University of Rochester

Laboratory V

Thermal and Mechanical Energy

Department of Physics & Astronomy

PHYSICS 113 - 121 - 181
General Physics I and Mechanics

Name: ________________________________ **Date:** ________________________

Collaborators: ____________________________ **Lab Section:** ______________

Prelab Exercises (2 points)

This prelab must be completed and handed in to the lab TA at the start of the lab.

Question 1 **1 point**

A 90 kg person jumps from a 30 m tower into a tub of water with a volume of $5\,\mathrm{m}^3$ initially at 20 °C. Assuming that all of the work done by the person is converted to heat in the water, what is the final temperature of the water? Note: first find the work done by the person, then find the temperature rise equivalent to that work. Make sure you have the correct value for the mass of the water, and include units.

Question 2 **1 point**

When you convert mechanical energy to heat, you are asked to continue taking temperature measurements even after the heat source has been turned off. What effect are we trying to observe, and how do we use this effect in our data analysis?

Objective

> *Conservation of Energy states that when energy changes form, the total amount of energy is unchanged. You will observe the conversion of mechanical energy, measured in Joules, to heat, measured in Calories, and estimate the constant of proportionality between the two units, known as Joule's constant.*

Theory

In this experiment, a measurable amount of work is performed by turning a crank that drives the rotation of an aluminum cylinder. The cylinder is subject to friction from a rope looped around it several times, with a mass M hanging from the rope. When the system is set up correctly, turning the crank will just lift the mass M off the ground. In this condition, the friction force between the rope and the cylinder equals the gravitational force $F = Mg$ on the mass. If we know this force and count the number of crank turns, we can compute the total work input to the system. Assuming all of this work is converted to heat through friction, we can relate the mechanical work to the temperature rise of the aluminum cylinder. Specifically, the mechanical work performed and the thermal energy gained by the cylinder are expected to be proportional.

A thermistor is embedded in the aluminum cylinder. By measuring the resistance of the thermistor with a multimeter, we can monitor the temperature of the cylinder and compute the thermal energy transferred to it. We calculate the ratio of mechanical work (in Joules) to heat gained (in Calories) to obtain Joule's constant,

$$J_{\text{mechanical}} = J_m = 4.19\,\text{J/Cal}, \tag{1}$$

also called the mechanical equivalence of heat[1].

We now derive the expression for the mechanical work performed by turning the crank. If the aluminum cylinder has radius R, the torque required to support a mass M is

$$\tau = MgR, \tag{2}$$

where g is the acceleration due to gravity near Earth's surface. The work performed by this torque is $W = \tau\theta$, where θ is the total angle through which the cylinder has been rotated. Each complete turn of the crank adds 2π to θ, so after N total turns the mechanical work is

$$W = \tau\theta = (2\pi N)MgR. \tag{3}$$

Next, we consider how to compute the heat Q imparted to the cylinder from the measured temperature change. The heat required to raise the temperature of an object by ΔT is

$$Q = mc\Delta T, \tag{4}$$

where m is the mass of the object and c is its specific heat capacity. In this experiment, we heat the aluminum cylinder, whose mass can be measured (approximately 200 g). The specific heat of aluminum is

$$c = 0.214\,\frac{\text{Cal}}{\text{g}\,^\circ\text{C}}. \tag{5}$$

The quantity ΔT is the measured temperature change of the cylinder. We will calculate it in several ways, as discussed in the Postlab. Combining eqs. (3) and (4), we can compute J_m:

$$J_m = \frac{W}{Q}\,[\text{J/Cal}]. \tag{6}$$

Experiment

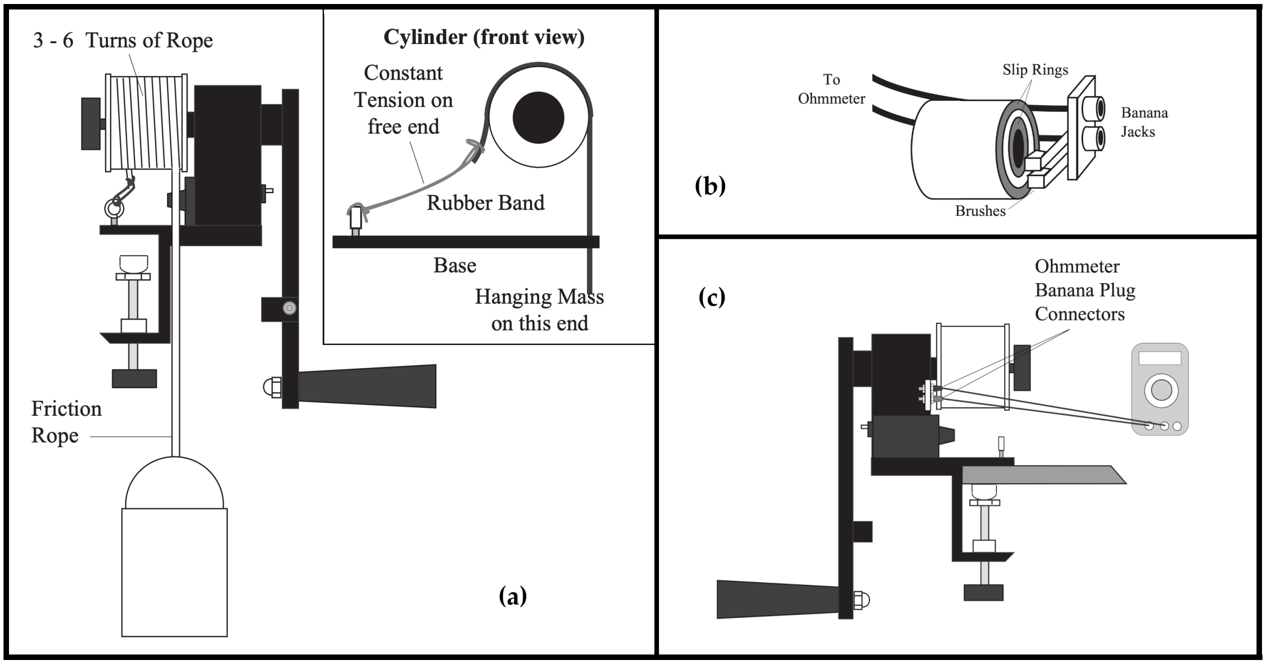

Figure 1: *(a) an aluminum cylinder wound with nylon rope will be turned with a crank, allowing friction from the rope to heat the cylinder. (b) a temperature-dependent resistor (thermistor) inside the cylinder allows you to measure the change in its temperature. (c) you will use a digital multimeter to measure the thermistor resistance at regular intervals during the experiment. (Credit: adapted from PASCO Scientific.)*

Conversion of Mechanical Energy: Preparing the Apparatus

The apparatus for this lab must be set up carefully in order to obtain a good result. The overall apparatus is shown in Fig. 1. A digital multimeter (ohmmeter) will be used to determine the temperature of the cylinder.

We convert mechanical work into heat through friction between a nylon rope and the aluminum cylinder. You provide the mechanical energy by turning the crank. Follow the steps below to set up the apparatus correctly:

1. Ensure the crank apparatus is set up on the tabletop as shown in Fig. **W**. Measure the mass of the aluminum cylinder, then replace it by screwing in the knob (see Fig. **W**). There are two brushes on the crank apparatus; make sure they are in contact with the side of the aluminum cylinder that has the brass slip rings exposed, as shown in Fig. **Z**. The brushes establish electrical contact with the thermistor inside the cylinder, which is used to monitor its temperature.

2. Spray some powdered graphite on the cylinder. This acts as a lubricant. The graphite is harmless so long as it is not inhaled — avoid spraying it near your face!

3. Measure the mass of the bucket and whatever masses have been placed in it. The total, $M = M_{\text{bucket}} + M_{\text{in}}$, is the mass supported by the rope (the rope's own mass is neglected). A total mass of $M = 2\,\text{kg}$ to $3\,\text{kg}$ is recommended.

4. Tie the nylon rope to the bucket, leaving as little extra rope below the bucket as possible. You will need as much rope length above the bucket as possible.

