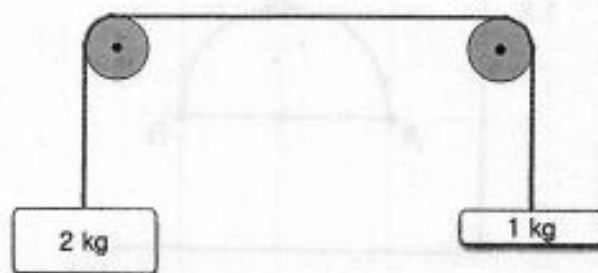


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1. Two masses are connected by a rope, which is pulled over two pulleys as shown below. The masses are placed as in the diagram below, but start to move when both masses are "released" (i.e. the person holding the masses in place lets go of both masses). The rope does not stretch as the masses move, and we may neglect any change of energy of the pulleys.



- (a) Indicate if the 1 kg mass goes up or down once released. [1%]

Up, because it's lighter.

- (b) Indicate if the 2 kg mass goes up or down once released. [1%]

Down, because it's heavier.

- (c) When the 1 kg mass is released and has moved 10 cm, how far has the 2 kg mass travelled? We will refer to this state the *final state* in subsequent problems. [2%]

Also 10 cm, because the string connecting them does not stretch.

- (d) What is the speed of the 1 kg mass moving in the final state? [10%]

Note that both masses are changing their KE and PE!

PE ₁ ↑ (h ↑)	KE ₁ ↑ (v ↑)	PE ₂ ↓ (h ↓)	KE ₂ ↑ (v ↑)
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$$\Delta PE_1 + \Delta KE_1 + \Delta PE_2 + \Delta KE_2 = 0$$

$$m_1 g \Delta h_1 + \frac{1}{2} m_1 \Delta(v_1^2) + m_2 g \Delta h_2 + \frac{1}{2} m_2 \Delta(v_2^2) = 0$$

$$1 \text{ kg} \cdot 10 \frac{\text{m}}{\text{s}^2} \cdot (+.1 \text{ m}) + \frac{1}{2} \cdot 1 \text{ kg} \cdot (v_f^2 - 0) + 2 \text{ kg} \cdot 10 \frac{\text{m}}{\text{s}^2} \cdot (-.1 \text{ m}) + \frac{1}{2} \cdot 2 \text{ kg} \cdot (v_f^2 - 0)$$

$$+1 \text{ J} + \frac{1}{2} \text{ kg} \cdot v_f^2 - 2 \text{ J} + 1 \text{ kg} \cdot v_f^2 = 0$$

- (e) What is the speed of the 2 kg mass moving in the final state? [4%]

Also $\sqrt{\frac{2}{3}} \frac{\text{m}}{\text{s}}$, because, again, the string does not stretch.

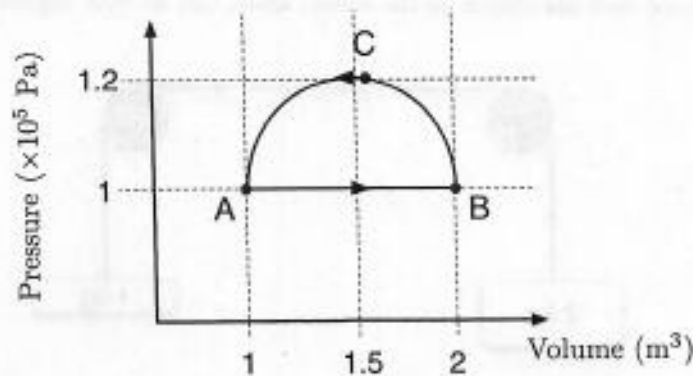
$$-1 \text{ J} + \frac{3}{2} \text{ kg} \cdot v_f^2 = 0$$

$$\frac{3}{2} \text{ kg} \cdot v_f^2 = 1 \text{ J}$$

$$v_f^2 = \frac{2}{3} \frac{\text{m}^2}{\text{s}^2} \rightarrow v_f = \sqrt{\frac{2}{3}} \frac{\text{m}}{\text{s}}$$

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2. One mole of a diatomic (ideal) gas undergoes a cyclic process $A \rightarrow B \rightarrow C \rightarrow A$, where A , B and C are the points shown in the PV diagram.



