Homework Assignment 6

PHYSICS 314 - THERMODYNAMICS & STATISTICAL PHYSICS (Spring 2018)

Due Friday, March 16th, by noon, Noyce 1135

I cannot award full credit for work that I am unable to read or follow. For my benefit and for yours, please:
- o   *Write neatly*
- o   *Show and EXPLAIN all steps*
- o   *Make diagrams large and clearly-labeled*

You are welcome to collaborate with others on this assignment. However, the work you turn in should be your own. Please cite collaborators and outside sources. See the syllabus for details.

Regardless of the number of parts, all homework problems are weighted equally. Regardless of the number of questions, all homework assignments are weighted equally.

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1) **Power Plant Heat Mitigation:** A power plant produces 1 GW of electricity at an efficiency of 40%. (This is typical of a modern coal-fired plant).
   a) At what rate does this plant expel waste heat into its environment?

   40% efficiency means that 40% of the energy is converted to useful work (in this case, in the form of electricity) and 60% of the energy is unusable waste heat. Use this fact and the known useable output to calculate waste heat.

   $$\frac{useable\ energy}{waste\ heat} = \frac{40\%}{60\%} = \frac{1\ GW}{Q_{waste}}$$

   $$Q_{waste} = 1\ GW \frac{60\%}{40\%}$$

   $$Q_{waste} = 1.5\ GW$$

   Alternatively, use the definition of efficiency, recognizing that Q_c is the waste heat. First rewrite the definition using the conservation of energy to replace energy in (Q_h) with energy out ($Q_c + W$).

   $$e = \frac{W}{Q_h} = \frac{W}{Q_c + W}$$

   Solve for Q_c.

   $$Q_c + W = \frac{W}{e}$$

   $$Q_c = \frac{W}{e} - W$$

   Plug in the known values.

   $$Q_c = \frac{1\ GW}{40\%} - 1\ GW$$

$$Q_c = 1.5 \; GW$$

b) Assume that the cold reservoir for this plant is a river whose flow rate is $100 \; m^3/s$. How much will the temperature of the river increase due to this waste heat? *Hint: You will have to look up some properties of water for this problem.*

Find the amount of energy dumped into the river per second.

$$1.5 \; GW \times 1 \; s = 1.5 \; {GJ}/{s} \times 1 \; s = 1.5 \; GJ = 1.5 \times 10^9 \; J$$

To find the amount of water per second, convert the flow rate into a mass flow rate using the density of water.

$$100 \frac{m^3}{s} \times \frac{1000 \; kg}{1 \; m^3} = 10^5 \; kg$$

Divide the amount of energy by the mass to find the energy per kilogram.

$$\frac{1.5 \times 10^9 \; J}{10^5 \; kg} = 1500 \; {J}/{kg}$$

For each kilogram, find the temperature increase by dividing the energy (the heat per unit mass) by the heat capacity of water. (Schroeder 1.41, 1.42)

$$\Delta T = \frac{Q}{C}$$

$$\Delta T = \frac{15{,}000 \; J}{4186 \; {J}/{°C}}$$

$$\Delta T \approx 3.6°C$$

c) To avoid this *thermal pollution* of the river, the plant could instead be cooled by evaporation of river water. (This is more expensive, but it is environmentally preferable in some areas.) At what rate must the water evaporate? What fraction of the river must be evaporated? Assume the water is initially at 25°C.

