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WIP: Building Novice Mechanical Engineers' Intuitions of Linkage Design through Guided Discovery Experimental Activities

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Abstract

This WIP research aims to craft and evaluate an in-class activity that builds undergraduate students' intuitions for the motions of four-bar linkages. This intuition-building is achieved through a Guided Discovery (GD), an active learning strategy in which students are given an activity that leads them to experimentally discover a given concept themselves, rather than being explicitly taught the concept. In-class GDs assume students have no prior knowledge in order to build intuition. The present paper details the design of the mechanism-based GD module focused on four-bar linkages that is currently under development. The linkage GD is designed to introduce Grashof's Law, a kinematic principle that states that in order for a link to make a full 360-degree rotation, the sum of the shortest and longest links must be less than the sum of the other two links. The studied GD includes five distinct mini-experiments. The first four mini-experiments use hardware to guide students through four common four-bar linkage architectures. Pairs of students predict joint motions, test their predictions with hardware, compare their observations to their predictions, and generalize their observations to apply to other four-bar linkages. In the fifth mini-experiment, pairs measure the link lengths from the prior mini-experiments to determine Grashof's Law. This paper presents the design of this GD and observations from a preliminary pilot study that evaluated its effectiveness. As this WIP project continues, we aim to open-source these activities so that future undergraduate students can benefit. (poster session preferred)

1. Introduction

The aim of this WIP paper is to present the creation and preliminary testing of an effective Guided Discovery (GD) that is designed to facilitate the active learning of a core engineering mechanism: the four-bar linkage. Traditional classroom instruction often follows a lecture–problem set–test format. In contrast, GDs are a form of discovery learning [1], an instructional approach in which students are presented with a question or problem. They are encouraged to construct understanding through exploration and guided reflection rather than direct instruction. In this framework, students "discover" key conceptual and factual knowledge by actively engaging with the system under study, supported by intentionally designed prompts and additional material. GDs are intentionally structured to lead students toward identifying the most important features of a mechanism while preserving student autonomy in the learning process. By prompting students to make predictions, test hypotheses, and reflect on discrepancies between expected and observed behavior, GDs aim to promote deep conceptual understanding and intuition building [10].

Prior work in engineering education has shown that active and inquiry-based learning approaches can improve student engagement, motivation, and learning outcomes when compared to traditional lecture-based instruction [9]. Prior work suggests that guided discovery can be especially valuable in engineering education when students must build intuition for phenomena that are difficult to visualize, physically interpret, or connect to formal theory [4], [6]. In engineering mechanics, Kypuros et al. argue that students often experience Statics and Dynamics as "disconnected facts and formulas" rather than as an interconnected conceptual system. They propose GD modules specifically to help students overcome misconceptions and develop "properly conceived engineering intuition" [6]. A similar strength appears in Johnson's and Klettner's recent work on a GD focusing on boundary layers; they show that a GD can be effective when the target concept is a threshold concept that students struggle to "see" or make sense of physically [4]. Similarly, Sachs has developed and implemented GD labs in structural mechanics courses and notes "discovery process naturally involves failed predictions" [3]. Sachs emphasizes that fostering student comfort with failure is a core component of the GD pedagogy and that it plays a key role in sustaining engagement [3]. Finally, Sarker et al.'s portable statics kit illustrates the value of low-cost, hands-on experimental tools for helping students visualize core engineering concepts outside the traditional lab [11]. This work differs from prior implementations by applying guided discovery to linkage mechanisms and structuring the activity around iterative predict–test–compare–analyze cycles that support intuition building through comparison across multiple 4-bar linkages.

2. Design of the GD Learning Activity

The main objective of this GD is for students to independently derive Grashof's Law. Grashof's Law, a kinematic principle of four-bar linkages, states that for a link to make a full 360-degree rotation, the sum of the shortest and longest link lengths (S and L, respectively) must to be less than or equal to the other two links (P and Q, respectively): $S + L \leq P + Q$. For this GD activity to work in a standard engineering classroom, the design specifications are that it is a 90-minute activity, students work in pairs, and that any hardware is made from low-cost, easy-to-manufacture materials. This was achieved by asking pairs to work through five mini-experiments. The first four are accompanied by hardware representing four four-bar linkages: parallelogram, crank-rocker, double rocker, and drag linkage. The first four mini-experiments are structured around a repeated cycle of asking students to predict, test, compare, and generalize. When they arrive at the final fifth mini-experiment, the students are prompted to independently discuss the aspects that allow these linkages to make a 360-degree rotation and produce a mathematical representation of Grashof's Law.

