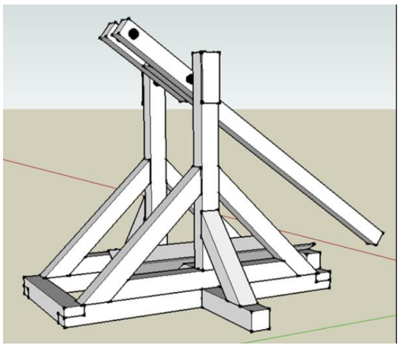
The Trebuchet Challenge

This summative project is intended to bridge the gap between theoretical mechanics and hands-on engineering. Below is a comprehensive project guide, timeline and rubric.

Reporting category: Science Practices



Project Overview: The Gravity-Powered Siege

Students will design, build and calibrate a **functional trebuchet.** The goal is to maximize **translational kinetic energy** of a projectile using the **gravitational potential energy** of a falling counterweight.

The Physics Deliverable

Since this is an AP class, you aren't just "building a toy". You must individually submit a **Technical Brief** that includes:

1. **Torque Analysis:** A diagram of the arm at the moment of release, identifying the center of mass and net torque.

2. **Energy Transformation:** Calculation of theoretical vs actual range
   - **Ug =mgh** (Counterweight) → **K=1/2mv²** (Projectile)

3. **Efficiency Calculation:** Calculate the ratio of work out vs work in.

Timeline

Phase	Dates	Focus
I. Design	Fri, May 8 – Tue, May 12	Researching mechanical advantage and torque; scale drawings/blueprints.
II. Build	Thu, May 14 – Thu, May 21	Construction of frame, throwing arm, and pivot assembly. The use recycled materials is strongly encouraged.
III. Test	Tue, May 26 – Mon June 1	Calibration of release pin angle and sling length. Data collection (*v*,*d*,*t*). Revisions as needed
IV. Siege	Wed. June 3	**Competition Day:** Distance and Accuracy trials *See ***Siege Day*** rules
V. Analysis	**DUE:** Fri, June 5	Final technical report and energy efficiency calculations

Grading Rubric

Category	Exhibit Depth	Exhibiting	Developing	Emerging
Structural Integrity	Device is stable, survives multiple launches without repair	Device is functional but requires minor maintenance between shots	Device fails or breaks during the first round of testing and requires repair	Device structure is incomplete and non-functional
Physics Analysis	FBDs and energy calculations are flawless	Analysis mostly correct but contains minor calculation errors	Analysis is missing significant sections or fails to connect theory to the build	Analysis missing
Performance **See performance metrics*	Distance to Arm Ratio is >20	Distance to Arm Ratio is = 10	Distance to Arm Ratio is <5	Distance to Arm Ratio is <1
	Energy Efficiency Ratio > 30	Energy Efficiency Ratio is = 20	Energy Efficiency Ratio is <10	Energy Efficiency Ratio is <5
	"Siege Factor" score is 1.3+	"Siege Factor" score is 0.6-1.2	"Siege Factor" score is 0.2-0.5	"Siege Factor" score is < 0.2
Technical Brief	Effectively organized and comprehensive communication of process with strong video/photo evidence	Organized communication of process with key video/photo evidence	Communication of process could be more organized and complete	Limited evidence of process

Design Criteria

- **The Projectile:** a **squash ball** or a **large marshmallow**. Enough mass to fly but won't break windows
- **The Counterweight:** Max **1.0 kg** to **1.5 kg** (standard lab masses)
- **The Frame:** Max height of **50 cm**. Base must fit a 50cm x 50 cm square. This allows the machine to sit on a lab bench or the floor without hitting the ceiling.
- **The Materials:** Open-ended (wood, PVC, metal), but must include a sling mechanism to be a true trebuchet.
- **Power Source:** Must be purely gravity-driven (no springs, motors, or compressed air)
- **The Range:** Aim for a **3-6 meter** launch zone.

Normalized Performance Metrics For Trebuchets

1. The Distance-to-Arm Ratio (R_L)

This is the "Geometric Effectiveness" of the design. It measures how much distance (d) the machine generates relative to the total length of the throwing arm (L_{arm}).

$$R_L = \frac{d}{L_{arm}}$$

- **Why it works:** It scales the output to the size of the machine
- **The Benchmarks:**
  - $R_L < 5$: Inefficient (likely a "floater" release or high friction)
  - $R_L = 10\text{-}15$: Solid engineering; good release pin timing.
  - $R_L > 20$: Elite design; optimized sling length and minimal mass in the throwing arm.