The heat added to the water per second (found above) must both raise the temperature of the water to its boiling point and then cause the phase change.

$$Q = mc\Delta T + mL$$

Solve for the mass to get the mass that can be raised in temperature and evaporated per second.

$$Q = m(c\Delta T + L)$$

$$m = \frac{Q}{c\Delta T + L}$$

Calculate the temperature change needed to raise the water to its boiling point.

$$\Delta T = 100°C - 25°C = 75°C = 75\ K$$

Plug in the heat per second from earlier in the problem and the heat capacity and latent heat of water.

$$m = \frac{Q}{c\Delta T + L}$$

$$m \approx \frac{1.5 \times 10^9\ J}{\left(4.18\ ^J/_{g\ K}\right)(75\ K) + 2260\ ^J/_g}$$

$$m \approx 5.83 \times 10^5\ g = 583\ kg$$

This is the mass of water evaporated per second. Write this as a rate.

$$583\ ^{kg}/_s$$

Divide the mass evaporated per second by the mass that passes by per second (from above) to get a percentage.

$$\frac{m_{evaporated}}{m_{total}} \approx \frac{583\ kg}{10^5\ kg} \approx 0.58\%$$

2) **Rectangular Heat Engine:** Look back to Schroeder 1.34 (pg. 23), a problem we did in class earlier in the semester. The problem looks at an ideal diatomic gas taken around a rectangular cycle on a P-V diagram. Suppose that this system is used as a heat engine to convert the heat added into mechanical work.
   a) Evaluate the efficiency of this engine for the case that $V_2 = 3V_1$ and $P_2 = 2P_1$.
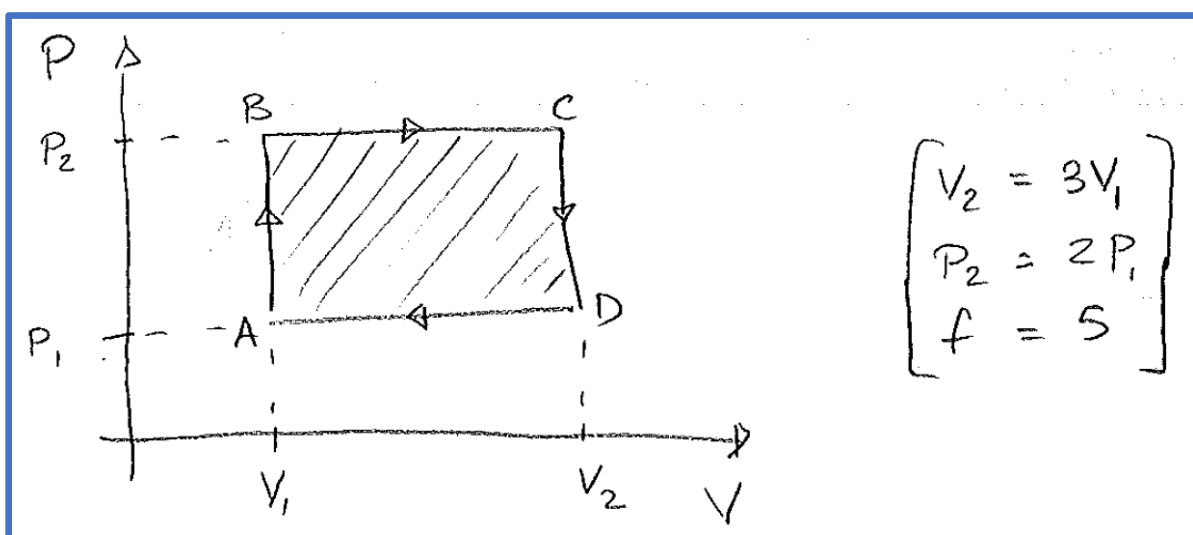
Efficiency is work out per heat added.

First calculate the work done **by** the system over the whole cycle. The work done **by** the system is the area under the curve.

$$W = + \int P dV$$

For the cycle, the net work is the area enclosed by the curve. $B \rightarrow C$ is work done **by** the system, and $D \rightarrow A$ is work done **on** the system. No work is done by the processes at constant volume.

$$W_{net} = \int_B^C P dV - \int_A^D P dV = enclosed\ area$$

Calculate the area of the enclosed rectangle.

$$W_{net} = (V_2 - V_1)(P_2 - P_1)$$

Plug in given values.

$$W_{net} = (3V_1 - V_1)(2P_1 - P_1)$$

$$W_{net} = 2V_1 P_1$$

Now calculate the heat added for each step. For each case, use the First Law.

