Heat and Thermal Energy

I. Why Study Heat?

(A) Important to Life

(1) Qualitatively

- Hypothermia

  Physiological activity slows, ceases → Death

- Hyperthermia

  Physiological activity speeds-up
  Enzymes ~~denature~~ → shut-down
  System exhausts resources → Death

- Global Warming

  Change in crop patterns → change in food supply. (Starvation - Abundance ?)

  Global Economy (That means your pocketbook). Mitigation plans will certainly affect your pocket (negatively). How good is the data? How much are you willing to spend?

(2) Quantitatively

- Understanding **Controlled Hypothermia** allows for extended operating times (e.g., Heart-Lung transplants.)

  Need to really understand heat loss/gain to keep your patient's whole body alive.

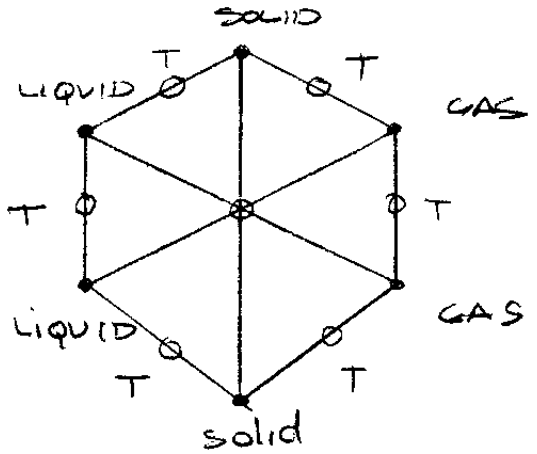
HEAT AND THERMAL ENERGY

II. HEAT AND TEMPERATURE

(A) Historically

(1) 17th - 18th cy.

- So now we have all these handy Thermometers going-around. Curious people everywhere sticking them into Things and noting that everything has some sort of affect on temperature.
- Whatever temperature is a measure of its obviously Universal.
  - Warm-blooded organisms (humans, rats) have different, but standard Temperatures.
  - Cold-blooded organisms are found to live within certain ranges of temperatures.
  - Nonliving matter is found to exist over widely-varying ranges of temperatures, the limits being peculiar to the matter.
- Doesn't take long to notice that solids, liquids, and gases at different temperatures, brought-together take-on the same temperature.



Heat and Thermal Energy

(B) "Common Bond" between Solids, Liquids, Gases and Temperature. In all cases, it is found that:

- Hotter substance cools; Cooler substance warms
  - This observation is independent of the substances or how much of them one has.
- Final Temperature is <u>between</u> the hottest and coldest temperatures.
  - This observation also independent of the substances and their amounts.
- The actual value of the final temp. depends on the types of substances involved and how much of each one has.
- (Note; we must obviously restrict that no <u>chemical</u> reactions are taking place. Various substances at the same temperatures can be brought together in endothermic or exothermic reactions where the final temperature of the system is lower/higher than either initial temp. This is <u>not</u> a violation of the above rules – its just that more is happening than what we now consider.)

(C) We can see what's going on, but <u>why</u>?

- We need to make a simple model and form a theory.

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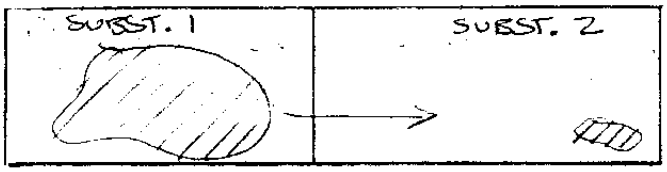
III. QUANTITY OF HEAT

(A) CALORIC THEORY (18TH cy.)

- Must be some sort of <u>material</u> substance that temperature measures the quantity of. Call it <u>Caloric</u>. Additionally caloric must <u>move</u> from hotter things to colder things until it is shared equally among them

(Aside: Compare this idea to social/political environment of the period. Recall also that Alchemy and the search for the "Prime Mover" was not all that old. Newton himself was principally an Alchemist!)



