Physics 231 – Lab 7
Thermal Energy and Air Resistance

You'll perform two experiments that deal with microscopic-scaled energy transfers that complicate any macroscopically-scaled model. First there's the thermal exchange of energy that occurs when objects of different temperatures interact. Second there's energy dissipation, or more specifically, drag.

(Equipment: metal slugs, Styrofoam calorimeter cups, pitcher of room-temp water, beakers of boiling water on hot plates, temperature probes, scale, motion sensor, ruler, stack of 10 fresh coffee filters.)

Objectives
In this lab, you will do the following:
- Predict and measure the final temperature when objects at different temperature are brought into contact with each other.
- Measure the terminal speed for objects with the same shape, but different masses, and use the results to verify how air resistance depends on speed.

I. Thermal Energy Transfer

You're going to heat up a slug of metal, then put it in a well insulated cup of cooler water and monitor the change in temperature. The water's and slug's internal energies, and thus temperatures, should evolve in a predictable way.

Background
According the Energy Principle, the change in energy for a system is $\Delta E_{sys} = W_{surr} + Q$, where W_{surr} is the work done by the surroundings and Q is the energy transfer due to a temperature difference. The change in thermal energy for an object is $\Delta E_{thermal} = mc\Delta T$, where m is the mass, c is the specific heat, and ΔT is the temperature change.

A. Set Up
- If it's not already been done for you, mostly fill a beaker with water and place it on your hot plate that set on 'high' to start bringing it to boiling.
- With Vernier's temperature probe connected to "CH 1" of the LabPro interface, open LoggerPro on the computer – it should automatically recognize that you're using a temperature probe.
- Use the scale at the back of the room to measure the mass of the metal.
- Identify the type of metal (if you're uncertain, ask your instructor) and use the table below to select the appropriate mass-specific heat capacity.

Material	mass-specific heat capacity
Copper	390 J/(kg·K) = 390 J/(kg·°C)
Steel	500 J/(kg·K) = 500 J/(kg·°C)
Aluminum	900 J/(kg·K) = 900 J/(kg·°C)
Water	4190 J/(kg·K) = 4190 J/(kg·°C)

- Suspend the metal in boiling water so that it does *not* touch the beaker. After it's been in the boiling water for a while, measure the water's (and thus the metal's) temperature.
- Plug the temperature probe into "CH 1" of the Lab Pro interface. Open the file "TemperatureSensor.xmbl " from "PHYS231" folder.
- Measure the mass of the Styrofoam calorimeter cup without its lid.

- Fill it about two thirds full (high enough that the metal slug will be submerged when you put it in) with room temperature water (*not* from the tap; some should be in pitchers by the sink). Measure the mass of the cup and water. Calculate and record the mass of just the water.
- Put the lid on the calorimeter cup and insert the temperature probe through the off-center hole in the lid. Record the water's temperature.

B. Experiment

Now let's see at what temperature the hot metal and cool water will equilibrate. The experiment needs to be carried out quickly to get good results, so read *all* of the instructions carefully before doing anything!

- Press the "Collect" button in the LoggerPro program.
- One person should lift up the lid of the calorimeter.
- Another person should carefully and quickly remove the metal from the boiling water and gently place it in the calorimeter.
- The person holding the lid should quickly put it back on such that the thermometer is fairly far from the metal it should *not* touch the metal cylinder.
- The temperature of the water will rise, then it will eventually drop because the calorimeter cup is not perfectly insulated. Use the maximum temperature that the water reaches as the *final* temperature. *While you're waiting for the temperature to max out, you can work through the theoretical model in the next section.*

C. Theory

- Use conservation of energy arguments to symbolically derive a relation for the final temperature that the water + metal will reach after the metal's put in water, T_f. Give it in terms of m_w, m_c, m_m, c_w, c_c, c_m, T_1 and T_2.

- Use this equation to calculate what you'd expect the final temperature to be. This should be within 10% of your measured value.

II. Air Resistance

The strength of air resistance has a fairly simple dependence on things like the moving object's mass, speed, and shape. You're going to experimentally investigate those dependencies with falling coffee filters. Conveniently, they quickly reach terminal speed because they have large areas (big air resistance) and low masses (small gravitational force).