$$\Delta U = W + Q$$

$$Q = \Delta U - W$$

To calculate the change in energy, use the Equipartition Theorem with $f = 5$ for a diatomic ideal gas.

$$Q = \frac{5}{2} Nk\Delta T - W$$

$$Q = \frac{5}{2}\left(NkT_f - NkT_i\right) - W$$

Use the Ideal Gas Law to rewrite the terms in parentheses in terms of pressure and volume, which can be read from the diagram.

$$Q = \frac{5}{2}\left(P_f V_f - P_i V_i\right) - W$$

In the case considered, the work is either zero (constant volume processes), or it is done at constant pressure, and thus can be written as that constant pressure times the volume change.

$$W_{V\ constant} = 0$$

$$W_{P\ constant} = - \int P dV = -P \int dV = -P(V_f - V_i)$$

Apply these methods to calculate the heat for each of the four processes.

$$Q_{AB} = \frac{5}{2}(P_f V_f - P_i V_i) - W_{AB}$$

$A \rightarrow B$ is a constant volume process.

$$Q_{AB} = \frac{5}{2}(P_f V_f - P_i V_i)$$

Plug in the values.

$$Q_{AB} = \frac{5}{2}(P_2 V_1 - P_1 V_1)$$

$$Q_{AB} = \frac{5}{2}(2P_1 V_1 - P_1 V_1)$$

$$Q_{AB} = \frac{5}{2}P_1 V_1$$

$$Q_{BC} = \frac{5}{2}(P_f V_f - P_i V_i) - W_{BC}$$

$B \rightarrow C$ is a constant pressure process.

$$Q_{BC} = \frac{5}{2}(P_f V_f - P_i V_i) + P(V_f - V_i)$$

$$Q_{BC} = \frac{7}{2}(P_f V_f - P_i V_i)$$

Plug in the values.

$$Q_{BC} = \frac{7}{2}(P_2 V_2 - P_2 V_1)$$

$$Q_{BC} = \frac{7}{2}(2P_1 3V_1 - 2P_1 V_1)$$

$$Q_{BC} = 14 P_1 V_1$$

$$Q_{CD} = \frac{5}{2}(P_f V_f - P_i V_i) - W_{CD}$$

$C \rightarrow D$ is a constant volume process.

$$Q_{CD} = \frac{5}{2}(P_f V_f - P_i V_i)$$

Plug in the values.

$$Q_{CD} = \frac{5}{2}(P_1V_2 - P_2V_2)$$

$$Q_{CD} = \frac{5}{2}(P_13V_1 - 2P_13V_1)$$

$$Q_{CD} = -\frac{15}{2}P_1V_1$$

Note the negative sign. This means that the system gives off heat during this part of the cycle.

$D \rightarrow A$ is a constant pressure process.

$$Q_{DA} = \frac{5}{2}(P_fV_f - P_iV_i) + P(V_f - V_i)$$

$$Q_{DA} = \frac{7}{2}(P_fV_f - P_iV_i)$$

Plug in the values.

$$Q_{DA} = \frac{7}{2}(P_1V_1 - P_1V_2)$$

$$Q_{DA} = \frac{7}{2}(P_1V_1 - P_13V_1)$$

$$Q_{DA} = -7P_1V_1$$

Note the negative sign. This means that the system gives off heat during this part of the cycle.

The relevant heat for calculating the efficiency is the sum of the heat added (the positive quantities).

$$Q_{added} = Q_{AB} + Q_{BC}$$

$$Q_{added} = \frac{5}{2}P_1V_1 + 14P_1V_1$$

$$Q_{added} = 16.5\, P_1V_1$$

Use the calculated net work and the heat added to find the efficiency.

$$e = \frac{W_{net}}{Q_{added}} = \frac{2V_1P_1}{16.5\, P_1V_1} = \frac{2}{16.5} \approx 12\%$$

b) Compare your answer from part a) to the efficiency of an ideal Carnot engine operating between the same temperature extremes.

