Mechanics Laboratory 1105, Spring 2025

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https://www.physics.smu.edu/tneumann/110X_Spring2025/

Lab 9 — Kinetic and potential energy transfer Max. points: 44

Your preparation: Work through before coming to the lab

- Prepare for the lab by thoroughly reading and understanding the measurement and analysis procedures on this worksheet. Photos of the equipment and further introductory material will be made available on https://www.physics.smu.edu/tneumann/110X_Spring2025/schedule-mechanics/.
- Collect all your questions and ask your instructor at the beginning of the lab.
- Work through the following topics in Halliday, Resnick, and Walker [1]:
  - Work and kinetic energy: Understand the relationship between work, kinetic energy, and the work-energy theorem.
  - Potential energy: Understand gravitational potential energy and elastic potential energy (spring potential energy). You will be analyzing energy transformations. Understand how to relate changes in gravitational potential energy to changes in height.
  - Conservation of mechanical energy: Know when mechanical energy is conserved and how to apply the principle of conservation of energy.
  - Perfectly inelastic collisions: Learn about the principles of momentum conservation in perfectly inelastic collisions. Understand that kinetic energy is *not* conserved in these collisions.

Pre-lab: Upload to Canvas before coming to the lab

A reminder: Upload your answers as a text document (exported as PDF) to Canvas before the lab begins (Canvas uploads are no longer possible 30 minutes before the lab starts!).

Pre-lab 1 8 points

1. (1 point) Define *mechanical energy*. What condition(s) must be met for mechanical energy to be conserved in a system?
2. (1 point) In this experiment, a spring launches a ball. Write down the formula for the potential energy stored in a compressed spring with spring constant k and compression distance x. What happens to this potential energy when the spring is released and launches the ball?

3. (1 point) The ball, with mass m, is launched with a muzzle velocity v. It then collides *inelastically* with a stationary pendulum of mass M. Write down the equation that expresses the conservation of *momentum* for this collision. Use v' to represent the velocity of the combined ball+pendulum immediately *after* the collision.

4. (2 points) Using your answer from question 3, derive an expression for v' (the velocity of the combined ball+pendulum immediately after the collision) in terms of m, M, and v. Show your work.

5. (1 point) After the collision, the pendulum (with the ball embedded) swings upward. What type of energy does the pendulum *gain* as it swings upward? What type of energy does it *lose*?

6. (2 points) Describe *two* sources of systematic uncertainty and *two* sources of random uncertainty in this experiment. Be specific about which part of the experiment is affected by each error source.

Lab measurements and report: submission by end of class

A reminder: All measurements must be fully documented. The final report must be uploaded to Canvas *by the end of the class* exported as PDF with plots and tables from Excel embedded as images. Canvas will stop accepting uploads 10 minutes after the class ends. If you have not fully completed your report, you must upload the documents as far as you have completed them for grading.

Measurement 1 *Ballistic Pendulum Measurements* 17 points

Equipment: Ballistic pendulum apparatus (spring gun, pendulum, sector gear, ratchet), steel ball, dual-beam photogate, ruler/meter Stick, triple beam balance, spreadsheet software.

1. (3 points) **Measuring the pendulum length (L):**
   (a) Remove the pendulum from the ballistic pendulum apparatus.
   (b) Using a ruler or meter stick, carefully measure the distance from the center of the pivot point (where the pendulum was attached) to the center of mass (CM) marked on the pendulum. This is the pendulum length, L.
   (c) Estimate the uncertainty in your measurement of L (e.g., due to the precision of the ruler and the difficulty of locating the exact center of mass).
   (d) Record the value of L and its uncertainty (ΔL) in your spreadsheet.

2. (4 points) **Measuring masses (m and M):**
   (a) Use the triple beam balance to measure the mass of the steel ball (m). Estimate and record the uncertainty in this measurement (Δm).
   (b) Use the triple beam balance to measure the mass of the pendulum (M). Estimate and record the uncertainty in this measurement (ΔM).
   (c) Record both masses and their uncertainties in your spreadsheet.

