Demo List for Chapter 18

- Matter model using balls & springs
- Brass sphere slightly larger than brass hole
- Bimetallic strips
- Conduction strips to dip into hot cup of water
- Infrared camera with acrylic and copper
- States of Matter Phet: https://clixplatform.tiss.edu/phet/sims/html/states-of-matter/latest/states-of-matter_en.html
- Hot wood, cold metal demo (various materials with thermometers attached)

Chapter 18: Temperature, Heat, & Intro to Thermodynamics

Be careful with these terms. Many have been misused for your whole life (e.g., objects don't *store heat*).
Also, the scientific terms associated with thermodynamics have changed since these terms were first defined.
As such, some of the terms in this chapter imply contradictory units, but we use them anyways.

Thermal Energy E_{int} Units of J	I associate *thermal energy* with *molecular motions* (i.e., translations, rotations, and vibrations). Thermal energy relates to certain types of potential energy associated with the molecules as well. These potential energies relate to chemical bonds, nuclear bonds, & intermolecular forces. For the most part, I want you to think of it this way: **More thermal energy → more molecular motion.**
Temperature T Units of K Units of ℃ Note: 1 K = 1 ℃.	A *measurement* directly related to thermal energy in units of K = kelvin. **More temperature → more thermal energy → more molecular motion.** Various units you will see: • Kelvin Scale – do <u>not</u> say <u>degrees</u> kelvin, just say kelvin. Get used to it. • Celsius Scale – say degree Celsius (℃) • Fahrenheit – say degree Fahrenheit (°F), technically should be pronounced <u>FAR</u>-EN-HEIGHT • Rankine scale – say "degree Rankine (°R)" not "Rankine (R)", pronounced RANG-KIN. Kelvin the name versus kelvin the unit: you should *capitalize the name but not the unit*. The same is true for Newton versus newtons, Joule versus joule, & Watt versus watts. Exceptions: we write "degree Celsius" <u>not</u> "degree celsius". While debated online to no end, most resources I saw indicate one should also write "degree Rankine". At one time temperature *differences* used "Celsius degree" instead of "degree Celsius". It is my understanding that this isn't true anymore (but I honestly just don't care about this distinction).
Heat Q Units of J	*Heat is a transfer of energy* from one object to another. **Heat an object → Change that object's E_{int} → change that object's T** Objects do NOT store heat; they store internal energy. In equations, Q can be positive *or negative*. When you add negative heat to an object, it cools down (T & E_{int} decrease). In some resources you may see the phrase "*heat flow*" in lieu of heat. In most resources I looked at, *heat flow* was defined as heat per unit area per unit time in units of $\frac{\text{Watts}}{\text{m}^2}$ while the vector quantity "*heat flux*" had the same units but included transfer direction.

Calorie (Cal) versus calorie (cal) versus joule (J)

In 1975, Gerald Ford signed into law the Metric Conversion Act of 1975.
Unfortunately, we still label our food in Calories (most countries in the world use kJ).
Even worse, our food Calories (big C) differs from the outdated physics unit of calories (little c).
If using Calories, I try to remember to clarify what I mean by saying "food Calories" or "big C Calories".

$$1 \text{ Cal} = 1000 \text{ cal} = 1 \text{ kcal} = 4.184 \text{ kJ}$$

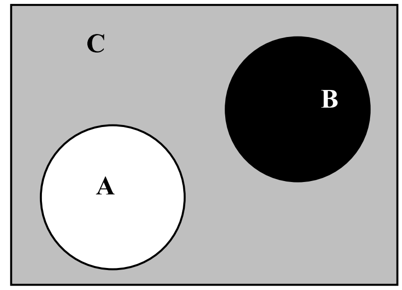
$$1 \text{ cal} = 4.184 \text{ J}$$

To space or not to space before ℃?

Many publishers do *not* use a space before the degree symbol when expressing temperatures (20.0℃).
NIST & ASTM International require the space (20.0 ℃). **I include the space but don't care which style you use.**
Note: everyone agrees you never include the space when describing angles (not temperatures).

Thermal Contact

Consider three objects (**A**, **B**, & **C**) in good *thermal contact*.
Good thermal contact implies the objects can easily exchange heat.



Assume object **C** is a pot of boiling water.
Object **A** is a piece of metal & object **B** is a temperature probe.
The water (**C**) is constantly touching **A** & **B**.
We say **C** is in good thermal contact with both **A** & **B**.

Example of *weak* thermal contact:
Water in an insulated water bottle is NOT in good thermal contact with air outside the bottle.
The point of insulating the bottle is to decrease thermal contact so hot water stays hot (or cold water stays cold).
When thermal contact is weak, it takes a long time for heat to transfer between objects.

Thermal Equilibrium

When two objects are at the same temperature, we say they are in thermal equilibrium.
Two objects are in thermal equilibrium if there is no NET transfer of thermal energy (no NET heat transferred).
Be careful: strictly speaking this does <u>not</u> mean zero heat transfers between the objects.
It means object 1 is transfers the same heat to object 2 as object 2 is transfers to object 1.

Zeroth Law of Thermodynamics

If object **A** is in thermal equilibrium with object **C**
AND object **B** is in thermal equilibrium with object **C**
THEN Object **A** and **B** are in thermal equilibrium.

Again, assume object **C** is boiling water, object **A** is a piece of metal, & object **B** is a temperature probe.
The zeroth law says the temperature of the water equals the temperature of the piece of metal in thermal equilibrium.

Historical note on the name:
At first glance this may seem incredibly obvious and pointless to say.
Nevertheless, this law was overlooked until after the 1^{st}, 2^{nd}, & 3^{rd} laws of thermodynamics were discovered.
The zeroth law establishes temperature as a fundamental property of matter that is measurable.
Because this is so fundamental, it gets first place in the list of thermodynamic laws.

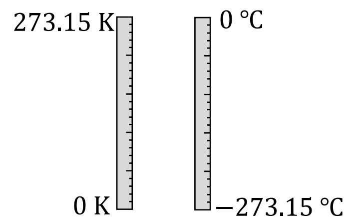
Temperature Scales

The Kelvin scale is the most fundamental scale.
Equations involving T imply units of kelvin (K) unless otherwise specified.
In the Kelvin scale, *absolute zero* is the lowest possible temperature for everything.
There are no negative temperatures on the Kelvin scale.