By the Ideal Gas Law, temperature is proportional to the product of pressure and volume. The extreme temperatures are thus at the extreme values of that product.

$$T_c = \frac{P_1 V_1}{NkT}$$

$$T_h = \frac{P_2 V_2}{NkT} = \frac{2P_1 3V_1}{NkT}$$

$$T_h = 6\frac{P_1 V_1}{NkT} = 6T_c$$

Plug these expressions into the efficiency for a Carnot engine.

$$e = 1 - \frac{T_c}{T_h}$$

$$e = 1 - \frac{T_c}{6T_c}$$

$$e = 1 - \frac{1}{6} \approx 83\%$$

The rectangular engine was significantly less efficient.

$$\frac{e_{Carnot}}{e_{rectangle}} \approx \frac{83\%}{12\%} \approx 6.9$$

The Carnot cycle is about 6.9 times more efficient.

3) **Refrigeration Cycle:** Suppose we have a device that takes n moles of air through the following cycle.

$A \rightarrow B$:   Adiabatic compression where the air is taken from the temperature of the cold reservoir, T_c, and pressure P_2 to temperature T_1 and pressure P_1.

$B \rightarrow C$:   Isobaric cooling to the temperature of the hot reservoir, T_h.

$C \rightarrow D$:   Adiabatic expansion to pressure P_2 to temperature T_2.

$D \rightarrow A$:   Return to the initial state by isobaric heating to the temperature of the temperature of the cold reservoir, T_c.

Assume that air is an ideal gas with (constant) heat capacity at constant pressure C_P and adiabatic exponent γ. Also assume that the ratio of pressures is $\frac{P_1}{P_2} \equiv a > 1$.

a) Sketch the cycle on a P-V diagram.
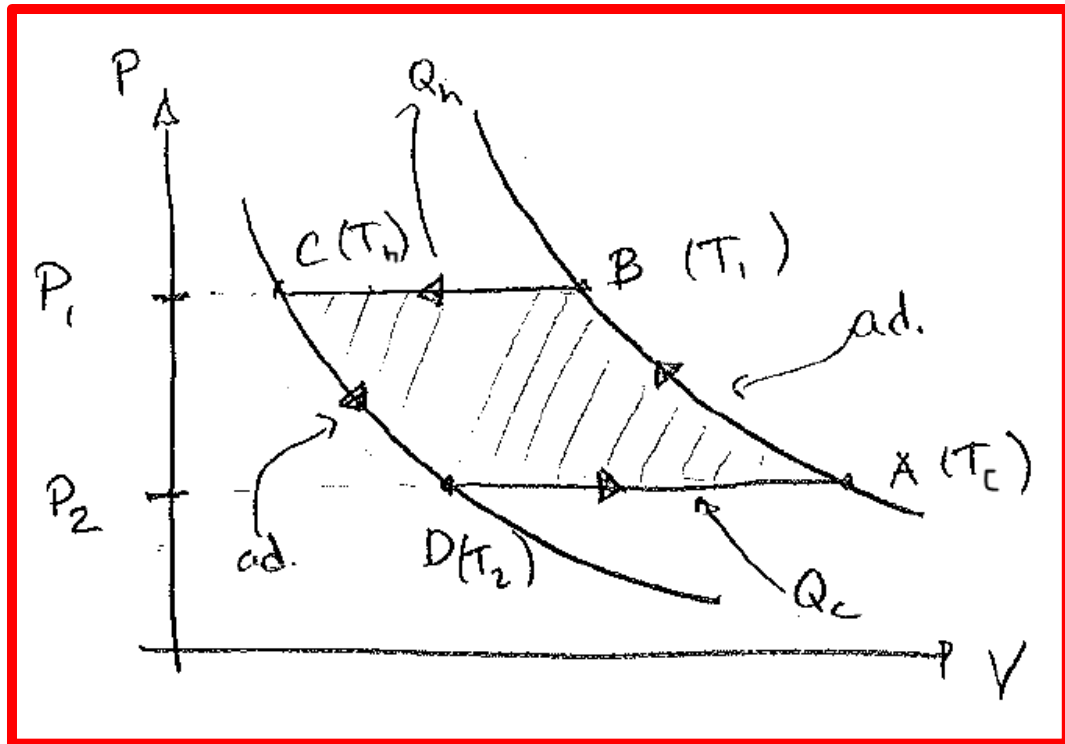
b) Calculate the total work exchanged by the system with the exterior over the course of one cycle, as a function of the temperatures $n, R, f, \ T_c, \ T_h, \ T_1$, and T_2.

