Temperature, Energy and the First Law of Thermodynamics

8.01t

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Temperature

- The ‘hotness’ or ‘coldness’ of an object is a macroscopic property of that object.
- When a cold object is placed in contact with a hot object, the cold object warms up and the hot object cools down until the two objects reach a state of thermal equilibrium.
- Temperature is a quantitative description of the hotness or coldness of a system.

What is temperature?

-A measure of energy

-Random Motion of Molecules (kinetic energy)

-Air at Mountaintop (potential energy)

-Only some of energy can become mechanical

Equipartition Assumption

- A system that has a temperature is in thermal equilibrium

- <energy in a degree of freedom> = 1/2 $k_B T$

What is a Degree of Freedom?

Each coordinate of each particle

$$\frac{1}{2} m \langle v_x^2 \rangle = \frac{1}{2} m \langle v_y^2 \rangle = \frac{1}{2} m \langle v_z^2 \rangle = \frac{1}{2} k_B T$$

$$m g \langle z \rangle = \frac{1}{2} k_B T$$

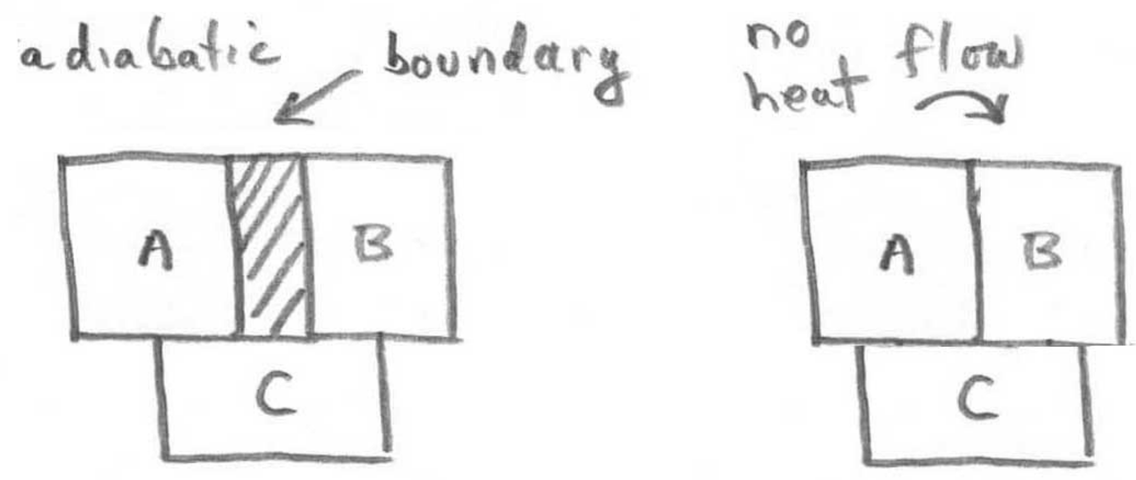
Heat

- If two bodies are in contact but initially have different temperatures, heat will transfer or flow between them if they are brought into contact.
- heat is the energy transferred, given the symbol Q.

Thermal Equilibrium

Definition: Adiabatic boundary means no heat flow

(*a* - not +*dia* - through + *bainein* go)



If both A and B are in thermal contact with a third system C until thermal equilibrium is reached, the average energy per mode is equal to 1/2kT for all parts of the system.

Then remove adiabatic boundary, no heat will flow between A and B

Zeroth Law of Thermodynamics

- Two systems in thermal equilibrium with a third system are in thermal equilibrium with each other.
- Temperature is that property of a system that determines whether or not a system is in thermal equilibrium with other systems.