"SPOOKY CALORIC"
Moving from "more" to "less".
T ~ "Caloric"

(B) DEATH OF CALORIC THEORY

- Rumford's Canons (ca. 1798)
  - Caloric appears to be inexhaustable therefore not material.
- Black (ca. 1760)
  - Who cares what it is study what it does to define what it is.
  - Postulate: $\Delta Q \sim m$

$$\Delta Q \sim \Delta T$$

$$\boxed{\Delta Q = c m \Delta T}$$

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- Let "Heat" be that amount of something required to raise a given mass of a substance by 1°C.

For H_2O, let

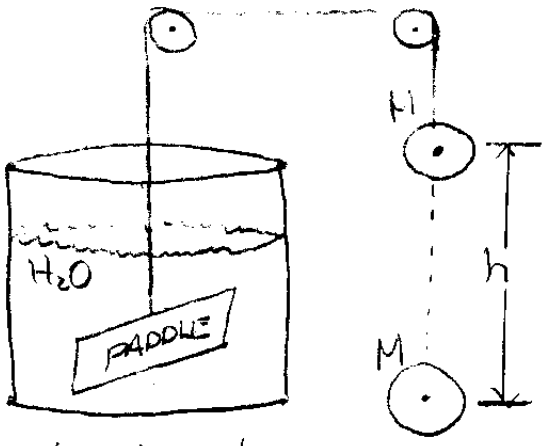
$$c = \frac{\Delta Q}{m\Delta T} = \frac{(\text{amount of heat})}{(1\,g)(1\,^\circ C)}$$

$$\equiv \frac{1 \text{ calorie}}{g \cdot ^\circ C}.$$

- Problem is still: What is ΔQ?

IV. Mechanical Equivalent of Heat

(A) Heat Quantified (Joule, ca. 1840's)



$PE = Mgh = W$ (work)

$(KE) = W$

(Work done by gravity on system) $\longrightarrow$ (Kinetic energy of H_2O)

(1) $\Delta W \rightarrow \Delta KE$

But (2) $\Delta KE \sim \Delta T$

So, (3) $\Delta W \sim \Delta T$

Thus (4) $\Delta Q \sim \Delta W$

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(B) EXPERIMENTALLY, FOR H_2O around 15.0 °C

- $\boxed{1\ cal = 4.186\ J}$

  $\boxed{1\ kcal = 4186\ J}$ $\left(= 1\ Cal \overset{\text{aside:}}{(\text{food calorie})}\right)$

Ex: How much energy must be put into a 200.g sample of H_2O to raise its temperature by 15.°C?

$$c = \frac{\Delta Q}{m\Delta T} = \frac{(\text{amount of heat (energy)})}{(1g)(1°C)}$$

$$= 4.186 \frac{J}{g \cdot C}$$

$m = 200.g \qquad \Delta T = 15.°C$

$$\Delta Q = c\, m\, \Delta T$$

$$= \left(\frac{4.186\ J}{g \cdot C}\right)(200.g)(15°C)$$

$$\boxed{\Delta Q = 1.3 \times 10^4\ J}$$

Heat and Thermal Energy

V.) Conservation of Energy & Closed Systems

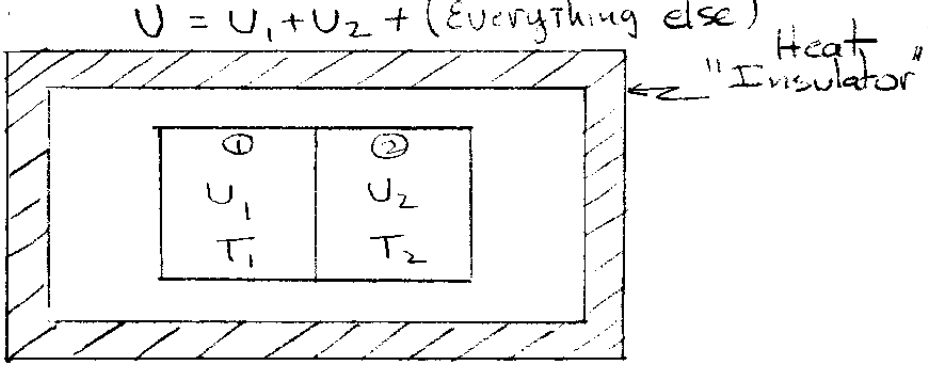
(A) What do we know now?

