CRI: Connecting Introductory Mechanics Courses With a Shared Trebuchet Classroom Demonstration

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I spent 10+ years in industry as an engineer in structural mechanics and structural health monitoring projects, earning professional licensure as PE and SE. My PhD research focused on the structural optimization of dynamic systems including random loading and vehicle-bridge interaction. Now as teaching faculty, I try to connect course concepts to real-world examples in a way that motivates and engages students.

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CRI: Connecting Introductory Mechanics Courses With a Shared Trebuchet Classroom Demonstration

Abstract

Traditional classroom lectures often focus on theory-based instruction and discussion to teach engineering concepts. However, some concepts are challenging to conceptualize and connect to real-world applications or practical examples. As a result, students may struggle to recognize the relevance of course content to their future engineering careers. To address this gap, we designed a physical demonstration to be integrated throughout three core mechanics courses: Statics, Dynamics, and Solid Mechanics. These demonstrations allow students to observe the operation of a machine that directly relates to course content, while using physical and numerical models and making predictions about its behavior. The chosen design, a trebuchet, was selected for its ability to engage students and readily observable engineering principles. The trebuchet consists of a frame supporting a rotating beam used to launch a projectile. In Statics, it demonstrates the summation of forces and moments. In Dynamics, it illustrates rigid body kinematics and projectile motion. Students can modify design parameters, such as pivot points and counterweights, to explore the impact of the trebuchet's design on the trajectory of the projectile. Finally, in Solid Mechanics, the trebuchet is used to demonstrate elastic deformation in the arm under static loading. This CRI includes complete materials list, fabrication plans for trebuchet construction, and standard operation plans to support instructors. Together, these components create an educational toolkit that promotes hands-on, data-driven learning across multiple core courses. This integrated lecture and demonstration strengthens students' ability to connect theoretical concepts to real-world applications while promoting coherence across core mechanics courses through repeated exposure to the same physical system.

Introduction

Traditional engineering instruction relies heavily on lectures, conceptual derivations, and symbolic problem solving [1]. While these approaches are foundational, they often fail to support students in developing a conceptual understanding of the physical meaning behind equations [1, 2, 3, 4]. In today's workforce, technical proficiency alone is insufficient; engineering graduates must also demonstrate problem-solving ability, critical thinking, and the capacity to create value for their organizations [5]. This broader set of skills, collectively known as an entrepreneurial mindset (EM) [6], can be effectively fostered through active learning in the classroom [7], an instructional strategy where students play an active role in the learning process [8].

Active learning through instructional demonstrations can significantly improve students' conceptual understanding, assimilation, and engagement when implemented thoughtfully [9, 10, 11]. Because demonstrations exhibit real-world tradeoffs, constraints, and system-level interactions, they provide opportunities to cultivate elements of an EM. There are numerous resources (websites, videos, education platforms, etc.) from which instructors can obtain ideas or inspiration for implementing demonstrations in their courses. However, most demonstrations are developed for a single course or concept, targeting only one specific principle. Implementing a single apparatus for demonstrating different concepts across courses could strengthen conceptual continuity and highlight how principles from multiple courses interact in real engineering systems.

At a large Midwestern university, recent efforts have explored ways to incorporate entrepreneurial mindset concepts in various introductory mechanics courses through real-world problems statements [12], examples in lecture [13], and online reference pages to help students build connections across courses [14]. Building on this work, we developed classroom demonstrations centered around a fully functional, classroom-scale trebuchet designed for use across Statics, Dynamics, and Solid Mechanics, suitable for large classroom settings. The trebuchet was selected for its readily observable mechanical behavior that combines force balance, rotational motion, energy transfer, projectile motion, and structural deformation. At the same time, the system remains intuitive, engaging, and safe for classroom use.

This Classroom Ready Innovation (CRI) paper presents the development and instructional design of a trebuchet-based demonstration intended for integration across three mechanics courses: Statics, Dynamics, and Solid Mechanics. We describe the design, the concepts covered, the specific demonstrations for each course, fabrication, materials, instrumentation for data collection, and general tips for effective classroom implementation. To support instructors, we created Standard Operating Procedures (SOPs) with setup guidelines for the trebuchet including example analyses using the open-source Tracker software, and recommendations for facilitating active-learning discussions (all provided in Appendix, CAD drawings are provided upon request). By developing a demonstration that spans multiple mechanics courses, this work aims to strengthen conceptual understanding, enhance student engagement, and illustrate how fundamental engineering principles manifest in authentic mechanical systems.