Background

The magnitude of the air resistance force on an object is approximately $F_{air} = \frac{1}{2}C\rho Av^2$, where C is the drag coefficient (*not* the specific heat!), ρ is the air density (around 1.18 kg/m³), A is the cross sectional area, and v is the speed. The direction of the air resistance is opposite to the velocity.

A. Experiment

Recall that the magnitude of the gravitational force is equal to the magnitude of the air resistance at terminal speed. By stacking different numbers of filters inside each other, you can vary the gravitational force; you should see terminal speed varying accordingly.

- Determine the approximate cross sectional area of a coffee filter when it is *not* squashed flat.

- Based on this and the given density of air, determine the value of ½ρA (in our equation for the force of air resistance, this will leave F_{air} and v for you to measure and C to determine based on those measurements.)

- Determine the mass of *one* coffee filter by weighing your stack of 10 and dividing by 10.

- Plug the motion sensor into LabPro's "DIG/SONIC 1" port. Switch LoggerPro over to display position vs. time (click on the vertical axis' label and select "position".)
- Rotate the motion sensor so that it is aimed upward and place it on the floor.
- Press the "Collect" button in LoggerPro, then drop the coffee filter on the motion sensor. Repeat until you get relatively smooth position data while the filter is dropping.

    Note: you'll look at the graph of *position* rather than velocity because momentary blips in position measurements show up as significant jags in the velocity plot.

    Pause and Consider: How can you tell from the position versus time graph that the filter has reached a terminal speed?

- To measure the terminal speed, you'll measure the slope of your position versus time graph over the appropriate region of the graph.
    - Click and drag the mouse to select a section of the position versus time graph when the filter is moving at a terminal speed. The selected section should be highlighted in gray.
    - Press the "linear fit" button (it has "R=" on it) in LoggerPro. The magnitude of the slope displayed is the terminal speed.
    - Record your measurement as the first trial for ten filters in the table on the next page.
    - Repeat the experiment with one filter three more times. Each time, adjust the boundaries of the region where the linear fit is done to the section of the position versus time graph where the filter is moving at a terminal speed.
    - Record the average for all four trials.
- Now repeat the whole process for eight, six, four, and then two filters.

To calculate the magnitude of the air resistance force, remember that, when the filter's falling at terminal speed, the air resistance force must balance the weight.

- Calculate the magnitude of the air resistance force at terminal speed for each number of filters to complete the table in WebAssign.

- From your data table, plot the magnitude of the air resistance force versus the *square* of the terminal speed. Feel free to include the point for F = 0, v=0.

- Determine the slope of your graph, and from that determine the drag coefficient *C* for a filter. As the text suggests, it should be in the range $0.3 \leq C \leq 1.0$, (though a few percent outside the range would be acceptable, given our experimental uncertainties.)

B. Simulation

Write a Vpython program to simulate **two** nested coffee filters falling. What I'd suggest doing is starting with a program you've already written, like the cart on a track one, save it under a new name, like "coffee filter.py" and then modify it. Here are some useful tips:

- You'll want to define an object to represent the coffee filters, might as well use a simple sphere, and give it the attributes (using the values you've experimentally determined): area (coffee.area = …), mass (coffee.m = …), and drag coefficient (coffee.c = …). Note: "filter" is a *special* word in VPython just like "while" or "sphere" so we can't name the falling object "filter."

- You'll also want to define the density of air (rho = …) and the acceleration due to gravity (g = vector(0,-9.8,0).)

- The two forces acting on the coffee filter are the Earth's gravitational pull down (Fe = coffee.m*g) and the air's drag force (Fa), so the net force (which figures in the momentum update relation) is Fe+Fa.

- As for Fa, written mathematically, that's $\vec{F}_a = -\frac{1}{2} C \rho A v^2 \hat{v}$. That can be rewritten, in terms of momentum (which is a variable you'll naturally use in the program) as

$$\vec{F}_a = -\tfrac{1}{2} C \rho A \frac{|p|^2}{m^2} \hat{p} = -\tfrac{1}{2} C \rho A \frac{|p|}{m^2} \vec{p} \,.$$

- Don't forget that you're simulating the fall of *two* nested coffee filters (so use the mass of *two.*)

Put a line inside the program's loop to print out the speed

    print(pmag/coffee.m);

you should quickly see it leveling off at the terminal velocity. How does it compare with the terminal velocity you measured (% difference)?

Save "CoffeeFilter.py" and upload it.