



B.S./B.A. in Physics

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Physics

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The department is authorized to combine the assessment efforts for the Bachelor of Science and Bachelor of Arts majors in Physics, herein referred to as "B.S./B.A. in Physics."



a) Subject knowledge	<p>1). After completing Introductory Physics courses (PHY 241/243, 242/244), each student takes 1-hr written test of one basic and major area (Mechanics). The same test and scoring rubrics have been used since 1995 (Appendix A).</p> <p>2). Chair and faculty solicit feedback from alumni and re their success in jobs and/or graduate school.</p>	<p><u>Fall 2008:</u> 18 students, Mean 74% (B-)</p> <p><u>Fall 2007:</u> 12 students, Mean 54% (C/D)</p> <p><u>Fall 2006:</u> 12 students, Mean 55% (C/D)</p> <p><u>AY 2004-05:</u> Mean 53% (D)</p> <p><u>1995-2004:</u> Mean 74% (B-)</p>	<p>Data in column to left were reviewed by the Physics Faculty on April 29, 2009.</p> <p>The Fall 2008 mean is considerably higher than those of previous four years. However, this is not statistically significant due to small numbers of students.</p> <p>This test is given one year after students take the Mechanics course (PHY 241/243). The time lapse should be taken into account when judging the test results.</p>	<p>Free tutoring by graduate students continues to be available to all students of PHY 241/243 and 242/244.</p> <p>Annual review of test results will continue to see if the Fall 2008 mean is part of a significant trend.</p>



<p>b) Ability to apply subject knowledge to concrete problems</p>	<p>1). During junior or senior year, each student does a Computer Project that demonstrates subject knowledge and ability to apply it to concrete problems. Since Fall 2005 the instrument has been a set of computer exercises in PHY 474 – Thermal Physics, added to the Project list by unanimous vote of full-time Physics faculty on Feb. 21, 2006. Course is required for all B.S. and B.A. majors. Projects and rubrics are described in Appendix B. 2). Chair and faculty solicit feedback from alumni and re their success in jobs and/or graduate school.</p>	<p>(Maximum possible = 100). <i>Mass of Atmosphere:</i> <u>Fall 2008</u> (7 student reports): Avg=87 ± 30, Range 20-100 <u>Fall 2007</u> (8 student reports): Avg=92 ± 5, Range 80-90 <u>Fall 2006</u> (7 student reports): Avg=80 ± 14, Range 50-90 <u>Fall 2005</u> (8 student reports): Avg = 83 ± 7, Range 80-100 <i>Ruchardt Cp/Cv Simulation:</i> <u>Fall 2008</u> (5 student reports): Avg = 66 ± 34, Range 20-95 <u>Fall 2007</u> (4 student reports): Avg = 66 ± 31, Range 20-90 <u>Fall 2005</u> (8 student reports): Avg = 76 ± 21, Range 50-100 Rubrics in Appendix B, Lab Manual in Appendix D.</p>	<p>Data in column to left were reviewed by the Physics Faculty on April 29, 2009. The instructor of PHY 474 indicated that the Ruchardt Cp/Cv exercise involves considerably more advanced math than Mass of Atmosphere. Taking account of this, plus the likelihood of yearly score fluctuation due to small student numbers, the Physics Faculty deemed the results to be consistently Very Good.</p>	<p>Annual review of computer exercise scoring will continue.</p>



<p>a) Logical, analytical and computational skills</p>	<p>1). During junior or senior year, each student does a Computer Project as part of a major Physics course. Among other things, this tests the student's logical, analytical and computational skills listed in Goal 2. The projects are graded by the professor teaching the course. Projects and rubrics are described in Appendices B and D.</p> <p>2). Chair and faculty solicit feedback from alumni and re their success in jobs and/or graduate school.</p>	<p>(Maximum possible = 100).</p> <p><i>Mass of Atmosphere:</i> <u>Fall 2008</u> (7 student reports): Avg=87 ± 30, Range 20-100 <u>Fall 2007</u> (8 student reports): Avg=92 ± 5, Range 80-90 <u>Fall 2006</u> (7 student reports): Avg=80 ± 14, Range 50-90 <u>Fall 2005</u> (8 student reports): Avg = 83 ± 7, Range 80-100</p> <p><i>Ruchardt Cp/Cv Simulation:</i> <u>Fall 2008</u> (5 student reports): Avg = 66 ± 34, Range 20-95 <u>Fall 2007</u> (4 student reports): Avg = 66 ± 31, Range 20-90 <u>Fall 2005</u> (8 student reports): Avg = 76 ± 21, Range 50-100</p> <p>Rubrics in Appendix B, Lab Manual in Appendix D.</p>	<p>Data in column to left were reviewed by the Physics Faculty on April 29, 2009.</p> <p>The instructor of PHY 474 indicated that the Ruchardt Cp/Cv exercise involves considerably more advanced math than Mass of Atmosphere. Taking account of this, plus the likelihood of yearly score fluctuation due to small student numbers, the Physics Faculty deemed the results to be consistently Very Good.</p>	<p>This goal was revised by the Physics faculty in AY 2005-2006 to update the list of relevant computer languages and mathematical packages.</p> <p>The Physics Faculty discussed the list of computer languages and mathematical packages on April 29, 2009 and decided to conduct a more formal review of this goal in AY 2009-2010.</p>
<p>b) Ability to apply subject knowledge to concrete problems</p>	<p>1). The Computer Project described in the cell above also tests the student's ability to apply subject knowledge to concrete problems relevant to the course in which it is done.</p> <p>2). Chair and faculty solicit feedback from alumni and re their success in jobs and/or graduate school.</p>	<p>Described in the cell above.</p>	<p>Described in the cell above.</p> <p>Results demonstrate high program effectiveness in teaching students to apply their subject knowledge to specific computational analyses.</p>	<p>Described in the cell above.</p>