- (a) Does the internal energy increase, decrease or stay the same over one cycle? (i.e. pick one) [2%]

It stays the same - energy is a state function, so it may change but returns to its starting value by the end of a full cycle.

- (b) Does heat flow into or out of the gas going from A to B ? Pick one! [5%]

We know that work is leaving the gas because its volume is expanding ($\Delta V > 0$, so $W = -P\Delta V < 0$)...

but $\Delta T = \frac{P\Delta V}{nR} > 0$ (ideal gas law), so internal energy is increasing.

Therefore $\Delta U = W + Q$, which only works if $Q > 0$, so heat flows into the gas.

- (c) Over an entire cycle, does more work enter the gas or leave it? (i.e. pick one!) [4%]

During $A \rightarrow B$, some work leaves, but during $B \rightarrow C \rightarrow A$, more work enters.

$W = (-\text{shaded}) + (+\text{shaded}) = (+\text{shaded})$. Thus in total work enters the gas.

- (d) Over an entire cycle, does more heat enter the gas or leave it? (i.e. pick one!) [4%]

For one full cycle, we already found that $W > 0$ and $\Delta U = 0$,

so we have $\Delta U = W + Q$, which only works if $Q < 0$, so heat leaves the gas.

- (e) Is ΔS_{gas} positive, negative or zero for one cycle? (i.e. pick one!) Is this in conflict with the second law of thermodynamics? Explain why or why not. [5%]

Entropy is a state function, so for one full cycle, $\Delta S_{\text{gas}} = 0$.

Presumably entropy increases during some part of the cycle and decreases during another part - but the gas is not a closed system, so the Second Law doesn't care.

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3. Two measurements of molar specific heat of the same substance are made in the temperature range 300–400 K. One is at constant pressure (c_p), the other is at constant volume (c_v). One experiment found a heat capacity of 20.8 J/(mol K) and the other experiment measured 29.1 J/(mol K). Useful information:

$$R = 8.31 \text{ J/(mol K)}, \quad k_B = 1.38 \times 10^{-23} \text{ J/K}, \quad N_A = 6.023 \times 10^{23} \text{ atoms/mol}$$

- (a) Which value is the molar specific heat at constant pressure? How can you tell? [5%]

c_{pm} is always greater than c_{vm} (specifically, $c_{pm} = c_{vm} + R$),

$$\text{so } c_{vm} = 20.8 \frac{\text{J}}{\text{K}\cdot\text{mol}} \text{ and } c_{pm} = 29.1 \frac{\text{J}}{\text{K}\cdot\text{mol}}$$

- (b) How many modes are activated at these temperatures (i.e. 300–400 K range)? [5%]

$$c_{vm} = \frac{R}{2} \cdot (\# \text{ modes}), \text{ so } (\# \text{ modes}) = \frac{2 \cdot c_{vm}}{R} = \frac{2 \cdot 20.8}{8.31} \approx 5 \text{ modes}$$

- (c) Based on the number of modes, is this substance a solid, liquid or gas? If it is a gas specify if it is monatomic, diatomic, or "other". [5%]

of the 5 modes, 3 must be translational KE, leaving 2 modes available for anything else. The only category that fits is linear polyatomic gas (possibly diatomic), with those 2 modes being rotational KE.

- (d) If we measured the molar specific heat at constant pressure at 2200 K, would you expect the value to be higher, lower or the same as the c_p at 300 K? (i.e. pick one). Explain. [5%]

At very high temperatures, the internal vibrational modes would be active, resulting in higher values of specific heat (both c_p and c_v).

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4. We start with a 2 gram ice-cube at -50°C , and place it in an insulated cup. The inside of the insulated cup starts at $+1^{\circ}\text{C}$ and has a very large heat capacity. (In practical terms, this means you may neglect the change in temperature of the cup). You may assume that heat is only transferred between the cup and the H_2O inside. The following values may be useful to you:

c_{ice}	$2.05 \text{ kJ}/(\text{kg K})$
$\Delta H_{\text{H}_2\text{O}, s \rightarrow l}$	$333.5 \text{ kJ}/\text{kg}$
c_{water}	$4.18 \text{ kJ}/(\text{kg K})$
0°C	273.15 K
Melting point of H_2O is 0°C	

- (a) How much heat is exchanged from the cup to the H_2O ? [5%]

Since the cup remains at 1°C , we can assume that the water will also reach 1°C , which means it will melt completely.