For the adiabats, $Q = 0$, and thus by the First Law, the work is equal to the change of energy.

$$\Delta U = W + Q$$

$$W = \Delta U$$

To calculate the change in energy, use the Equipartition Theorem to rewrite in terms of the change in temperature.

$$W = \frac{f}{2} nR\Delta T$$

$$W = \frac{f}{2} nR(T_f - T_i)$$

Apply this to the two adiabats.

$$W_{AB} = \frac{f}{2} nR(T_1 - T_c)$$

$$W_{CD} = \frac{f}{2} nR(T_2 - T_h)$$

For the constant pressure processes, the work can be calculated as in the rectangular cycle problem.

$$W_{P\ constant} = -\int PdV = -P\int dV$$

$$W_{P\ constant} = -PV_f + PV_i$$

Rewrite this in terms of temperature using the Ideal Gas Law.

$$W_{P\ constant} = -nRT_f + nRT_i$$

$$W_{P\ constant} = nR(-T_f + T_i)$$

Apply this to the two constant pressure processes.

$$W_{BC} = nR(-T_h + T_1)$$

$$W_{DA} = nR(-T_c + T_2)$$

Sum the work contributions for all of the sections to get the work of the cycle.

$$W_{cycle} = W_{AB} + W_{BC} + W_{CD} + W_{DA}$$

$$W_{cycle} = \frac{f}{2}nR(T_1 - T_c) + nR(-T_h + T_1) + \frac{f}{2}nR(T_2 - T_h) + nR(-T_c + T_2)$$

$$W_{cycle} = nR\left[\frac{f}{2}(T_1 - T_c) + (-T_h + T_1) + \frac{f}{2}(T_2 - T_h) + (-T_c + T_2)\right]$$

$$W_{cycle} = nR\left(\frac{f}{2} + 1\right)(T_1 + T_2 - T_c - T_h)$$

c) Calculate the coefficient of performance of this cycle in terms of the four temperatures.

The coefficient of performance (COP) is given by the heat extracted from the cold reservoir divided by the work of the cycle.

$$COP = \frac{Q_c}{W_{cycle}}$$

Examine Q_c, the heat transferred during the process $D \rightarrow A$. By the First Law, we can rewrite the heat in terms of the energy change and the work done.

$$Q_c = \Delta U - W_{DA}$$

To calculate the change in energy, use the Equipartition Theorem to rewrite in terms of the change in temperature.

$$Q_c = \frac{f}{2}nR\Delta T - W_{DA}$$

$$Q_c = \frac{f}{2}nR(T_c - T_2) - W_{DA}$$

Plug in the expression for work from part b).

$$Q_c = \frac{f}{2}nR(T_c - T_2) - nR(-T_c + T_2)$$

$$Q_c = \frac{f}{2}nR(T_c - T_2) + nR(T_c - T_2)$$

$$Q_c = \left(\frac{f}{2} + 1\right)nR(T_c - T_2)$$

Use this expression and the expression for the work of the cycle from part b) to calculate the COP.

$$COP = \frac{Q_c}{W_{cycle}}$$

$$COP = \frac{\left(\frac{f}{2} + 1\right)nR(T_c - T_2)}{nR\left(\frac{f}{2} + 1\right)(T_1 + T_2 - T_c - T_h)}$$

$$COP = \frac{T_c - T_2}{T_1 + T_2 - T_c - T_h}$$

d) Calculate T_1 and T_2 in terms of T_c, T_h, a, and γ.