<p>a) Ability to set up an experiment and to acquire and analyze data</p>	<p>Effective Fall 2005, the lab skills assessment tool is a set of three hands-on lab experiments in thermodynamics done by students in PHY 474 – Thermal Physics (required course for all B.S. and B.A. Physics majors). This tests students’ skills in experiment setup, data collections/analysis and presentation of results. The written lab reports are graded by the professor teaching the course. Projects and rubrics are described in Appendices C and D.</p> <p>This change of assessment tool was approved by unanimous vote of the full-time Physics faculty on Feb. 21, 2006.</p>	<p>(Maximum possible = 100).</p> <p><i>Constant Volume Gas Thermometer</i> <u>Fall 2008</u> (9 student reports) Avg = 88 ± 19, Range 40-100 <u>Fall 2007</u> (9 student reports) Avg = 92 ± 4, Range 85-100 <u>Fall 2006</u> (7 student reports) Avg = 66 ± 20, Range 50-80 <u>Fall 2005</u> (8 student reports) Avg = 85 ± 6, Range 80-95</p> <p><i>Mechanical Equivalent of Heat</i> <u>Fall 2008</u> (8 student reports) Avg = 89 ± 12, Range 60-100 <u>Fall 2007</u> (7 student reports) Avg = 94 ± 8, Range 45-100 <u>Fall 2006</u> (7 student reports) Avg = 70 ± 24, Range 40-100 <u>Fall 2005</u> (8 student reports) Avg = 67 ± 20, Range 45-90</p> <p><i>Ruchardt C_p/C_v Experiment</i> <u>Fall 2008</u> (5 student reports) Score = 66 ± 34, Range 20-95 <u>Fall 2007</u> (4 student reports) Avg = $83 \pm$ Range 50-100 <u>Fall 2006</u> (7 student reports) Avg = 75 ± 5, Range 70-80 <u>Fall 2005</u> (8 student reports) Avg = 73 ± 14, Range 60-98</p>	<p>Data in column to left were reviewed by the Physics Faculty on April 29, 2009.</p> <p>Scores are consistently Very Good to Excellent, given the variation expected due to small student numbers.</p> <p>The instructor of PHY 474 reports that the students gained a substantial appreciation of experimental accuracy, possible errors, etc.</p>	<p>Annual Physics Faculty review of results from PHY 474 will continue.</p> <p>Our new elective lab course, PHY 335 – Modern Physics Laboratory, was given formally for the first time in Spring 2009. Thus, student performance data were not available for the April 29, 2009 Physics Faculty meeting. Data from this course will be reviewed when sufficient numbers of students have taken it. (The next offering is scheduled for Spring 2011).</p>



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b) Ability to apply subject knowledge to concrete problems	The lab experiments described above also test the student's ability to apply knowledge of physics, particularly thermodynamics, to the concrete problems of measuring the heat capacity of matter, the pressure-temperature relationship of gases, and the mechanical equivalent of heat.	Described in the cell above.	Described in the cell above.	Described in the cell above.
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Appendices

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Appendix A **General Physics Test**

Goal #1, Outcome a)

Test has 15 questions – 4 informational (not graded) and 11 on basic knowledge of Mechanics (graded with equal weight).

Scoring rubrics for each graded question: Correct equations and numerical output – 100%. Correct equations, incorrect numerical output – 50%. Incorrect equations – 0%.



Appendix B

Assessment – Spring 2009

Thermal Physics Laboratories PHY474 – Fall 2008

Number of Students: 10

Lab 1: Latent Heat of Fusion of Ice [Experiment]

Objective: (1) Find latent heat from measured temperatures
(2) Find temperatures from empirical value of latent heat

Q1: Record data	25 pts
Q2: Calculation of latent heat	25 pts
Q3: Error analysis of latent heat	25 pts
Q4: Calculation of mixing temperature	25 pts
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Total	100 pts

Statistics: Score 78 ± 26 , range 21-100 (number of reports: 10)

Lab 2: Constant Volume Gas Thermometer [Experiment]

Objective: (1) Ideal gas law
(2) Find estimate of absolute zero temperature

Q1: Find ambient pressure in kPa	10 pts
Q2: Record pressure for temperatures $0^\circ\text{C} - 100^\circ\text{C}$	20 pts
Q3: Plot data	20 pts
Q4: Extrapolation to zero pressure	20 pts
Q5: Error for absolute zero temperature	20 pts
Q6: Discuss error	10 pts
<hr/>	
Total	100 pts

