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Failing Forward: A Mastery-based Learning Approach in a Theory of Machine Kinematics and Dynamics Course

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Introduction

Researchers have recently identified past failure as an "essential prerequisite" for future success [1]. Developing course structures to promote productive failure has received considerable interest in engineering education community. Failures during the undergraduate curriculum can help students build resiliency, humility and grit. However, persistence through failure is only productive if students are capable of learning from their past failures [1, 2]. Unfortunately, the high stakes assessments typically used in traditional courses do not give students the opportunity to practice productive failure or demonstrate an ability to learn from their mistakes. As a result, students prioritize earning "good grades" instead of actually learning the course content.

Alternatively, competency or mastery-based learning (MBL) can shift students from a grade-driven mentality to a learning-oriented mindset. MBL approaches have been described and evaluated in depth elsewhere [3, 4, 5]. In mastery-based learning, students must demonstrate mastery of fundamental skills in order to pass the course. Their final grades are then improved by mastering more complex, higher-level skills throughout the semester. As part of the learning process, the students are able to repeat individual skill assessments as needed until the semester ends. As such, each failed assessment becomes a learning opportunity as the students progress towards mastery. MBL approaches are normally delivered with flipped classroom pedagogy, allowing the students to workshop difficult skills with instructor feedback during course meetings.

Within the mechanical engineering curriculum, MBL approaches have been developed for statics [6], dynamics [7], fluid mechanics [8] and computer applications courses [9]. The purpose of this paper is to describe and evaluate the development of a mastery-based learning scheme for a theory of machine kinematics and dynamics course over four years. This paper is divided into three main sections. First, this paper explores the lessons learned from failures made during a first attempt to incorporate MBL. Reflecting on these failures, a set of four best practices for MBL development is presented. Second, the paper describes a successful MBL approach developed using these best practices. Third, this paper evaluates the effectiveness of the MBL approach using post-course evaluations, student performance, and student surveys.

1. Best Practices for MBL Development

Background

The author first integrated a flipped classroom and MBL approach during the Fall '20 semester at the University of Mount Union (UMU). The course, Kinematics and Dynamics of Machinery, was a four credit, required course for junior mechanical engineering students. This course was offered in-person with the content split evenly between rigid body dynamics (2-hr) and theory of machines (2-hr). Fourteen total students were enrolled in the course during Fall 2020. Based on a previously published MBL approach [7], 18 mastery skills were developed: 12 for rigid body dynamics and six for theory of machines. While not the focus of this paper, this initial MBL scheme is included in Appendix 1 for the purpose of comparison. Resulting post-course evaluations indicated the MBL approach was a success. Statistically significant ($p<0.05$, T-test) improvements were observed across all post-course evaluation prompts when compared to the previous three-year average (Tab. 1; '20). The flipped classroom enabled better feedback to students as they completed coursework. The multiple opportunities to test mastery skills resulted in a greater understanding of fundamental course skills.

Table 1: Changes to average post-course evaluations with the adoption of a flipped classroom pedagogy and mastery based-learning assessment. All scores are based on Likert scale (*5:Strongly Agree; 1:Strongly Disagree*). Higher scores were desirable for all evaluations.

	UMU '17-'19	UMU '20*	ONU '21**	ONU '22-'23
Mean:	4.27	4.51	3.49	4.38
St.dev:	(0.21)	(0.15)	(0.46)	(0.16)

**First MBL at Mount Union (UMU). **First MBL at Ohio Northern (ONU)*

Motivated by this positive experience, an MBL assessment was developed for a similar course at a new institution, Ohio Northern (ONU), for the Fall 2021 semester. Mechanical Design 1 (MD1), was a required, 3-credit hour course for junior mechanical engineering students. The 15-week course covered the theory of machine kinematics and dynamics and focused on common one-degree-of-freedom mechanisms including pin-jointed four bar linkages and crank sliders. Two sections of Mechanical Design 1 were offered each fall and taught by the same instructor. The course had a total enrollment of 73 students in Fall 2021, 53 students in Fall 2022, and 80 students in Fall 2023. While not the focus of this paper, a list of the 2021 mastery skills is also included Appendix 2 for the sake of comparison.

During the 2021 MBL course, both student motivation and learning outcomes were lower than in Fall 2020 at Mount Union. Direct assessments revealed lower course grades than previous years and a drop in post-course evaluation scores (Tab. 1; '21). Post-course evaluations revealed significant issues with the design of the new MBL approach. Reflecting on the student feedback led to the establishment of a set of best practices that could improve the development and delivery of future MBL assessments. Redesigning the MBL assessment following these principles resulted improved post-course evaluations during the 2022 and 2023 offerings of MD1 (Tab. 1; '22-'23).

The best practices used to improve the MBL approach for MD1 are briefly summarized below:

<u>Best Practice 1</u>*: Each mastery skill should only evaluate one well-defined skill*

It is recommended that skills requiring complex multistep solutions are broken into separate skills. For example, a vaguely defined skill from 2021 ("Use vectors to evaluate the positions of links in a mechanism.") was split into multiple, specific skills for the 2022 course:

- R3: Write vector loop equations for a mechanism of four or more links
- R4: Calculate the position of points on a mechanism with four or more links
- R5: Perform position analysis on a crank slider

- R8-C: Perform analytical position analysis on a four-bar linkage using MATLAB

Practically, applying this best practice improved the consistency of test questions for the mastery-skills. As a result, students demonstrated higher pass rates for the mastery skills and reported higher levels of competence on post course surveys (see Section 3).

<u>Best Practice 2:</u> Lecture materials should match the mastery assessments

It is recommended that lectures are developed after the mastery-skills are defined to ensure that at least one entire lecture is dedicated to each competency skill. This best practice was applied in 2022 by recording new videos for all course lectures. New content was also included to match the MBL assessments. For example, in 2021 vector loops were only briefly covered when deriving the position equations for 4-bar linkages. For 2022, a new skill was defined ("R3: Write vector loop equations for a mechanism of four or more links.") and a dedicated lecture was created for vector loop equations. All new lectures included example problems designed to represent the test assessments.

<u>Best Practice 3:</u> Example problem sets should be available for students

Retaking assessments is a characteristic of MBL, but most students will want to feel prepared to pass mastery assessments on their first try. Practice problems should be identified and provided for the students. If sufficient examples matching the MBL assessments are not commercially available, then the instructor should develop these materials. This best practice was applied for Fall 2022 by creating a test review sheet for each testing skill. Each review sheet included the main concepts associated with the skill and listed the relevant lectures and homework assignments where the skill was previously addressed. Each review sheet also included an example test problem with a full solution. An example test review sheet is included in Appendix 4. For Fall 2023, all previous mastery-skill assessment questions were also posted online to help the students prepare for testing days.

