calculus-based physics-2: electricity, magnetism, and thermodynamics (phys180-02): unit 1

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UNIT 0 REVIEW

Physics - $\phi\upsilon\sigma\iota\kappa\acute{\eta}$ - "phusiké": *knowledge of nature*
from $\phi\acute{\upsilon}\sigma\iota\varsigma$ - "phúsis": *nature* **Reading: Chapters 1 and 2 (for Unit 1)**

1. Estimation/Approximation
   - Estimating the correct order of magnitude
   - Building complex quantities
   - Unit analysis
2. Review of concepts from Newtonian mechanics
   - Kinematics and Newton's Laws
   - Work-energy theorem, energy conservation
   - Momentum, conservation of momentum

Two molucules collide elastically. Which of the following is true?

- A: Both potential energy and momentum are conserved for each molecule
- B: Only the momentum is conserved for each molecule
- C: Momentum and kinetic energy are conserved for each molecule
- D: Neither momentum nor energy is conserved for each molecule

Suppose a molecule is headed towards the wall of a container with speed v and mass m. If it collides elastically with the wall and returns in the exact same direction from which it came, what is the change in momentum of the molecule?

- A: mv
- B: $\frac{1}{2}mv^2$
- C: mv^2
- D: $2mv$

Do you remember how to take the derivative of an exponential function? Let $f(t) = \exp(\alpha t)$. What is $f'(t)$?

- A: $\exp(\alpha t)$
- B: $\alpha \exp(\alpha t)$
- C: $\exp(\alpha t)/\alpha$
- D: $\exp(2\alpha t)$

What about multiplying exponentials? What is $f(t)g(t)$, if $f(t) = \exp(\alpha t)$ and $g(t) = \exp(\beta t)$?

- A: $\exp(\alpha\beta t)$
- B: $\exp(\frac{\alpha}{\beta}t)$
- C: $\exp(\frac{\beta}{\alpha}t)$
- D: $\exp((\alpha + \beta)t)$

UNIT 1 SUMMARY

Reading: Chapters 1 and 2

1. Temperature, Heat, and the 0th Law of Thermodynamics
2. Heat flow and transfer mechanisms
3. Kinetic Theory of Gases

JITT - READING QUIZ RESULTS

temperature, heat, and the 0th law of thermodynamics

Figure 1: The zeroeth law of thermodynamics. We need this idea to have a firm understanding of temperature readings, because a **thermometer** is itself a thermal system.

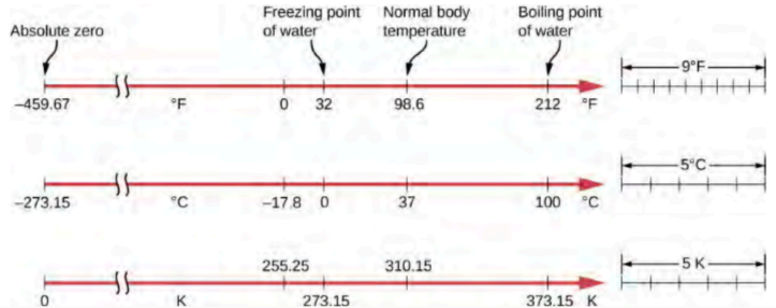

Figure 2: Three temperature scales.

To convert from...	Use this equation...
Celsius to Fahrenheit	$T_F = \frac{9}{5}T_C + 32$
Fahrenheit to Celsius	$T_C = \frac{5}{9}(T_F - 32)$
Celsius to Kelvin	$T_K = T_C + 273.15$
Kelvin to Celsius	$T_C = T_K - 273.15$
Fahrenheit to Kelvin	$T_K = \frac{5}{9}(T_F - 32) + 273.15$
Kelvin to Fahrenheit	$T_F = \frac{9}{5}(T_K - 273.15) + 32$

Figure 3: Three temperature scales. The Fahrenheit scale places 0 for a solution of brine and ice, with 180 degrees between freezing and boiling of water. Celsius scale has 0 for freezing and 100 for boiling. Absolute zero of Kelvin scale will be discussed below.

Suppose the temperature of a system is raised by 10° F. Which of the following is true?

- A: The increase is more than 10 degrees in °C.
- B: The increase is smaller than 10 degrees in °C.
- C: The increase is the same in °C.
- D: Depends on the initial temperature in °F.

Suppose the temperature of a system is raised by 10°C. Which of the following is true?

- A: The increase is more than 10 degrees in °K.
- B: The increase is smaller than 10 degrees in °K.
- C: The increase is the same in °K.
- D: Depends on the initial temperature in °C.

The formula for conversion from Celcius temperature to Fahrenheit temperatures is $T_{\mathrm{F}} = \frac{9}{5}T_{\mathrm{C}} + 32$. Which of the following is true?