Statistics: Score 88 ± 19 , range 40-100 (number of reports: 9)



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Lab 3: Adiabatic Compression of Air [Experiment]

Objective: (1) Adiabatic gas laws
(2) Confirm relationships between exponents

Q1: Derivation of adiabatic gas laws	20 pts
Q2: Find relationships between exponents	20 pts
Q3: Logarithmic plots and exponents	20 pts
Q4: Errors for exponents	20 pts
Q5: Discuss error	20 pts
<hr/>	
Total	100 pts

Statistics: Score 76 ± 23, range 30-100 (number of reports: 8)

Lab 4: Mechanical Equivalent of Heat [Experiment]

Objective: (1) Comparison of mechanical and thermal energy
(2) Determine mechanical equivalent of heat

Q1: Determine mass of aluminum cylinder	10 pts
Q2: Measurement of resistance vs number of “cranks”	20 pts
Q3: Convert resistance to temperature using table	20 pts
Q4: Determine mechanical equivalent	20 pts
Q5: Identify errors	10 pts
Q6: Error analysis	20 pts
<hr/>	
Total	100 pts

Statistics: Score 89 ± 12, range 60-100 (number of reports: 8)

Lab 5: Heat Engine [Experiment]

Objective: (1) Understand the operation of the heat engine;
Identify heat input and output
(2) Calculate the mechanical energy from the phase diagram

Q1: Data collection of 4-5 cycles	20 pts
Q2: Calculation of the mechanical work	20 pts
Q3: Calculation of gravitational potential energy	20 pts
Q4: Identify errors	20 pts
Q5: Error analysis	20 pts
<hr/>	
Total	100 pts

Statistics: Score 91 ± 7, range 75-95 (number of reports: 8)



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Lab 6: Mass of Atmosphere [Computer]

Objective: (1) Familiarize with MathCad
(2) Numerical solution of ordinary differential equation

Q1: Find characteristic length scale	25 pts
Q2: Graph pressure vs height from iteration	25 pts
Q3: Find exact solution	25 pts
Q4: Use MathCad to find value of definite integral	25 pts

Total	100 pts
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Statistics: Score 87 ± 30 , range 20-100 (number of reports: 7)

Lab 7: Brunt-Vaisalla Oscillations (Parcel of Dry Air) [Computer]

Objective: (1) Derive the equations of motion for a parcel of air
(2) Numerical integration of a nonlinear ordinary differential equation (ODE)

Q1: Derive nonlinear differential equation for the parcel of air	25 pts
Q2: Derive linearized equation of motion	25 pts
Q3: Numerical integration of differential equation using Runge-Kutta	25 pts
Q4: Plot the height of the parcel as a function of time	25 pts

Total	100 pts
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Statistics: Score 69 ± 18 , range 50-100 (number of reports: 6)

Lab 8: Ruchardt Method for Measuring C_p/C_v [Experiment]

Objective: (1) Derive the equation of motion of motion of the steel ball
(2) Extract the adiabatic exponent from the data

Q1: (Measure pressure inside jug)	10 pts
Q2: (Derive equation for damped harmonic oscillator)	20 pts
Q3: (Measure pressure vs time using data acquisition)	20 pts
Q4: (Plot data using MathCad)	10 pts
Q5: (Use nonlinear regression fit for data)	20 pts
Q6: (Find value for adiabatic constant)	10 pts
Q7: Error analysis	10 pts

Total	100 pts
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Statistics: Score 66 ± 34 , range 20-95 (number of reports: 5)

PHY 474 THERMAL PHYSICS
Computational Projects and Laboratories

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APPENDIX C

Laboratory Schedule (tentative)

Date	Experiment
9/4	Mass of Atmosphere [Simulation]
9/11	Gas Thermometer
9/25	Equivalence of Heat and Work
10/9	Stability of Dry Air [Simulation]
10/23	C_P/C_V Ruchardt Oscillations [Simulation]
11/6	C_P/C_V Ruchardt Oscillations
11/20	Vapor Pressure

APPENDIX C

I. MASS OF THE ATMOSPHERE

A. Objectives

1. To familiarize with MathCad.
2. To find a numerical solution of an ordinary differential equation

B. Theory

We consider a horizontal slab of air whose thickness [height] is dz . If this slab is at rest, the pressure holding it up from below must balance both the pressure holding it up from below must balance both the pressure from above and the weight of the slab:

$$P(z + dz) \cdot A + Mg = P(z) \cdot A, \quad \text{or} \quad P(z + dz) - P(z) = -\frac{Mg}{A},$$

where A is the area of the slab and M is its total mass. The mass is given by $M = \rho Adz$ so that

$$\frac{P(z + dz) - P(z)}{dz} = -\rho g, \quad \text{or} \quad \frac{dP}{dz} = -\rho g.$$

[Is the density ρ constant over the entire atmosphere? *Explain!*]

The density of the gas is $\rho = M/V = Nm/V = Pm/kT$, where m is the average molecular mass and in the last step, we used the ideal gas law. Inserted above, we find

$$\frac{dP}{dz} = -\frac{mg}{kT}P.$$

Q1: Show that a *characteristic length scale* for the problem is given by

$$L = \frac{kT}{mg}$$

Air is about 80% N_2 and 20% O_2 . Find the numerical value of the characteristic length scale for air.

