac{N\mu^2 B^2}{kT^2}$

e. $C_V = \frac{Nk^2 T}{\mu B}$

6. Now let there be 10^6 spins and let B go to zero. After the spins have completely randomized, approximately what is the probability of observing $N_{up} - N_{down} = 1000$?

a. $P = 5 \times 10^{-2}$
b. $P = 5 \times 10^{-3}$
c. $P = 5 \times 10^{-4}$
d. $P = 5 \times 10^{-5}$
e. $P = 5 \times 10^{-6}$

The next two questions pertain to the following situation:

7. A box of total volume V initially has an insulating partition, which separates N_{Ar} Argon atoms (monatomic, each with mass m_{Ar}) at initial temperature T_{Ar} from N_{N2} nitrogen molecules (diatomic, each with mass m_{N2}) at initial temperature T_{N2}. The partition is suddenly removed, and the gases allowed to equilibrate. The final temperature T_f is

a. $T_f = \dfrac{3N_{Ar}T_{Ar} - 5N_{N2}T_{N2}}{3N_{Ar} + 5N_{N2}}$

b. $T_f = \dfrac{N_{Ar}T_{Ar} - N_{N2}T_{N2}}{N_{Ar} + N_{N2}}$

c. $T_f = \dfrac{5N_{Ar}T_{Ar} + 3N_{N2}T_{N2}}{5N_{Ar} + 3N_{N2}}$

d. $T_f = \dfrac{3N_{Ar}T_{Ar} + 5N_{N2}T_{N2}}{3N_{Ar} + 5N_{N2}}$

e. $T_f = \dfrac{N_{Ar}T_{Ar} + N_{N2}T_{N2}}{N_{Ar} + N_{N2}}$

8. If U'_{Ar} and U'_{N2} are the final energies of each component, which of the following is true in equilibrium:

a. $\dfrac{U'_{Ar}}{N_{Ar}} = \dfrac{U'_{N2}}{N_{N2}}$

b. $U'_{Ar} = U'_{N2}$

c. $m_{Ar}\langle v^2{}_{Ar}\rangle = m_{N2}\langle v^2{}_{N2}\rangle$

9. The vibrational mode of the N_2 molecule acts like a harmonic oscillator with energy spacing, ε = 0.292 eV. Estimate the probability that a molecule of N_2 in equilibrium at room temperature (T = 300 K) is in the **first excited vibrational state** (not the ground state).

a. Probability = 1.54×10^{-10}
b. Probability = 1.24×10^{-5}
c. Probability = 0.0885
d. Probability = 0.292
e. Probability = 0.99999

10. As absolute temperature goes to zero, the heat capacity of N one-dimensional harmonic oscillators approaches

a. 0
b. $\frac{1}{2}$Nk
c. Nk

The next two questions pertain to the following situation:

11. The semiconductor silicon (Si) has a band gap of 1.14 eV, and a density of $5 \times 10^{28}/m^3$. The quantum density associated with its valence and conduction bands is $1.72 \times 10^{25}/m^3$. How many free holes are there in the valence band at 300K if one in 500 million Si atoms is replaced with a phosphorous (an electron donor)?

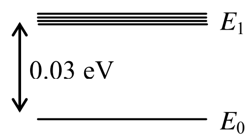
a) $n_h = 2.1 \times 10^7/m^3$
b) $n_h = 2.1 \times 10^9/m^3$
c) $n_h = 2.1 \times 10^{11}/m^3$

12. What will be the carrier density in the doped silicon as the temperature goes to zero?

a) 0
b) $5 \times 10^{15}/m^3$
c) $10^{20}/m^3$

The next two problems are related:

13. A molecule has one electronic state with energy E_0, and four with energy $E_1 = E_0 + 0.03$ eV. At T = 273K, what is the relative number of molecules at each energy level?



a. $N_1 < N_0$
b. $N_1 > N_0$
c. The answer cannot be determined from the information given.

14. What is the average energy of a molecule in the previous case (assume $E_0 = 0$)?

a. 0.0065 eV
b. 0.016 eV
c. 0.021 eV

The next two problems are related:

A sphere of radius 1m is released into deep space (away from the sun), with an initial temperature of 72 °C.