5. Align the bucket with the slot on the edge of the tabletop crank apparatus so that the nylon rope passes vertically through the slot. Wrap the rope several times around the aluminum cylinder (4–5 turns recommended), maintaining tension as you wrap so that it lies tightly against the cylinder.

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[1] Note that we contrast J_m with the mechanical equivalent of electrical energy, $J_{\text{electrical}} = J_e$, used in the second part of the lab.

6. Tie the rope to a rubber band anchored to the base plate of the crank, as shown in Fig. **X**. Thread the rubber band through the hook so that it forms two loops[2]. Pull the rubber band's loops toward the aluminum cylinder before securing that end of the rope, so that the rubber band maintains tension in the rope when you are not cranking. Make sure the rope does not cross over itself anywhere on the cylinder.

7. Turn the crank a few times and observe how far the mass rises off the floor. The friction between the rope and cylinder is determined by the rope tension and the number of wraps. If the mass rises more than 3 cm from the floor, there is too much friction; re-tie the rope to the rubber band with less tension, or unwind one turn of rope from the cylinder. If the mass does not leave the floor entirely, there is not enough friction; add a turn of rope or re-tie with more tension. All of the mass must leave the floor while cranking in order for the force calculation to be correct.

8. When set up correctly, the mass will just leave the floor while you crank, and will fall back to the floor if you stop cranking but hold the crank handle still. Repeat the previous step until this condition is met.

9. Use the banana plug connectors to attach the multimeter (see Figs. **Y** and **Z**), and set it to the 200 kΩ range or a similar resistive range. Your apparatus is ready. Some tips for setting up the multimeter are provided at the end of the instructions.

Using the Apparatus for Data Collection

As the aluminum cylinder heats up, its thermistor resistance will change. You will measure the resistance R at regular time intervals and convert it to temperature T using an empirical relation. Table 1 shows the resistance of the thermistor as a function of temperature.

R [kΩ]	T [°C]	R [kΩ]	T [°C]	R [kΩ]	T [°C]	R [kΩ]	T [°C]	R [kΩ]	T [°C]	R [kΩ]	T [°C]
351.020	0	146.580	17	66.356	34	32.253	51	16.689	68	9.121	85
332.640	1	139.610	18	63.480	35	30.976	52	16.083	69	8.816	86
315.320	2	133.000	19	60.743	36	29.756	53	15.502	70	8.523	87
298.990	3	126.740	20	58.138	37	28.590	54	14.945	71	8.241	88
283.600	4	120.810	21	55.658	38	27.475	55	14.410	72	7.969	89
269.080	5	115.190	22	53.297	39	26.409	56	13.897	73	7.708	90
255.380	6	109.850	23	51.048	40	25.390	57	13.405	74	7.456	91
242.460	7	104.800	24	48.905	41	24.415	58	12.932	75	7.214	92
230.260	8	100.000	25	46.863	42	23.483	59	12.479	76	6.981	93
218.730	9	95.447	26	44.917	43	22.590	60	12.043	77	6.756	94
207.850	10	91.126	27	43.062	44	21.736	61	11.625	78	6.539	95
197.560	11	87.022	28	41.292	45	20.919	62	11.223	79	6.331	96
187.840	12	83.124	29	39.605	46	20.136	63	10.837	80	6.130	97
178.650	13	79.422	30	37.995	47	19.386	64	10.467	81	5.936	98
169.950	14	75.903	31	36.458	48	18.668	65	10.110	82	5.749	99
161.730	15	72.560	32	34.991	49	17.980	66	9.767	83	5.569	100

Table 1: *Resistance-temperature data measured for the aluminum cylinder.*

The data from Table 1 is plotted in Fig. 2. While you can convert resistance to temperature by interpolating in the table, it is more convenient to use the polynomial fit

$$T(R) = 67.03 - (0.7136)R + (3.801 \times 10^{-3})R^2 - (8.680 \times 10^{-6})R^3. \tag{7}$$

Near room temperature, in the 20 °C to 35 °C range relevant for this experiment, the polynomial approximates the resistance-temperature relation very well (see Fig. 2 inset).