Some of you may now the solution of the differential equation for the pressure. Here, we first want to find a *numerical* solution. To this end, we write $P = P_0\hat{P}$, where P_0 is the pressure at sea level:

$$\frac{d(P_0\hat{P})}{dz} = P_0\frac{d\hat{P}}{dz} = -\frac{P_0\hat{P}}{L}, \quad \text{or} \quad \frac{d\hat{P}}{dz} = -\frac{\hat{P}}{L}.$$

Note that $\hat{P}(0) = 1$. We re-write the differential equation as a difference equation:

$$\frac{\hat{P}(z + \Delta z) - \hat{P}(z)}{\Delta z} = -\frac{\hat{P}(z)}{L}, \quad \text{or} \quad \hat{P}(z + \Delta z) = \hat{P}(z) - \hat{P}(z)\frac{\Delta z}{L}.$$

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That is, once we know $\hat{P}(z)$, we can compute $\hat{P}(z + \Delta z)$. Using this result, we then find $\hat{P}(z + 2\Delta z)$. This is called an *iterative* solution. We define

$$\hat{P}(n) = \hat{P}(n \cdot \Delta z), \quad \hat{P}(z + \Delta z) = \hat{P}(n + 1), \quad \text{etc,}$$

with the initial condition $\hat{P}(0) = 1$. We observe that the ratio $\kappa = \Delta z/L$ is dimensionless. We find

$$\hat{P}(n + 1) = (1 - \kappa)\hat{P}(n).$$

In MathCad, the iterative scheme is implemented in the following way [we choose $\kappa = 0.02$]:

$$P(n) := \left. \begin{array}{l} \kappa := 0.02 \\ P \leftarrow 1 \\ \text{for } x \in 1..n \\ P \leftarrow (1 - \kappa) \cdot P \end{array} \right\}$$

Q2: Graph P as a function n . Find an estimate for the pressure at Mt. Whitney [14,500 feet] and Mt. Everest [29,000 feet].

Q3: Show that the (exact) solution of the differential equation is given by

$$P(z) = P(0)e^{-z/L},$$

where $P(0)$ is the pressure at sea-level [$z = 0$]. Compare the exact and numerical solutions.

The density follows

$$\rho(z) = \frac{P(0)m}{kT}e^{-z/L}.$$

Calculate the density at sea level.

The total mass is obtained by integrating the density:

$$M_{\text{atm}} = 4\pi \int_0^\infty \rho(z) \cdot (z + R_e)^2 dz = \frac{4\pi P(0)m}{kT} \int_0^\infty z^2 e^{-z/L} dz.$$

Now use the substitution $z = R_e \cdot \hat{z}$ so that

$$M_{\text{atm}} = \frac{4\pi P(0)R_e^3 m}{kT} \int_0^\infty (1 + \hat{z})^2 e^{-\lambda \hat{z}} d\hat{z},$$

where

$$\lambda = \frac{R_e}{L} = \frac{6.37 \times 10^6 \text{ m}}{8.04 \times 10^3 \text{ m}} \simeq 792.$$

Q4: Now use MathCad to find the numerical value of the (definite) integral: we find 1.27×10^{-3} . For the mass of the atmosphere, we thus find [$m = 28.8 \text{ u}$]

$$\begin{aligned} M_{\text{atm}} &= \frac{4\pi P(0)R_e^3 m}{kT} \cdot 1.27 \times 10^{-3} \\ &= \frac{4\pi \cdot 1.27 \times 10^{-3} \cdot 1.013 \times 10^5 \text{ Nm}^{-2} \cdot 2.58 \times 10^{20} \text{ m}^3 \cdot 28.8 \times 1.661 \times 10^{-27} \text{ kg}}{1.38 \times 10^{-27} \text{ JK}^{-1} \cdot 300 \text{ K}} \\ &\simeq 5 \times 10^{18} \text{ kg.} \end{aligned}$$

We observe that the mass of the atmosphere is very small compared to the mass of the Earth $M_e \simeq 6 \times 10^{24} \text{ kg}$.

APPENDIX C

II. CONSTANT VOLUME GAS THERMOMETER

A. Objectives

1. To check a mercury-in-glass thermometer against an air thermometer.
2. To obtain an experimental graph of the pressure-temperature relationship for a real gas.
3. To use an extrapolation method to estimate “absolute zero.”

B. Theory

At low densities, the (absolute) pressure of a real gas held at constant volume is proportional to its absolute temperature. This relationship can be expressed as

$$P = b + mT, \quad (1)$$

where P is the absolute pressure, T is the temperature in degree Celsius, m is the slope in the $P - T$ diagram and b is the intercept with the pressure axis at $T = 0$.

