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# GIFTS: Using Marionette Design to Teach Forces, Moments, and Equilibrium in a First-Year Mechanical Engineering Course

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## Introduction

This GIFTS paper presents an interdisciplinary, hands-on design project that reimagines the traditional first-year mechanical engineering experience by incorporating principles of art, design, and creative exploration. Co-developed by faculty from mechanical engineering and arts, the project invites student teams to design and fabricate a dynamic, one-meter-long marionette that demonstrates core mechanical concepts, such as forces, moments, and equilibrium, through mechanisms like linkages, pulleys, or levers. Beyond technical functionality, the marionette challenge emphasizes aesthetic expression, storytelling, and visual impact, introducing students to ambiguity, play, and surprise within an engineering context. The project is conducted in a studio-like learning environment, more open, flexible, and exploratory than a traditional engineering lab, where students are encouraged to experiment with materials, engage with unfamiliar tools, and take creative risks. Rooted in the engineering design process but inspired by arts education and low-risk iteration, the activity fosters collaboration, material exploration, and process-based thinking. By blending analytical rigor with fun, imagination, and expressive freedom, the project promotes active learning [1], systems thinking [2], and early professional identity formation [3] within a welcoming and creatively charged space.

## Motivation

Teaching statics to first-year students can present challenges, particularly in conveying abstract ideas like force vectors and torque in an intuitive and lasting way. These topics are often introduced with equations and diagrams but without a tangible connection to real-world systems. This marionette project was developed to address this pedagogical gap by offering students a meaningful and creative physical context in which to apply mechanical principles. The guiding idea was to make statics "come alive" by embedding it in a whimsical but technically constrained design task by building a marionette for a fictional arts festival. The project aims to motivate students by merging engineering analysis with artistic expression, encouraging engagement and intellectual ownership of concepts traditionally taught through textbook problems.

## Objectives

This activity is designed with several interrelated educational goals:

- *Conceptual Understanding:* Help students internalize the principles of static equilibrium, force decomposition, and moment calculation through direct application.
- *Design Thinking:* Introduce the stages of the engineering design process, from problem definition to prototype testing, in a structured but flexible framework.
- *Hands-On Prototyping:* Provide experience working with physical materials, tools, and basic mechanical components within real-world constraints such as budget, weight, and available workspace.
- *Teamwork and Communication:* Develop collaboration, planning, and presentation skills through a group-based, peer-assessed project.
- *Creative Confidence:* Foster early engineering identity and problem-solving confidence by giving students permission to explore unconventional and artistic solutions to technical challenges.

## Implementation Details

The marionette design project is implemented across a four-week segment of a first-year mechanical engineering course, providing students with structured opportunities to apply concepts of statics, moments, equilibrium, and design thinking in a creative, hands-on environment. Teams of three to four students are challenged to create a one-meter-long dinosaur marionette puppet, capable of at least two mechanically actuated joint movements (see Appendix A). The final product must function reliably while also showcasing aesthetic quality, narrative character, and mechanical complexity.

The project is framed as a design challenge from a fictional arts organization preparing for a global cultural festival, emphasizing creative engagement and problem-solving through storytelling. Students receive a design brief outlining functional, budgetary, and technical constraints, as well as aesthetic and performative expectations. Each team is allocated a $75 budget for materials, and guidance is provided for cost-effective sourcing from recommended lists (e.g., PVC joints, dowels, foam, ping pong balls, fabric, and cable ties).

The instructional environment mirrors a studio-based pedagogy rather than a rigid lab setting. Students have access to a variety of prototyping tools housed in the department's makerspaces, including 3D printers, a laser cutter, sewing machines, and hand tools. Makerspaces function as collaborative, flexible design studios that support exploration and iterative problem-solving [4].