System Description

The trebuchet is a medieval catapult that relies on gravity to launch projectiles. Its key components are a lever arm, counterweight, a sling and a projectile (Figure 1). The machine works by raising the counterweight to store potential energy, then releasing it. When the weight drops, it swings the long arm which whips a sling to launch the projectile.

Figure 1: Medieval trebuchet. © Quistnix (2018) (CC BY-SA).

Our modern trebuchet design made from aluminum provides adjustable sling lengths, counterweights, and interchangeable beams that allow instructors to tailor demonstrations to course-specific learning outcomes (Figure 2). Simple data-collection methods such as a spring-scale, ruler, and open-source video tracker, provide real-time data that students can observe and analyze to reinforce conceptual understanding. The trebuchet uses an aluminum frame that is 34" tall, 12" wide and 24" long. The use of lightweight aluminum structural members allows it to be stored, transported, and deployed on tabletops or laboratory benches without requiring special equipment or multiple people for setup and operation.

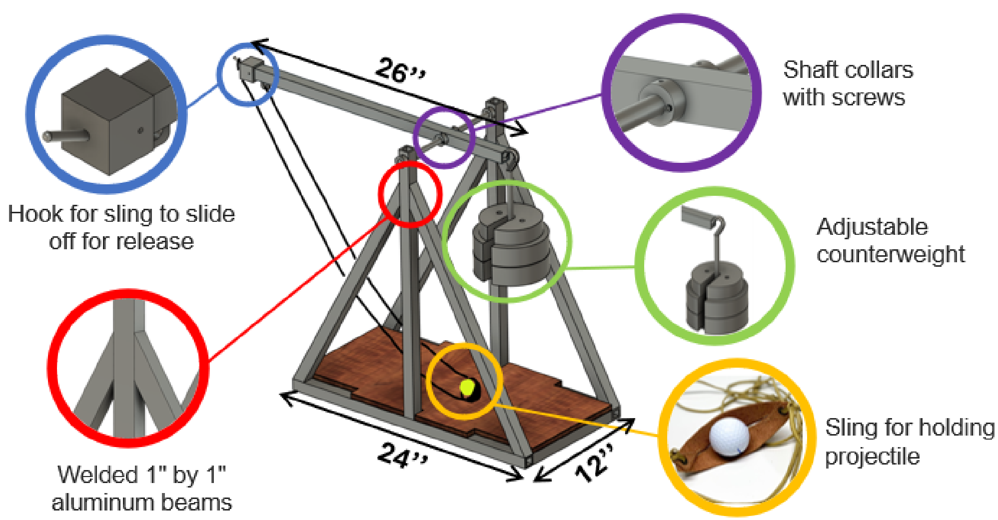

Figure 2: Trebuchet CAD model highlighting design details.

The trebuchet demonstrations are currently shown in three introductory courses in the Theoretical and Applied Mechanics (TAM) sequence which is part of the Mechanical Science and Engineering Department at the University of Illinois Urbana-Champaign. In Statics, the trebuchet is used to examine moment and force balance. It reappears later in Dynamics, where students analyze angular acceleration, predict projectile range, and compare theoretical motion with experimental data. Finally, in Solid Mechanics, the same trebuchet allows students to observe beam deflection under static loading. By returning to the same physical system across three courses, students build deeper conceptual connections and continuously relate abstract mechanics concepts to a tangible machine that they have studied across multiple perspectives.

Applications Across Courses

Statics

In Statics, the trebuchet functions as a controlled system for examining equilibrium. The throwing arm is fixed in place at a horizontal angle, and a spring scale is attached at the sling connection point provides a direct measurement of the force required to maintain static equilibrium. Students will relate these measured values to their free-body diagrams and apply $\sum F = 0$ and $\sum M = 0$ to validate predictions about moment arms, force components, and torque balance (Figure 3). The activity is implemented as a lecture demonstration that helps students transition from idealized textbook examples to real mechanical assemblies with measurable forces.