<u>Best Practice 4</u>: Sufficient opportunities for feedback should be provided

MBL requires timely feedback so students can prepare for their next assessment. It is recommended that test results are returned to the students at the next course meeting after the assessment. Additional methods were incorporated in 2022 to ensure each student had one-on-one opportunities to receive feedback. Senior-level students were hired as teaching assistants (TAs) to attend the course meetings. These TAs provided additional help while the students completed assignments for the flipped classroom. The instructor also offered weekly evening office hours on nights before the tests. These office hours were well attended, and a continuous flow of students typically lasted 2-3 hours. Many students commented about the office hours on the final course evaluation: "a huge strength was AUTHOR having Thursday evening office hours before tests, that helped me pass multiple [questions]."

Part 2: Mastery Based Learning in Machine Design

Applying the best practices, a total of 33 course competencies were developed for 2022 and 2023 (Tab. 2). The mastery skills were organized into three levels:

- Level 1 (Required) Skills (R-Level): These skills must be passed to receive a passing grade for the course (D). Content associated with defining mechanisms (R1, R2) and performing position analysis (R3-R5) were established as skills required to pass the course.

- Level 2 (Proficiency) Skills (P-Level): These skills built upon the Level 1 skills. Content associated with velocity analysis (P1, P2, P3), acceleration analysis (P4), and gear trains (P5, P6) were established as proficiency skills. Passing addition skills increased the overall course grade.

- Level 3 (Advanced) Skills (A-Level): Passing at least 3 advanced skills was required to achieve a an "A" in the course. Advanced skills included complex multistep solutions and therefore were not evaluated on tests. Successfully performing dynamic force analysis for a four-bar mechanism (A1-C) was required to earn an "A" in the course.

Skill mastery was measured using in-person tests, homework assignments, and a semester-long project. A total of 11 skills were assessed on tests (Tab. 3). Starting during the 5th week of the semester, the students had the option to test up to 3 skills during Friday course meetings (Table 4). The students could test a specific skill on consecutive weeks as needed until the skill was passed or the semester ended.

The MBL approach was incorporated with a flipped-classroom pedagogy. The students watched pre-recorded lectures before course meetings and then worked in teams to complete homework assignments in-class. Ten computer application (Tab. 2; -C) skills were evaluated on homework assignments and mostly completed during the in-class work time. The students were able to seek help from the instructor, TAs, and their peers to complete these assignments. Students were given at least three attempts to demonstrate mastery on Level 1 computer apps skills (Tab. 4). Eight skills (Tab. 2; -HW) were developed to motivate the students to regularly watch the lectures, attend class, and complete homework assignments. Essentially, these eight homework skills provided a "participation" grade for this system. Finally, a semester long project, described elsewhere [10], accounted for a total of four skills. For comparison, a table relating the 2021 mastery-skills to the 2023 skills is provided in Appendix 3.

Table 2: 2023 Mastery Skills

Level 1 (Required) Competencies		
Tested	R1	Draw and label kinematic diagrams
	R2	Classify four-bar linkages according to Grashof condition and Barker's classification
	R3	Write vector loop equations for a mechanism of four or more links
	R4	Calculate the position of points on a mechanism with four or more links
	R5	Perform position analysis on a crank slider
Comp Apps	R6-C	Apply graphical synthesis methods for function generation in SolidWorks
	R7-C	Analyze a linkage using graphical position analysis in SolidWorks
	R8-C	Perform analytical position analysis on a four-bar linkage using MATLAB
HW	R9-HW	Homework average ≥ 60%
	R10-HW	Lecture notes average ≥ 60%
Proj.	R11-P	Complete a design and analysis project (overall score ≥ 60%)

Level 2 Competencies		
Tested	P1	Evaluate indices of merit on four bar linkages (transmission angle, angular velocity ratio, and mechanical advantage)
	P2	Use instantaneous centers of velocity to calculate the velocity of links
	P3	Calculate the velocity of points on a mechanism with four or more links
	P4	Perform velocity and acceleration analysis on a crank slider
	P5	Calculate power, forces, and efficiency across spur gear trains
	P6	Design a gear box to achieve specified torque or speed characteristics
Comp Apps	P7-C	Apply graphical synthesis methods for motion generation in SolidWorks
	P8-C	Perform analytical velocity analysis on a four-bar linkage using MATLAB
	P9-C	Perform analytical acceleration analysis on a four-bar linkage using MATLAB
	P10-C	Generate *svaj* diagrams for cam design using MATLAB
Homework	R11-HW	Homework average ≥ 70%
	R12-HW	Homework average ≥ 80%
	R13-HW	Lecture notes average ≥ 70%
	R14-HW	Lecture notes average ≥ 80%
Proj.	R15-P	Complete a design and analysis project (overall score ≥70%)
	R16-P	Complete a design and analysis project (overall score ≥80%)

Level 3 Competencies		
Comp Apps	A1-C	Perform dynamic force analysis on a four-bar linkage using MATLAB
	A2-C	Apply the method of virtual work using MATLAB
	A3-C	**Independent Study**: Write a .m script to perform analytical synthesis
HW	A4-HW	Homework average ≥ 90%
	A5-HW	Lecture notes average ≥ 90%
Proj.	A6-P	Complete a design and analysis project (overall score ≥ 90%)

Table 3: Evaluation methods for MBL assessment.

Category	2021	2022-23
Tested	14	11
Computer Applications	1	10
Homework and Lecture Notes	0	8
Project	5	4

Table 4: Course schedule for MD1. Friday testing began during week 5 and continued to the end of the semester. No test was administered week 7.

Week	Topic	Lecture Skills	HW Assessment	Test
1	Kinematic diagrams and 4-bar mechanisms	R1, R2		
2	Graphical synthesis	R2, R6-C, P7-C		
3	Position analysis	R7-C, R3	R6-C, P7-C	
4	Position analysis	R4, R5, R8-C	R8-C	
5	Velocity analysis	P2	Retry: R6-C, P-7	Test 1
6	Project introduction	Project skills	Retry P8-C	Test 2
7	Indices of merit and velocity analysis	P1, P2, P8-C	A3-C Retry: R6-C, R7-C, R8-C	
8	Velocity analysis	P3, P8-C	P8-C	Test 3
9	Acceleration analysis	P4, P9-C	P9-C, Retry P8-C	Test 4
10	Power and gears	P5		Test 5
11	Gear train design	P5, P6		Test 6
12	Dynamic force analysis	A1-C		Test 7
13	Force analysis and balancing	A1-C	A1-C, Retry P9-C	Test 8
14	Cam design	P10-C	P10-C	Test 9
15	Project work days	Project skills	A2-C, Retry A1-C	Test 10
Exam	Final project report due	Project skills	Project skills	

Course grades were determined by the total number of skills mastered during the semester (Tab. 5A). Ohio Northern used a whole letter scale (only A, B, C, etc.). Passing the 5 required testing skills (R1-R5) along with the other Level 1 skills was required to earn a “D”. The inclusion of the computer apps and homework skills generally improved grades from a “D” to “C” without the need to pass additional tested skills. Passing additional testing skills was required to progress to an “A” or “B.” Overall, a student needed to pass seven total skills to improve a letter grade. MBL learning adapts even better to plus/minus grading scales (A, A-, B+, etc.) because course progress is enabled by passing fewer total skills (Tab.5B).