The Celsius scale is convenient in many applications.
0 °C corresponds to the temperature at which water freezes (at standard atmospheric pressure $P_0 = 1.013 \times 10^5$ Pa).
100 °C corresponds to the temperature at which water boils (at standard atmospheric pressure).

Kelvin Scale	Celsius Scale
The Kelvin scale is the most fundamental scale. Assume equations involving T use units of kelvin (K). *Absolute zero* (0 K) is the lowest possible temperature. Negative temperatures do not exist on the Kelvin scale.	Water freezes at 0 °C at standard atmospheric pressure. Water boils at 100 °C at standard atmospheric pressure. Standard atmospheric pressure = $P_0 = 1.013 \times 10^5$ Pa

Derive Conversion Equations between Temperature Scales.



This skill may come in handy when deriving your own conversions to speed up work.
Assume a linear relationship between the scales.

$$T_C = c_1 T + c_2$$

Here T_C is temperature in °C while T is temperature in K.
Use 2 data points from each scale to set up a system of equations to find c_1 & c_2.

$$-273.15\ ^\circ\text{C} = c_1(0) + c_2 \quad \rightarrow \quad c_2 = -273.15\ ^\circ\text{C}$$

$$0\ ^\circ\text{C} = c_1(273.15\text{ K}) + c_2 \quad \rightarrow \quad c_1 = -\frac{c_2}{273.15\text{ K}} = 1\frac{^\circ\text{C}}{\text{K}}$$

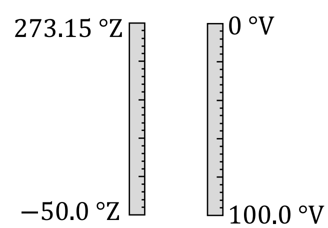
Since an 1 K = 1 °C by definition (original way Kelvin scale increment size was defined) we let $c_1 = 1$.
Putting all this together gives

$$T_C = T - 273.15\ ^\circ\text{C}$$

18.1 We know water freezes at 32 °F and boils at 212 °F. We also know water freezes at 0 °C and boils at 100 °C. Derive a conversion from temperature on the Fahrenheit scale to temperature on the Celsius scale.

18.2 The Rankine temperature scale assumes absolute zero is 0 °R while using the same increment size as the Fahrenheit scale. Derive a conversion from temperature on the Rankine scale to the Celsius scale.

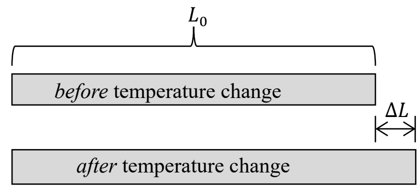
18.3 Two (fictitious) temperature scales are linearly related.
On the Vampire scale, water boils at 0 °V while water freezes at 100.0 °V.
Believe it or not, this matches the scale originally proposed by Celsius!
On the Zombie scale, water freezes at −50.0 °Z and boils at +175.0 °Z.



Derive a conversion equation from the Zombie scale to the Vampire scale.
Properly track sig figs for this problem. Assume 0 °V has infinite sig figs.

Thermal Expansion

Linear expansion occurs for 1D-objects (i.e., a wire or thin rod).



$$\Delta L = L_0 \alpha \Delta T \quad \rightarrow \quad L_{after\ expansion} = L_0(1 + \alpha \Delta T)$$

The parameter α is called the *coefficient of linear expansion*.

Things to note about linear thermal expansion:

1) Think: a *change* of 1.00 K is *by definition* equal to a *change* of 1.00 ℃.
   Because the equation uses ΔT, you can use either K or ℃.
2) The numbers are TINY (notice that 10^{-6} in the units).
   For small objects, you need big ΔT's to have significant ΔL.
3) We see ΔL scales with length L_0.
   If L_0 is big (e.g., railroad tracks), small ΔT's can cause big problems.
4) The exact type of metal (i.e., 3003 vs. 6061 Aluminum) as well as the temperature range used during expansion affect the value of α.
   The values of α vary depending on which resource you read.
   Don't stress on this right now…focus on the concept.
5) The value of α for every material varies a little bit with temperature.
   You might realize this means thermal expansion is actually *non-linear*.
   Fortunately, the non-linearity is usually unimportant unless you have *enormous* ΔT's.

Substance	$\boldsymbol{\alpha}\left(\frac{\mathbf{10^{-6}}}{℃}\right)$ **valid for $T \approx 20$ ℃**
Aluminum	24 (or 23)
Brass	19
Concrete	12
Copper	17
Diamond	1.2
Fused quartz	0.59 (or 0.5)
Glass (ordinary)	9
Glass (Pyrex)	4 (or 3.2)
Gold	14
Iron	12
Lead	29
Silver	18
Steel	11
Ice (at 0 ℃)	51

I compiled these values from Halliday & Resnick and HyperPhysics. The numbers in parentheses indicate instances where these two resources had different values.

If you were doing extremely important work which requires extreme precision, you would probably request material data sheets with linear expansion coefficients from the vendor.

Volume expansion occurs in a similar manner to *linear expansion*.

$$\Delta V = V_0 \beta \Delta T$$

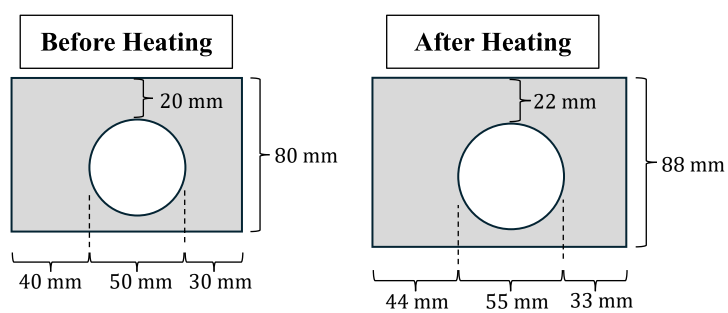
Here β is called the coefficient of volume expansion.
For liquids you can look up tables of β. For solids use

$$\beta = 3\alpha$$

Area expansion is given by the following formula. The factor 2 is explained in problem **18.8**.

$$\Delta A = A_0(2\alpha)\Delta T$$

Holes in a material also expand:
When an object undergoes thermal expansion,
all dimensions expand at the same rate.
This applies to the dimensions of holes cut in the object as well!!!