Temperature and Equilibrium

- Temperature is Energy per Degree of Freedom
  - More on this later (Equipartition)

- Heat flows form hotter to colder object

  Until temperatures are equal

  Faster if better thermal contact

  Even flows at negligible Δt (for reversible process)

- The Unit of Temperature is the Kelvin

  Absolute zero (no energy) is at 0.0 K

  Ice melts at 273.15 Kelvin (0.0 C)

  Fahrenheit scale is arbitrary

Heat and Work are Processes

- Processes accompany/cause state changes
  - Work **along particular path** to state B from A
  - Heat added along path to B from A

- Processes are **not state variables**
  - Processes change the state!
  - But Eq. Of State generally obeyed

State Variables of System

- **State Variables - Definition**

  Measurable Static Properties

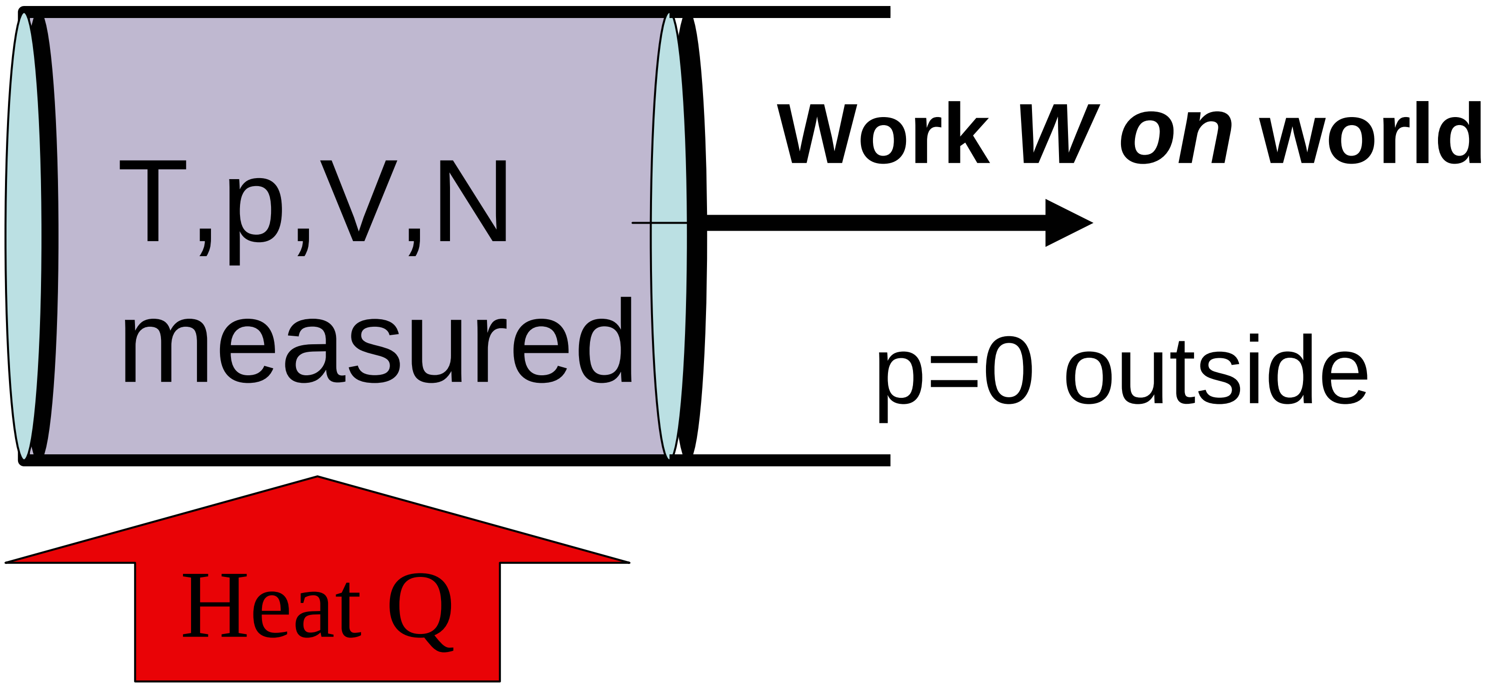
  Fully Characterize System (if constituents known)

  e.g. Determine Internal Energy, compressibility

  Related by Equation of State

- **State Variables: Measurable Static Properties**
  - Temperature - measure with thermometer
  - Volume (size of container or of liquid in it)
  - Pressure (use pressure gauge)
  - Quantity: Mass or Moles or Number of Molecules
    - Of each constituent or phase (e.g. water and ice)