Table 5: Grade progression at ONU (A) and suggested progression for plus/minus scales (B).

(A)

Whole Letter (A,B,C) Grading Scale		
Grade	**Skills Passed**	**Additional Requirements**
F	<11	Failure to pass all Level 1 competencies
D	11	Pass all Level 1 competencies
C	18	
B	25	Pass at least two Level 2 testing skills (P1-P6)
A	30	Pass five Level 2 testing skills and A1-C

(B)

Plus/Minus (A,A-,B+) Grading Scale		
Grade	**Skills Passed**	**Additional Requirements**
F	<11	Failure to pass all Level 1 competencies
D-	11	Pass all Level 1 competencies
D	12	
D+	13	
C-	15	
C	18	
C+	20	
B-	22	Pass one Level 2 testing skill (P1-P6)
B	25	Pass two Level 2 testing skills
B+	27	Pass three Level 2 testing skills
A-	29	Pass four Level 2 testing skills and A1-C
A	30	Pass five Level 2 testing skills and A1-C

Part 3: Evaluation of MBL

Applying best practices: Improvement from 2021 – 2023

The effect of applying the best practices was evaluated by 1) comparing course evaluations, 2) tracking overall student performance, and 3) comparing student self-efficacy. Because course grades in the MBL approach were largely based on passing the testing skills, the following evaluations of the MBL-approach will focus on the testing skills (R1-R5 and P1-P6).

Applying best practices, the overall course evaluations improved as was shown in Table 1. From the university course evaluation survey, five prompts specifically addressed the best practices. Figure 1 compares scores for these prompts from the 2021, 2022, and 2023 offerings of MD1. Overall, the students reported that the course was better organized (best practices 1 and 3 - Q1, Q3), feedback was improved (Best Practice 4 – Q4), and lecture videos better served the needs of the course (best practice 2 – Q2). As a result, students found the instructor’s overall teaching to be effective (Q5).

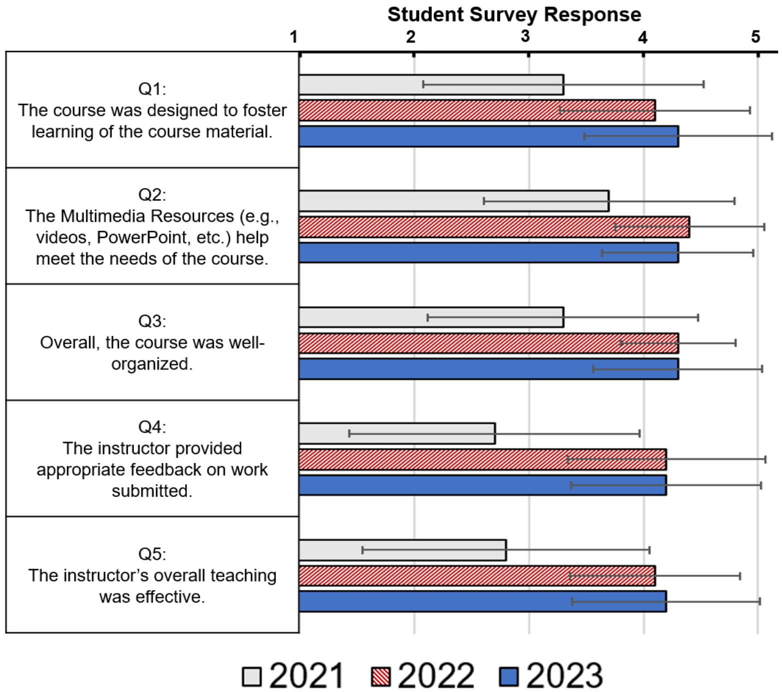


Figure 1: Post-course evaluations for prompts related to best practices. Significant improvements ($p<0.05$, T-test) were observed for all prompts. All scores are based on Likert scale (*5-Strongly Agree, 1-Strongly Disagree*).

Overall course grades (Fig. 2) revealed a drop in “A” grades during the 2021 iteration of the course. Course design with the best practices (2022 and 2023) resulted in a greater percentage of students mastering enough skills to earn an “A.” The grade distribution also suggests that the current MBL assessment is neither too difficult nor too easy to achieve an “A” grade. Moreover, almost all students are able to pass the course with at least a “C”. Students earning a “D” passed all the required Level 1 skills, but did not regularly submit homework or daily class notes. Students earning an “F” did not pass the required Level 1 skills. All students earning an “F” did not regularly attend in-person meetings, submit homework, or sit for test assessments.

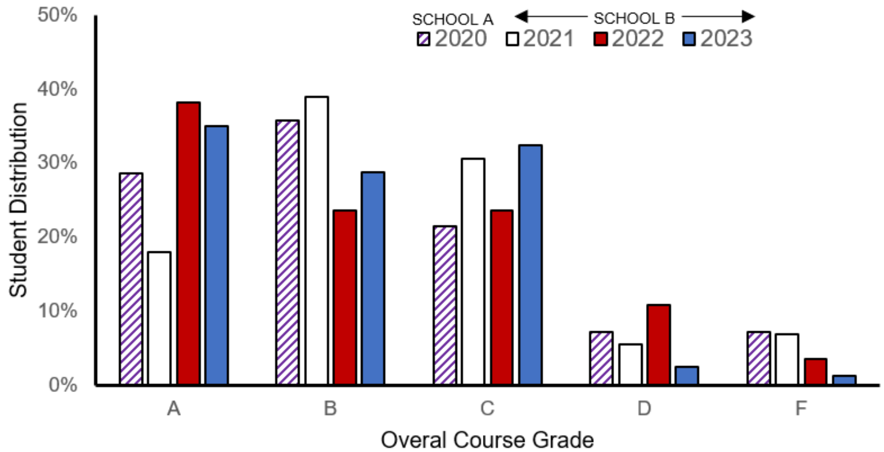


Figure 2: Overall course grades for MBL system at UMU (2020) and ONU (2021-23).