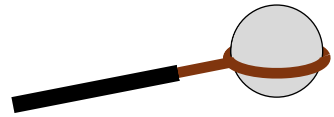


A 10% expansion is completely absurd. I used this absurdly large increase to make it easy to see the math.

Weird Exception for H_2O

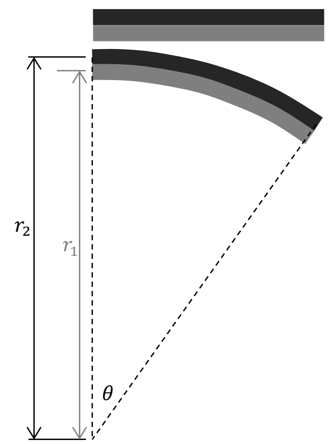
Water is a very special thermodynamic material in several ways.
One way it is special: Between 0 ℃ and approximately 4 ℃ water *contracts* (negative expansion) when heated.
This implies the value of β is negative for water in that very limited temperature range.
As a result, very cold water is slightly *more dense* than ice…thus ice forms on the *top* of lakes instead of the bottom.

18.4 A brass sphere has diameter 23.6 mm at the typical room temperature of 20.0 °C. A brass ring just large enough to pass over the sphere has an inner diameter 23.9 mm. The brass sphere is heated until its diameter matches the inner diameter of the ring. At this point, it can no longer fit through the hole. The density of brass used for both parts is $8.64 \frac{\text{g}}{\text{cm}^3}$ at room temperature.



a) Determine the mass of the brass sphere.
b) At what temperature will the brass sphere no longer fit through the ring?
c) Determine density of the brass sphere at the temperature found in part b. Use these values to determine the percent change in density from room temperature. In your opinion, is it reasonable to assume density is constant even though the volume expands?
d) Once the sphere has heated well beyond the minimum temperature found in part a, the sphere is placed on top of the ring as shown at right. The ring will heat up and the sphere will cool slightly. What happens to the inner diameter of the ring while this occurs? Does the inner diameter increase or decrease?

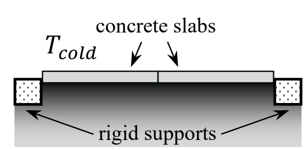
18.5 A bimetallic strip is created from two ribbons of brass and steel with length L_0 at room temperature of 20.0 °C (*upper* figure at right). When the bimetallic strip's temperature is increased by ΔT, it curves as shown in the *lower* figure at right. At this temperature, both r_1 & r_2 are known.

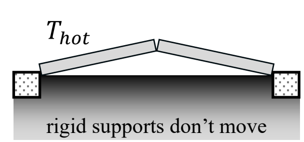


a) Which strip is steel: the upper strip or the lower strip? Explain your reasoning.
b) Determine the bending angle θ in terms of $\Delta r = r_2 - r_1, L_0, \Delta T, \alpha_{Steel}, \& \ \alpha_{Brass}$.
c) How would this problem change if the bimetallic strip was *cooled* instead of heated? Would your result from the previous step still be valid?

18.6 A 55-gallon steel tank is filled to the brim with mercury at 20.0 °C. Through web research you discover the *volume* expansion coefficient for mercury is 17 times larger than the *linear* expansion coefficient for steel. How many gallons of mercury will spill out if the temperature increases to 35.0 °C?

18.7 Imagine two concrete slabs, each length d, laid end to end on the ground. The slabs are installed to just barely fit between two rigid supports shown at the left and right ends of the slabs in a lab when T_{cold}. Later, the air conditioning in the lab fails and the temperature rises to T_{hot}. Assume the rigid supports were installed in such a way that they cannot move. As a result, the two slabs of concrete buckle upwards as shown.

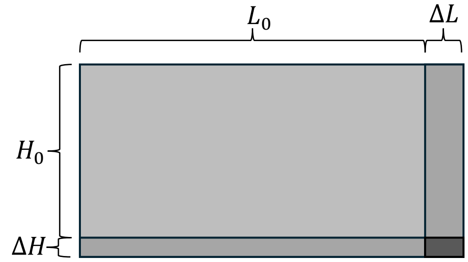




a) Determine the height of the air gap created at the center of the two slabs.
b) Get a numerical result assuming $d = 4.44\text{ m}, T_{cold} = 10.0\text{ °C}, \& \ T_{hot} = 40.0\text{ °C}$.

18.8 Consider a rectangular plate of length L_0 and height H_0 with linear expansion coefficient α. The plate is heated, causing an increase in temperature of ΔT.

a) Determine an exact expression for the *change* in area after the temperature increases. Answer in terms of $L_0, H_0, \alpha, \& \Delta T$.
b) Compare your previous result to $\Delta A = A_0(2\alpha)\Delta T = 2L_0H_0\alpha\Delta T$. Is the exact result from part a larger or smaller than this expression?
c) Explain why the discrepancy between the result of part a) and the expression from part b) is negligible for most materials.



18.9 Just as aluminum, brass, and steel come in many forms, so too does glass. Compare the linear expansion coefficients of ordinary glass and Pyrex.

a) Considering only thermal expansion characteristics, which glass would be better suited for creating mirrors to be used in astronomy applications. Explain why.
b) Now think about using fused quartz instead of Pyrex. You may find it interesting to research the story of George Hale building a mirror for the telescope in the Palomar Observatory around 1936…

18.9½ The equation $\Delta L = L_i\alpha\Delta T$ is a great approximation when $\alpha\Delta T$ is small. Here $L_i = L_0$ is initial length. A more general expression for the change in length can be found by integrating

$$dL = L\alpha\, dT$$

In this formula, L is the length at temperature T…not L_i! Notice dL grows faster as the object grows.

a) Determine the exact expression for ΔL assuming α is constant.
b) Determine the percent difference of the approximation from the exact expression for a 50.0 cm piece of copper raised by $100\underline{0}$ °C. See what you think about the quality of the approximation…

Solids & Liquids Absorbing Heat
Definitions in this chapter can be frustrating for students.
Notice the following terms all include the term "heat" even though none of them have units of J!
This choice of wording is a holdover from terms used during early experiments.
You are expected to know these terms *relate* to heat but are not actually measured in the same units as heat.
We'll cover gases (which are more complicated) immediately following this discussion of solids and liquids.