Examine a generic adiabat with endpoints x and z. Recall that for adiabats, $P^{1-\gamma}T^\gamma$ is constant.

$$P_x^{1-\gamma}T_x^\gamma = P_z^{1-\gamma}T_z^\gamma$$

Solve for T_z.

$$T_z^\gamma = \frac{P_x^{1-\gamma}T_x^\gamma}{P_z^{1-\gamma}}$$

$$T_z = T_x\left(\frac{P_x}{P_z}\right)^{\frac{1-\gamma}{\gamma}}$$

Apply this to adiabat $A \rightarrow B$.

$$T_1 = T_c\left(\frac{P_2}{P_1}\right)^{\frac{1-\gamma}{\gamma}}$$

Use the definition of a for the pressure ratio.

$$T_1 = T_c \left(\frac{1}{a}\right)^{\frac{1-\gamma}{\gamma}}$$

Take the reciprocal and add a negative sign to the exponent.

$$T_1 = T_c a^{\frac{\gamma-1}{\gamma}}$$

Apply this to adiabat $C \to D$.

$$T_2 = T_h \left(\frac{P_1}{P_2}\right)^{\frac{1-\gamma}{\gamma}}$$

Use the definition of a for the pressure ratio.

$$T_2 = T_h a^{\frac{1-\gamma}{\gamma}}$$

e) Calculate the coefficient of performance for this refrigerator in terms of <u>only</u> the adiabatic exponent γ and the ratio of pressures a.

Start with the expression from part c).

$$COP = \frac{T_c - T_2}{T_1 + T_2 - T_c - T_h}$$

Insert the expressions for T_1 and T_2 from part d).

$$COP = \frac{T_c - T_h a^{\frac{1-\gamma}{\gamma}}}{T_c a^{\frac{\gamma-1}{\gamma}} + T_h a^{\frac{1-\gamma}{\gamma}} - T_c - T_h}$$

Rearrange terms.

$$COP = \frac{T_c - T_h a^{\frac{1-\gamma}{\gamma}}}{\left(T_c a^{\frac{\gamma-1}{\gamma}} - T_h\right) + \left(-T_c + T_h a^{\frac{1-\gamma}{\gamma}}\right)}$$

$$COP = \frac{T_c - T_h a^{\frac{1-\gamma}{\gamma}}}{\left(T_c a^{\frac{\gamma-1}{\gamma}} - T_h\right) - \left(T_c - T_h a^{\frac{1-\gamma}{\gamma}}\right)}$$

$$COP = \frac{1}{\left(\dfrac{T_c a^{\frac{\gamma-1}{\gamma}} - T_h}{T_c - T_h a^{\frac{1-\gamma}{\gamma}}}\right) - 1}$$

Multiply and divide the term in parentheses by $1 = \dfrac{a^{\frac{\gamma-1}{\gamma}}}{a^{\frac{\gamma-1}{\gamma}}}$.

$$COP = \cfrac{1}{\left(\cfrac{T_c a^{\frac{\gamma-1}{\gamma}} - T_h}{T_c - T_h a^{\frac{1-\gamma}{\gamma}}}\right)\left(\cfrac{a^{\frac{\gamma-1}{\gamma}}}{a^{\frac{\gamma-1}{\gamma}}}\right) - 1}$$

Distribute the denominator.