2. The Energy Efficiency Ratio (η)

While distance is fun, real physics students should measure how much of the **Potential Energy (U_g)** from the counterweight actually converts into the **Kinetic Energy (*K*)** of the projectile.

$$\eta = \left(\frac{\frac{1}{2} m_p v^2}{M_{cw} g \Delta h_{cw}} \right) \times 100\%$$

Variables:

- m_p: Mass of the projectile
- v: Launch velocity (calculated from range d and launch angle θ)
- M_{cw}: Mass of the counterweight
- Δh_{cw}: The vertical distance the counterweight drops.

3. The "Siege Factor" (S)

If you want a single number for a leaderboard that accounts for size, weight and distance, use the Siege Factor. This rewards machines that throw heavy things far using a light machine.

$$S = \frac{d \cdot m_p}{L_{arm} \cdot M_{cw}}$$

Score	Mechanical Implication
0.1-0.5	Heavy counterweight, but most energy is lost to friction or arm inertia
0.6 - 1.2	Good balance. The sling is likely 0.8x to 1.0x the length of the long arm.
1.3+	Highly optimized. Likely uses a "falling" or hinged counterweight to maximize vertical drop.

Siege Day Competition Logistics (3 trials)

Trial 1: The High Wall (Verticality)

Students must clear a "castle wall" (a horizontal bar or PVC pipe) placed 5 meters away.

- **The Challenge:** Start the bar at 2 meters high. Teams get two shots. If they clear it, the bar moves up 0.5 meters.

- **The Physics:** This tests student understanding of launch angle. A steeper release pin angle is required here than for max distance.

Trial 2: The Moat (Distance)

Classic distance trial, but with a "minimum qualifying distance" to prevent low-effort builds.

- **The Challenge:** Measure the absolute furthest bounce-point.

- **The Physics:** Tests the optimal sling-to-arm ratio. Usually, a sling length roughly equal to the long arm length provides the best "whip" effect.

Trial 3: The Keep (Accuracy)

Place a hula hoop or a bucket a fixed distance (eg. 3-6 m). Points are awarded for landing inside (Direct Hit) or hitting the rim (Structural Damage).

- **The Physics:** This tests repeatability. Can you reset the machine to the exact same state every time?

Scoring Details

The High Wall	10 pts per 0.5m cleared	Projectiles: Calculating y-component of velocity
The Moat	Distance / 2 (max 50 pts)	Work-Energy: Maximize K from Ug
The Keep	15 pts per direct hit	Precision vs Accuracy: Identifying sources of error

Technical Report: Trebuchet Engineering Lab

Name: ____ Block: ______

Group member's name: _____________________________________

1. Design Specifications

- Mass of Counterweight (M_{cw}): _______ kg
- Mass of Projectile (m_p): _______ kg
- Length of Long Arm (L_{long}): ________ m
- Length of Short Arm (L_{short}): ________ m
- Sling Length (L_s): _________ m

2. Theoretical Analysis (Pre-Trial)

- **Calculate Maximum Potential Energy:**
  Measure the height of the counterweight at its highest point (hi) and lowest point (hf).

$$U_g = M_{cw}g(h_i - h_f)$$

  Result: _______________ J

- **The Design Hypothesis:** Explain how your chosen arm ratio ($L_{long} : L_{short}$) will affect the angular velocity of the launch.

3. Data Collection (Siege Trials)

Trial Type	Distance (d)	Time in Air (t)	Height Cleared (y)
Wall			
Moat			
Keep			

4. Performance Metrics (Calculations)

- **Horizontal Velocity (v_x):** Using your best distance, $v_x = d/t$

Result: __________ m/s

- **Launch Velocity** (v_0): Using $v_y = v_0 \sin\theta - gt$, solve for the resultant velocity at release. (Assume 45° for max distance if launch angle wasn't measured).

Result: ___________ m/s

- **Distance-to-Arm Ratio (R_L)**: $R_L = d/L_{total\ arm}$

Result: ____________

- **System Efficiency (η)**:

$$\eta = \frac{\frac{1}{2} m_p v_0^2}{U_g} \times 100$$

Result: _________ %

5. Post-Mortem Analysis

1. Energy Loss: Where did the missing energy go? (Identify at least two specific non-conservative forces in your build with evidence).

2. Modifications: If you had one more day, what specific change would you make to the **release**

pin angle or **sling length** to increase the Siege Factor? Why?

3. Torque: Draw a FBD of the arm at the moment of release. Label the pivot, the center of mass of the arm, and the tension forces.

Final Grade Summary (Teacher Use Only)

- **Build Quality: ________/30** (Stability, Trigger Mechanism)
- **Performance:** ________ / 40 (Trial Results)
- **Analysis :** ________ / 30 (Accuracy of Calculations, Communication)

- **Total Score:** ________ / 100