***Specific* Heat** $c = \frac{1}{m} \cdot \frac{dQ}{dT}$	$\frac{\text{J}}{\text{kg} \cdot \text{K}}$ $\frac{\text{J}}{\text{kg} \cdot {}^\circ\text{C}}$	Heat required to raise the temperature of <u>1 kg of material</u> by $1\text{ K} = 1\ {}^\circ\text{C}$. Notice we use a <u>lowercase</u> c. In general, this is affected by experimental conditions (temperature, pressure, if enclosed in constant volume, etc.). In *most* cases, when c is approximately constant, this goes to $Q = mc\Delta T$ as mentioned at the bottom of the page. Use the context of the question to determine if c means specific heat, speed of sound, or speed of light.
Heat *Capacity* $C = mc$	$\frac{\text{J}}{\text{K}} = \frac{\text{J}}{{}^\circ\text{C}}$	Heat required to raise the temperature of <u>*an object*</u> by $1\text{ K} = 1\ {}^\circ\text{C}$. Notice we use a <u>CAPITAL</u> C. In general, this is affected by experimental conditions (temperature, pressure, if enclosed in constant volume, etc.).
Specific *Latent* Heat L (aka heat of transformation)	$\frac{\text{J}}{\text{kg}}$ *or* $\frac{\text{J}}{\text{mol}}$	Energy (per unit mass) required to cause a phase change (i.e., melt ice, condense gas to liquid). This is a total misnomer since L's represent *heat required* <u>*per unit mass*</u>. The word latent is derived from a Latin word meaning "to lie hidden". While melting a block of ice, you won't register a ΔT. In this sense, ΔE_{int} is latent (hidden). **Use subscripts on *L* to indicate the type of state change.** For example, we use L_f = latent heat of fusion for melting/freezing problems. We use L_v = latent heat of vaporization for boiling/condensing problems. Carbon dioxide has latent heat associated with sublimation from solid to gas ($32.3\ \frac{\text{kJ}}{\text{mol}}$)!

$Q = mc\Delta T = C\Delta T$	Heat (Q) can be positive or negative. Negative heat corresponds to a temperature decrease ($\Delta T < 0$). Check the units in a problem to figure out if you should use c or C!
$Q = \pm mL$	Use this equation when materials change state. Determine the sign by thinking about the type of phase change. For example, to melt ice $Q = +m_{ice}L_f$
1 food Calorie = 1 Cal = 1000 cal = 1 kcal = 4.184 kJ 1 cal = 4.184 J	

Watch out for the units in the tables below. Notice the left table uses J while the right table uses kJ.
In thermodynamics (and science in general), you must constantly pay close attention to units in tables.

Assumes standard atmospheric pressure $P_0 = 1.013 \times 10^5$ Pa = 1 atm		
Substance	**Specific heat** $\left(\frac{\text{J}}{\text{kg} \cdot \text{K}}\right)$	***Molar* specific heat** $\left(\frac{\text{J}}{\text{mol} \cdot \text{K}}\right)$
Aluminum	900	24.3
Brass	380	
Copper	386	24.5
Ethyl alcohol	2400	111
Glass	840	
Gold	126	25.6
Granite	790	
Ice (at -10 °C)	2200	36.9
Lead	128	26.4
Mercury	140	28.3
Silver	235	24.9
Steam (at 110 °C)	2100	35.2
Tungsten	134	24.8
Water	4186*	75.2
Zinc	387	25.2

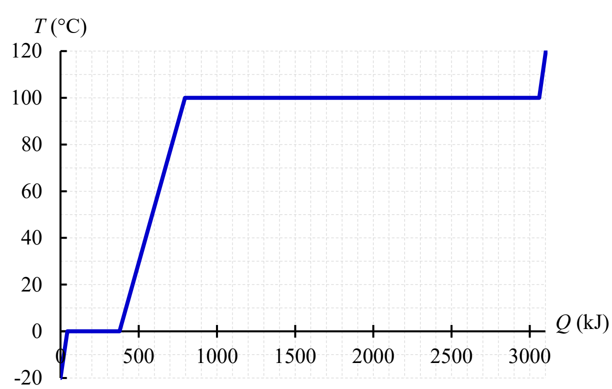
	Assumes standard atmospheric pressure $P_0 = 1.013 \times 10^5$ Pa = 1 atm			
	Melting		Boiling	
Substance	$T_{melting}$ (°C)	$L_f \left(\frac{\text{kJ}}{\text{kg}}\right)$	$T_{boiling}$ (°C)	$L_v \left(\frac{\text{kJ}}{\text{kg}}\right)$
Aluminum	660	380	2450	2720
Copper	1083	134	2595	5069
Ethyl alcohol	-114	104	78.3	854
Gold	1063	64.5	2660	1578
Hydrogen	-259.3	58.6	-252.9	452
Lead	327	24.5	1750	871
Mercury	-38.9	11.8	357	272
Nitrogen	-210	25.5	-195.8	199
Oxygen	-218.8	13.8	-183.0	213
Silver	961	88.3	2193	2336
Water	0.00	334	100.0	2256

*In many resources you may see 4184 or 4187. The value listed is for warming water from 14.5 °C to 15.5 °C. Don't stress on the 4th sig fig!
Don't forget, **ALL** of these numbers change as conditions change & every resource may use different values.
If precision is required, get reputable material data sheets. Otherwise, these values are adequate for getting decent ballpark estimates.

Specific Heats of Gases

Except for steam, notice the substances in the specific heat table are solids or liquids.
For gases, specific heat differs if the experiment is done *at constant pressure* (c_p) or *at constant volume* (c_v).
For example: one resource stated steam (water vapor) has $c_p \approx 2100 \frac{\text{J}}{\text{kg·K}}$ and $c_v \approx 1600 \frac{\text{J}}{\text{kg·K}}$.
We will discuss gases in depth (in the next chapter) after doing problems involving mainly liquids & solids.