The implementation is scaffolded through the structured engineering design process:
1. *Requirements Development:* Students analyze the design challenge, identifying constraints related to structural integrity and mechanical movements. These include functional requirements (joint movement), aesthetic goals, and material limitations. Social and cultural aspects are considered, encouraging students to reflect on the symbolic significance of their dinosaur and its presentation.
2. *Conceptual Design:* Each team generates a minimum of 20 design concepts based on their brainstorming and research. They then evaluate these ideas using a custom decision matrix, scoring each concept for functionality, originality, and visual appeal. The converged idea is documented, supported by inspirational references, and further developed using sketching and systems mapping.
3. *Detailed Design:* The selected dinosaur concept is broken down into geometric forms for structural clarity. Students develop 2D sketches and free-body diagrams (FBDs) to explore force interactions across the puppet's joints. CAD models are developed to visualize internal mechanics and joint articulation. Materials are selected based on availability, performance needs, and visual properties.
4. *Prototype Fabrication & Testing:* Students physically construct their marionette, beginning with a skeletal frame, adding functional joint mechanisms, and iterating on design for movement, balance, and aesthetics. Functionality is validated through hanging-scale force measurements, angle calculations, and component testing. Students are encouraged to experiment with simple (e.g., string and pulley) and complex (e.g., multi-joint linkage) systems. Troubleshooting and iteration are emphasized to support low-risk exploration.

Finally, each team delivers a presentation highlighting their design evolution, mechanical rationale, and lessons learned. The marionettes are showcased in a public gallery exhibit, accompanied by a narrative placard explaining the concept, materials, and engineering challenges addressed.

**Assessment Methods**

Assessment is aligned with ABET-aligned course learning objectives and is multidimensional, targeting technical analysis, creative execution, teamwork, and communication. The grading is structured using rubrics that evaluate the process and product, integrating instructor, peer, and external feedback.

*Report and Presentation Assessment*

Students submit a comprehensive design report that demonstrates technical rigor and reflective practice. The report follows a structured format that includes a cover page, executive summary, main body, and appendices, and adheres to IEEE paper style with labeled figures, correct units, and appropriate citations.

Finally, each team member contributes a personal reflection that highlights their individual learning, challenges faced, and takeaways from the collaborative design process [5]. See Appendix B and C for the rubrics.

During the final presentations, each team must demonstrate that their marionette meets key functional and mechanical performance criteria. The puppet is expected to maintain structural stability under light disturbances or slack in its support system and to perform two distinct and controllable joint movements. These motions should be actuated using clearly articulated mechanical systems such as linkages, pulleys, or levers, with visible evidence of thoughtful engineering design. Additionally, the marionette must retain movement integrity after repositioning or minor manipulation, indicating robust construction and repeatable performance. These demonstrations are evaluated by instructors, teaching assistants, and invited guests using a rubric that emphasizes movement quality, reliability, and mechanical sophistication. To be considered for top marks, each puppet must pass a live functionality check during the team's presentation.

The visual appeal and originality of each marionette is also assessed, emphasizing the integration of artistic and engineering design principles. Evaluation criteria include craftsmanship and finish, such as clean joints, geometric symmetry, and thoughtful transitions between materials. Reviewers consider how well form and function are integrated, whether the puppet looks visually compelling and conveys the potential for dynamic movement. Creativity is further evaluated through the use of theme, color palette, shape, and character identity, encouraging teams to develop unique and expressive designs. Inventiveness in material selection is also rewarded, with examples such as the use of ping pong balls for eyes or layered fabric for texture showcasing imaginative problem-solving. This component of assessment challenges students to move beyond pure functionality and embrace design as a communicative and expressive practice.

Visual communication is evaluated based on the clarity and professionalism of CAD renderings, Free Body Diagrams (FBDs), and labeled visuals integrated into clean, well-organized slides. Oral delivery, considers pacing, equitable distribution of speaking roles, and smooth transitions between presenters. Engineering explanation, which emphasizes the team's ability to clearly link their design process to underlying theory, mechanical testing, and final outcomes was also evaluated. Each student is expected to contribute meaningfully to the presentation, demonstrating detailed knowledge of their assigned subsystem and articulating how core mechanical principles informed specific design decisions.

*Guest faculty, peer and self-evaluation*

Peer and self-evaluation components were supported by the CATME peer assessment tool for the design report and presentation grades, measuring individual contributions, collaboration, and accountability [6]. In addition to team-member evaluation, projects were assessed during the final gallery presentations by faculty judges and students using the same structured rubric.

Additionally, for each project, evaluators assigned scores across four primary criteria: Functionality & Movement, Originality & Creativity, Aesthetic Design & Craftsmanship, and Engineering Communication. These categories required evaluators to determine whether the marionette demonstrated two reliable and stable joint movements, whether creativity was effectively integrated into both form and mechanics, the quality and craftsmanship of construction, and the clarity of engineering explanation supported by visuals such as CAD models and Free Body Diagrams (FBDs). In addition to numeric scoring, students provided open-ended feedback identifying strengths, areas for improvement, and questions raised by the mechanical implementation.