Absolute zero is the temperature T_0 that brings the absolute pressure in the constant volume thermometer to zero. From Eq. (1), we have $0 = b + mT_0$, or

$$T_0 = -\frac{b}{m}. \quad (2)$$

The usual way to do this experiment is to use the mercury manometer (Fig. 1) to measure the gauge pressure in the bulb. Calibration is no problem with this gauge since the readings in mm Hg also serve as standard pressure units. In our apparatus, however, we use a modern silicon pressure device (Fig. 2). Its electrical output is a voltage proportional to the pressure difference between its ‘positive’ and ‘negative’ ports. To measure positive gauge pressures we will leave the negative port open to the atmosphere and connect the bulb to the positive port. To use this gauge we must depend on the formula provided by the manufacturer for converting the voltage reading V_G from the pressure sensor to the gauge pressure P_g :

$$P_g = V_G \frac{1250 \text{ KPa}}{\text{V}}. \quad (3)$$

The absolute pressure in the bulb is then

$$P = P_g + P_B, \quad (4)$$

where the barometric pressure P_B is measured with a mercury barometer:

$$P_B = (\text{barometer reading in mm Hg}) \frac{101.13 \text{ KPa}}{760 \text{ mm Hg}}. \quad (5)$$

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C. Procedure

1. Read the wall barometer and record P_B . Be sure the screw at the bottom of the barometer has been adjusted so that the ivory peg just makes contact with the surface of the mercury in the cup. Convert the reading to KPa. In the handbook, look up the corresponding boiling temperature of water. The freezing temperature of water is much less temperature dependent and can be taken to be exactly 0°C .
2. Leave the thin tube connected to the bulb but disconnect it from the pressure sensor at the other end. Place the weighted bulb in the can and fill the can with a mixture of ice and water. The open thin tube prevents any water from getting inside the bulb but allows air in the bulb to come to equilibrium at ice temperature and atmospheric pressure. Stir the mixture with the glass rod until the mercury-in-glass thermometer indicates equilibrium is established.
3. Connect the thin tube to the positive port [marked red]. Record the temperature and pressure sensor reading. The temperature may not be exactly 0°C . The gauge pressure reading will be a very small positive or negative voltage.
4. Remove the surplus ice and replace with water. Heat the can with the *Bunsen burner*, removing when the temperature reaches $10\text{--}15^\circ\text{C}$. Stir thoroughly to obtain a uniform temperature, allowing time for the heat to flow into the air in the flask, and take readings as before. This time the sensor output will be a positive voltage. To avoid wasting time, begin with the data analysis [see part D].
5. Continue heating the can, removing the flame and taking readings of the thermometer and pressure sensor roughly every 10°C . As higher temperatures are reached, the flame should be only partially removed each time so that you can maintain a constant temperature for each reading.
6. Take your last reading with the water boiling vigorously. Do not expect to reach 100°C , since that figure holds only for a room pressure of exactly 760 mm Hg.
7. As the water cools, recheck several of your previous high temperature readings. You may have to supply heat to keep the temperature constant for a sufficient length of time before rechecking each pressure sensor reading.

D. Data Analysis

1. Using a sheet of graph paper, label the horizontal axis in units of $^\circ\text{C}$, with the scale extending from -300°C to $+100^\circ\text{C}$. Label the vertical axis in units of the absolute pressure P [in KPa], extending from 0 to the largest absolute pressure calculated from your observations of P_G .
2. Plot the absolute pressure as a function of the temperature. Draw in the straight line for the best fit for your points. The value obtained for the temperature intercept is “absolute zero.” Find an estimate for the error of the absolute zero.
3. From the results of part D.7 determine the error (including sign) of your mercury thermometer at boiling and freezing temperatures.

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E. Discussion

1. The error caused by the gas in the connecting tubes differing in temperature from the gas in the bulb becomes greater as the water bath temperature increasing differs from that of the surrounding air. From the fact that a confined gas tends to increase in pressure when heated, deduce the sign of this error in the recorded P_G when the water is (a) above room temperature and (b) below room temperature.
2. What effect does the answer to part 6a have on (a) the slope of your graph and (b) the temperature used to obtain your value of the absolute zero?
3. List any other possible sources of systematic error you may have observed or become aware of in carrying out this experiment.
4. List any possible sources of random error.

APPENDIX C

III. MECHANICAL EQUIVALENT OF HEAT

A. Objective

1. Experimentally measure and compare the mechanical energy of work done to the produced thermal energy [friction].
2. Determine the mechanical equivalent of heat, i.e., the conversion between *joules* and *calories*.

B. Theory

Heat is defined as a transfer of energy due to a temperature difference while no work is done. One calorie [1 cal] is the amount of heat needed to raise the temperature of a gram of water by 1° C. [Note that *one calorie* in everyday life - “this can of soup has only 250 calories!” - is actually 1 Kcal. In the experimental set-up, mechanical work done on the system is used to overcome frictional loss; that is, it is transferred into heat. We measure both the mechanical work and the heat and thus obtain the desired conversion factor.