Plots of T vs. Q



The plot at right shows heat added to 1.00 kg of H_2O as it was heated from ice at -20 °C to steam at 120 °C.

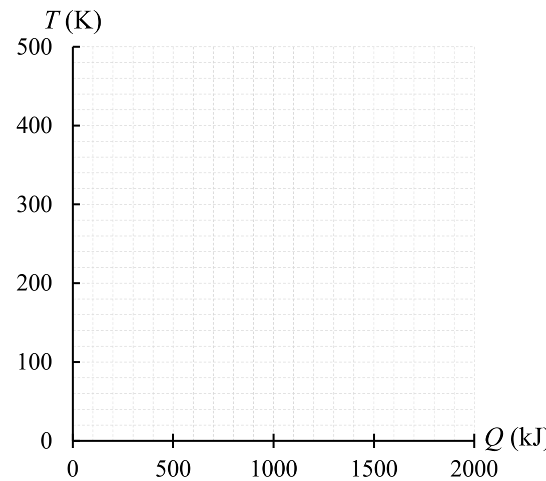
Regions with zero slope correspond to phase changes.
Example: from 44 kJ to 377 kJ the ice is melting.

Regions with non-zero slopes correspond to temperature changes.
From 377 kJ to 795.7 kJ the water warms from 0 °C to 100 °C.
Example: $slope = \frac{rise}{run} = \frac{100\ ^\circ\text{C}}{418.7\ \text{kJ}} = \frac{1}{\text{C}} \rightarrow slope \times mass = \frac{\text{kg·K}}{4.187\ \text{kJ}} = \frac{1}{c}$

Smaller values of c cause steeper slopes (**small c, easy to *change T***).
For objects which are cooled we expect $Q < 0$. Plot $|Q|$ instead of Q.
Plotting temperature versus *time* is more complicated if the rate of heat transfer is not constant.

18.10 Your goal for this problem is to create a plot of T versus Q for a 1.00 kg sample of ethyl alcohol. Assume the sample starts as a solid at $10\underline{0}$ K and we heat it until it is a gas at $50\underline{0}$ K. I looked up some numbers online and estimated $c_{gaseous\ ethyl\ alcohol} \approx 1750 \frac{\text{J}}{\text{kg·K}}$ over the temperature range of interest (very rough estimate). After digging around a bit longer on the internet I found $c_{solid\ ethyl\ alcohol} \approx c_{liquid\ ethyl\ alcohol} = 2400 \frac{\text{J}}{\text{kg·K}}$. These numbers assume the ethyl alcohol is heated while held at constant pressure.

a) Determine the boiling point & melting point temperatures of the sample on the Kelvin scale.
b) Determine the heat required to raise the $10\underline{0}$ K sample to the melting point.
c) Determine the heat required to melt the sample.
d) Determine the heat required to raise the liquid to its boiling point.
e) Determine the heat required to vaporize the liquid.
f) Determine the heat required to raise the temperature of the vapor to the final temperature of 500 K.
g) Use your previous results to sketch the curve for T versus Q on the plot at right.

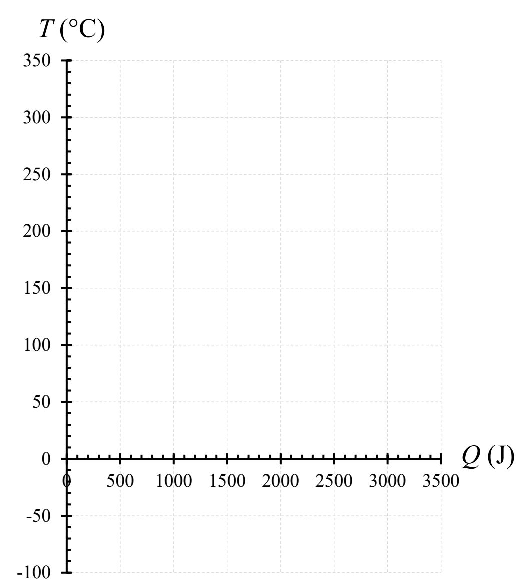


18.11 A sample of a mystery substance has mass 55.5 g at room temperature $(20.0\ °\text{C})$. The sample temperature rises to 44.4 °C when 333 J.

a) Determine the specific heat of the sample.
b) Determine the heat capacity of the sample.

18.12 A 74.5-gram lead mass is dropped onto a 10.00-gram block of ice inside a Styrofoam cooler. Assume the initial lead temperature is 325 °C and the initial ice temperature is -100.00 °C. Because they are sitting inside a cooler, we can assume the two objects reach thermal equilibrium with negligible energy loss to the surroundings.

a) Determine the energy required to cool the lead to the melting point of ice.
b) Determine the energy required to warm the ice to its melting point.
c) Use your previous two results to explain how you can tell at least some of the ice will melt.
d) Determine the energy required to melt *all* the ice.
e) Will the lead transfer enough heat to warm the ice to its melting point AND melt *all* the ice? Explain.
f) Determine the final temperature of the lead and the masses of ice/water present after the system reaches thermal equilibrium.
g) Sketch a plot of T versus Q showing both the lead and the ice/water on the same plot.



18.13 Suppose you could somehow combine 77.7 g of steam at 100.0 °C and some ice (at 0 °C) inside an insulated container. You want the ice & steam to reach thermal equilibrium and form water at 62.5 °C.

a) Determine the required mass of ice.
b) Sketch plot of T versus Q as the two masses come to thermal equilibrium.

18.14 You encounter a situation requiring more precision than normal. You get some material data sheets for a material which indicate the specific heat as a function of temperature is modeled by

$$c(T) = 0.275T + 0.0425T^2$$

Here c is given in units of $\frac{\text{J}}{\text{kg·K}}$ and T is measured using the Kelvin scale.

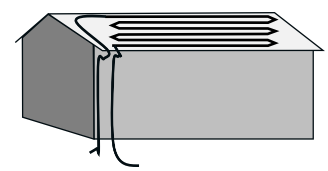
Recall the definition of specific heat is

$$c = \frac{1}{m} \cdot \frac{dQ}{dT}$$

a) Determine the units assumed on 0.275 & 0.0425.
b) Determine the heat required to change 3.33 g of this substance from 24.0 K to 40.0 K.