2.1. Hardware:

The hardware consists of laser-cut, ⅛" eucaboard links and interlocking magnets (magnets with dimple feature) as their pin joints (Figure 1). This achieved the goals of low-cost and easy manufacturability. Eucaboard enabled rapid prototyping and quick iteration on overall size, geometry, and layout during early testing. Reconfigurable joints were implemented using embedded magnets, allowing links to be repeatedly assembled, repositioned, and disassembled without tools. A dedicated hardware configuration was developed for each of the four linkage types, ensuring consistency across activities while allowing students to directly compare kinematic behavior across mechanisms.

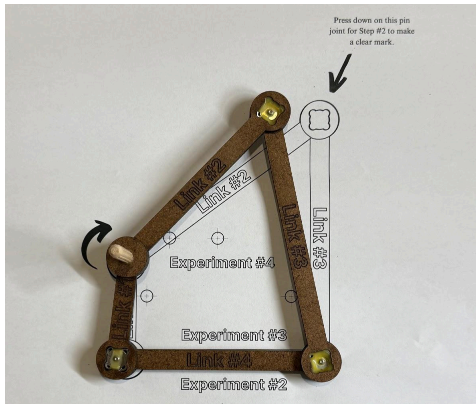

Figure 1: Mini-experiment #2 mechanism hardware shows a crank-rocker mechanism.

2.2. Written Activity:

Phase 1: Predict. The first phase asks students to observe the hardware (Figure 1) and prompts, "*Without moving the mechanism, predict the range of movement of the pin joint and draw out the line of movement the pin joint connecting Link #2 and Link #3 would create.*" The prediction phase is intentionally designed to slow down students' initial physical interaction with the hardware. By asking students to predict the movement of the link's pin joints, they are encouraged to articulate their assumptions and map out their thoughts. This prompting invites rich discussions with their partner.

Phase 2: Test Your Predictions. Students then test their predictions by placing a sheet of carbon copy paper between the hardware and the printed paper and turning a handle attached to the linkage. A feature on the backside of the pin presses onto the carbon copy sheet, and the joint's full or limited line of movement is traced on the printed sheet.

Phase 3: Compare. Students reflect on their assumptions and note what was different between their predictions and observations. What aspects of the linkage made them predict that specific movement? What aspects made that motion or a different motion possible? While these are simple questions, they help spark conversation between partners. This reflection aims to kickstart students' perspectives on what characteristics these links have that make them move the way they do.

Phase 4: Generalize. This phase asks students to identify what important aspects these links have that are able to make them work. And asks, "*If you changed the order in which the links are layered with each other, would they still work?*"

Pairs repeat Phases 1-4 for the first four mini-experiments, one for each of the four linkage architectures. Vocabulary is introduced at the beginning and end of each mini-experiment in order to build the participants' knowledge base as they go. For example, before they begin mini-experiment #1, students read the definition of a 'pin joint.' At the end of mini-experiment #1, students learn the term 'frame.'

<u>Final mini-experiment #5.</u> The final mini-experiment does not follow the four phase-structure described above. Instead, it aims to cement all the knowledge and guide students through deriving Grashof's Law. The fifth mini-experiment asks participants to measure the lengths of the links and draw conclusions; this is where they fill out as shown in Figure 2. Then they are asked a series of questions that guide students to derive their own mathematical representation that could dictate which linkages will rotate 360 degrees and which will not. It is intended that students arrive at a representation similar to Grashof's Law.

Linkage Type	S	L	P	Q	Did a link rotate 360°? (Y/N)
Linkage #1 Parallelogram					
Linkage #2 Crank Rocker					
Linkage #3 Double Rocker					
Linkage #4 Drag Link					

Figure 2: Mini-Experiment #5 Chart activity

3. Methods for Initial User Testing

Before we can fully integrate this linkage GD activity into the classroom, initial user testing was conducted to evaluate the clarity, usability, and educational effectiveness of the GD Linkage activity. Two undergraduate engineering students participated in the study and gave us sufficient feedback to share in this WIP research paper. Neither participant was a mechanical engineering major, had no prior experience designing or working with linkages, and had not previously worked together on engineering projects.

Participants were asked to complete the full GD activity while verbalizing their thought processes. Two researchers observed the session, took written notes, and collected participants' completed activity worksheets at the conclusion of the session. The researchers only interrupted to answer clarifying questions or to keep participants progressing through the activity. A brief meta-discussion was conducted at the end of the activity to capture participants' overall impressions, points of confusion, and suggestions for improvement. This protocol was approved by the Brandeis University Human Research Protection Program (#26101R-E).