Student self-efficacy was measured by surveys administered during the 15th week of the semester during 2021, 2022, and 2023. The students ranked their competence with each skill on Likert Scale, and then the student responses were compared across the course offerings (Fig. 3). Overall, the updated MBL-approach resulted in higher student self-efficacy. As noted in part 1, one vaguely defined 2021 skill was split into three better defined skills: R3, R4, and R5. This change resulted in statistically higher self-efficacy at the completion of the course in 2022 and 2023 (Fig. 2A). The Level 2 skills P2 and P4 were also more clearly defined for '22-'23 (Appendix 3). Both these skills also showed statistical increases in self-efficacy. R1, R2, P1 and P3 remained essentially unchanged from 2021 and no change in self efficacy was observed for these skills. Gear dynamics and gear train design skills (P5 and P6) were split from a single 2021 skill. The survey results showed improvements to self-efficacy the gear-related skills, but statistical difference was not observed (p =.112, and p=.060 respectively).

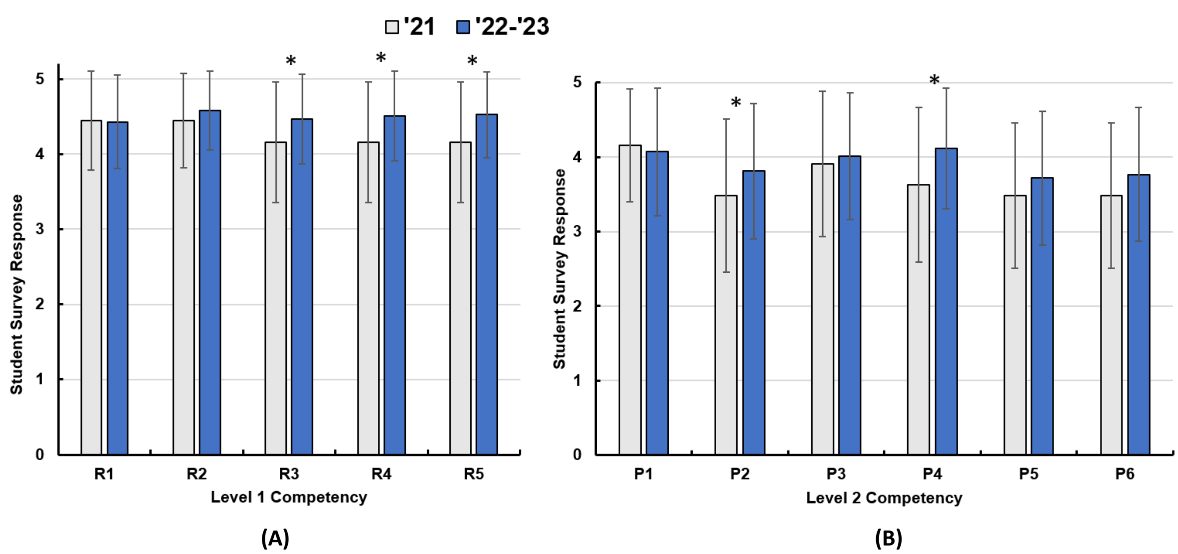


Figure 3: Compared student self-efficacy for Level 1 skills (A) and Level 2 skills (B). 2022 and 2023 scores are pooled because no statistical difference was observed between them for any prompt ('21:n = 56, '22-23: n=128). All scores were based on a Likert scale (*5 – Strongly Agree that I am competent; 1 Strongly Disagree that I am competent*). ** p<0.05, T-test*

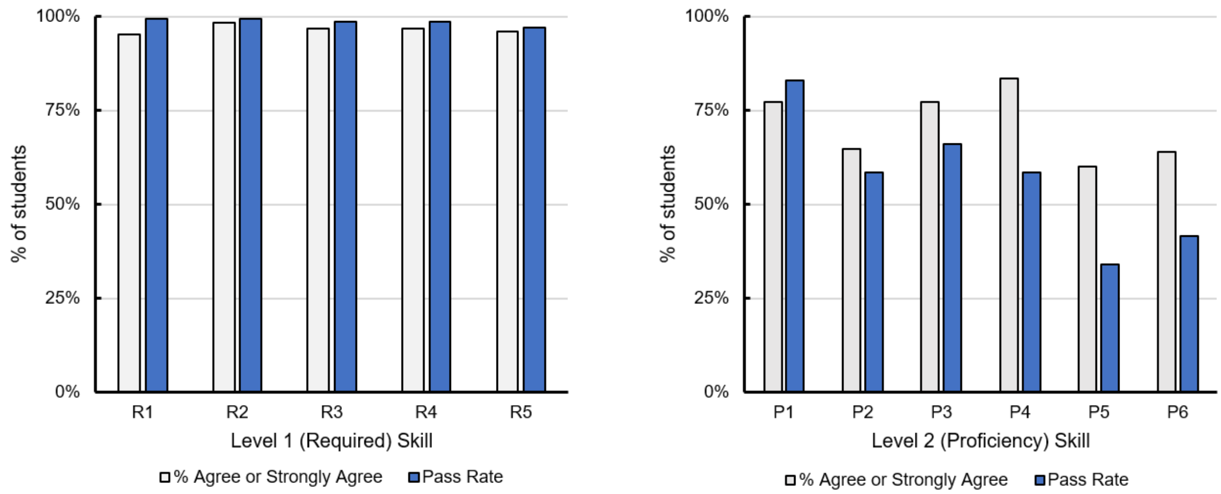
Evaluation of student performance

Student performance in the MBL scheme was evaluated by tracking weekly skill pass rates and evaluating self-efficacy through post-course surveys. Pass rates for each skill were tracked across the 2022 and 2023 course offerings (Fig. 4). Only three Level 1 skills (R1-R3) were assessed on Test 1, but all eleven testing skills (R1-R5, P1-P6) were available on Tests 7-10. Skill pass rates revealed that some students were prepared to pass each skill on the first attempt, but most students required two or more attempts before passing a particular skill. Level 1 skills had higher initial, second try and final pass rates than Level 2 skills. While not explicitly required, most students tested for Level 2 skills in numerical order and, therefore, a lower overall pass rate was observed for the gear-related skills (P5 and P6). Generally, the pass rate of each mastery skill increased an additional 10% during each successive week following its first assessment. Significantly lower increases to pass rates were observed for Test 10. This is likely attributed to less students attempting Test 10 because they had either already passed all the skills, or passing additional skills would not improve their overall grade. More students would likely attempt the last test for a plus/minus grading system since progress requires fewer passed skills (Tab. 5). Overall, weekly improvements to pass rate across the skills suggest that all students could pass every skill if time allowed for unlimited attempts.