Using a shared rubric for faculty judges and peers ensured consistency in evaluation criteria while promoting transparency and fairness (see Appendix D). The combination of quantitative scoring and qualitative commentary reinforced critical observation, encouraged comparative evaluation of multiple mechanical solutions, and deepened students' understanding of how engineering analysis translates into functional and aesthetic design outcomes.

**Instructor Reflections and Recommendations**

Faculty who have facilitated the marionette project observed that students initially express skepticism, particularly regarding the integration of artistic elements into a mechanical engineering course. Some students question the relevance of aesthetics to engineering rigor. However, as the project progresses, this skepticism often shifts toward engagement, especially once students recognize that mechanical performance and visual expression are deeply interconnected in the functioning of their marionette.

One of the most consistent early challenges involves time management and teamwork. Students frequently underestimate the time required for fabrication and overestimate their engineering analysis skills and their making abilities. In particular, teams often underestimate the complexity of joint mechanisms and the precision required for reliable movement. When mechanisms fail student responses vary between seeking instructor intervention and engaging in productive redesign. Over time, instructors observed that normalizing iteration and explicitly framing failure as a design tool fosters resilience and deeper conceptual understanding.

The studio-like makerspace environment noticeably shifts classroom dynamics. Compared to traditional lecture settings, the project space becomes more energetic and collaborative, with increased peer-to-peer teaching and spontaneous problem-solving. Students demonstrate greater ownership of their work, and enthusiasm tends to increase as prototypes take physical form. Faculty noted that some students who are less vocal become highly engaged when working hands-on.

Several positive outcomes exceeded instructor expectations. The craftsmanship achieved by many teams demonstrated remarkable care and attention to detail. Faculty also observed heightened creativity in mechanism design and aesthetic interpretation. Importantly, some students explicitly reported that constructing and testing their own marionette improved their understanding of forces and moments more effectively than traditional problem sets.

Instructors identified several practical recommendations for future implementations. First, materials ordering should begin earlier, as delays can constrain iteration time. Second, limiting CAD software to accessible platforms (e.g., Tinkercad) reduces inequity in prior experience and prevents excessive time spent learning advanced modeling tools. Third, adequate workspace and storage are essential; concurrent fabrication requires sufficient physical space and organized material tracking to manage budgets effectively. Finally, collaborating with arts faculty enriches the experience and strengthens the integration of aesthetics and engineering.

Faculty recommend three specific practices for instructors adopting this project: (1) provide a simple working joint demonstration early to reduce perceived risk and clarify expectations; (2) limit mechanism complexity to ensure analytical depth rather than mechanical overreach; and (3) intentionally integrate interdisciplinary perspectives, particularly from arts education, to reinforce that design quality extends beyond pure functionality.

**References**

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[5] P. L. Hirsch and A. F. McKenna, "Using reflection to promote teamwork understanding in engineering design education," *Int. J. Eng. Educ.*, vol. 24, no. 2, pp. 377–385, 2008.
[6] Purdue University, "CATME Smarter Teamwork", 2026, [Online]. Available: https://info.catme.org.