A nylon cord is wrapped around an aluminum cylinder several times with one end of the cord attached to a heavy weight. The cylinder is then rotated in a direction such that the frictional force of the cylinder on the cord will lift the heavy weight, ideally keeping the weight in equilibrium position several inches above the floor. The work done on the cylinder is $W = \tau\theta$, where τ is the torque exerted by the nylon cord and θ is the angle through which the cylinder is rotated. In mechanical equilibrium, with the mass above the floor, the tension is equal to the weight of the hanging mass. The torque is then given by $\tau = RMg$, where R is the radius of the cylinder and Mg is the weight of the mass. If the cylinder rotates a total of N times, then the angle is given by $\theta = 2\pi N$ [in radians!]. The total amount of mechanical work done on the cylinder is

$$W = RMg2\pi N. \quad (1)$$

The cylinder is made of aluminum with a specific heat

$$c \simeq 215 \frac{\text{calories}}{\text{kg } ^\circ\text{C}}. \quad (2)$$

If the temperature of the cylinder raises from T_i to T_f , the necessary amount of heat follows from the mass of the cylinder m , the specific heat of aluminum $c \simeq 215 \text{ cal/kg } ^\circ\text{C}$, and the temperature increase ΔT :

$$Q = mc(T_f - T_i). \quad (3)$$

The mechanical equivalent of heat is defined

$$J = \frac{W}{Q}. \quad (4)$$

Note that J has units $[J] = \text{J/cal}$.

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C. Procedure

1. Determine the weight of the aluminum cylinder and cool it to about 10°C below room temperature by placing it in the freezer. The calorimeter is cooled below room temperature to allow ambient heat transferred into the calorimeter from the room to help offset the heat transferred out of the calorimeter when it gets to temperatures above room temperatures. The starting and stopping temperatures should equally straddle room temperature.
2. Replace calorimeter onto rotating shaft and monitor its temperature.
3. Make sure that surface is dry and apply a thin film of graphite. item Wrap four (4) turns of rope around the calorimeter.
4. Turn the crank handle and observe temperature to raise. Note that the temperature is measured by a thermistor [see below].
5. Record the number of turns and measure the radius of the cylinder.

Thermistor

R [k Ω]	T [°C]	R [k Ω]	T [°C]
269.08	5	95.45	26
255.38	6	91.13	27
242.46	7	87.02	28
230.26	8	83.12	29
218.73	9	79.42	30
207.85	10	75.90	31
197.56	11	72.56	32
187.84	12	69.39	33
178.65	13	66.36	34
169.95	14	63.48	35
161.73	15	60.74	36
153.95	16	58.14	37
146.58	17	55.66	38
139.61	18	53.30	39
133.00	19	51.05	40
126.74	20	48.91	41
120.81	21	46.86	42
115.19	22	44.92	43
109.85	23	43.06	44
104.80	24	41.29	45
100.00	25	39.61	46

APPENDIX C

IV. STABILITY OF DRY AIR AND BRUNT-VAISALA OSCILLATIONS

A. Stability of Dry Air

We consider a volume V of dry air [‘parcel’] with density ρ surrounded by air with density ρ' . Archimedes principle then gives for the acceleration of the volume of dry air: $\rho V \cdot a = \rho' V \cdot g - \rho V \cdot g$ so that the acceleration of the dry air parcel follows

$$a = g \frac{\rho' - \rho}{\rho} = g \left(\frac{\rho'}{\rho} - 1 \right). \quad (1)$$

We assume the ideal gas law to write $\rho/\rho' = T'/T$, where T is the temperature of dry air and T' is the temperature of atmosphere.

$$a = g \left(\frac{T}{T'} - 1 \right). \quad (2)$$

Q1: Use numerical examples to test this equation. Does it agree with your expectations?

B. Temperature Profile

As a result of this acceleration, a parcel of air initially at the height z_0 moves to a height z . We assume that the parcel does not exchange heat with the surrounding so that the process is adiabatic. This means that dry moving up (down) will cool down (warm up). As a result, the temperature depends on the height: temperature profile $T = T(z)$. We apply the first law to one mole of gas:

$$C_p(T - T_0) = -Mg(z - z_0), \quad (3)$$

where M is the molar mass. We solve for T :

$$T = T_0 - \frac{Mg}{C_p}(z - z_0) = T_0 - \Gamma(z - z_0). \quad (4)$$

where we introduced the *lapse rate* $\Gamma = Mg/C_p$.

Q2: Derive Eq. (3).

Q3: Find the lapse rate for dry air [i.e., an ideal, diatomic gas].

C. Brunt-Vaisala Oscillations

We assume that the lapse rate of the ambient air is different from the lapse rate for dry air:

$$T'(z) = T_0 - \gamma(z - z_0), \quad \gamma \neq \Gamma. \quad (5)$$

Inserted into Eq. (2), we get

$$\frac{d^2 z}{dt^2} = g \left(\frac{T(z)}{T'(z)} - 1 \right). \quad (6)$$

Q4: Discuss *qualitatively* the cases $\gamma < \Gamma$ and $\gamma > \Gamma$.