	Level 1: Required Skills					Level 2: Proficiency Skills					
	R1	R2	R3	R4	R5	P1	P2	P3	P4	P5	P6
Test 1	43%	59%	33%								
Test 2	66%	86%	54%	35%	16%						
Test 3	76%	89%	67%	70%	29%	13%	11%				
Test 4	83%	94%	80%	84%	41%	24%	20%	13%			
Test 5	90%	96%	84%	86%	49%	33%	23%	17%	3%		
Test 6	96%	98%	88%	93%	64%	44%	30%	33%	16%		
Test 7	96%	99%	93%	95%	76%	55%	36%	41%	26%	6%	12%
Test 8	98%	99%	94%	98%	87%	70%	40%	50%	40%	16%	20%
Test 9	98%	99%	98%	99%	95%	81%	53%	59%	50%	26%	32%
Test 10	99%	99%	99%	99%	97%	83%	59%	66%	59%	34%	41%

Figure 4: Accumulated tested skill pass rate across 2022-2023 offerings.

Student self-efficacy for tested skills was measured through surveys administered during the 15th week of the semester in 2022 and 2023. The students ranked their competence with each skill on Likert Scale, and then the student responses were compared to the skill's final pass rate (Fig. 5). For Level 1 skills, the students reported high self-efficacy corresponding with the high pass rates (Fig. 5A). The students reported a lower self-efficacy for Level 2 skills than the Level 1 skills. Surprisingly, more students reported competency for Level 2 skills than actually passed the particular skills (Fig. 5B). Potentially these students understood the material, but ran out of testing opportunities to demonstrate mastery. Overall, the results suggest that the MBL approach described in this paper effectively measures students learning at the conclusion of the semester.



(A) **(B)**

Fig. 5: Student self-efficacy compared to pass rate for Level 1 skills (A) and Level 2 skills (B) from 2022-2023. Gray columns show the percentage of students that *Strongly Agree or Agree* that they are competent in the specific skill.

Comparing MBL in MD1 to previous student experience

All MD1 students had previous experience with flipped classroom and MBL in a computer applications course offered during sophomore year [9]. In 2023, student perception of the flipped classroom and MBL assessment were tracked by survey questions administered during week 1 and week 15 (Fig. 6). On average, students agreed or strongly agreed that the mastery-based assessment required them to learn the material (Q2) and gave them the opportunity to learn at their own rate (Q5) both before and after taking MD1. At week 15, significantly more students found the flipped classroom helped them understand the course material (Q1). Additionally, more students thought they performed better in the competency-based assessment compared to traditional courses when surveyed at the conclusion of the course (Q6). These improvements suggest that the MBL assessment developed for MD1 is at least as effect as the MBL approach the students experienced sophomore year [9].

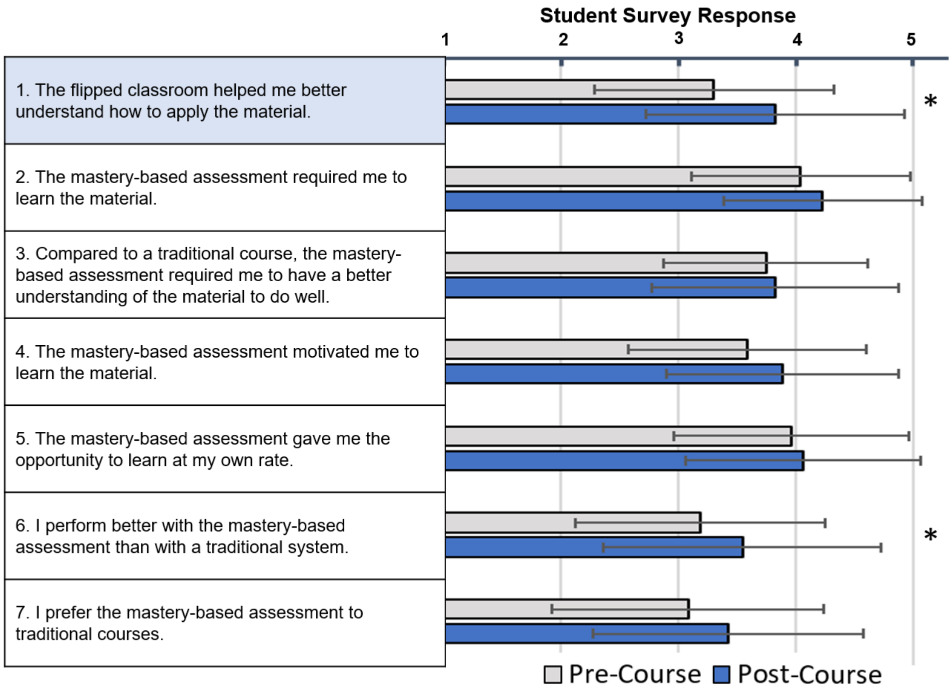


Fig. 6: Comparison of student responses on pre-course (week 1; n = 78) and post-course (week 15; n = 79) surveys. Scoring is based on a Likert Scale *(5 -Strongly Agree; 1-Strongly Disagree)*.* *p<0.05, T-test*

Assessing Failure Tolerance and Test Anxiety

The MBL assessment's effect on failure tolerance was assessed through surveys administered during week 1 and week 15 in 2023 (Fig. 7). Prompts 1-3 assessed the students' failure tolerance associated with homework assignments. For 2022-23, homework solutions were posted online after the students completed a first attempt during class meetings. The students were required to revise their work and reflect on any mistakes before submitting. Homework was then graded for completion rather than correctness. On week 15 surveys, students demonstrated a greater recognition of their own failure tolerance and were more likely to admit that they were uncomfortable making mistakes on homework assignments (Q2).

Four prompts specifically addressed test anxiety and learning from failure (Q4-Q7). Students were more likely to *agree* or *strongly agree to* all four prompts on the post-course survey. A significant increase was observed for Q5, suggesting that the MBL assessment developed for MD1 successfully reduced testing anxiety compared with courses with traditional examinations. Additionally, significant increases for Q6 suggest the MBL assessment was successful in allowing students to learn from their mistakes. Taken together, the improvements in post-course surveys suggest the MBL approach created an environment where students could make mistakes and had the opportunity to demonstrate that they had learned from those mistakes.