$$COP = \cfrac{1}{\left(\cfrac{T_c a^{\frac{\gamma-1}{\gamma}} - T_h}{T_c a^{\frac{\gamma-1}{\gamma}} - T_h a^{\frac{1-\gamma}{\gamma}} a^{\frac{\gamma-1}{\gamma}}}\right) a^{\frac{\gamma-1}{\gamma}} - 1}$$

$$COP = \cfrac{1}{\left(\cfrac{T_c a^{\frac{\gamma-1}{\gamma}} - T_h}{T_c a^{\frac{\gamma-1}{\gamma}} - T_h a^{\frac{1-\gamma+\gamma-1}{\gamma}}}\right) a^{\frac{\gamma-1}{\gamma}} - 1}$$

$$COP = \cfrac{1}{\left(\cfrac{T_c a^{\frac{\gamma-1}{\gamma}} - T_h}{T_c a^{\frac{\gamma-1}{\gamma}} - T_h a^{0}}\right) a^{\frac{\gamma-1}{\gamma}} - 1}$$

$$COP = \cfrac{1}{\left(\cfrac{T_c a^{\frac{\gamma-1}{\gamma}} - T_h}{T_c a^{\frac{\gamma-1}{\gamma}} - T_h}\right) a^{\frac{\gamma-1}{\gamma}} - 1}$$

$$COP = \cfrac{1}{a^{\frac{\gamma-1}{\gamma}} - 1}$$

4) In order to more evenly cool your living room, you consider putting your "window" air conditioning unit in the middle of the room rather than in the window. Make a thermodynamic argument for or against this idea.

If the air conditioner is in the middle of the room, the only place that it can dump waste heat is the room. Thus, the cycle extracts heat from the room and dumps heat to that same room. Conservation of energy dictates that the heat extracted from the room (Q_c) plus the electrical work (W) equals the waste heat dumped in the room (Q_h).

$$Q_c + W = Q_h$$

Because the electrical work is necessarily positive, the heat dumped into the room must be greater than the heat extracted from the room. Thus, this plan is not a good way to effectively cool the room; it would actually heat up the room!

5) **Laser Cooling:** Rubidium (Rb) atoms are often used in atomic physics experiments. There are several reasons for this. Rb is easily vaporized, and thus can be studied in a gaseous state. It is one of the alkali metals, a group of elements with relatively simple electronic configurations that have only one electron in their outer shell. Rb also has atomic transition frequencies that are easily accessible with common lasers. *Our book does not discuss laser cooling much. Here is another resource that might be of some help.*

a) Two commonly interrogated atomic transitions in ^{87}Rb, the D_1 and D_2 lines, correspond to wavelengths of 795 nm (D_1) and 780 nm (D_2). Calculate the magnitude of the momentum of a single photon at each of those wavelengths.

The momentum of a photon is equal to Planck's constant over wavelength.

$$p = \frac{h}{\lambda}$$

$$p_{795\ nm} \approx \frac{6.63 \times 10^{-34}\ J\ s}{795 \times 10^{-9}\ m} \approx 8.33 \times 10^{-28}\ J\ s/m$$

Recall that a joule has units of mass times velocity squared.

$$1\ J = 1\ kg\ (m/s)^2$$

$$p_{795\ nm} \approx 8.33 \times 10^{-28}\ kg\ m/s$$

$$p_{780\ nm} \approx \frac{6.63 \times 10^{-34}\ J\ s}{780 \times 10^{-9}\ m}$$

$$p_{780\ nm} \approx 8.49 \times 10^{-28}\ kg\ m/s$$

b) Suppose an initially stationary ^{87}Rb atom absorbs a single 780 nm photon that was traveling in the positive x direction. What is the velocity of the atom after it absorbs the photon?

To conserve momentum, the atom must have the same momentum as the incident photon. Use the result from part a). This momentum must be directed in the positive x direction.

$$p_{Rb} \approx 8.49 \times 10^{-28}\ kg\ m/s$$

To get velocity, divide momentum by the mass of the Rb atom, 87 amu.

$$v_{Rb} = \frac{p_{Rb}}{m_{Rb}} \approx \frac{8.49 \times 10^{-28}\ kg\ m/s}{87\ amu \times \left(\frac{1.66 \times 10^{-27}\ kg}{1\ amu}\right)}$$

$$v_{Rb} \approx 5.9 \times 10^{-3}\ m/s$$

The velocity is in the positive x direction.

c) At some point after absorbing a 780-nm photon, the atom will reemit a photon at the same wavelength. Suppose the photon is emitted in the positive z direction. What is the change in momentum of the atom when this happens?