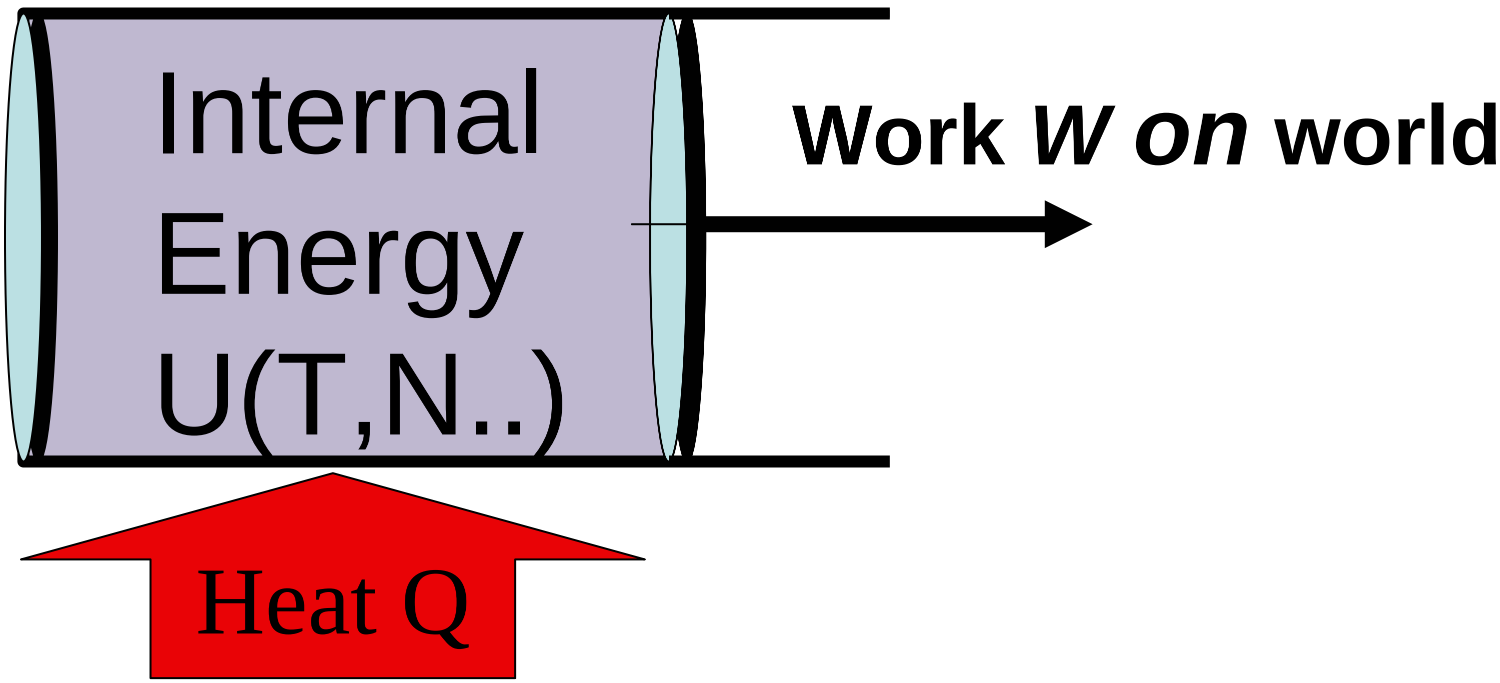
Thermodynamic Systems



The state variables are changed only in response to Q and W

No other work or heat enters

First Law - Energy Conservation



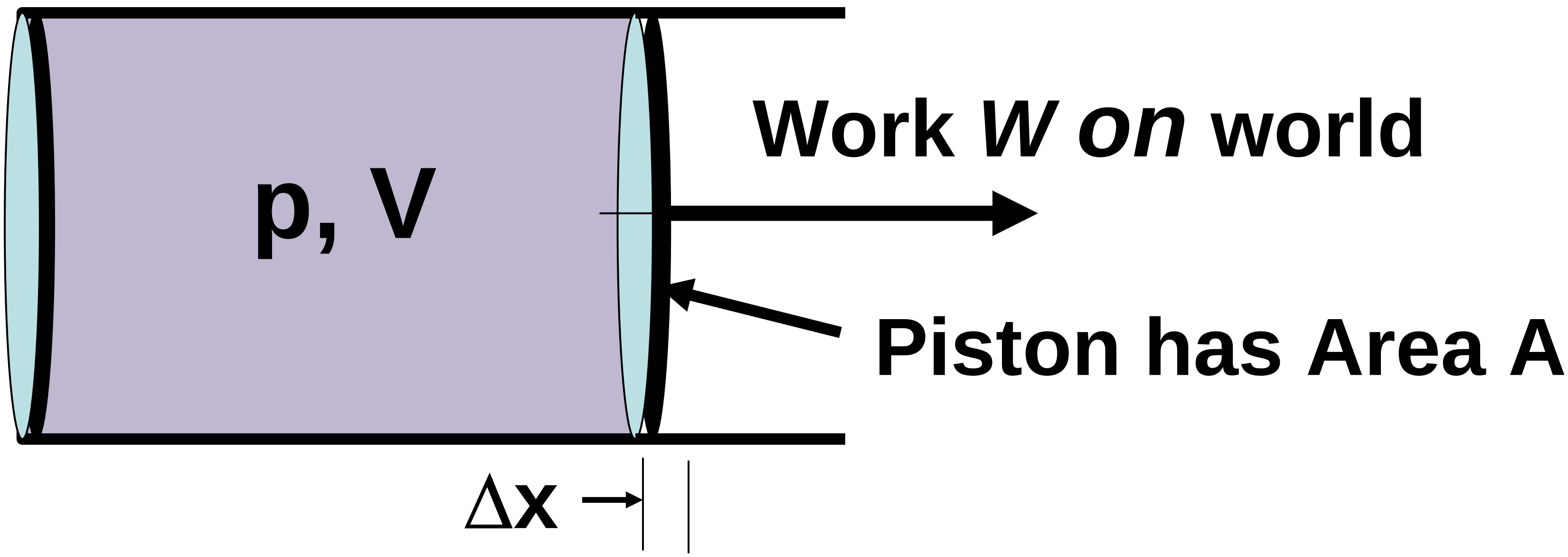
$$Q = W + \Delta U = W + U_f - U_i$$

stress: Q & W are processes,
U is a state variable

Variables in First Law

- Q is the **Heat Added**