4. Initial Results

Throughout the early mini-experiments, participants frequently made incorrect or incomplete predictions about linkage motion: *"I predict it will work like an arm, like an elbow,"* and *"I think the motion will be limited in some way, I just don't know how."* We observed that these misconceptions became opportunities for sense-making rather than obstacles. As participants tested and revised their predictions, they began to identify key relationships governing motion, such as the role of relative link lengths and the order in which the links were layered on top of each other. After mini-experiment #2, a participant reflected, *"Link 1 is smaller than Link 3, so I think it's more about ratio."* Participants appeared to learn through reflection of their incorrect predictions. When they reached Mini-experiment #5, participants made connections to Grashof's Law. They recognised the small changes in link length that altered the joints' motion ranges, and they independently proposed a new task, such as modifying the double-rocker linkage to move 360 degrees. Notably, after the participants successfully derived Grashof's Law and finished the activity, one participant expressed, *"I really like the part where I derive the equation to get the answer, it's extremely gratifying instead of seeking the answer from the professor,"* suggesting that the activity supported independent, deeper conceptual engagement.

The physical hardware played a critical role in supporting the participants' learning during the GD. When asked how they like working with physical models one participant responded, *"I don't know how I would learn this without the physical models,"* indicating that the triangle mechanisms were essential for understanding four-bar linkage behavior. This response suggests that the hands-on hardware enabled a learning experience that differed from prior lecture-based instruction and supported intuition building through guided instruction. This finding aligns with prior research in engineering education, which shows that GD approaches are more effective than traditional lecture-based methods for promoting conceptual understanding and engagement [9], [10]. Overall, these results indicate that the GD enabled students to explore, make correct hypotheses, and organically deduce key mechanism principles. This demonstrates that the activity objectives, such as developing intuition for linkage behavior and deducing Grashof's Law, were achieved.

5. Discussion

This work represents an early-stage exploration of GD, and Table 1 summarizes the improvements that should be made before being integrated into the course. The activity successfully met its design goals by using low-cost, easily manufactured materials (hardboard, magnets, and carbon copy paper) and by emphasizing hands-on interaction over formal explanation. Initial user testing suggests that the GD format shows promise for supporting intuition building and conceptual understanding of linkages.

Several limitations exist. The assessment was conducted with only one pair of students, which was appropriate for the WIP status of this project, but should be addressed as the project continues. Moreover, the assessment took place outside of a true classroom environment. The presence of researchers and the lack of peer-to-peer dynamics may have influenced the amount of time the participants dedicated to the prediction phases. In several instances, participants spent over ten minutes discussing predictions; in a typical classroom setting, time constraints and peer dynamics would likely limit this level of sustained attention. Additionally, because the participants were in a research setting, their participation motivation may differ from that of

Table 1. Top three design improvement suggestions from challenges observed in user-testing.

	Challenge observed during user-testing	Improvement to be made
1.	Magnet joints slipped apart, particularly for the parallelogram linkage	Magnets enabled reconfiguration as students tested, so will continue iterating a secure magnet joint.
2.	Participants found some examples too complex or unfamiliar such as the robotic arm example.	Supplement examples with everyday mechanisms (e.g., folding chairs or desk lamps)
3.	Confusion with wording of questions, particularly ones about constructing linkages	Review the phrasing of questions and how new concepts are introduced

students in a class setting. Despite these limitations, the results indicate that GD has the potential to complement existing instructional approaches in early mechanical design courses.

To address these limitations, a future study should include approximately 8-12 students (4-6 pairs) who have not completed an introductory mechanical engineering course. The GD activity should be conducted in a familiar classroom environment, with each pair seated at a shared table equipped with a complete set of linkage hardware and GD written packet. At the start of the session, students would be instructed to document their reasoning in writing, including predictions, observations, and reflections throughout each phase of the activity. During the activity, researchers would take on a non-intrusive observational role, circulating throughout the classroom to record field notes on students' interaction, time spent on tasks, and problem-solving strategies. With appropriate consent, audio recordings of student conversations would be conducted to capture real-time reasoning and peer-to-peer discussion. At the conclusion of the session, all written material would be collected, and students would complete a brief exit survey or short interview, providing feedback, perceived learning, and engagement with the GD. The collected data, including written responses, the researcher's field notes, and audio transcripts, would be analyzed using qualitative coding methods.

6. Conclusion and Future Work

Although this learning was derived from one pair of user testing, this study demonstrated that the GD learning technique shows potential for supporting the development of core mechanism understanding in novice engineers. Future work will involve implementing the GD in a full classroom setting and collecting data from a larger and more diverse population, as described in Section 5a. Additional GDs targeting other mechanisms (e.g., gear ratios and Scotch yokes), are currently under development and will be evaluated in future studies. Finally, the GD materials, CAD for the hardware, and activity documentation will be open-sourced to enable broad access and adoption. This will allow other educators to readily implement or adapt the activity within their own courses.

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