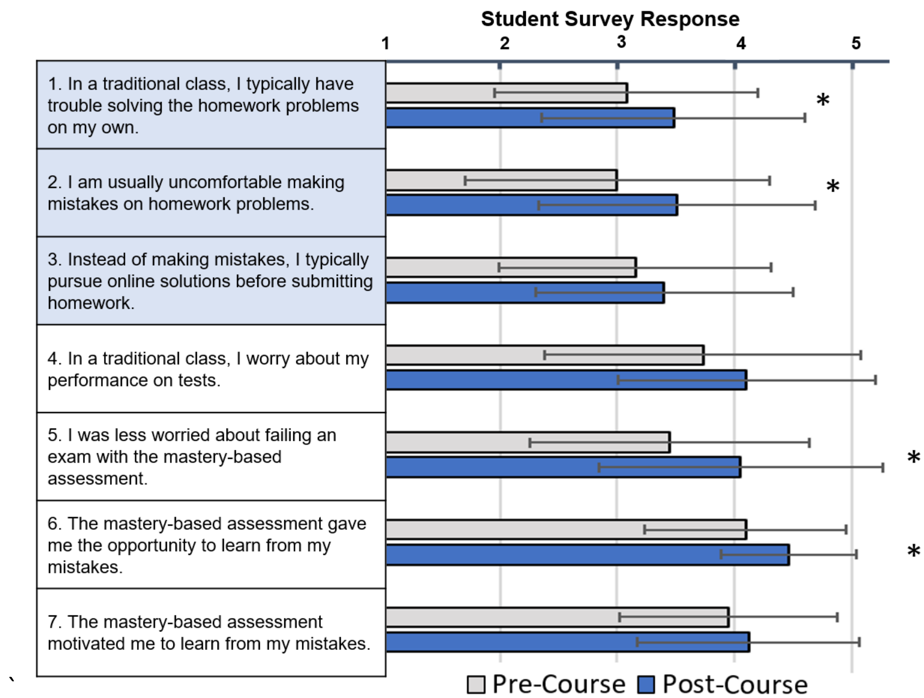


Fig. 7: Comparison of student responses on pre-course (week 1, n = 78) and post-course (week 15, n = 79) surveys. Scoring is based on Likert Scale where 5 corresponds with *Strongly Agree* and 1 corresponds with *Strongly Disagree*. * *p<0.05, T-test*

In 2023, students were asked an open-ended question during the week 15 survey: "What are the primary advantages of the mastery-based learning assessment?" Their responses (n= 79) were coded into the categories shown in Figure 8. The most frequent responses mentioned the opportunity to learn from previous mistakes or the need to better understand the material to succeed. 16 students specifically mentioned that the weekly assessments created a low-stakes testing environment that reduced pressure, reduced test anxiety, or improved overall mental health. Learning flexibility included responses mentioning that students could control their pace of learning and could decide which skills (if any) to test in a given week. One category, *the ability to retake tests,* was inherently related to the other categories. Responses were only coded into this category if students did not mention the reason it was beneficial to retake tests (to learn from mistakes, reduce stress, etc.). Sample student responses are included below.

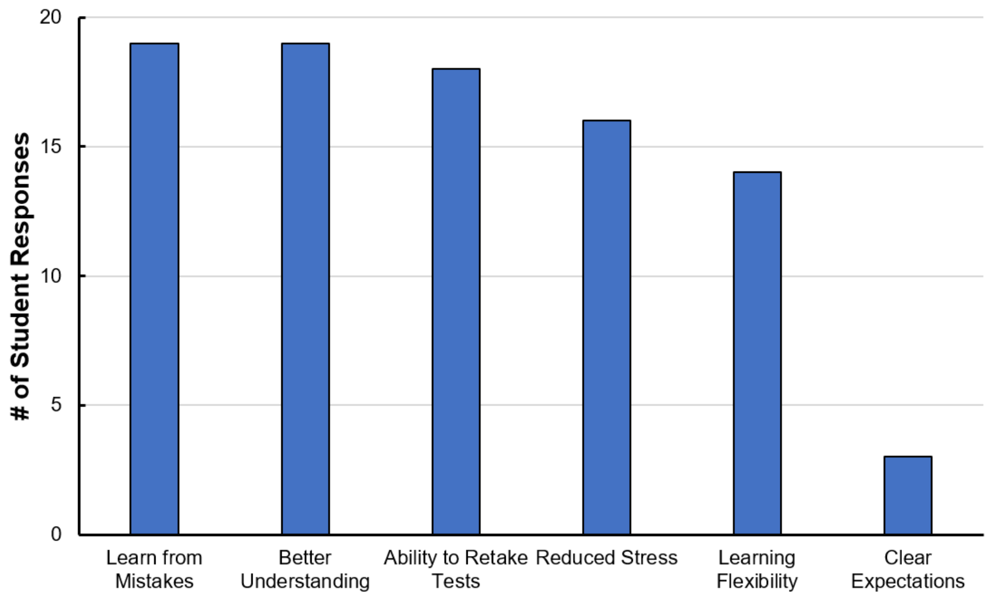


Figure 8: Student responses to open-ended question: "What is the primary benefit of the mastery-based learning assessment?" Some student responses are counted in more than one category.

Sample student responses:

I like that this makes you actually learn the material and not rely on partial credit to "get you through" I feel like this way I also am not memorizing things just to get the grade I want I am actually studying and comprehending the material given. It also allows you to review your past work and try again to improve unlike exams where if you miss a question you rarely ever have to go back and look at it again

I wasn't nervous when it came time to take tests because I knew if I made a mistake, I could learn from it and take the test again. I was also able to learn at my own pace which really helps me retain the material.

They allowed for me to learn from my mistakes and be more motivated to understand why I messed up and what to fix because I was provided the opportunity to retry.

It took the pressure off of us during the tests, because we were able to retake tests as needed. It also allowed us to work at our own pace, and gave us some flexibility in when to take what tests, which was nice when we had hard deadlines in other classes.

I think with exams in a traditional setting, students tend to cram and causes us to store information in our short-term memory. I found with this system and the exam Fridays, I felt at ease to take time to look thoroughly through how to do a skill. When I did take the time I almost always passed. I feel like this is more beneficial overall.

Discussion

This paper is the first to describe and evaluate a mastery-based learning approach for a theory of machine kinematics and dynamics course. The author's first experience with MBL at Ohio Northern went poorly, but applying the best practices described in this paper resulted in significant improvements in post-course evaluations (Fig. 1), overall student grades (Fig. 2) and student self-efficacy (Fig. 3). Post-course surveys indicated that the MBL approach enabled students to learn the material (Fig. 5) and learn at their own rate (Fig. 6). This paper also evaluated whether MBL could improve failure tolerance, motivate learning from mistakes, and reduce test anxiety in an upper-level, mechanical engineering course. Overwhelming, survey responses showed the MBL approach reduced test anxiety and created a lower-stakes environment where students could learn from previous mistakes (Fig.7, Fig.8).