**Appendix A**

Marionettes examples

**Appendix B**
Rubric Used for Assessing the Design Report

| Criteria | Excellent | Proficient | Developing | Beginning |
|---|---|---|---|---|
| **Report Structure & Professional Writing** (25 pts) | Fully follows template with cover page, executive summary, body, and appendices. Consistent formatting, labeled figures/tables, clear units, citations, and professional tone. | Mostly follows template; minor format or clarity issues; a few typos. | Some sections missing; inconsistent formatting reduces readability. | Incomplete, poorly organized, or unclear writing throughout. |
| **Requirements & Concept Development** (25 pts) | Clearly defines problem and constraints. Includes ≥20 ideas, success metrics, and decision matrix with justification. | Most elements present; minor issues. | Limited metrics or ideas (<20); vague decision rationale. | Minimal ideation or missing selection process. |
| **System Decomposition & Modeling** (30 pts) | Includes 2D sketches, systems map, initial FBDs, and 3D CAD model. | Most visuals included; minor clarity issues. | Some artifacts missing or low-fidelity. | Few or no visuals or modeling evidence. |
| **Engineering Analysis — Forces & Equilibrium** (40 pts) | Accurate measurements of masses and angles; computes components with correct units; updates FBDs and discusses equilibrium and error. | Generally correct calculations with minor issues. | Partial data or incomplete analysis; limited discussion. | No coherent force analysis. |
| **Engineering Analysis — Moments & Mechanisms** (30 pts) | Two joints analyzed with detailed FBDs, lever arms, moment calculations, and discussion of mechanical advantage. | Both joints analyzed; minor omissions or shallow discussion. | One joint analyzed well or both shallow; unclear assumptions. | No moments analysis provided. |
| **Build, Testing & Iteration Evidence** (20 pts) | Clear testing logs; ≥2 iterations per joint documented with results and changes. | Good testing but with minor gaps. | Sparse logs or limited iteration. | No testing or iteration evidence. |
| **Reflection & Team Insights** (10 pts) | All members submit thoughtful reflections (100–150 words) linking skills, challenges, and growth. | Most members reflect meaningfully; some lack depth. | Generic or incomplete reflections. | Missing or poor-quality reflections. |

**Appendix C**

Rubric Used for Assessing the Design Presentation

| Criteria | Excellent | Proficient | Developing | Beginning |
|---|---|---|---|---|
| **Functionality Demonstration** (60 pts) | Marionette maintains stability and performs two distinct, controllable joint movements using reliable mechanisms. Movement remains intact after minor disturbances or repositioning. | Puppet stands independently and performs two joint movements reliably; recovers from small disruptions. | Partial functionality; movements inconsistent or puppet unstable during motion. | No stable posture or functional movement. |
| **Visual Communication** (30 pts) | Uses SD Mines template with high-quality visuals (CAD, FBDs, systems map) that are clearly labeled with appropriate units and minimal text. | Visuals are mostly clear and well-integrated; minor layout or label issues. | Visuals are present but unpolished or poorly organized. | Visuals are missing or unclear; slides are overly text-heavy. |
| **Oral Presentation & Team Delivery** (25 pts) | All members speak confidently within time limit; smooth transitions and strong preparation are evident. | All members speak; minor timing or delivery issues present. | Uneven participation; disorganized flow or poor timing. | Unprepared or unclear speaking roles. |
| **Engineering Explanation** (25 pts) | Clear narrative links requirements, concept, modeling, forces/moments, testing, and final design. Includes thoughtful discussion of limitations and future steps. | Covers all major phases of design with minor gaps in depth or clarity. | Vague or incomplete rationale connecting engineering analysis to design choices. | Minimal or incorrect explanation of engineering reasoning. |

**Appendix D**

Judges and Peer Evaluation Rubric

| Criterion | Excellent | Proficient | Developing | Beginning |
|---|---|---|---|---|
| **Functionality & Movement** (5 pts Judges / 2.5 pts Peers) | Marionette demonstrates two reliable and stable joint movements using well-executed mechanisms. Movement remains functional after minor disturbances or repositioning. | Movements mostly functional; minor instability or motion issues. | One functional movement or moderate stability concerns. | Movements do not function properly, or marionette is unstable. |
| **Originality & Creativity** (5 pts Judges / 2.5 pts Peers) | Unique and imaginative concept; strong integration of creativity in both form and mechanical design. | Creative representation with notable design elements. | Some creative features; fairly standard interpretation. | Unoriginal or unclear concept; lacks creative execution. |
| **Aesthetic Design & Craftsmanship** (5 pts Judges / 2.5 pts Peers) | Highly detailed and polished; excellent use of materials and strong visual impact. | Neat and visually appealing; minor finish or construction issues. | Adequate appearance; visible roughness or unfinished elements. | Poor construction; lacks visual appeal and care in craftsmanship. |
| **Engineering Communication** (5 pts Judges / 2.5 pts Peers) | Clear, confident presentation; excellent use of visuals (CAD, FBDs, sketches); well-articulated design decisions. | Mostly clear and organized; visuals used adequately; good engineering understanding. | Presentation lacks structure or depth; limited clarity or visual support. | Disorganized or unclear presentation; little connection to engineering rationale. |

**Open-Ended Feedback Prompt**

Please provide any feedback for the team (e.g., strengths, areas for improvement, questions raised by the design, or suggestions for improving mechanical reliability or aesthetics).