$$Q = \Delta E_{\text{th}}^{\text{ice}} + \Delta E_{\text{bond}}^{\text{melt}} + \Delta E_{\text{th}}^{\text{lig. water}}$$

$$= mc\Delta T + \Delta m \Delta H + mc\Delta T$$

$$= .002 \text{ kg} \cdot 2.05 \frac{\text{kJ}}{\text{kg} \cdot \text{K}} \cdot (0^{\circ}\text{C} - (-50^{\circ}\text{C})) + (.002 \text{ kg} - 0 \text{ kg}) \cdot 333.5 \frac{\text{kJ}}{\text{kg}} + .002 \text{ kg} \cdot 4.18 \frac{\text{kJ}}{\text{kg} \cdot \text{K}} \cdot (1^{\circ}\text{C} - 0^{\circ}\text{C})$$

$$= .205 \text{ kJ} + .667 \text{ kJ} + .00836 \text{ kJ}$$

$$= \boxed{.88 \text{ kJ or } 880 \text{ J}}$$

- (b) What is $\Delta S_{\text{H}_2\text{O}}$ in going from the initial state to the equilibrium state? [5%]

$$\text{ice warming up: } \Delta S = C \cdot \ln\left(\frac{T_f}{T_i}\right) = .002 \cdot 2.05 \frac{\text{kJ}}{\text{K}} \cdot \ln\left(\frac{273\text{K}}{223\text{K}}\right) \approx .83 \frac{\text{J}}{\text{K}}$$

$$\text{ice melting: } \Delta S = \frac{Q}{T} = \frac{667 \text{ J}}{273\text{K}} \approx 2.44 \frac{\text{J}}{\text{K}}$$

$$\text{liquid warming up: } \Delta S = C \cdot \ln\left(\frac{T_f}{T_i}\right) = .002 \cdot 4.18 \frac{\text{kJ}}{\text{K}} \cdot \ln\left(\frac{274\text{K}}{273\text{K}}\right) \approx .03 \frac{\text{J}}{\text{K}}$$

$$\text{total: } \boxed{\Delta S = +3.3 \frac{\text{J}}{\text{K}}}$$

(c) What is ΔS_{cup} in going from the the initial state to the equilibrium state?[4%]

$$Q_{\text{cup}} = -Q_{\text{water}} \quad (\text{closed system})$$

$$Q_{\text{cup}} = -880 \text{ J}$$

$$\Delta S_{\text{cup}} = \frac{Q}{T} = \frac{-880 \text{ J}}{274 \text{ K}} \approx \boxed{-3.2 \frac{\text{J}}{\text{K}}}$$

(d) What is the *total* change in entropy of the universe for this process? Does this process violate the second law of thermodynamics?[2%]

$$\Delta S_{\text{tot}} = \Delta S_{\text{H}_2\text{O}} + \Delta S_{\text{cup}}$$

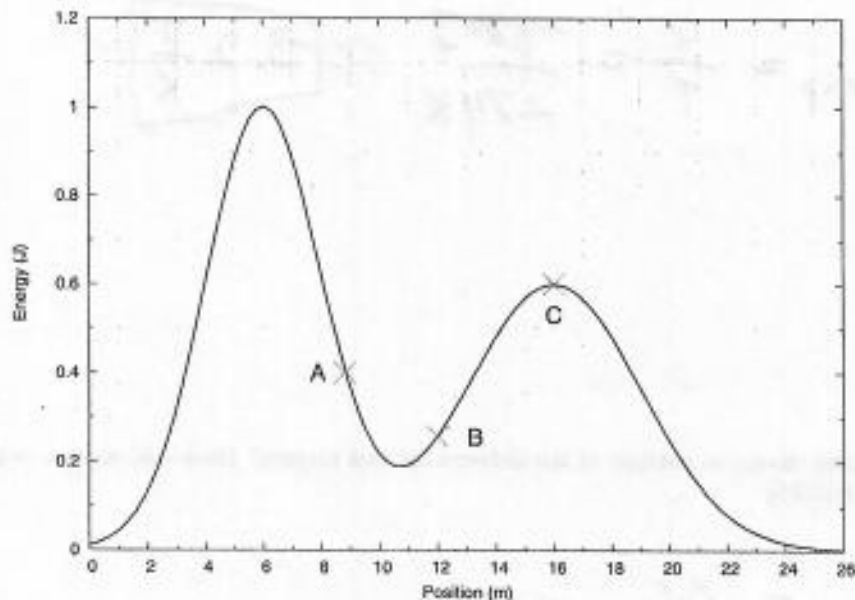
$$= \left(+3.3 \frac{\text{J}}{\text{K}}\right) + \left(-3.2 \frac{\text{J}}{\text{K}}\right)$$

$$= \boxed{+0.1 \frac{\text{J}}{\text{K}}}$$

It's a closed system, and its total entropy has not decreased, as was foretold by ~~prophecy~~ the 2nd Law of Thermodynamics.