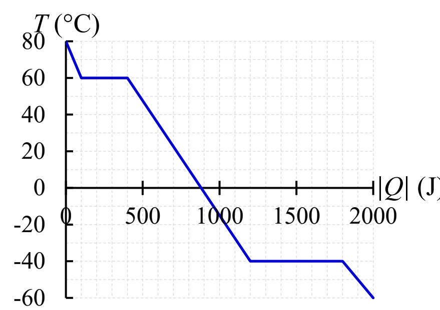
18.15 At the time of writing this question, I read somewhere the best electric tea kettles are about 80% efficient.
Assume this is true for a tea kettle with a power rating of 1500 W.
How long should it take to bring 25$\underline{0}$ g of water from 20.0 °C to boiling?

18.16 *Disclaimer:* When modelling real-life applications, we tend to make a lot of assumptions and expect our final result hopefully the correct order of magnitude.



Passive solar heating can be used to reduce energy consumption.
Consider a long black hose running back and forth on a rooftop.
Assume only the top half of the hose surface area receives incident solar energy.
Assume 15% of incident sunlight energy goes into heating the water in the hose.
Assume sunlight hits the roof with an average intensity of 777 $\frac{\text{W}}{\text{m}^2}$.
We want to increase the temperature of water from 20.0 °C to 45.0 °C in 90.0 min.
Determine the required diameter of hose.

18.17 A 3.33-gram sample of material is initially in the gas phase.
A plot of T versus $|Q|$ is shown for the sample as it cools.

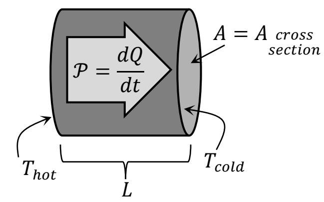
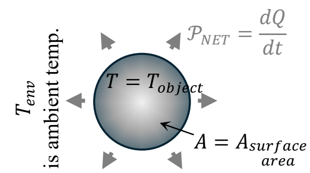
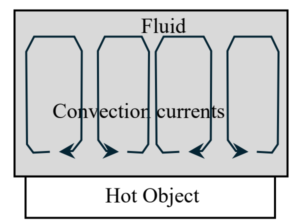


a) Determine specific heat for the gaseous state in units of $\frac{\text{cal}}{\text{g·K}}$.
b) Determine specific heat for the liquid state in units of $\frac{\text{cal}}{\text{g·K}}$.
c) Determine the latent heat of vaporization for this material in units of $\frac{\text{cal}}{\text{g}}$.
d) Determine the latent heat of fusion for this material in units of $\frac{\text{cal}}{\text{g}}$.

18.18 You have 325 g of room temperature (20.0 °C) water in an insulated cup.
You add 22.2 g of ice at −5.00 °C to the cup.

a) Determine the final temperature in thermal equilibrium & how much ice melts.
I have no clue if none of it, some of it, or all of it melts. You must determine that somehow.
b) How would your results change if the cup was not thermally insulated? Explain your reasoning.

Heat Transfer Mechanisms

Conduction	$\mathcal{P}_{delivered} = kA\frac{dT}{dx}$ $\mathcal{P}_{delivered} \approx \frac{kA\Delta T}{L}$ where $\Delta T = T_{hot} - T_{cold}$ "R-value" $= R = \frac{L}{k}$	Applies for two objects touching each other. A = cross-section area at contact point. L = length of material k = thermal conductivity in units $\frac{\text{W}}{\text{m·K}}$ ΔT in eqt'n implies it is ok to use K or ℃	
Radiation	$\mathcal{P}_{radiated} = \sigma A \epsilon T^4$ $\mathcal{P}_{absorbed\ from\ environment} = \sigma A \epsilon T_{env}^4$ $\mathcal{P}_{NET\ emitted} = \sigma A \epsilon (T^4 - T_{env}^4)$	Applies to any object…even in a vacuum! Must use K (don't use ℃). σ = Stefan-Boltzmann constant $\sigma = 5.67 \times 10^{-8} \frac{\text{W}}{\text{m}^2 \cdot \text{K}^4}$ ϵ = emissivity Emissivity is dimensionless between 0 & 1. An ideal blackbody uses 1.	 ϵ between 0 & 1
Convection	Usually handled with coding. No computational questions about convection on the test.	Occurs in fluids. Fluid flow caused by contact with hot object. Fluid flow transfers energy to different parts of fluid…further affecting fluid flow.	

As with pretty much every table of constants for thermodynamics, the following values cannot be trusted for precise calculations. They are fine for estimation problems and for comparing relative values amongst various materials.

Thermal Conductivities

Substance	$k\ \left(\frac{\text{W}}{\text{m} \cdot \text{K}}\right)$
Aluminum	220
Brass	110
Red Brick	0.6
Concrete	0.8
Copper	400
Fiberglass	0.048
Ice @ 0 ℃	2
Lead	35
Silver	420
Glass	1.0
Steel	50
Dry Air @ 20 ℃ Used in multi-pane windows	0.026

Emissivity in Infrared

Substance	ϵ
Aluminum (anodized)	0.77
Aluminum (polished)	0.05
Brass (highly polished)	0.03
Brass (oxidized)	0.61
Copper (polished)	0.05
Copper (oxidized)	0.65
Red Brick	0.90
Glass	0.90
Ice	0.97
Paper (white)	0.68
Paper (white bond)	0.93
Paper (black)	0.90
Cardboard	0.81

R-values In Conduction Problems

R = Thermal Resistance

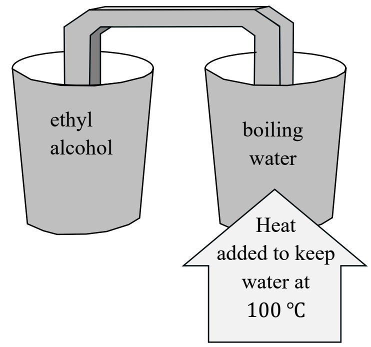
$$R = \frac{L}{k}$$

If you have N slabs with equal cross-sectional areas:

$$\mathcal{P}_{delivered} \approx \frac{A\Delta T}{\sum_{i=0}^{N} \frac{L_i}{k_i}} = \frac{A\Delta T}{\sum_{i=0}^{N} R_i}$$

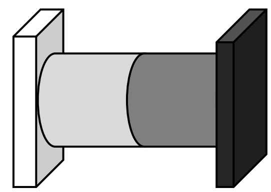
Each slab acts like a resistor opposing the current (heat flow). This is commonly used in determining the insulation required for homes.