To conserve momentum, the atom must have the *opposite* momentum of the incident photon. Use the result from part a).   This momentum must be directed in the *negative* z direction.

$$p_{Rb} = p_{780\ nm} \approx 8.49 \times 10^{-28}\ kg\ ^m/_s$$

d) In general, the reemission process happens in a random direction. Assume that the absorption and reemission process happens many, many times and that all of the photons come from a laser that emits light in the positive x direction.
    i)   What is the net change in momentum *due to emission only*?

        The emission is randomly directed each time. Over many, many emissions, the randomly-oriented momentum changes will average out, and the net change in momentum due to emission is zero.

    ii) What is the direction of the *overall* change in momentum (due to both absorption and emission)?

        From part i), the emission process contributes a net change of zero. The momentum change must come entirely from the absorption. To conserve momentum, the momentum of the atom must be the same as the moment of the incident photon, which is the positive x direction.

e) The previous parts of the problem refer to how to impart a force on an atom. However, this does not necessarily cool (that is, slow down) the atom. If the atom is moving away from the laser, it would actually heat (speed up) the atom. To cool an atom, the force needs to be velocity dependent, so that the photons only impart a force on atoms that are moving towards the laser. Considering that atoms only absorb particular wavelengths of light, explain how the Doppler shift can be exploited to create a velocity dependent force to slow atoms *in three dimensions*.

Due to the Doppler shift, atoms with different velocities relative to the photons will experience the photons as having different wavelengths. The Doppler shift means that atoms with velocities directed towards the photons will experience shorter wavelengths. Thus, the laser should be tuned to a wavelength *above* the normal absorption wavelength. Thus, atoms that are stationary will not absorb the photons and thus will not receive a momentum kick. Similarly, atoms that are moving away from the photons will see a wavelength even further above the normal absorption wavelength, and they will not receive a momentum kick. The atoms moving towards the photons, however, will see a wavelength that is Doppler-shifted down in wavelength so that it is the right wavelength to be absorbed. They will absorb the photon and receive a momentum kick that opposes their velocity, thus slowing them down.

To slow atoms in three dimensions, six laser beams are needed. The atoms are located at the origin, and the beams are oriented along the positive and negative x, y, and z axes, all pointing towards the origin. Each beam slows atoms moving in a direction opposite of the beam direction.

6) Read (or listen to) the following two stories discussing recent topics from class.

Negative temperatures that are hotter than the sun
https://www.npr.org/2013/01/04/168624854/negative-temperatures-that-are-hotter-than-the-sun
How strong can a hurricane get?
https://physicstoday.scitation.org/do/10.1063/PT.6.1.20170908a/full/

Write a short response to the two articles. One paragraph per article is sufficient.
- Summarize the main points of each article in a sentence or two.
- For each article, discuss in a few sentences the connections between the science discussed in the article and the material covered in this course.
- Which article did you feel better conveyed the relevant science? Why? (Note that unlike the *Physics Today* article, the *NPR* piece is intended for a broader audience that does not necessarily have a background in physics.)
- Fulfilling the above requirements will earn you a $^{3.25}/_4$. The rest of the points will be awarded based on the depth and quality of your explanations of the connections. (For example, a response that discusses the energy flow of a negative temperature system will earn more points than a response that simply states that negative temperature is something we saw in class.)

7) List *three* main ideas from this homework assignment. For example, you could write a few-sentence explanation of a concept, or list an equation and explain the variables and in what circumstances the equation applies.
The goal is for you to review and to reflect on the big picture. Think about what you might want to remember when you look back at this homework before the test. I hope that this will be useful for your studying. I am not looking for anything specific here; you will be graded on effort and completion.