  - Could find from Temperature Gradient
    - But need Heat Conductivity and Area
  - Generally determine from First Law
- W is the **Work done by** system
  - Equal to $p\Delta V$
- U is the **Internal Energy of** system
  - It is determined by state variables
  - From equipartition, proportional to T

Expression for Work



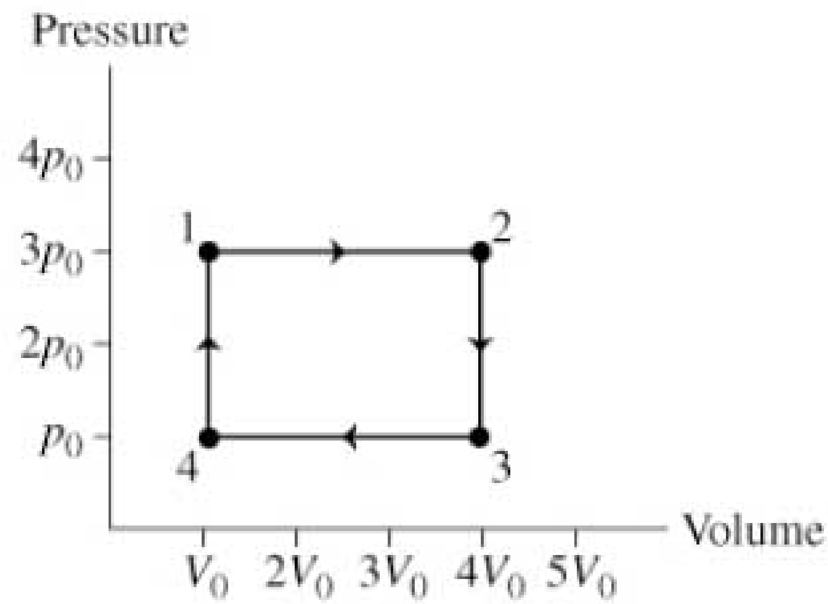
Find Work if piston moves Δ**x**:

$$W = F\,\Delta x = pA\,\Delta x = p\Delta V$$

$$\text{In General}: \quad W_{fi} = \int_i^f p(V,T)\; dV$$

PRS: Work in p-V plane:

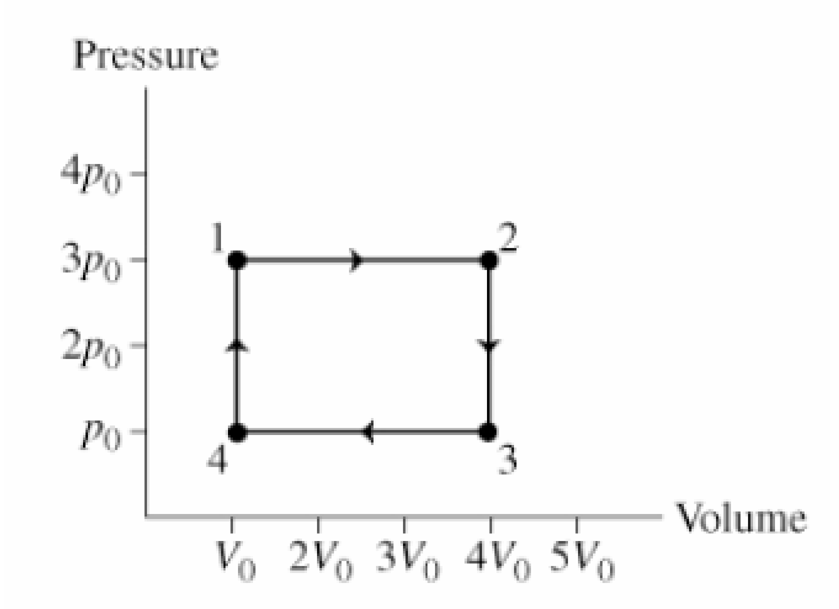
In the cycle shown what is the work done by the system going from state 1 to state 2 clockwise along the arrowed path?



1. $12\ p_0 V_0$
2. $9\ p_0 V_0$
3. $4\ p_0 V_0$
4. $3\ p_0 V_0$
5. $-12\ p_0 V_0$
6. $-9\ p_0 V_0$
7. $-4\ p_0 V_0$
8. $-3\ p_0 V_0$
9. None of above

PRS: Work in p-V plane:

In the cycle shown what is the work done by the system going from state 2 to state 4 clockwise along the arrowed path?



1. $12\ p_0 V_0$
2. $9\ p_0 V_0$
3. $4\ p_0 V_0$
4. $3\ p_0 V_0$
5. $-12\ p_0 V_0$
6. $-9\ p_0 V_0$
7. $-4\ p_0 V_0$
8. $-3\ p_0 V_0$
9. None of above

Internal Energy

Based on Equipartition:

-each coordinate of each particle

$$1/2\ m \langle v_x^2 \rangle = 1/2\ m \langle v_y^2 \rangle = 1/2\ k_B T$$

$$1/2\ \mu \langle v_{rel}^2 \rangle = 1/2\ k_B T \text{ ..molecule}$$

For an ideal monatomic gas:

$$U(T) = 3/2\ N\ k\ T$$

For an ideal diatomic molecular gas:

$$U(T) = 5/2\ N\ k\ T \quad \text{(no vibration)}$$

Specific Heat - Constant Volume

Consider a **monatomic** ideal gas in a container of **fixed volume.** A small amount of heat, dQ is added with $dV = 0$ so $W = 0$. The First Law then gives:

$$dQ = dW + dU = dU$$

But $\quad dU(T) = 3/2\ N\ k\ dT,$

so $\quad dQ/dT = 3/2\ N\ k = 3/2\ n\ R$

$c_V = 3/2\ R$ is defined as the **specific heat**

- heats one mole one degree Kelvin

Class Problem: Heat the room

A room is 3x5x6 meters and initially at T = 0C. How long will it take a 1 kW electric heater to raise the air temperature to 20C?