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Numerical solution using MathCad: Define the temperature profiles:

$$T(z) := T_0 - \Gamma \cdot (z - z_0), \quad (\text{dry air}) \quad (7)$$

$$Te(z) := T_0 - \gamma \cdot (z - z_0). \quad (\text{ambient air}). \quad (8)$$

We define

$$z_0 = z, \quad z_1 = v = \frac{dz}{dt}. \quad (9)$$

The second-order differential equation can then be written:

$$\frac{dz_0}{dt} = z_1 \quad (10)$$

$$\frac{dz_1}{dt} = g \cdot \left(\frac{T(z_0)}{Te(z_0)} - 1 \right). \quad (11)$$

This is implemented in MATHCad as:

$$D(t, z) := \begin{pmatrix} z_1 \\ g \cdot \left(\frac{T(z_0)}{Te(z_0)} - 1 \right) \end{pmatrix}. \quad (12)$$

The initial conditions are written

$$\text{init_cond} = \begin{pmatrix} z_0 \\ v_0 \end{pmatrix}. \quad (13)$$

We use the Runge-Kutta method to integrate the coupled differential equations:

$$\text{solut_dfq} = \text{rkfixed}(\text{init_cond}, 0.2000, 2000, D). \quad (14)$$

Note that rkfixed returns a matrix in which the first column contains time, the second column contains position, and the third column contains the velocity:

$$t := \text{solut_dfq}^{\langle 0 \rangle}, \quad (15)$$

$$z := \text{solut_dfq}^{\langle 1 \rangle}, \quad (16)$$

$$v := \text{solut_dfq}^{\langle 2 \rangle}. \quad (17)$$

Q5: Use $\Gamma \simeq 1 \times 10^{-2} \text{ Km}^{-1}$ and $\gamma = 0.6 \times 10^{-2} \text{ Km}^{-1}$. Plot the graph z vs. t .

Q6: We found a periodic motion of the parcel of dry air. Derive an expression for the period and compare with your numerical results.

Q7: Discuss the cases $\Gamma > \gamma$ and $\Gamma < \gamma$.

Q8: The ambient lapse rate can become negative [in what atmospheric condition?]. For $\Gamma \simeq 1 \times 10^{-2} \text{ Km}^{-1}$, find the lapse rate γ that corresponds to a period of 3 minutes.

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V. RUCHARDT METHOD FOR MEASURING C_p/C_v

A precision tube of cross section A is attached large vessel of volume \mathcal{V}_0 . A stainless steel ball fits perfectly inside the tube. You take the ball and lower it slowly down the tube until the increased air pressure supports it.

Q1: Determine the distance below the tube's top at which the sphere is supported.

The ball is in (mechanical) equilibrium when

$$mg + AP_{\text{atm}} = AP_0. \quad (1)$$

We choose a coordinate system such that $z = 0$ at the equilibrium position. If the pressure inside the vessel is $p > 0$, the air pushes the ball upwards,

$$m \frac{d^2 z}{dt^2} = -mg + A(P - P_{\text{atm}}). \quad (2)$$

We assume that the compression and expansion of the air inside the vessel is “fast,” and thus ignore heat exchange with the environment. That is, we assume that the process is adiabatic, $PV^\gamma = P_0V_0^\gamma$, where V_0 is the volume of the vessel *plus* the volume of the tube when the ball is in equilibrium. If the ball is at a height z , we have $V = V_0 + Az$, and

$$P = P_0 \left(\frac{V_0}{V_0 + Az} \right)^\gamma = P_0 (1 + z/l)^{-\gamma}, \quad (3)$$

where $l = V_0/A$ is a characteristic length scale for the problem. Thus the equation of motion is

$$m \frac{d^2 z}{dt^2} = -mg + A [P_0(1 + z/l)^{-\gamma} - P_{\text{atm}}] \quad (4)$$

Q2: How are “small” oscillations characterized?

Q3: Find the “linearized” equation of motion.

Since $AP_{\text{atm}} + mg = AP_0$ this can be simplified:

$$m \frac{d^2 z}{dt^2} = AP_0 [(1 + z/l)^{-\gamma} - 1]. \quad (5)$$

For $z/l \ll 1$, we have

$$\frac{1}{(1 + z/l)^\gamma} \simeq \frac{1}{1 + \gamma z/l} \simeq 1 - \gamma \frac{z}{l}. \quad (6)$$

Inserted above we have

$$m \frac{d^2 z}{dt^2} = -\frac{\gamma AP_0}{l} z = -\frac{\gamma A^2 P_0}{V_0} z. \quad (7)$$

This is the equation for a harmonic oscillator. The (angular) frequency ω follows

$$\omega^2 = \frac{\gamma A^2 P_0}{mV_0} \quad (8)$$

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A. MathCad Implementation

We define

$$T_{\text{approx}} := 2\pi \sqrt{\frac{V_0 m}{A^2 P_0 \gamma}} \quad (9)$$

and

$$N := 800, \quad T_{\text{tot}} := \frac{N}{200} T_{\text{approx}}, \quad n := 0..N. \quad (10)$$