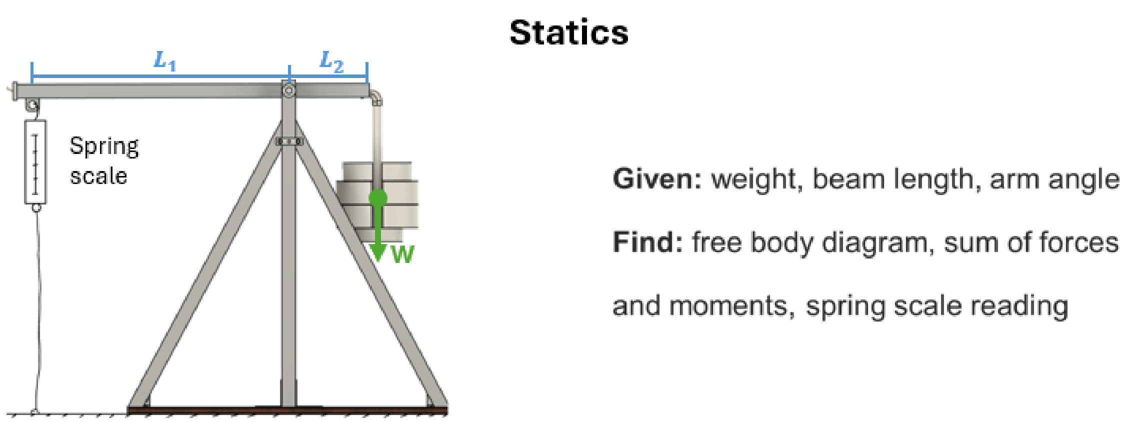

Figure 3: Schematic of trebuchet problem setup for Statics.

Dynamics

In Dynamics, the device shifts from a static structure to a dynamic machine. Students record the projectile launch and trajectory using smartphone cameras and analyze the motion using Tracker video analysis. The projectile can be a ping pong or tennis ball. By varying sling length and counterweight mass, students observe how these parameters influence angular acceleration, projectile range, and energy transfer from the counterweight to the projectile (Figure 4). These experiments are used both in lecture demonstrations and extended discussion-section activities, enabling students to compare theoretical predictions with experimentally observed kinematics and to explore sources of error and model limitations.

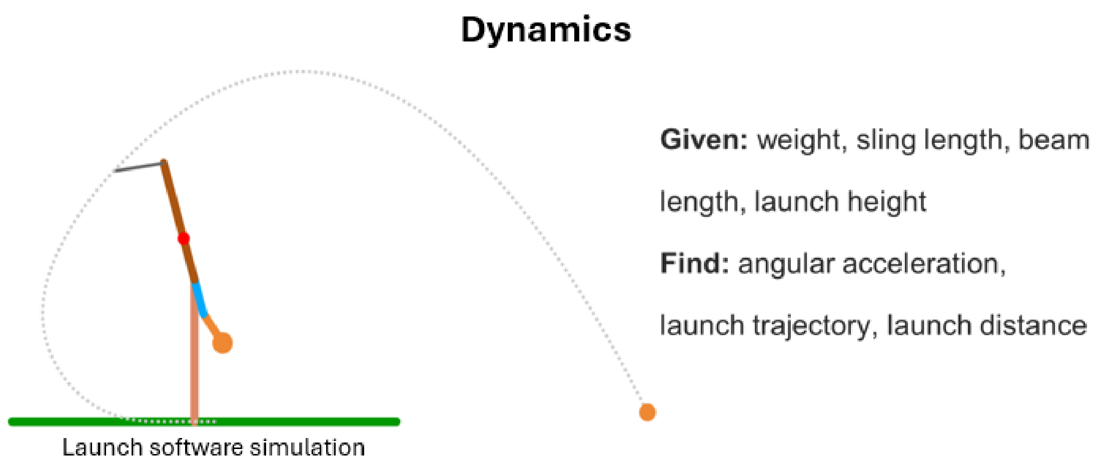

Figure 4: Schematic of trebuchet demonstration for Dynamics.

Solid Mechanics

In Solid Mechanics, the trebuchet arm is replaced with a thinner, intentionally flexible aluminum beam to make deformation visually observable. Students measure deflection under load (counterweight using cylindrical steel plates ranging from 1–26 lb) with a ruler and connect these measurements to shear force, bending moment, curvature, rotation and deflection diagrams they construct for the system. This demonstration helps students bridge the gap between internal force distributions and component behavior. The activity is delivered as a lecture demonstration that reinforces concepts such as beam stiffness, bending stress, and the practical implications of cross-sectional geometry.