15. What is the wavelength of the peak in the 'blackbody radiation' from the sphere?

a. 830 nm
b. 8.4 micrometers
c. 40 micrometers

16. Approximating the sphere as a perfect "black body", and assuming its heat capacity is 10^4 J/K, about how long does the sphere take to cool to 335 K?

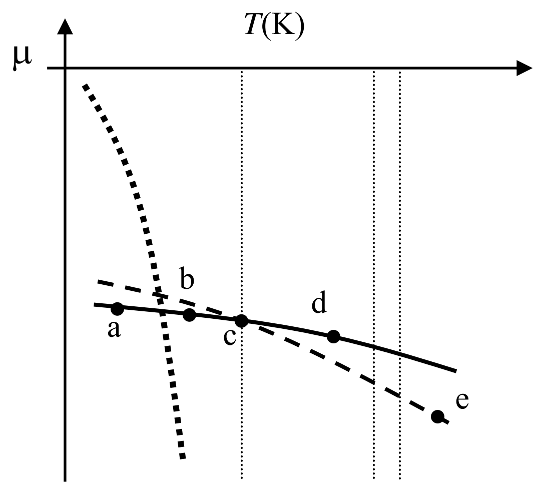
a. 0.01 s
b. 0.1 s
c. 1 s
d. 10 s
e. 100 s

17. Brick A has mass $m_A = 1$ kg, with specific heat $c_A = 1000$J/kg-K, initially at temperature $T_A = 100$ K. Brick B has mass $m_B = 2$ kg, with specific heat $c_B = 2000$J/kg-K, initially at temperature $T_B = 200$ K. The bricks are put in thermal contact with each other (but are isolated from the rest of the world). After the two-brick system reaches thermal equilibrium, by how much, ΔS_{tot}, has their total entropy changed?

a. $\Delta S_{tot} = -81$ J/K
b. $\Delta S_{tot} = 0.0$ J/K
c. $\Delta S_{tot} = 81$ J/K
d. $\Delta S_{tot} = 166$ J/K
e. $\Delta S_{tot} = 1009$ J/K

The next two problems are related:

A substance has the following chemical potential vs T diagram at a particular pressure.



18. Which of the points corresponds to a substance that is in thermal equilibrium?

a.
b.
c.
d.
e.

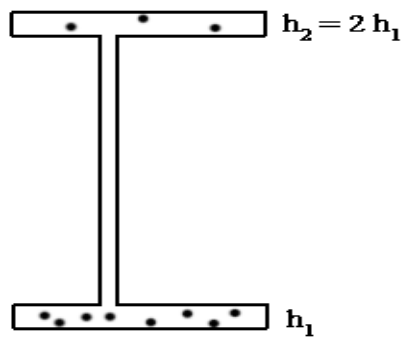
19. Which of the points corresponds to a substance that is about to sublime?
a.
b.
c.
d.
e.

20. Calculate the chemical potential, μ, of Argon gas at room temperature, $T = 300$ K, and atmospheric pressure, $p = 1.01\times10^{5}$ Pa. Ignore the effect of external forces, such as gravity.

a. $\mu = -2.49\times10^{-9}$ eV
b. $\mu = -0.42$ eV
c. $\mu = 0$ eV
d. $\mu = +0.42$ eV
e. $\mu = +2.49\times10^{-9}$ eV

Can compute changes, but not total μ!

21. A container holds N_{total} gas molecules in equilibrium at two different heights as pictured. What is the relationship between the chemical potentials of the molecules at height h_1 and $h_2 = 2h_1$?



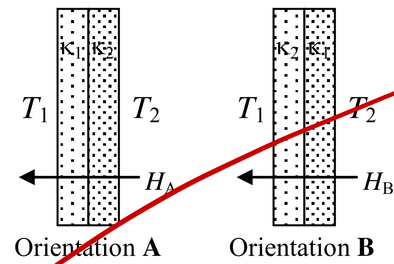
a) $\mu_1 = \mu_2/4$
b) $\mu_1 = \mu_2/2$
c) $\mu_1 = \mu_2$
d) $\mu_1^2 = \mu_2$
e) $\mu_1 = \mu_2^2$

22. The gas molecules are 80% N_2 and 20% O_2 at sea level, i.e., $n_{N2}/n_{O2} = 4$. Neglecting the effects of thermal mixing, at what height is the ratio $n_{N2}/n_{O2} = 1$? (Assume a constant temperature T = 260 K.)

a. 33 km
b. 76 km
c. There is no altitude above sea level where the ratio is 1.