18.19 An insulated cup is filled with mass 222 g of ethyl alcohol at 20.0 °C. Nearby we have a boiling pot of water with a heat source. The two containers are placed in thermal contact using an aluminum bar with rectangular cross-section $A = 2.75\ \text{cm}^2$ bent into the shape of an inverted letter U. The system heats the ethyl alcohol to temperature 55.5 °C in 38.5 minutes. While not strictly true, assume heat conducts from the water at constant rate (given by the average temperature difference) with negligible losses.



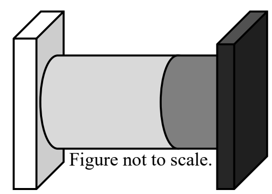
a) How much heat is required to warm the room temperature ethyl alcohol?
b) What is the length of the aluminum rod?
c) Explain how environmental factors which negatively affect our result. To warm the alcohol in 38.5 minutes, what must be true about the *real-world* length of the rod (compared to the result of part b)?
d) **Going further:** determine the *exact* result for the length of the aluminum rod using calculus.

18.20 In the figure for the previous problem I attempted to show a fairly realistic depiction of how a conduction experiment might be designed. For most problems, however, we draw an oversimplified model like the one shown at right. Assume the left slab is a reservoir of ice water. Assume the right slab is a reservoir of boiling water. Connecting the two slabs are two cylindrical pieces of metal with diameter d. The pieces of metal have equal lengths. The left piece of metal is aluminum while the right piece of metal is brass. The system is allowed to reach steady state. Steady state implies the rate of heat conduction has stabilized to a constant value.



a) In steady state, which rod conducts more heat: aluminum or brass? Explain your rationale.
b) Determine the steady state temperature at the junction between the aluminum and brass rods.
c) How would the junction temperature change if we doubled the length of each rod?

18.21 Assume the left slab is a reservoir of ice water. Assume the right slab is a reservoir of boiling water. Connecting the two slabs are two cylindrical pieces of metal with diameter d. Notice one the left metal cylinder is longer than the right metal cylinder. The junction temperature is 50.0 °C in steady state. One cylinder is aluminum while the other is silver.

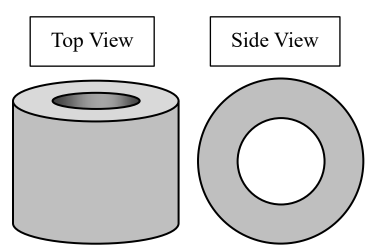


a) Which rod must be longer: the aluminum rod or the silver rod? Explain your rationale.
b) Determine the ratio of the aluminum rod's length to the silver rod's length.

18.22 A large window measuring 0.500 m by 1.00 m is to be installed in a house. On cold winter days, we expect the temperature inside the house to be maintained at 20.0 °C while the temperature outside the house is −10.0 °C. The window could either be single pane 4.00 mm thick or doubled pane (two panes of glass each 4.00 mm thick with an 8.00 mm air gap in between).

a) Determine how much additional heat is lost per day for each type of window.
b) If we spend $\frac{\$0.30}{\text{kW}\cdot\text{hr}}$ to heat the house with electricity, how much money is saved per day using double pane?

18.23 A cylindrical pipe of height H has inner diameter D and outer diameter $2D$. The pipe is filled hot water at T_1 with outer surface temperature T_2. Our goal is to determine the rate at which thermal energy is conducted from the water to the room through the walls of the pipe. Because heat flows *radially outwards*, our conduction equation changes to $\mathcal{P}_{delivered} = kA\frac{dT}{dr}$. Figure not to scale.



a) As heat flows radially outwards, is the cross-sectional area A constant, increasing, or decreasing?
b) Write an expression for the cross-sectional area at some arbitrary radius r.
c) Determine the rate of energy transfer *per unit height* in steady state.

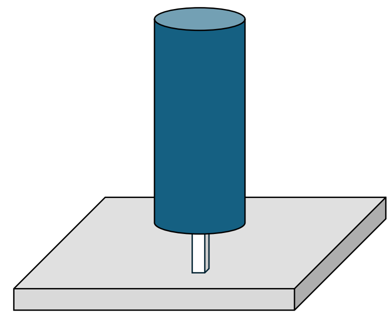
18.24 Fifty students sit in a room at temperature 22 °C. The temperature of a student is about 37 °C. Assume each student has an emissivity of about 0.7 and surface area of about $2.0\ \text{m}^2$.

a) Determine thermal energy per second emitted by a single student.

b) Determine the *net* energy added to the room by all students during a one-hour lecture. For this part, assume the room temperature is maintained at 22 °C using air conditioning.

c) Suppose there is insufficient air conditioning in the room. Does room M311 in August at 2:15 p.m. come to mind? How would *net* energy added to the room by all students be affected over time? Explain your reasoning.

18.24½ A 1.000 kg glass (ordinary) rod has density $2.50\,\frac{\text{g}}{\text{cm}^3}$. The rod was left inside a freezer for several days. At time $t = 0$, the rod is removed from the freezer and balanced atop a tiny pedestal of Styrofoam in a room at 20.0 °C. We are told the combined area of the rod's end caps is half of the area of the rod's sidewalls. Figure not to scale.



a) Determine the radius of the rod.

b) Assume the rod absorbs 666 J of heat (net) during the first 175 s in the room. For now, assume this heat is absorbed at a constant rate with negligible temperature change. Estimate the temperature of freezer.

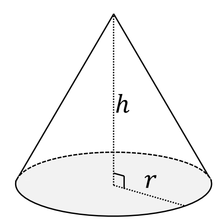
c) Estimate the percent change in length of the rod once it finally reaches room temperature.

d) Discuss with your partners if it is reasonable to assume a constant rate of temperature change.

e) Why did I write those comments about placing the rod on a tiny Styrofoam pedestal? Discuss with your partners at least *two* ways this simplifies the calculations in parts b & c.

f) What if the rod was placed on the table instead. Do you think it would warm up more or less compared to using the tiny Styrofoam pedestal. Note: Styrofoam has a thermal conductivity of about $0.035\,\frac{\text{W}}{\text{m}\cdot\text{K}}$. See if you can give rationale for either way.