Given the success of the MBL approach at Mount Union, it was surprising that its first iteration at Ohio Northern went so poorly. It is hypothesized that this original success was due largely to the over-representation of rigid-body dynamics content in the mastery skills. Developing MBL for MD1 was inherently difficult because unlike dynamics, theory of machines content is not divided into neatly defined skills. Therefore, while the instructor applied best judgment when determining what content should become a mastery skill, some skills were poorly defined. Furthermore, current machine design textbooks do not contain practice problems that align well to the mastery-skills. To remedy this concern, a collection of test questions was developed and provided to the students.

The effectiveness of the MBL approach depended on the ability to design consistent assessment questions. Mastery skills that were too ambiguous were difficult for students to effectively prepare for. Additionally, ambiguous skills allowed for too much variability when developing assessment questions. In 2021, this variability resulted in student perception that the test questions got progressively more difficult or seemed like “luck of the draw”. Practically speaking, excessive question variability limited the students’ ability to learn from their previous mistakes.

This paper presents an MBL approach with 33 total skills, a number much greater other MBL schemes [7, 9] . However, only 11 of the skills were directly assessed by tests, comparable to the 10 presented by DeGoede [7]. Although they were not specifically evaluated in this paper, the computer application, homework, and project skills were important components in this MBL system. Passing these skills improved morale and maintained student motivation by enabling course progression for students struggling to master difficult skills. Designating the computer-based assignments as mastery-skills emphasized the usefulness of the computer applications. Students often commented on post-course evaluations that applying MATLAB and SolidWorks to actual engineering problems is a strength of the course. After a student passed the required Level 1 skills, the combined effect of the computer application and homework skills raised their grade from a “D” to a “C” and reduced the number of tested skills needed to progress to a “B.” Passing Level 2 tested skills was required to earn a “B” or “A”. The semester project required the students to apply all the mastery skills to a real-world engineering problem [10]. The project was useful to reinforce skills that may have been passed earlier in the semester and kept students who completed the testing early engaged until the end of the semester.

The MBL approach described in this paper adds to a growing body of literature describing similar approaches across the mechanical engineering curriculum. Ideally, engineering programs will adapt learning-focused pedagogy like MBL across the entire curriculum. However, more work must first be completed to develop and evaluate BML approaches for other upper-level, mechanical engineering courses.

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Appendix 1: MBL for Kinematics and Dynamics of Machinery at Mount Union

R-Level: Required Skills

Required Kinematics Skills		Required Dynamics Skills		Required Project Completion	
K-R1	Identify the difference between a particle and a rigid body	D-R1	Apply the parallel axis theorem to calculate the moment of inertia	P-R1	Complete a design and analysis project (solution score above 70%)
K-R2	Use calculus to determine position, velocity, and/or acceleration of a point on a rigid body	D-R2	Draw appropriate Free-body diagrams and kinetic diagrams for a dynamics problem		
K-R3	Solve for the velocity of a point using vectors analysis	D-R3	Apply Newton's laws of motion analyze rigid bodies in motion		

P-Level: Proficiency Skills

Kinematics Proficiency Skills		Dynamics Proficiency Skills	
K-P1	Use the instant center of rigid body in complex motion to perform velocity analysis.	D-P1	Apply the principle of Work-Energy to solve dynamics problems
K-P2	Apply the vector analysis to determine the acceleration of points on a rigid body	D-P2	Apply the principles of linear and/or angular impulse momentum on rigid bodies
		D-P3	Analyze the impact between rigid bodies

Project Proficiency Skills		Mechanisms Proficiency Skills	
P-P1	Oral Presentation Proficiency (score above 80%)	M-P1	Draw and label skeleton diagrams of a complex mechanism
P-P2	Written Report Proficiency (score above 80%)	M-P2	Classify Four-bar linkages according to Grashof condition and Barker's classification
P-P3	Teamwork Score (score above 80%)	M-P3	Use vector loops to perform position analysis on a mechanism
		MP-4	Take derivatives of vector loops to derive equations and calculate the velocity and/or acceleration at points in 4-bar linkages

A-Level: Advanced Skills

Dynamics Advanced Skills		Mechanisms Advanced Skills	
D-A1	Solve a complex, multistep dynamics problem	M-A1	Calculate input or output dynamics in a 4-bar linkage using the method of virtual work
		M-A2	Demonstrate proficiency in MATLAB with dynamic force analysis .m script.

The overall course grade was determined based on the number of skills perfected:

Grade*	**Requirement**
F	Pass <7 required skills
D-	Pass all 7 required skills
D	Pass 8 skills
D+	Pass 9 skills
C-	Pass 11 skills
C	Pass 12 skills
C+	Pass 13 skills
B-	Pass 15 skills
B	Pass 16 skills
B+	Pass 17 skills
A-	Pass 19 skills
A	Pass 20 skills
Each missing/low effort HW: - 1 skill (1 mulligan)	
Every 3x unfinished/poor Quizzes: - 1 skill	

Appendix 2: 2021 MBL for Mechanical Design 1 at Ohio Northern

Required Skills	
R1	Identify and describe key concepts related to the synthesis and evaluation of machines.
R2	Draw and label kinematic diagrams
R3	Classify four-bar linkages according to Grashof condition and Barker's classification
R4	Apply graphical methods to synthesize linkages
R5	Analyze a linkage using graphical position analysis
R6	Use vectors to evaluate the positions of links in a mechanism
R7-P	Complete a design and analysis project (Overall Score >70%)

Proficiency Skills	
P1	Apply the instant center method to evaluate linkages
P2	Evaluate the angular velocity ratio and mechanical advantage of a linkage
P3	Use vectors to evaluate the velocity of links in a mechanism
P4	Use vectors to evaluate the acceleration of links in a mechanism
P5	Design or evaluate gear trains
P6	Design or evaluate cams
P7	Draw free-body diagrams and derive equations for force analysis
P8-P	Oral Presentation Proficiency (score ≥ 80%)
P9-P	Written Report Proficiency (score ≥ 80%)
P10 -P	Peer Evaluation (score ≥ 80%)

Advanced Skills	
A1	Perform dynamic force analysis using MATLAB
A2	Calculate input or output linkage dynamics using the method of virtual work
A3-P	Project Solution Proficiency (score ≥ 90%)

Table A2: 2021 Grade Progression. Penalties were enforced for missing assignments or quizzes.