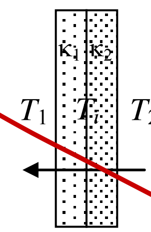
The next two problems are related:

23. A window is made of two layers of material that have different thermal conductivities, $\kappa_2 > \kappa_1$. The temperature on one side of the window is higher than the other: $T_2 > T_1$. Which orientation of the window (see the figure) gives more heat flow through the window?



a. $H_A > H_B$ (**A** has more heat flow.)
b. $H_A = H_B$ (The heat flows are equal.)
c. $H_A < H_B$ (**B** has more heat flow.)

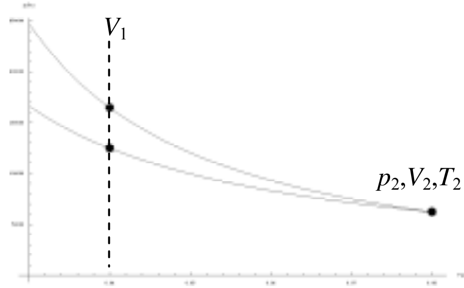
24. Now consider that the layers have equal thickness, and $\kappa_2 = 3\kappa_1$. The temperatures $T_1 = 10°C$ and $T_2 = 20°C$. What is the relative temperature T_i at the interface between the two layers?



a. 12.5°C
b. 15°C
c. 17.5°C
d. 18°C
e. 20° C

$\gamma = \frac{N_{DOF} + 2}{N_{DOF}}$

25. Compare the isothermal and adiabatic expansions from $V_1 = 0.04\ m^3$ to $V_2 = 0.08\ m^3$ of two moles of an ideal diatomic gas, as shown in the figure. Both processes end up at the same state, $T_2 = 300$ K, and $p_2 = 62.3$ kPa. Calculate the ratio, W_I/W_A, of the work done by the two processes (isothermal divided by adiabatic).



Isothermal! $pV = const$

Adiabatic: $pV^\gamma = const$

a. $W_I/W_A = 0.40$
b. $W_I/W_A = 0.87$
c. $W_I/W_A = 1.40$
d. $W_I/W_A = 2.00$
e. $W_I/W_A = 3.46$

26. A Carnot heat engine achieves 33.3% efficiency when operating between temperatures T_h and T_c. If it is operated as a refrigerator operating between the same two reservoirs, how much work, W, must we supply in order to remove 1 kJ of heat from the cold reservoir?

a. $W = 500$ J
b. $W = 666$ J
c. $W = 1$ kJ
d. $W = 2$ kJ
e. $W = 3$ kJ

27. The following chemical reaction occurs: $2N_2O_5 \rightarrow 4NO_2 + O_2$. Which of the following correctly expresses the relationship between the chemical potentials of all three species?

a) $2\mu_{N_2O_5} = 4\mu_{NO_2} + \mu_{O_2}$
b) $2\mu_{N_2O_5} = \mu_{NO_2} + 4\mu_{O_2}$
c) $\mu^2{}_{N_2O_5} = \mu^4{}_{NO_2} + \mu_{O_2}$
d) $\mu_{N_2O_5} = \mu_{NO_2} + \mu_{O_2}$
e) $2\mu_{N_2O_5} = 4\mu_{NO_2} = \mu_{O_2}$

28. Two identical blocks each have heat capacity 100 J/K. One block is at temperature 500K and the other is at temperature 100K. Which block has the higher free energy relative to the environment at 300 K?

a) the cold block
b) the hot block
c) they have the same free energy

29. A block of material has a temperature-dependent heat capacity given by $C_V(T) = 5$ J/K + T×(2 J/K^2). How much does the entropy of this object change as its temperature is increased from 10ºC to 40ºC at constant volume?