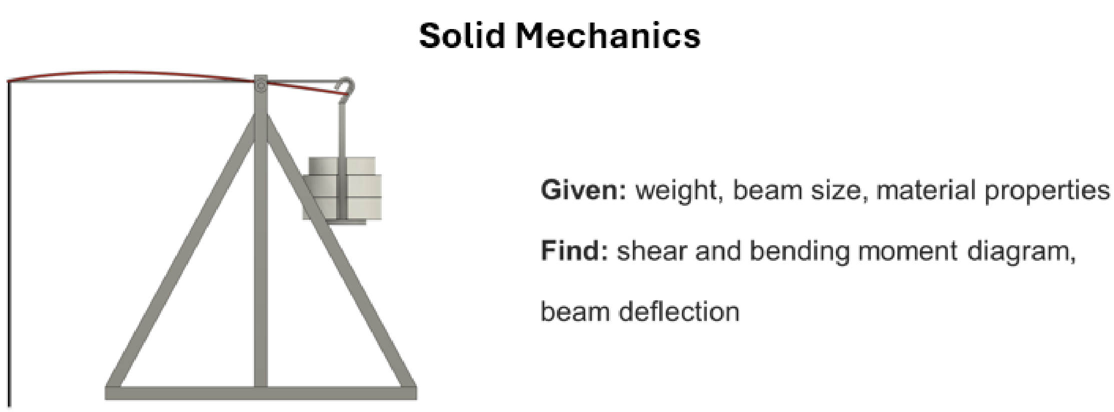

Figure 5: Schematic of trebuchet problem setup for Solid Mechanics.

Materials and Construction

The cost associated with the materials and the construction of the system is in Appendix A, Table 1. The trebuchet is constructed using aluminum components to ensure structural stability and long-term classroom usability (Figure 6). The base frame is assembled from hollow 1-in × 1-in × 1/8-in wall aluminum beams, each 2-ft in length. These beams are arranged into a rigid triangular support structure on each side of the base, with two beams cut at 61.4° and 28.6° and welded to a horizontal 2-ft beam to form each triangle. The two sides are connected by 1-ft beams, creating a footprint of 1-ft × 2-ft. A 0.5-in thick plywood plank is cut to size and placed on the frame to provide a smooth runway for the sling and projectile release.

The rotational axle is a 0.5-in aluminum rod supported by dry sleeve bearings to minimize friction and enable smooth, repeatable launches. The throwing arm is fabricated from a 1-in × 1-in × 1/4-in wall, 26-in long aluminum beam, configured with a 3.33:1 length ratio between the launch side and counterweight side. A D-ring attachment point anchors one end of the sling, while a custom ABS 3D-printed end cap secures the release pin. Shaft collars on either side of the arm prevent axial movement during operation. For demonstrations emphasizing elasticity (e.g., Solid Mechanics), a secondary arm can be substituted to intentionally exhibit measurable deflection. This secondary arm has the same material and length, but is instead a flat 3/16-in thickness bar instead of the primary arm's hollow rectangular cross-section.

Sling ropes of 30" to 4' in length allow instructors to demonstrate how sling geometry influences projectile kinematics. Counterweights consist of slotted cylindrical steel plates ranging from 1–26 lb; these plates stack into a compact 9-in assembly and are secured with long steel bolts.

Parts List		
Item #	Quantity	Part Name
1	2	Long Base 25.4x25.4x609.6
2	2	Short Base 25.4x25.4x254
3	2	Vertical Beam 25.4x25.4x609.6
4	4	Diagonal Beam 25.4x25.4x609.6
5	1	Arm 25.4x25.4x670.56
6	1	Axle 328.8
7	6	Shaft Collar
8	2	Bearing

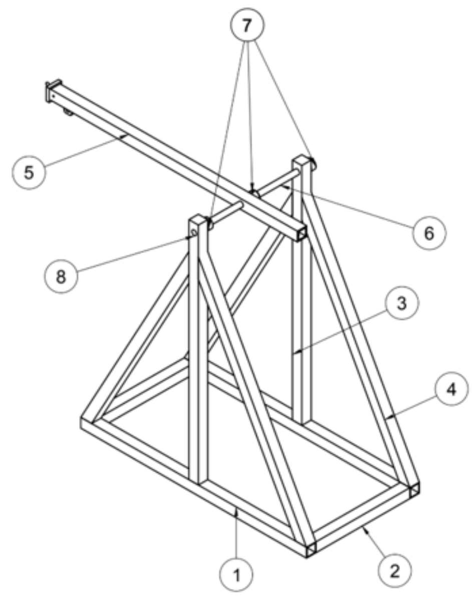

Figure 6: Engineering drawing of trebuchet parts (right) and table specifying part details (left).