1. Make sure the turn counter for the crank is reset to zero. Turn the knob of the counter to reset it.

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[2] A single loop is not strong enough to maintain proper tension for most rubber bands. Loop it through so that it is doubled. Ask your TA/TI for help if needed.

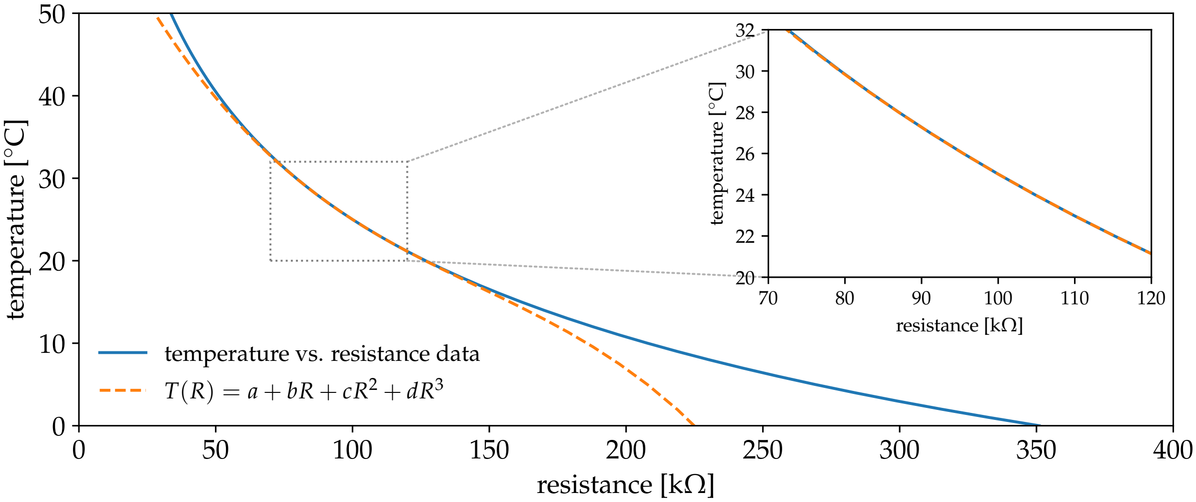

Figure 2: *Conversion of cylinder resistance in* kΩ *to temperature in* °C*. The orange dashed line shows a polynomial fit to the data, which is an excellent approximation at room temperature (see inset).*

2. Make sure your multimeter is on, and record your starting resistance R at time $t = 0$ in Data Table 1 in the Postlab Exercises. To save time, record all resistances during the experiment and convert them to temperatures afterward.

3. Start your hand timer and begin cranking the apparatus. Every 30 seconds, stop cranking briefly to record the resistance and revolution count in Data Table 1. Note that the thermistor reading will fluctuate while cranking, but will quickly settle to a steady value when you stop. The person cranking should pause for no more than five (5) seconds at each 30-second interval before resuming.

4. Continue in 30-second intervals until the recorded temperature has risen by 10 °C to 12 °C. You can estimate this from the table above (or the reduced table on the apparatus itself) during the experiment, then perform careful calculations once data collection is complete. Expect a total cranking time of about 5 minutes (300 seconds), during which 500–700 crank revolutions are performed.

5. When you reach the target temperature rise of approximately 10 °C to 12 °C at a 30-second interval, stop cranking. Record this time as t_{stop}.

6. Continue monitoring the apparatus for the same duration that you were cranking, taking readings every 30 seconds until the time reaches $2t_{\text{stop}}$. The revolution count N no longer changes, but the resistance will rise slowly as the aluminum cylinder cools toward thermal equilibrium with the environment. This step provides a rough estimate of how much energy was lost to the surroundings during the experiment. A temperature change of 1 °C to 4 °C during this phase is typical; consult your TA if you observe something outside this range.

7. Convert all resistance readings to temperatures using Table 1 and/or eq. (7). The table is sufficient for an acceptable level of precision; using the polynomial form will give smoother results if a calculator is available.