1. 1/2 min
2. 3/4 min
3. 1 1/4 min
4. None of above
5. 11 min
6. 17 min
7. 28 min

Note: In reality it will take several times this long because the walls and furnishings in the room have to be warmed up also.

Specific Heat of Aluminum

Aluminum has an atomic weight of 27 (grams per mole), and has 3 translational and 3 vibrational degrees of freedom per atom. What is its specific heat in j/kg/K?

1. 1806
2. 903
3. 452
4. None of above

Young and Freedman gives 910 as the correct answer this shows how close the simple ideas come to reality.

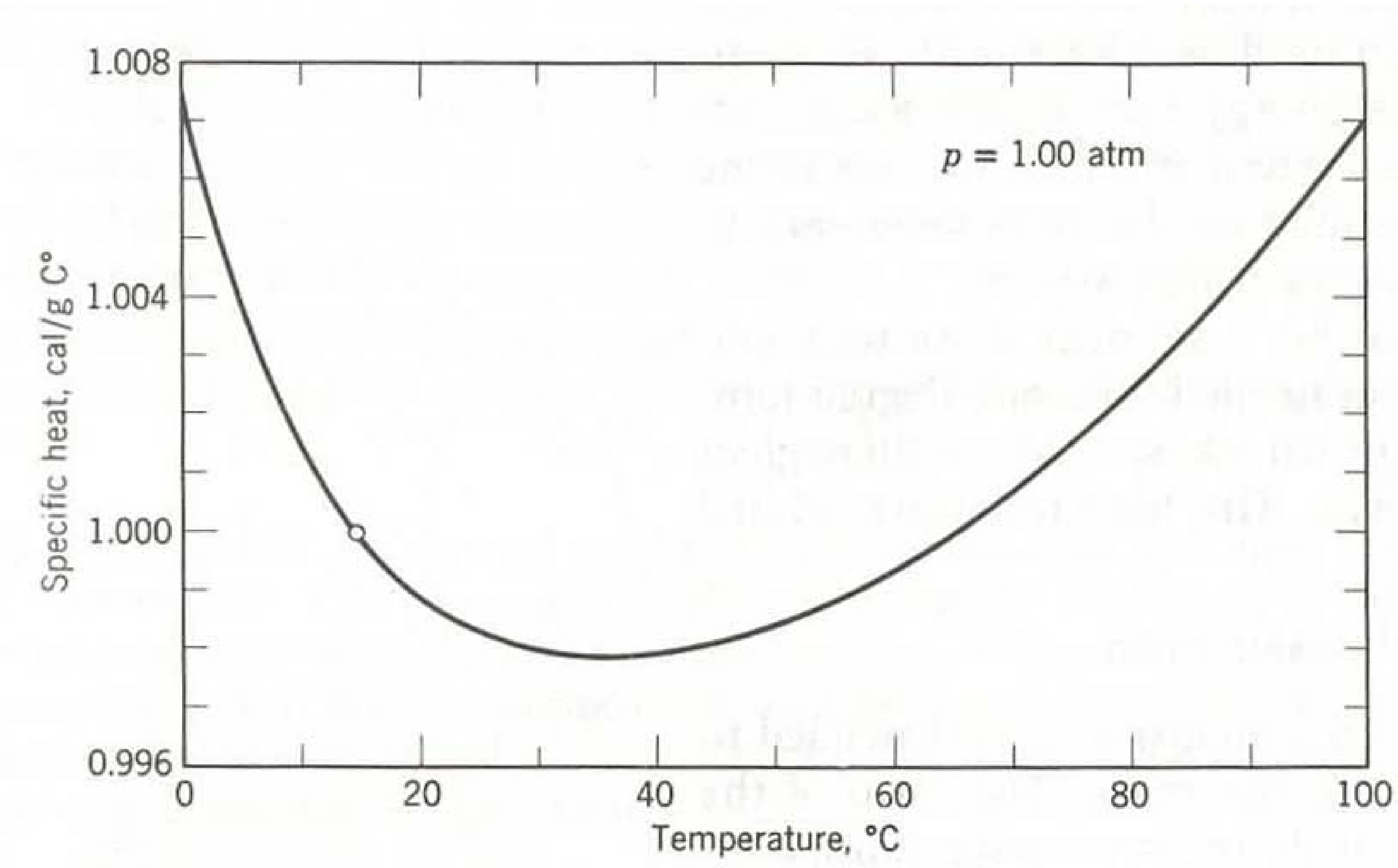
Class Problem: Heat the walls

How much longer will it take a 1 kW electric heater to raise the wall temperature to 20C? Assume the walls and ceiling are Aluminum 1 cm thick that is initially at T = 0C.

Mechanical Equivalent of Heat

Calorie

- thermal unit for heat is the calorie defined to be the amount of heat required to raise one gram of water from 14.5 ^oC to 15.5 ^oC



Calibration of Thermistor

- thermometric property: electrical resistance in wire varies as wire becomes hotter or colder.

- *thermistor* : semi-conductor device with a temperature dependent electrical resistance given by

$$R(T) = R_0 e^{-\alpha T}$$

- where R_0 is the value of the resistance at T=0 ^{o}C, and α is a constant

Thermistor: Data Analysis

- Take a natural logarithm and make a best fit straight line to find coefficients R_0 and α