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5. A ball rolls along a (frictionless) hill. The potential energy of the ball versus the horizontal location of the ball x is plotted below. Three points A , B and C are labelled and referenced in the problems below. You may neglect the kinetic energy due to rotation of the ball, but do *not* neglect the translational kinetic energy of the ball. Also assume that the potential energy approaches zero for $x < 0$ and $x > 26$ m (i.e. there are no "hills" hiding just off the graph).



- (a) For each labelled point A , B and C indicate if the force on the particle points to the left, right or if it vanishes altogether. Note: we are not interested in the vertical direction of the force, only the horizontal direction. [4%]

A: to the right, because slope < 0

B: to the left, because slope > 0

C: no force, because slope $= 0$

generally: $F = -\frac{d(PE)}{dx}$

- (b) Rank the magnitude of the forces at each of A , B and C . [2%]

stronger at A (steep)

weaker at B (less steep)

no force at C (flat)

- (c) If the ball starts at point B travelling *left*, is it possible for the ball to reach $x = 24$? If it is possible, what do we know about E_{tot} of the ball? Note: do **not** assume the ball starts at rest. [5%]

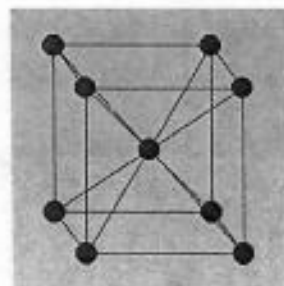
Yes, but only if $E_{\text{tot}} < 1 \text{ J}$ (so ball turns around)

and $E_{\text{tot}} > 0.6 \text{ J}$ (so ball gets over peak at $x=16$)

- (d) If the ball starts at point B travelling *right*, is it possible for the ball to reach $x = 0$? If it is possible, what do we know about E_{tot} of the ball? Note: do **not** assume the ball starts at rest. [5%]

No — to do so, it would need $E_{\text{tot}} < 0.6 \text{ J}$ and $E_{\text{tot}} > 1 \text{ J}$,
which is mathematically impossible.

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6. Every atom inside (i.e. not on the surface) of a solid block of sodium can be thought of the central atom in the diagram to the right. The nearest neighbours are 3.72\AA apart. Recall $1\text{\AA} = 10^{-10}\text{ m}$.

- (a) How many nearest neighbours does a sodium atom have? [1%]

8 (count them, using center as reference point)

- (b) Using your answer above, and the fact that $\Delta H_{\text{Na}, l \rightarrow g} = 96.960\text{ kJ/mol}$, estimate the well-depth for the Lennard-Jones interaction between two sodium atoms. [8%]

ΔH_{mol} is the energy required to vaporize N_A particles,

$$\text{so } \Delta H_{\text{mol}} = \epsilon \cdot \frac{(\# \text{ bonds}) \cdot N_A}{2}$$

$$\text{Solve for well depth: } \epsilon = \frac{2 \cdot \Delta H_{\text{mol}}}{(\# \text{ bonds}) \cdot N_A}$$

$$\epsilon = \frac{2 \cdot 96960\text{ J}}{8 \cdot 6.02 \times 10^{23}}$$

$$\boxed{\epsilon \approx 4 \times 10^{-20}\text{ J}}$$

- (c) Use the equilibrium distance between nearest neighbours to estimate the diameter (i.e. "size") of a sodium atom. **Note:** The size of the atoms are not to scale with the bond lengths in the picture above. [1%]

In general, $r_0 \approx 1.12 \cdot \sigma$, and here $r_0 = 3.72\text{\AA}$,

$$\text{so } \sigma = \frac{3.72\text{\AA}}{1.12} \approx 3.32\text{\AA} = \boxed{3.32 \times 10^{-10}\text{ m}}$$