- A: $0° - 10°$C is comparable to room temperature
- B: $35° - 40°$C is comparable to human body temperature
- C: $30° - 35°$C is comparable to human body temperature
- D: $15° - 20°$C outdoors would correspond to hot weather

How do thermometers work? What is temperature, really? *Temperature is a macroscopic indication of microscopic kinetic energy*. We need the idea of **thermal expansion**:

$$\frac{dL}{dT} = \alpha L \tag{1}$$

In Eq. 1, T is the temperature, L is the length of an object, and α is the coefficient of linear thermal expansion, in units of inverse degrees.

Material	Coefficient of Linear Expansion $\alpha(1/°C)$
Solids	
Aluminum	25×10^{-6}
Brass	19×10^{-6}
Copper	17×10^{-6}
Gold	14×10^{-6}
Iron or steel	12×10^{-6}
Invar (nickel-iron alloy)	0.9×10^{-6}
Lead	29×10^{-6}
Silver	18×10^{-6}
Glass (ordinary)	9×10^{-6}
Glass (Pyrex®)	3×10^{-6}
Quartz	0.4×10^{-6}
Concrete, brick	$\sim 12 \times 10^{-6}$
Marble (average)	2.5×10^{-6}

Figure 4: Linear thermal expansion coefficients.

$$\frac{dL}{dT} = \alpha L \tag{2}$$

Equation 2 is a differential equation with a particular solution:

$$L(T) = L_0 \exp(\alpha T) \tag{3}$$

We've seen that in practice, α values are small. In this case we may approximate:

$$L(T)/L_0 \approx 1 + \alpha T \tag{4}$$

$$\Delta L \approx \alpha L_0 \Delta T \tag{5}$$

Equation 5 is the equation found in Chapter 1 of the reading.

(a) (b)

Figure 1.5 (a) Thermal expansion joints like these in the (b) Auckland Harbour Bridge in New Zealand allow bridges to change length without buckling. (credit: "ŠJů"/Wikimedia Commons)

Figure 5: Bridge expansion joints.

Chapter 1 also contains these formulae for two and three-dimensional expansion:

$$\Delta A \approx 2\alpha A_0 \Delta T \tag{6}$$

$$\Delta V \approx 3\alpha V_0 \Delta T \tag{7}$$

Why? Properties of exponentials. **Group board exercise**: prove Eq. 7 using Eq. 3.

Pipe Transport: Some oil and gasoline pipelines are above ground, exposed to the elements. The coefficient of thermal volumetric expansion for gasoline is much larger than that of steel. Why would it be a bad idea to completely fill a pipeline with gasoline, knowing there will be large temperature variations?

- A: For large increases in temperature, the pipeline expands more rapidly than gasoline, leaving gaps for leaks.
- B: For large increases in temperature, the gasoline expands more rapidly than the pipeline, building pressure and causing pipeline bursts.
- C: For large decreases in temperature, the gasoline shrinks more rapidly than the pipeline, building pressure and causing pipeline bursts.
- D: None of these.

If an object has a length of 10 cm, and a linear thermal expansion coefficient of 100×10^{-6} 1/°C, what is the change in length of the object if the temperature is increased from 0 °C to 100 °C?

- A: 0.1 mm
- B: 1 mm
- C: 1 cm
- D: 10 cm

Recall from last semester that we studied *stress* and *strain*:

$$\frac{F}{A} = Y\frac{\Delta L}{L} \tag{8}$$

$$stress = Y \times strain \tag{9}$$

Now we can predict strain from temperature changes, and make statements about the implied *thermal stresses*. This is important for mechanical engineering designs.

$$\frac{F}{A} = Y\alpha\Delta T \tag{10}$$

$$\frac{F}{A} = Y\alpha\Delta T \tag{11}$$

Steel pipeline design: Suppose a steel pipeline ($\alpha = 12 \times 10^{-6}$ 1/°C, $Y = 30 \times 10^{9}$ N/m) is designed and built at temperatures of 30 °C, but experiences temperatures of 0 °C. What stress does the pipeline experience at the attachment point?

- A: 0.1 MPa
- B: 1 MPa
- C: 10 MPa
- D: 100 MPa

Is the pipeline pulling or pushing on the attachment point?

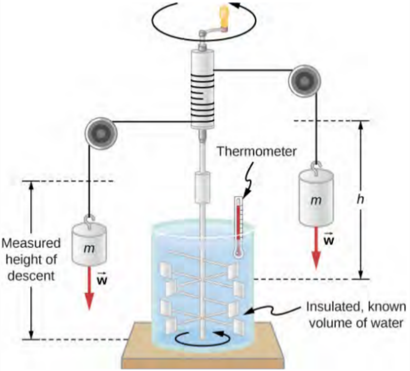

Figure 6: Demonstrating that work and heat are equivalent (paper topic from last semester).