a) –66.9 J/K
b) –60.5 J/K
c) 0.50 J/K
d) 60.5 J/K
e) 66.9 J/K

30. The star Rigel (in the constellation Orion) is a blue supergiant. It is very large ($R_{\mathrm{Rigel}} = 70R_{\mathrm{Sun}}$) and very bright, i.e., has very high total radiated power $P_{\mathrm{Rigel}}/P_{\mathrm{Sun}} = 80{,}000$). How much hotter is it than the sun? That is, what is the ratio, $T_{\mathrm{Rigel}}/T_{\mathrm{Sun}}$?

a. $T_{\mathrm{Rigel}}/T_{\mathrm{Sun}} = 2$
b. $T_{\mathrm{Rigel}}/T_{\mathrm{Sun}} = 16$
c. $T_{\mathrm{Rigel}}/T_{\mathrm{Sun}} = 70$
d. $T_{\mathrm{Rigel}}/T_{\mathrm{Sun}} = 4{,}900$
e. $T_{\mathrm{Rigel}}/T_{\mathrm{Sun}} = 78{,}000$

31. Consider a 2-dimensional gas, in which particles are allowed to move only in a plane. What is the root-mean-square velocity of the particles in this 2-d gas?

a. $v_{rms} = 0$
b. $v_{rms} = \sqrt{\dfrac{2kT}{m}}$
c. $v_{rms} = \sqrt{\dfrac{3kT}{m}}$

32. A 1-liter (non-elastic) balloon is filled with pure helium gas. The balloon is in a room 10x10x10m at 300 K and 1 atm. (Assume the air in the room is all nitrogen and oxygen molecules.) Now we pop the balloon, allowing the He to diffuse throughout the room. By what amount does the Free energy of the He gas change?

(F) $S = Nk \ln(V) + f(U,N)$

a) -1382 J
b) -691 J
c) 0
d) + 691 J
e) +1382 J

The next two problems are related:

33. Argon (molecular weight 40 g/mole) is a monatomic compound. If liquid argon is confined to a container and held at a constant temperature of 80.5 K, what is the approximate vapor pressure of gaseous argon, assuming the liquid has no entropy and a binding energy of 0.1 eV? [Note: At 1 atm, the boiling point is 87.3 K.]

$N \propto e^{-\Delta/kT}$

a) 2 atm
b) 0.2 atm
c) 0.02 atm
d) 0.002 atm
e) 0.0002 atm

34. The measured value of the latent heat of vaporization of argon (at 1 atm) is 6.43 kJ/mol. Use this to estimate the binding energy.

a) 0.027 eV
b) 0.059 eV
c) 0.067 eV
d) 0.11 eV
e) 0.4 eV

The next two questions pertain to the following situation:

In a hydrogen atom, the electron (e) is electrostatically bound to the proton (p) with an energy –13.6 eV. Inside a star, the density is ~$10^{24}/m^3$, and the temperature is 7000 K.

35. ***Note: This problem may be longer/more difficult; therefore, you may want to do it last.***
What is the density of free electrons (and protons)? You may assume that $n_H = 1 \times 10^{24}\ m^{-3}$ and that $m_H = m_p = 1836\ m_e$.

a. $6.0 \times 10^{13}\ m^{-3}$
b. $2.7 \times 10^{15}\ m^{-3}$
c. $5.1 \times 10^{17}\ m^{-3}$
d. $2.1 \times 10^{18}\ m^{-3}$
e. $4.7 \times 10^{20}\ m^{-3}$

36. Which of the following would *increase* the *fraction* of unbound protons?

a. increase the temperature.
b. increase the pressure.
c. increasing the binding energy Δ.

Answers:

1	d
2	b
3	b
4	a
5	d
6	c
7	d
8	c
9	b
10	a
11	c
12	a
13	b
14	b
15	b
16	d
17	d
18	a
19	b
20	b
21	c
22	c
23	b
24	c
25	b
26	a
27	a
28	a
29	d
30	a
31	b
32	a
33	b
34	b
35	e
36	a