Furthermore, we define a two-dimensional vector containing the position $z = \zeta_0$ and the velocity $dz/dt = \zeta_1$. The Initial conditions are

$$\zeta := \begin{pmatrix} 10 \\ 0 \end{pmatrix}. \quad (11)$$

The equations of motion read

$$Z(t, \zeta) := \begin{bmatrix} \zeta_1 \\ -g + (A/m) \cdot (P_0 \{1 + A\zeta_0/V_0\}^{-\gamma} - P_{atm}) \end{bmatrix}. \quad (12)$$

The integration is done using the Runge-Kutta method:

$$z := \text{rkfixed}(\zeta, 0, T_{\text{tot}}, N, Z). \quad (13)$$

MathCad gives the result in matrix form:

$$\text{time} := z^{<0>}, \quad \text{position} := z^{<1>}, \quad \text{velocity} := z^{<2>}. \quad (14)$$

Q4: What happens if the initial displacement is large?

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VI. RUCHARDT METHOD FOR MEASURING C_p/C_v : EXPERIMENT

A. Objective

To measure the ratio of $\gamma = C_p/C_v$ of air at room temperature.

B. Theory

In the preceding lab we have derived an equation for the displacement of the ball in the tube:

$$\frac{d^2 z}{dt^2} = -\frac{\gamma A^2 P_0}{m V_0} z, \quad (1)$$

where V_0 is the volume of the jug *plus* the volume of the tube when the ball is in (mechanical) equilibrium, $P_0 = P_{\text{atm}} + mg/A$.

Q1: We measure the pressure inside the jug instead of the position of the ball. Show that

$$z = -\frac{V}{\gamma P A} \Delta P. \quad (2)$$

Show that the pressure change obeys the same differential equation:

$$\frac{d^2 \Delta P}{dt^2} + \omega^2 \Delta P = 0, \quad (3)$$

where $\omega^2 = \gamma A^2 P_0 / m V_0$.

We see that the ball stops moving after 10 or twelve oscillations. This shows that we have to include damping [HRW 16-8 p. 360ff]. The equation of motion reads:

$$\frac{d^2 \Delta P}{dt^2} + \beta \frac{d \Delta P}{dt} + \omega^2 \Delta P = 0. \quad (4)$$

The solution reads:

$$\Delta P(t) = (\Delta P)_0 e^{-\beta t/2} \cos(\omega' t + \phi). \quad (5)$$

Here $(\Delta P)_0$ is the maximum amplitude. The angular frequency is given by

$$\omega' = \sqrt{\omega_0^2 - \frac{\beta^2}{4}} \quad (6)$$

Q2: What are possible sources of damping?

C. Procedure

1. The tube and ball have to be very clean. Otherwise there will be unwanted friction. Also the tube may become scratched or broken if excessive force is used to push the ball out past dirt on the inside of the tube. Therefore, we use a method that makes it possible to lift the ball to the top of the tube without handling it. First the ball is prevented from falling into the jug by a wire stop attached to the rubber stopper at the top of the jug. Secondly a pressure bulb air pump connected to the stopcock at the bottom of the jug is used to levitate the ball to where it can be held just above the tube by an electromagnet.

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2. The mass of the ball is 16.7 g, the diameter of the tube is 16 mm, and the volume of the jug is 10.9 L.
3. The pressure gauge is connected to the jug through the rubber stopper at the bottom of the jug. The pressure gauge is powered by a power supply and has a calibration of 1250 KPa when the power supply is set at 10V. Adjust and record the power supply voltage.
4. Set parameters on the control panel for the data acquisition system. If you ask for 500 points of data and make a sample period of 0.02 sec you will be able to follow several oscillations of the ball over a time interval of 10 sec. Select Channel and Ranges. The pressure gauge output requires the most sensitive range of 0.05 V. Because the pressure gauge puts out a low level signal of only about 1 mV in this experiment, electronic noise in this experiment is very noticeable. The data acquisition board is capable of taking accurate measurements at the rate of about 5,000 voltage samples per sec. Therefore, you may set the number of samples to be averaged to 500. Then each of the 500 data points reported will be an average of 500 measurements.
5. You are now ready to get the ball into position at the top of the tube. First, turn on the electromagnetic power supply and adjust its current to 200 mA so that the ball will stick to it when levitated. Use the pressure bulb attached to the stopcock to levitate the ball.
6. Turn off the power supply to the electromagnet to release the ball. The ball will typically hit the wire stop once or twice after this the ball oscillates in the tube. Now click RUN on the acquisition program to measure the pressure as a function of time. The data is saved on a floppy by the command WRTEPRN("a:FileData"):Vdata statement.

D. Analysis

Determine the frequency of the damped oscillation ω' and the time constant β . Use this result to determine the undamped angular frequency ω . Now determine the adiabatic exponent γ , and do an error analysis. Compare with known result $\gamma = 1.4$. Discuss any discrepancy.