Data Collection

A spring scale (0-10 lbs capacity, ± 0.1 lb resolution) can be attached to the sling connection point for Statics demonstrations to measure the force required to maintain equilibrium. Dynamic motion is captured using smartphone cameras and analyzed with Tracker, an open-source video analysis tool that allows students to extract position–time data, compute angular acceleration, and compare theoretical and experimental flight trajectories. All components can be assembled using basic hand tools, enabling rapid reconfiguration for different course demonstrations.

Classroom Integration

The trebuchet is designed for integration into lecture demonstrations and discussion sessions. Prior to its design, we conducted a literature review on best practices for active learning and in-class demonstrations. Prior work suggests that students should first be introduced to the relevant theory in a traditional lecture setting before participating in a demonstration and should be given structured opportunities for prediction, discussion, observation, and reflection [9]. Providing time for students to predict the outcome of a demonstration before seeing it substantially improves understanding compared to passive observation [9]. Adding a brief peer discussion after the prediction stage further supports conceptual learning [10]. Integrating prediction and discussion requires minimal additional time (2–8 minutes) yet leads to significantly higher rates of correct responses and explanations compared to traditional demonstrations [10]. Each demonstration should be kept simple, clear, and focused on one conceptual idea [9]. Meaningful engagement, not mere hands-on activity, is essential [11]. Therefore, the trebuchet demonstration was designed with these recommendations in mind.

Instructors begin each demonstration by configuring key mechanical parameters corresponding to the learning objectives of the course module. Students are asked to predict system behavior using relevant theoretical models prior to the demonstration. During operation, instructors draw attention to the specific principles under investigation. Students observe from a distance to ensure a safe demonstration environment.

Instructor guide and suggestions:

1. Configure corresponding mechanical parameters (sling length, counterweight mass, arm stiffness) based on the learning objectives of the course module.
2. Introduce and describe a physical demonstration.
3. Students predict outcomes individually (recorded on a worksheet).
4. Small-group discussion to compare reasoning.
5. Students finalize their predictions.
6. The demonstration is performed with real-time measurements shown.
7. Students compare predictions with observed results and discuss discrepancies.
8. Reinforce the concepts and address any questions.

Conclusion

The trebuchet developed in this project offers a practical and scalable way to strengthen students' real-world connections and critical thinking through active learning. Its compact construction, interchangeable components, and flexible data-collection methods allow it to be used across multiple mechanics courses without specialized equipment or lab space. By enabling evidence-based learning cycles with a single apparatus, the platform reinforces conceptual understanding, supports long-term retention, and highlights how theoretical principles appear in real mechanical systems. Future work will assess its effectiveness through semester-long implementation and student feedback.

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Appendix (Supporting Materials)

Appendix A: Cost of materials

Table 1: Cost of materials

Item	Unit Price [$]	Quantity	Total [$]
Base Aluminum Beams (1”×1”×24”)	22.65	8	181.20
Arm Aluminum Beams (1”×1”×24”)	35.56	1	35.56
Plywood Sheet (0.5”×3’×2.24”)	25.67	1	25.67
Rolling Cart	**246.08**	**1**	**246.08**
0.5” Aluminum Rod	36.72	1	36.72
0.5” Dry Sleeve Bearing	1.37	2	2.74
0.5” Shaft Collars	6.48	6	38.88
Sling	14.99	1	14.99
Machine shop	**69.00**	**12.5**	**847.50**
10 lb Slotted Plate	93.10	2	186.20
5 lb Slotted Plate	75.05	1	75.053
Weight Hanger	109.25	1	109.2
10 lb Spring Scale	172.06	1	172.06
Ruler	6.81	1	6.81
Bronze Sleeve Bearing	8.29	1	8.29
Filament	5.00	1	5.00
Thin Aluminum Beam	8.82	1	8.82
Hardware	30.00	1	30.00
Easy-Carry Tape Measure	33.25	1	33.25
Polyethylene Square Plugs	10.99	1	10.99
		Total Cost [$]	2065.06
		Without Machining and Rolling Cart [$]	**971.48**

Note that most of the cost is associated with machining and a rolling cart. If the items are self-assembled and you already have a rolling cart or similar, the cost is closer to **$971.48** for the three courses.