3. (5 points) **Measuring the muzzle velocity (v):**
   (a) Secure the dual-beam photogate to the launcher base such that the photogate beams are positioned just in front of the ball when the spring is fully extended (but not yet released).
   (b) Cock the spring gun, loading the steel ball.
   (c) Start data recording in Capstone.
   (d) Launch the ball by releasing the spring. Be careful to not launch the ball into equipment or other students.
   (e) Record the velocity (v) measured by the photogate in your spreadsheet.
   (f) Repeat steps (c)-(e) at least *five* times, recording the velocity for each trial.
   (g) Calculate the *average* muzzle velocity ($\bar{v}$) from your five trials.
   (h) Calculate the *standard deviation of the mean* of the velocity measurements. This will serve as your uncertainty in the muzzle velocity ($\Delta\bar{v}$).
4. (5 points) **Measuring the angle of repose (θ):**
   (a) Remove the dual-beam photogate.
   (b) Reattach the pendulum to the apparatus.
   (c) Cock the spring gun, loading the steel ball.
   (d) Launch the ball into the pendulum, allowing the pendulum to swing up and be caught by the ratchet mechanism.
   (e) Carefully read and record the angle of repose (θ) indicated on the scale. Remember that the scale has a resolution of 2 degrees, with odd-numbered angles estimated between the markings.
   (f) Estimate the systematic uncertainty in your angle measurement ($\Delta\theta_{\text{syst.}}$). Consider the width of the indicator and the discrete nature of the ratchet mechanism. *Explain your reasoning for your uncertainty estimate in your report.*
   (g) Repeat steps (c)-(f) at least *five* times, recording the angle for each trial.
   (h) Calculate the *average* angle of repose ($\bar{\theta}$) from your trials.
   (i) Calculate the *standard deviation of the mean* of the angle measurements. This will serve as the random uncertainty in the angle ($\Delta\bar{\theta}$).

Analysis 1 *Energy and momentum analysis* 19 points

1. (4 points) **Initial kinetic energy of the ball:**
   (a) Calculate the initial kinetic energy (K_{ball}) of the ball *just before* it impacts the pendulum, using the average muzzle velocity ($\bar{v}$) and the mass of the ball (m): $K_{\text{ball}} = \frac{1}{2}m\bar{v}^2$.

(b) Propagate the uncertainties in m and $\bar{v}$ to determine the uncertainty in the initial kinetic energy (ΔK_{ball}). Show your error propagation calculation.

2. (4 points) **Velocity and kinetic energy after the collision:**

   (a) Using the principle of conservation of momentum, calculate the velocity (v') of the combined ball+pendulum system *immediately after* the collision. Use the formula you derived in the pre-lab (which should be $v' = \frac{m}{m+M}\bar{v}$).

   (b) Calculate the uncertainty in v' ($\Delta v'$) by propagating the uncertainties in m, M, and $\bar{v}$. Show your error propagation calculation.

   (c) Calculate the kinetic energy (K_{pend}) of the combined ball+pendulum system *immediately after* the collision: $K_{\text{pend}} = \frac{1}{2}(m + M)v'^2$.

   (d) Calculate the uncertainty in K_{pend} (ΔK_{pend}) by propagating the uncertainties in m, M, and v'. Show your error propagation calculation.

3. (5 points) **Potential energy and predicted angle:**

   (a) Calculate the change in height (Δh) of the center of mass of the pendulum+ball system as it swings from its lowest point to its maximum height. Use trigonometry and the pendulum length (L) and the *average* angle of repose ($\bar{\theta}$): $\Delta h = L(1 - \cos\bar{\theta})$.

   (b) Calculate the uncertainty in Δh ($\Delta(\Delta h)$) by propagating the uncertainties in L and $\bar{\theta}$. Show your error propagation calculation.

   (c) Calculate the gravitational potential energy (E_P) gained by the pendulum+ball system at its maximum height: $E_P = (m + M)g\Delta h$, where $g = 9.81\,\text{m/s}^2$.

   (d) Calculate the uncertainty in E_P (ΔE_P) by propagating the uncertainties in m, M, and Δh. Show your error propagation.

4. (6 points) **Energy conservation analysis:**

   (a) Compare the initial kinetic energy of the ball ($K_{\text{ball}} \pm \Delta K_{\text{ball}}$) to the kinetic energy of the combined system immediately after the collision ($K_{\text{pend}} \pm \Delta K_{\text{pend}}$). Was kinetic energy conserved in the collision? Explain why or why not, referring to the type of collision.

   (b) Compare the kinetic energy of the combined system immediately after the collision ($K_{\text{pend}} \pm \Delta K_{\text{pend}}$) to the potential energy at the maximum height ($E_P \pm \Delta E_P$). Was mechanical energy conserved during the swing of the pendulum? Explain your reasoning, considering potential sources of energy loss. Do your results agree within uncertainties?

   (c) Calculate the predicted maximum angle of swing (θ_{pred}) assuming perfect energy conservation during the pendulum's swing (i.e., setting $K_{\text{pend}} = E_P$). You will need to rearrange the equations from part 3 to solve for $\theta_{pred} = \arccos(1 - \frac{v'^2}{2gL})$. Show your derivation.

   (d) Compare the predicted angle (θ_{pred}) with the *average measured* angle of repose ($\bar{\theta}$). Discuss any significant differences and relate them to the ratchet mechanism and other sources of energy loss. Quantify the level of agreement or disagreement.

References

[1] D. Halliday, R. Resnick, and J. Walker. *Fundamentals of Physics*. Fundamentals of Physics. John Wiley & Sons.