8. Follow the instructions and questions in the Postlab Exercises to complete the data analysis.

Name: ______________________________ **Date:** ______________________

Collaborators: ___________________________ **Lab Section:** ____________

POSTLAB EXERCISES (10 points)

Submit the postlab to the TA at the end of the lab.

Conversion of Mechanical Energy into Heat (10 points)

Question 3 **2 points**

Fill in your data from the mechanical equivalence of heat experiment in Data Table 1. Convert measured resistance R to temperature T using Table 1 and/or eq. (7).

Data table 1: *Data for mechanical equivalence of heat.*

Time [s]	0	30	60	90	120	150	180	210	240
R [kΩ]									
N [revs]									
Temp [°C]									

Time [s]	270	300	330	360	390	420	450	480	510
R [kΩ]									
N [revs]									
Temp [°C]									

Time [s]	540	570	600	630	660	690	720	750	780
R [kΩ]									
N [revs]									
Temp [°C]									

Next, plot temperature versus time from Data Table 1 in Graph 1. Draw two best-fit straight lines: one for the interval $t = 0$ to $t = t_{\text{stop}}$, and another for $t = t_{\text{stop}}$ to $t = 2t_{\text{stop}}$.

In Graph 1, mark the initial temperature T_{initial}, the peak temperature T_{peak}, and the final temperature T_{final}, as shown in Fig. 3. These three temperatures must be read from the two best-fit straight lines, not from the data points directly. The initial temperature T_{initial} is the y-intercept of the first line; the peak temperature T_{peak} is at the intersection of the two lines; and the final temperature T_{final} is the value of the second line at $t = 2t_{\text{stop}}$.

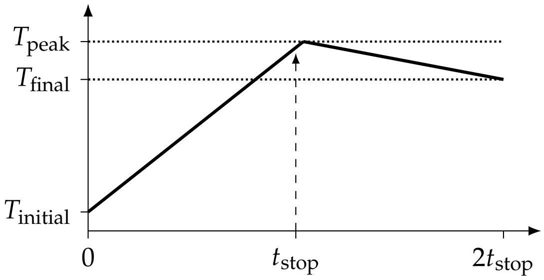

Figure 3: *Expected time dependence of the temperature of the aluminum cylinder in this experiment.*

As usual, include the title and axis labels (with units) in your plot to receive full credit.

Graph 1: *Temperature vs. time.*

Question 4

1 point

The peak temperature in your graph may not coincide exactly with the temperature at t_{stop}. Why might the temperature reading continue to rise for a short time after you stop cranking?

Question 5

2 point

(a) ($^1\!/_2$ point) Using eq. (3), calculate the work done, W, to lift the mass while cranking.

Total number of revolutions: $N =$ ________________

Mass you lifted off the ground: $M =$ ________________ kg

Mass of the aluminum cylinder: $m =$ ________________ kg

Radius of the aluminum cylinder: $R =$ ________________ m

(b) ($^1\!/_2$ point) Compute the change in temperature $\Delta T = T_{\text{peak}} - T_{\text{initial}}$.

(c) ($^1\!/_2$ point) Using eqs. (4) and (5), calculate the heat Q added to the system by raising its temperature by ΔT:

(d) ($^1\!/_2$ point) Using eq. (6), estimate Joule's constant. Don't forget units.

Question 6

1 point

After you stop cranking, the aluminum cylinder loses heat to the environment because it is hotter than its surroundings. Calculate the temperature drop $\Delta T_{\text{lost}} = T_{\text{peak}} - T_{\text{final}}$.

Question 7 **2 points**

Heat was also being lost to the environment while you were cranking (though the cylinder was cooler then than at T_{peak}). If we tried to correct for this by using $\Delta T + \Delta T_{\text{lost}}$ as the total temperature rise due to cranking, why would this likely overestimate the actual heat lost during cranking?

Question 8 **2 points**

Discuss one major source of error in this experiment besides ambient cooling, and explain how it may have affected the measured Joule's constant. If that error were removed, would the measured Joule's constant increase or decrease? Explain.