Appendix B: Trebuchet Operation and Safety

Trebuchet Operation and Safety Manual

Objective

This Standard Operating Procedure (SOP) document establishes the proper methods, safety requirements, and operational guidelines for assembling, testing, and launching a trebuchet. Its goal is to ensure safe, consistent, and effective operation for educational and engineering project use.

Scope

This SOP applies to all team members involved in the construction, handling, testing, maintenance, transportation, and operation of the trebuchet.

❶ Preparation

1. Only personnel (professors and teaching assistants) who have read this document can operate the trebuchet. If a student is operating the trebuchet it must be under the supervision of either the professor or a TA.
2. Never stand in front of or behind the throwing arm.
3. Inspect the machine for any visible damage or issues. Verify that the knots on the sling are tight.
4. Observe a minimum safe distance of 30 feet downrange.

❷ Assembly Procedure for TAM 210 Statics Demonstration

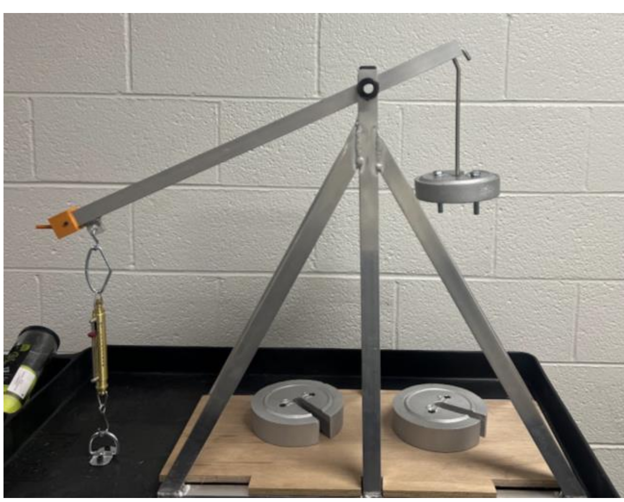


Figure 1

Figure 2

1. Place the base on the rolling cart with the base flush to the edge as shown in the figure 1.
2. Lock the wheels on the rolling cart.
3. Remove the bolts and plates from the counterweight
4. Attach the spring scale to the hook on the rolling cart, and attach the S-hook to the trebuchet arm. The top of the red slider indicates the reading.
5. Load the counterweight with the 5lb and 10lb weights, using the long or short bolt to fasten.
6. Remove all weights before removing the spring scale configuration.

❷ Assembly Procedure for TAM 212 Dynamics Demonstration

Figure 3 **Figure 4**

Figure 5

1. Place the base on the rolling cart with the base flush to the edge.
2. Lock the wheels on the rolling cart.
3. Roll out the measuring tape.
4. Ensure that the bolt on the orange arm endcap is fully screwed in.
5. Tie ends of the sling onto the trebuchet arm and the leather loop, using the white markings as length references (for 6lbs).
6. Measure the sling lengths using figure 5 shown above, which shows 17 inches from knot to knot.
7. Ensure that the shaft collars are tight, and the through screw is tight. The outer shaft collars should not be in direct contact with the aluminum beams, as it causes loud squeaking, friction, and less efficiency.
8. Load the counterweight(s) and secure them using the long or short bolts.
9. If loaded with full weight (25lb) and not being launched from the cart, use additional weights (textbook, dumbbell, etc.) to hold down the base.

❸ Launch Procedure

Figure 6

1. Test the rotation of the arm - there should be little resistance and creaking.
2. Load the tennis ball in the center of the sling
3. While holding the tennis ball in place, pull it downwards and through the chassis, holding it at the edge of the cart as shown in figure 6.
4. Verify that the area around arm rotation is clear and that the launch trajectory is clear.
5. Release the ball, moving your hand out of the way without obstructing the launch and altering the true motion of the sling and arm.