$$\ln(R) - \ln(R_0) = -\alpha T$$

- Finding Temperature from resistance measurements. Use linear relation

$$T = (\ln(R_0) - \ln(R))/\alpha$$

Mechanical Equivalent of Heat Experiment 1: Power Input

- The power P delivered to the reservoir due to the frictional torque τ between the plastic pot scrubber rotating at an angular frequency ω against a thin metal disk that forms the bottom of the plastic reservoir is

$$P_f = \left(\frac{dW}{dt}\right)_{reservoir} = \tau_f \omega$$

Mechanical Equivalent of Heat Experiment 1: Summary

- Assumption: all the heat generated by the frictional torque flows into the reservoir .So power in equals rate of heat flow

$$\tau_f \omega \propto \left(\frac{dQ}{dt} \right)_{reservoir}$$

Mechanical Equivalent of Heat: Experiment 2

- System: calorimeter, resistor, and thermistor.
- Surroundings: power supply and electrical circuit.
- The power delivered from the electrical power supply to resistor

$$P_{resistor} = \left(\frac{dW}{dt}\right)_{resistor} = \Delta VI$$

- flow of heat from resistor into reservoir,

$$\Delta VI \propto \left(\frac{dQ}{dt}\right)_{reservoir}$$

Heat Capacity of Water

- Assumption: all the heat ΔQ goes into raising the temperature of the water, then the rate of heat flow $\Delta Q/\Delta t$ is proportional to the rate of change of temperature $\Delta T/\Delta t$