Which of the following is true, regarding Fig. 6?

- A: The temperature increase is proportional to the decrease in height of the masses.
- B: The temperature increase is proportional to g.
- C: A and B
- D: None of these

Regarding Fig. 6, if total mass is 1.0 kg (two 0.5 kg masses), $g = 10$ m/s^2, and $h = 1$ m, what is the temperature increase in the water?

- A: 10 J
- B: 10 °K
- C: 10 °C
- D: Cannot determine

The heat required to obtain a change in temperature is proportional to the mass of the substance to be heated (obvious if you understand heat to be caused by motions of molecules). The coefficient is called the *specific heat capacity*:

$$Q = mc\Delta T \tag{12}$$

More generally,

$$c = \frac{1}{m}\frac{dQ}{dT} \tag{13}$$

Units: Joules per unit temperature per unit mass (J/(kg C)). 1 *calorie* is the energy required to heat 1 gram of water 1 degree C. For food, 1 kcal = 1 Calorie $\rightarrow$ endless debates about food science...

Substances	Specific Heat (c)	
Solids	$J/kg \cdot °C$	$kcal/kg \cdot °C$ [2]
Aluminum	900	0.215
Asbestos	800	0.19
Concrete, granite (average)	840	0.20
Copper	387	0.0924
Glass	840	0.20
Gold	129	0.0308
Human body (average at $37\,°C$)	3500	0.83
Ice (average, $-50\,°C$ to $0\,°C$)	2090	0.50
Iron, steel	452	0.108
Lead	128	0.0305
Silver	235	0.0562
Wood	1700	0.40
Liquids		
Benzene	1740	0.415
Ethanol	2450	0.586
Glycerin	2410	0.576
Mercury	139	0.0333
Water ($15.0\,°C$)	4186	1.000

Figure 7: Notice how water is on a different scale than most other substances.

A 0.500 kg aluminum pan on a stove and 0.250 L of water in it are heated from 20.0 °C to 80.0 °C. a) How much heat is required? What percentage of the heat is used to raise the temperature of b) the pan and c) the water?

Group board exercise: $c_W = 4186$ J/kg/C and $c_{Al} = 900$ J/kg/C.

For a thermodynamically isolated system, we have

$$Q_{\mathrm{cold}} + Q_{\mathrm{hot}} = 0 \tag{14}$$

That is, if heat is conserved, the heat lost by a hot system is equal and opposite to the heat gained by the cold object. This sort of balancing is known as *calorimetry*.

Es como la palabra “calor” en español: hace calor hoy.

Suppose two systems in contact have the same mass, and are otherwise isolated from other systems. System 1 has a much larger heat capacity than system 2, and they are at different temperatures. Which temperature change is the largest?

- The temperature change corresponding to system 1.
- The temperature change corresponding to system 2.
- The changes corresponding to system 1 and 2 are equal.
- The changes are zero because the total heat is conserved.

Suppose two systems in contact have the same mass, and are otherwise isolated from other systems. System 1 has the same heat capacity than system 2, and they are at different temperatures. Which temperature change is the largest?

- The temperature change corresponding to system 1.
- The temperature change corresponding to system 2.
- The changes corresponding to system 1 and 2 are equal.
- The changes are zero because the total heat is conserved.

The brakes in a car increase in temperature by T when bringing the car to rest from a speed v. How much greater would T be if the car initially had twice the speed? You may assume the car stops fast enough that no heat transfers out of the brakes.

- Higher by a factor of 2
- Higher by a factor of 4
- Same temperature difference (no potential energy change).
- Higher by a factor of 8

The survival situation: Suppose two people (60 kg each) are cuddling to stay warm in a tent because it is cold outside. One person is at 37 Celsius, and the other is at 30 Celsius. What is their final temperature, assuming they are calorimetrically isolated?

Group board exercise: $c_{\mathrm{Human}} = 3500$ J/kg/C.

Hint: We need Eq. 14, but ΔT is a variable and we need to use the heat capacity. Moral of the story: The temperature of one person has to go down so the temperature of the other person can go up.

Bonus problem: Temperature-dependent heat capacities. Repeat Example 1.8 in the text, except substitute NaI (sodium iodide) for NaCl (sodium chloride) and look up the relevant heat capacity functions. Turn this in for +2 bonus points on this week's homework (homeworks are usually out of 10 points).

Materials have four phases, and three are relevant for the classical physics in this course.

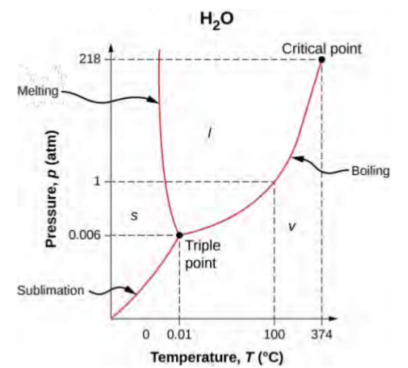

Figure 8: *Phase transitions* occur when crossing the lines. Boiling, melting, and sublimation are the three possible processes.