❹ Assembly Procedure for TAM 251 Solid Mechanics Demonstration

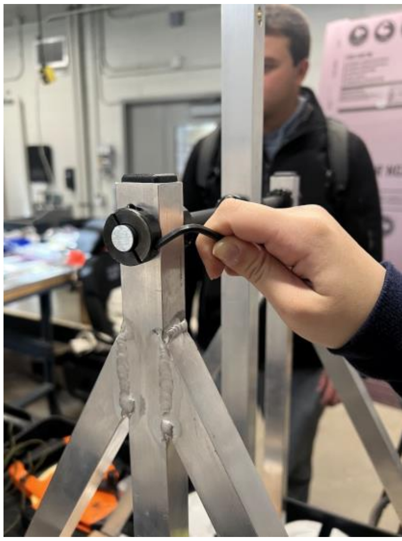


Figure 7

Figure 8

Figure 9

Figure 10

Figure 11

1. Remove the counterweights.
2. Remove the the shaft collars using a M7 Allen wrench, seen in figure 7. Slide the rod out, to remove the main trebuchet arm. Note that two shaft collars are screwed to the arm, and should stay on the arm, seen in figure 8.
3. Tie the rope to the large hook, and to the handle of the cart handle. The rope length should be approximately 15 inches long, as seen in figure 9.
4. Place the thin beam on the rod, with the white line indicating 6 inches sitting directly on top. Screw the shaft collars on so that they are touching the sides of the beam, as seen on

figure 10. Also screw on the shaft collars on one side of the frame (there should be 4 shaft collars on the rod).

5. After adjusting the rope length and ensuring that the beam can balance correctly, load the counterweight hook and weights carefully and slowly. The beam should deflect as seen in figure 11.

❹ Post Demonstration Procedure

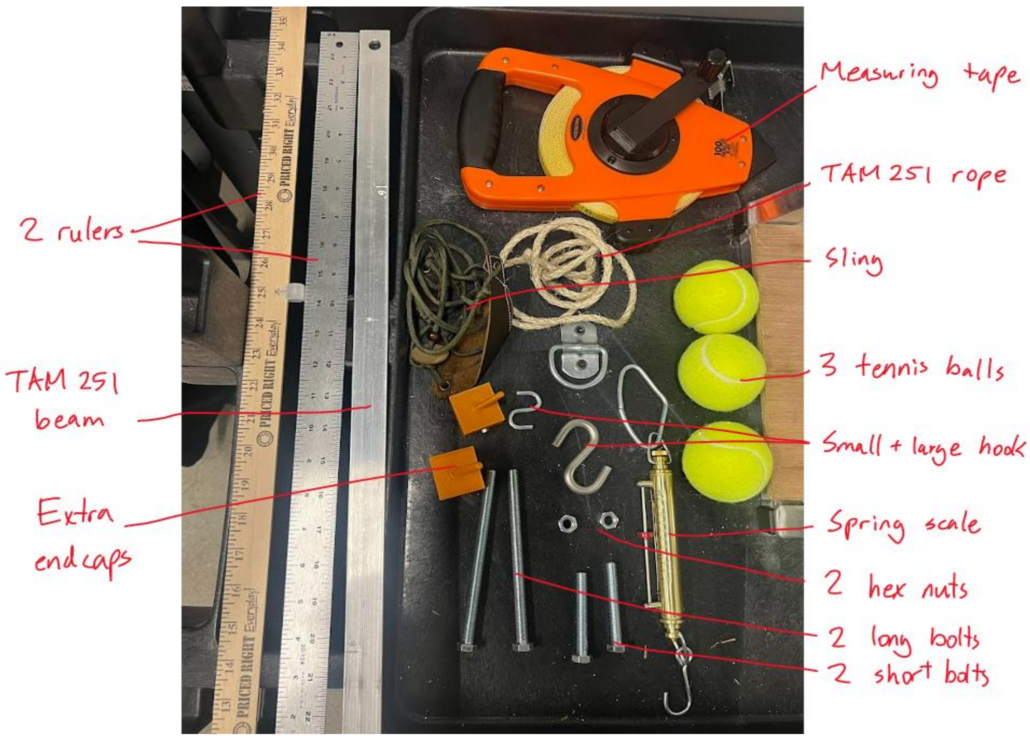


Figure 12

1. Remove all weights and place them flat on the rolling cart.
2. Check that all components are present, refer to figure 12.
3. Put away projectiles in containers.

❺ Maintenance and Troubleshooting

- Perform regular inspections to identify potential issues early.
- Check that the shaft collars aren't adding friction to the system by coming in contact with the frame.