18.24¾ A student named Carlos comes to class one day with a deep desire for doing a radiation problem involving a right circular cone. Using a quick web search, he discovers the volume of a right circular cone is $\frac{1}{3}\pi r^2 h$ and the surface area is $\pi r(r+h)$. In these expressions r is the radius of the circular base and h is the cone's height (see figure at right). A cone made of red brick is heated in a kiln to a high temperature then placed on a wire mesh cooling rack in a room at temperature 20.0 °C.



a) How hot must the cone be to assume heat absorbed from the room causes a 1% correction to the initial radiative heat loss?

b) Which of the following best describes the radiative heat loss of the cone over time?

Heat loss rate *Increases* over time	Heat loss rate *constant* over time	Heat loss rate *decreases* over time	Impossible to determine without more info

c) Defend your answer to the previous statement.

d) For fun, contemplate how one might make a cone out of brick (then web search to see if you were correct).

e) Assume $r = h$ for some cone in room at 20.0 °C. The cone is heated to 500 °C and placed on a cooling rack in the room. The cone initially radiates heat 555 J per second. Determine radius.

18.25 *Disclaimer:* this problem was an attempt to get an order of magnitude estimate for temperature change of an asphalt driveway due to radiative cooling. Don't put too much faith in this result (see part c).

An asphalt driveway is 5.55 m long by 6.66 m wide by 77.7 mm thick. The driveway sits in the sun all day, heating up to 50.0 °C. Late in the day, after the sun goes down, the air temperature is 23.4 °C. The emissivity of asphalt is estimated to be 0.9. Assume asphalt has density $2.3\,\frac{\text{g}}{\text{cm}^3}$ and specific heat $900\,\frac{\text{kJ}}{\text{kg}\cdot\text{K}}$.

a) Estimate the net rate at which thermal energy is emitted from the asphalt to the air by radiation.
b) Estimate the temperature change of the asphalt slab after one hour of radiative cooling.
c) Is your previous result an overestimate or an underestimate? Discuss your rationale.
d) **Challenge:** Determine a more precise value using $\mathcal{P} = \frac{dQ}{dt}$.

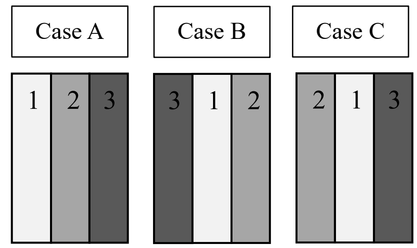
18.26 Assume the average solar intensity reaching the earth's upper atmosphere is $1360\,\frac{\text{W}}{\text{m}^2}$. Assume 30% of the incident energy is reflected while the rest is absorbed by the earth. The earth is approximately a sphere of radius 6.38×10^6 m and mass 5.96×10^{24} kg. The sun is approximately a sphere of radius 6.96×10^8 m and mass 1.99×10^{30} kg. The average earth-to-sun distance is 1.496×10^{11} m.

a) Determine the intensity of light emitted at the *sun's* surface.
b) Assume the sun is a perfect blackbody and the temperature of empty space is about 3 K.
Estimate the temperature of the sun's surface.
Compare this to the stated average surface temperature of the sun you find online (~ 5800 K).
c) One web search I used stated the earth has an average emissivity of about 0.935.
https://terra.nasa.gov/news/aster-global-emissivity-database-100-times-more-detailed-than-its-predecessors retrieved on 05/17/25.
Estimate earth's surface temperature required for thermal equilibrium with absorption from the sun.
For this problem, ignore the greenhouse effect.
WATCH OUT! Light waves from the sun reaching the earth can be modeled as essentially *plane* waves.
Light waves radiated by the earth are *spherical* waves.

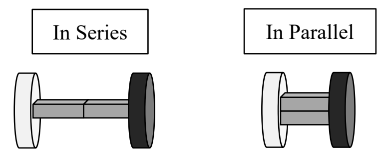
18.27 A sphere of diameter 555 mm and a cube of side length 555 mm are each heated to 200 °C. The sphere and the cube are made of the same material. Which object radiates energy more rapidly? Is it a tie? Explain.

18.28 Consider three slabs of material in thermal contact. In each case, the left slab is in thermal contact with a hot reservoir (hot room) while the right slab is in contact with a cold reservoir (cold outdoor air). The slabs can be arranged in the three possible ways shown at right.
The slabs have thermal conductivities $k_1 < k_2 < k_3$.
Assume each case is in steady state.

a) Rank the cases according to energy transferred in one hour from highest to lowest, clearly indicating any ties.
b) Rank slabs according to temperature difference for Case A.
c) How would your answers to the previous question change if Case B had been used instead?



18.29 Two identical rods have square cross-sections. The rods can either be placed *in series* or *in parallel* to conduct energy between a hot reservoir (temperature T_{hot}) and a cold reservoir (temperature T_{cold}). When placed in series, the rods conduct heat Q in time Δt. How much time is required to conduct the same amount of heat when the rods are in parallel?



18.30 A cylinder of diameter d and length L contains a material with a thermal conductivity which increases according to $k(x) = k_0 e^{\alpha x}$.
The temperature difference between the right and left ends is $\Delta T > 0$.

a) Determine the units appropriate for positive constants k_0 & α.
b) Determine the steady state rate of energy transfer.
c) Imagine starting at the origin and moving to the right.
How far would one need to go to see a temperature difference of $\Delta T/2$?

18.31 A spherical shell of insulating material has inner radius R and outer radius $3R$. The material has thermal conductivity k. The interior of the shell is maintained at temperature T_{max} in units of °C. The exterior of the shell is at 0 °C. The cross-section of the shell at right shows heat flowing radially outwards through an arbitrary slice with radius r and thickness dr.

a) What is the area of the cross-sectional surface through which heat flows?
b) Determine the rate of heat transfer in steady state.
c) In a steady state, what radius has temperature $\frac{T_{max}}{3}$?