A pressure cooker contains water and steam in equilibrium at a pressure greater than atmospheric pressure. How does this greater pressure increase cooking speed?

- A: Raises the boiling point
- B: Raises the vapor pressure
- C: Both A and B
- D: Changes the heat capacity of water and steam

Triple point explained:
`https://www.youtube.com/watch?v=MP6MVLWuNZQ`

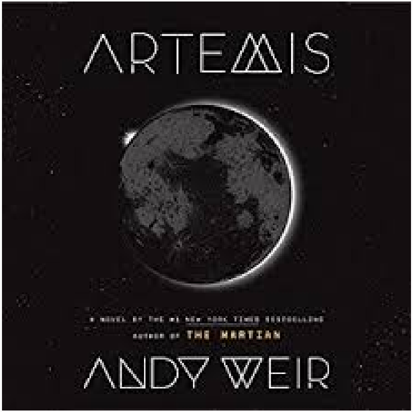

Figure 9: Idea for bonus paper or group project: read *Artemis* by Andy Weir and pick a chapter. Explain each of the statements about surviving on the moon with lower artifical **vapor pressure**, artificial **boiling point**, no atmosphere, and a different g value, etc.

During a phase transition, the temperature of a substance does not change. The heat energy required to drive the phase transition is just proportional to the mass, for liquids and solids:

$$Q = mL_{\mathrm{f}} \tag{15}$$

$$Q = mL_{\mathrm{v}} \tag{16}$$

These coefficients are known as the laten heats of *fusion* and *vaporization*. These numbers have a molecular interpretation.

	L_f			L_v		
Substance	**Melting Point** (°C)	**kJ/kg**	**kcal/kg**	**Boiling Point** (°C)	**kJ/kg**	**kcal/kg**
Helium[2]	−272.2 (0.95 K)	5.23	1.25	−268.9(4.2 K)	20.9	4.99
Hydrogen	−259.3(13.9 K)	58.6	14.0	−252.9(20.2 K)	452	108
Nitrogen	−210.0(63.2 K)	25.5	6.09	−195.8(77.4 K)	201	48.0
Oxygen	−218.8(54.4 K)	13.8	3.30	−183.0(90.2 K)	213	50.9
Ethanol	–114	104	24.9	78.3	854	204
Ammonia	–75	332	79.3	–33.4	1370	327
Mercury	–38.9	11.8	2.82	357	272	65.0
Water	0.00	334	79.8	100.0	2256[3]	539[4]
Sulfur	119	38.1	9.10	444.6	326	77.9
Lead	327	24.5	5.85	1750	871	208
Antimony	631	165	39.4	1440	561	134
Aluminum	660	380	90	2450	11400	2720
Silver	961	88.3	21.1	2193	2336	558

Figure 10: As usual, look at water! (and aluminum).

Three ice cubes are used to chill a soda at 20 °C with mass 0.25 kg. The ice is at 0 °C and each ice cube has a mass of 6.0 g. Assume that the soda is kept in a foam container so that heat loss can be ignored and that the soda has the same specific heat as water. Find the final temperature when all ice has melted. **Group board exercise**: Latent heat of fusion of the ice: 334 kJ/kg, and heat capacity of water: 4186 J/kg/C.

Greenhouse effect as heat transfer problem:
`https://phet.colorado.edu/en/simulation/greenhouse`

- What is the CO_2 concentration in the previous ice age, and what temperature does this allow on the Earth's surface? With clouds?
- Repeat, but with the numbers of today. Add clouds, and repeat. Write down all the temperatures you think are the equilibrium temperatures.
- Open the photon absorption tab. Create three different atmospheres: all methane, all carbon dioxide, and all nitrogen. What happens to the infrared photons in each?

CONCLUSION

Reading: Chapters 1 and 2

1. Temperature, Heat, and the 0th Law of Thermodynamics
2. Heat flow and transfer mechanisms
3. Kinetic Theory of Gases

ANSWERS

ANSWERS

- Momentum and kinetic energy are conserved for each molecule
- $2mv$
- $\alpha \exp(\alpha t)$
- $\exp((\alpha + \beta)t)$
- The increase is smaller than 10 degrees in °C
- The increase is the same in °K
- $35° - 40°$C is comparable to human body temperature
- Answer B
- 1 mm
- 1 MPa
- A and B
- Cannot determine (would have needed the heat capacity of water)
- The temperature change corresponding to system 2
- The changes corresponding to system 1 and 2 are equal
- Higher by a factor of 4
- Both A and B