Appendix C: Tracker Software

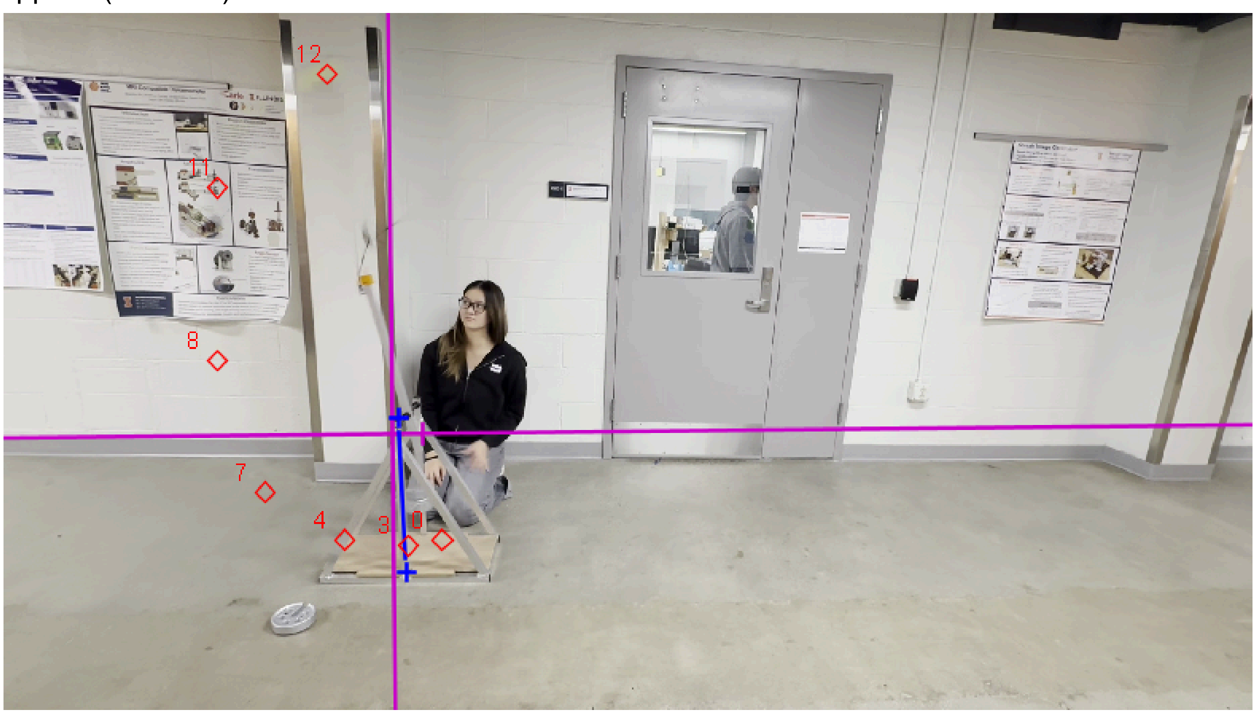
Tracker Software SOP

Step 1)
Download Tracker on following website
[Tracker Video Analysis and Modeling Tool for Physics Education]

Step 2)
Follow the steps shown in "Getting Started" provided by the tracker website, linked below
[Tracker Help]

Alternatively, follow the youtube tutorial found in the link below
[Tracker Video Analysis Tutorial]

Step 3)
When setting up the model, select the trebuchet axle as the origin. Apply a scale using a known length of 24 inches (2 ft), corresponding to the horizontal aluminum beam shown. Figure X shows a completed Tracker setup with the axle at the origin (purple x- and y-axes) and the scale applied (blue line).



Step 4)
Ensure that theta and time are selected in the chosen data and export to Microsoft Excel. Please note that theta is automatically in degrees and can be converted to radians if desired. Once in excel, utilize the central difference theorem to calculate angular velocity and acceleration:

Angular Velocity:

$$\omega = \frac{\theta_{i+1} - \theta_{i-1}}{2\Delta t}$$

Angular Acceleration:

$$\alpha = \frac{\theta_{i+1} - 2\theta_{i} + \theta_{i-1}}{(\Delta t)^2}$$

Step 5)
Use the angular velocity and angular acceleration along with time to generate plots for angular velocity and angular accelerations vs time.