Grade*	Requirement
F	Pass <7 required skills
D	Pass all 7 required skills
C	Pass 11 skills
B	Pass 15 skills
A	Pass 19 skills
Each missing/low effort HW: - 1 skill (1 mulligan)	
Every 2x missing/poor Quizzes: - 1 skill	

Appendix 3: Evolution of Course Competencies

Original (2021) course competencies are listed in the left two columns and relate horizontally to their corresponding final (2023) skill(s) in the right columns

Color Key: Blue: Tested, Green: Computer Apps (HW), Yellow: Project, Red: HW/Lecture.

2021 - Original Competency Skills		2023 - Updated Skills	
#	Description	#	Description
R1	Identify and describe key concepts related to the synthesis and evaluation of machines.		Removed: Questions too variable
R2	Draw and label kinematic diagrams	R1	Draw and label kinematic diagrams
R3	Classify four-bar linkages according to Grashof condition and Barker's classification	R2	Classify four-bar linkages according to Grashof condition and Barker's classification
R4	Apply graphical methods to synthesize linkages	R6-C	Apply graphical synthesis methods for function generation in SolidWorks
		P7-C	Apply graphical synthesis methods for motion generation in SolidWorks
R5	Analyze a linkage using graphical position analysis	R7-C	Analyze a linkage using graphical position analysis in SolidWorks
R6	Use vectors to evaluate the positions of links in a mechanism	R3	Write vector loop eqns for a mechanism of four or more links
		R4	Calculate the position of points on a mechanism with four or more links
		R5	Perform position analysis on a crank slider
		R8-C	Perform analytical position analysis on a four-bar linkage using MATLAB
R7-P	Complete a design and analysis project (Overall Score >70%)	R11-P	Complete a design and analysis project (overall score >60%)
P1	Evaluate the angular velocity ratio and mechanical advantage of a linkage	P1	Evaluate indices of merits on four bar linkage (transmission angle, angular velocity ratio, and mechanical advantage)
P2	Apply the instant center method to evaluate linkages	P2	Use instantaneous centers of velocity to calculate velocity of links
P3	Use vectors to evaluate the velocity of links in a mechanism	P3	Calculate the velocity of points on a mechanism with four or more links
		P8-C	Perform analytical velocity analysis on a four-bar linkage using MATLAB
P4	Use vectors to evaluate the acceleration of links in a mechanism	P4	Perform velocity and acceleration analysis on a crank slider
		P9-C	Perform analytical acceleration analysis on a four-bar linkage using MATLAB
P5	Design or evaluate gear trains	P5	Calculate power, forces, and efficiency across spur gear trains
		P6	Design a gear box to achieve specified torque or speed characteristics
P6	Design or evaluate cams	P10-C	Generate *svaj* diagrams for cam design using MATLAB
P7	Draw free-body diagrams and derive equations for force analysis		Removed: Difficult to grade
P8-P	Oral Presentation Proficiency (score ≥ 80%)	R15-P	Complete a design and analysis project (overall score ≥70%)
P9-P	Written Report Proficiency (score ≥ 80%)	R16-P	Complete a design and analysis project (overall score ≥80%)
P10 - P	Peer Evaluation (score ≥ 80%)		
A1	Perform dynamic force analysis using MATLAB	A1-C	Perform dynamic force analysis on a four-bar linkage using MATLAB
A2	Calculate input or output linkage dynamics using the method of virtual work	A2-C	Apply the method of virtual work using MATLAB or by hand
A3-P	Project Solution Proficiency (score ≥ 90%)	A6-P	Complete a design and analysis project (overall score ≥ 90%)
Added to challenge high achieving students		A3-C	**Independent Study**: Write a .m script to perform analytical synthesis
Added to motivate a reward class attendance and homework completion. Also reduced penalty for missed assignments		R9-HW	Homework average ≥ 60%
		R11-HW	Homework average ≥ 70%
		R12-HW	Homework average ≥ 80%
		A4-HW	Homework average ≥ 90%
Added to motivate and reward watching the recorded		R10-HW	Lecture notes average ≥ 60%
		R13-HW	Lecture notes average ≥ 70%
		R14-HW	Lecture notes average ≥ 80%
		A5-HW	Lecture notes average ≥ 90%

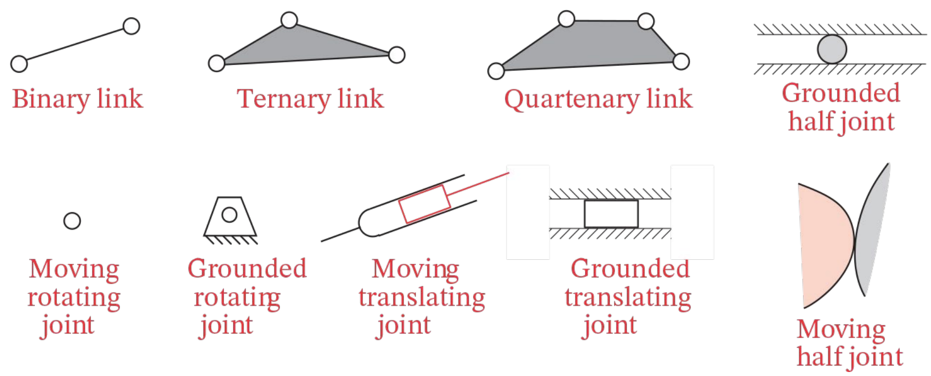
Appendix 4: Example Test Review Document

Skill:

R1 - Draw and label kinematic diagrams and calculate mobility

Key Concepts

1. Creating the Kinematic Diagram
   - Remember the Notation:



2. Calculating Mobility: M = 3(L-1) – J1 – J2

Lectures to Review

- Lecture 01 – Kinematic Diagrams
- Note sheet: 01 – Kinematic Diagrams and Mobility

Homework to Review:

- Homework 1
  - Problem 1 (construction toys)
  - Problem 2 – Four bar linkage examples

Advice:

- Don't forget that you will need a ground link. Typically, only joints are drawn for ground links.
- Make sure that you can distinguish between binary, ternary, quaternary, and etc. links
- We focus on planar mechanisms. Any motion outside our plane is not included in the diagram.
- If the picture is unclear – then ask Dr. Gargac! It's better to ask that get misinterpret the image.
- Don't forget the easy mobility check – You should calculate the same DOFs as you have inputs into the system.

Review Problem - This is what the test problem would look like

Skill R2: Draw and label kinematic diagrams

Include all units and directions for final and intermediate calculations. Box all answers.

For the scissor lift shown below, draw the kinematic diagram. Label all links and joints and calculate mobility. Assume the wheels are fixed. The hydraulic cylinder connects between points A and B.

These joints can also translate along a slot. Otherwise, this would be a structure