$$\left(\frac{dQ}{dt}\right)_{reservoir} = cm\frac{dT}{dt}$$

- where c is the specific heat of water and m is the mass of the water

Calorie

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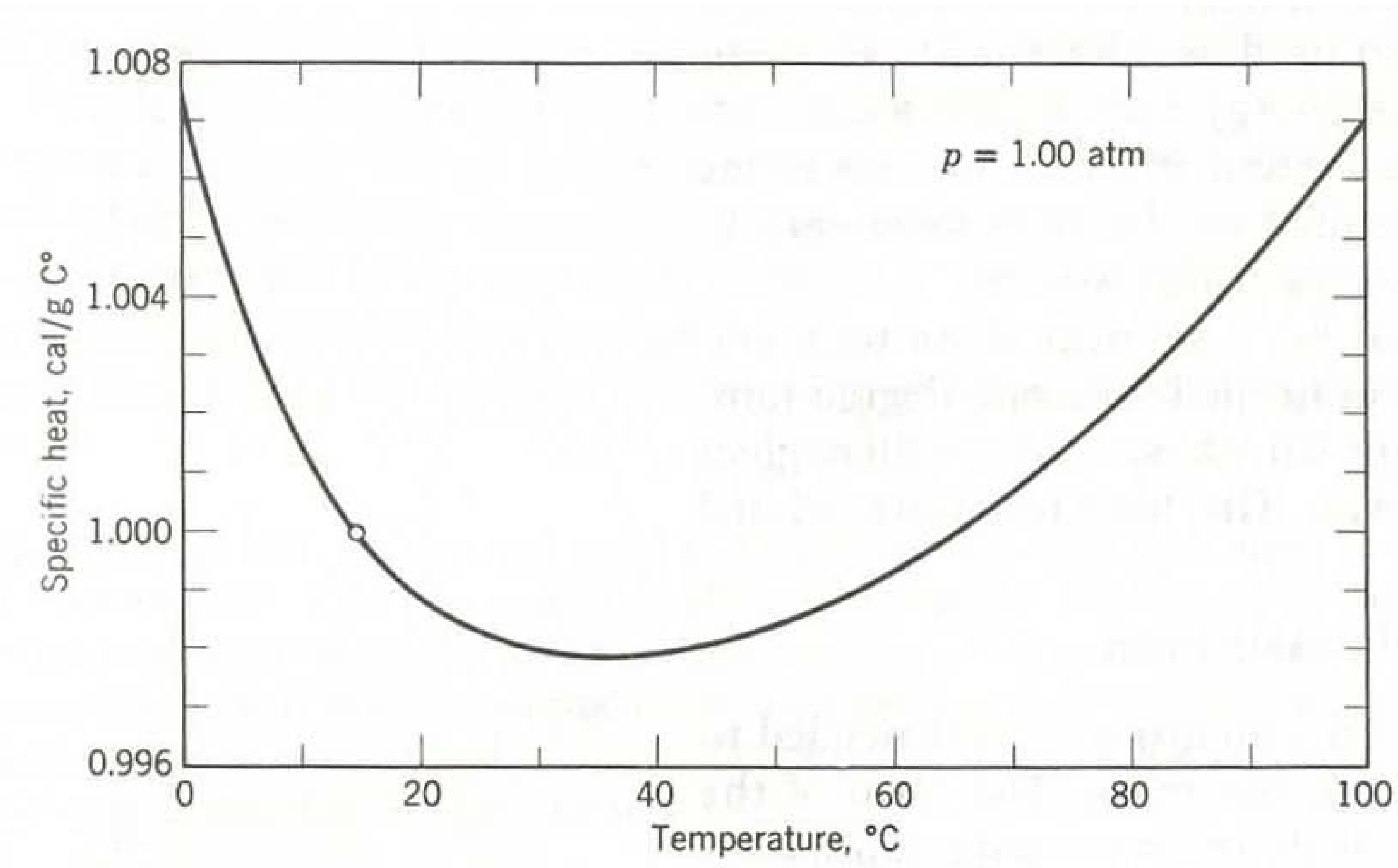

Specific Heat of Water

- For water, the specific heat varies as a function of temperature. For the range 14.5 0 C to 15.5 0 C, the value is

$$c_{H_2O} = 1\,\mathrm{cal} \cdot \mathrm{g}^{-1} \cdot {}^{o}C^{-1}$$

- Note that this defines the calorie

Specific Heat of Water

- Experiment 1:

$$c = \frac{\tau_f \omega}{m\left(dT/dt\right)}$$

- Experiment 2:

$$c = \frac{\Delta VI}{m\left(dT/dt\right)}$$

Mechanical Equivalent of Heat

The rate of loss of mechanical energy, measured in joules, is proportional to the rate of increase in heat, measured in calories

$$\frac{dE_{mech}}{dt} = -k\frac{dQ}{dt}$$

where k is the constant of proportionality

The result at 15^oC is 4.186 J = 1 cal