- Heat *is* energy
- Heat is transferred from hotter to colder objects.
- More heat means higher temperatures
- We can measure how much heat has been transferred by measuring temperature changes

> We don't know how to measure total heat - only how much is transferred from one system (or form) to another.

(B) "Abstacting it all away"

- Don't know the total energy content of the universe or how much of it is contained in each little piece. Don't care, really (we are finite).
- Isolate what you're thinking about



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- Based on everything we've been able to observe so far

> ENERGY IS CONSERVED

i.e.,

> A change in energy of one system can always be accounted for by a change in another system it interacts with.

$$\Delta Q = 0 \qquad \text{(Energy conservation)}$$

Ex: (a) Two systems in thermal contact

$$\Delta Q = \sum_{i=1}^{2} \Delta Q_i = 0$$

$$\Delta Q_1 + \Delta Q_2 = 0$$

(b) Three systems

$$\Delta Q = 0$$

$$\Delta Q_1 + \Delta Q_2 + \Delta Q_3 = 0$$

(c) N- systems

$$\Delta Q = 0$$

$$\Delta Q_1 + \Delta Q_2 + \cdots + \Delta Q_N = 0$$

- Zeroth Law of Thermodynamics

① in thermal equilib w/ ②

② in thermal equilib w/ ③

$\Rightarrow$ ① in thermal equilibw/ ③

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Ex Block of Lead @ $T_{1i} = 100.°C$ in thermal contact with block of Copper @ $T_{2i} = 0.00°C$

① $C_{Pb} = C_1 = 0.13\ J/g\cdot K$ ② $C_{Cu} = C_2 = 0.39\ J/g\cdot K$

$m_1 = 5.00g$ $m_2 = 5.00g$

$T_{1i} = 100.C = 373K$ $T_{2i} = 0.00°C = 273K$

$T_{final} = ?$

(1) $\Sigma \Delta Q = 0$

$\Delta Q_1 + \Delta Q_2 = 0$

$C_1 m_1 \Delta T_1 + C_2 m_2 \Delta T_2 = 0$

(simplifies, since $m_1 = m_2$)

$C_1 \Delta T_1 + C_2 \Delta T_2 = 0$

$C_1 (T - T_{1i}) + C_2 (T - T_{2i}) = 0$

$$T = \frac{C_1 T_{1i} + C_2 T_{2i}}{(C_1 + C_2)}$$

$$T = \frac{(0.13\ J/g\cdot K)(373K) + (0.39\ J/g\cdot K)(273K)}{(0.13\ J/g\cdot K + 0.39\ J/g\cdot K)}$$

$$\boxed{T = 298K \quad (25°C)}$$

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EX: Mix 10.0 g of $H_2O(\ell)$ @ $T_{1i} = 20.^\circ C$
into 100.0 g of $H_2O(\ell)$ @ $T_{2i} = 90.^\circ C$

$T_{final} = ?$

(1) $\sum_i \Delta Q_i = 0$

$\Delta Q_1 + \Delta Q_2 = 0$

$c_1 m_1 \Delta T_1 + c_2 m_2 \Delta T_2 = 0$

(Can simplify, since $c_1 = c_2 = 4.186\ J/g \cdot K$)

$m_1 \Delta T_1 + m_2 \Delta T_2 = 0$

$m_1 (T_{1f} - T_{1i}) + m_2 (T_{2f} - T_{2i}) = 0$

$m_1 (T - T_{1i}) + m_2 (T - T_{2i}) = 0$

$(m_1 + m_2) T = m_1 T_{1i} + m_2 T_{2i}$

$$T = \frac{m_1 T_{1i} + m_2 T_{2i}}{(m_1 + m_2)}$$

$$T = \frac{(10.0g)(293K) + (100.g)(363K)}{(10.0g + 100.g)}$$

$\boxed{T = 357K \quad (84^\circ C)}$

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VI. Range of Validity

- Generally applicable to all solids, liquids or gases as long as they remain completely in the same ~~state~~.
- Phase transitions are special and don't follow $\Delta Q = cm\Delta T$ laws (More next lecture.)
- Conservation of energy is very fundamental, so

$$\Sigma \Delta Q = 0$$

applies no matter what. The functional form of each ΔQ can change depending on the ~~state~~ that the matter is in.