Embedding Productive Failure: A Mastery-Based Embedded Systems Course

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Introduction

Engineering students benefit from learning to fail, developing resilience, humility, and persistence- valuable habits for their academic experience and for their future careers. As a result, some engineering educators are introducing low-stakes failure opportunities into their courses to help students engage productively with failure and to move from a grades-first mindset to a learning-first mindset. This approach is backed by many experiments which indicate that when students are encouraged to make early mistakes, they are more likely to retain the correct information [1].

One model that is becoming increasingly popular to introduce students to productive failure is competency- or mastery-based learning (MBL) [2]. In this model, students must demonstrate mastery of required skills in order to pass the course, primarily through low stakes quizzes that can be repeated after failure. In order to earn a higher grade, students can master more complex skills introduced throughout the semester. A recent engineering education study emphasizes the "importance of mastery-oriented goals" as they predict higher academic achievement through positive association with deep learning strategies [3]. Recent examples include MBL in kinematics [4, 5], statics [6], fluid mechanics [7], dynamics [8], and mechanics of materials [5]. Other examples include MBL in introductory math courses for engineers [5], a mechanical engineering computer applications course [9], project-based design courses [10], and competency-based lab skills checks [11]. Examples more relevant in electrical and computer engineering (ECE) include circuits [12, 13], computer architecture [14], and signals and systems [15].

One key to productive failure is to pair these failures with feelings of success to avoid threatening the ego [16]. The MBL model need not focus only on failure, but can also allow students to focus on their progress and completion (successes), which is the task focus linked to deep learning [3]. Low stakes quizzing with the option to retake is an effective way to allow students to track their progress and success.

There has been some work on measuring failure tolerance in engineering students with the goal of assessing how MBL affects student failure tolerance. Attempts to measure the impact of a single course on students' failure tolerance show that this tolerance does not change significantly over the course of a single semester. This is attributed to students "likely overestimating their failure tolerance" at the beginning of the semester, supported by students comments that they "realized that [they're] not as good at handling failure as [they] thought [they were] at the beginning of the semester" [5]. Despite this, it is clear from literature that providing students with the opportunity to master skills and observe success, as well as fail in a low-stakes environment are valuable experiences for developing engineers.

In addition to the benefits of low-stakes failure opportunities, mastery-based learning is also linked to the development of an entrepreneurial mindset (EM) [5]. Persisting through and learning from failure is identified as a core outcome associated with creating value in the EM Framework within the Kern Entrepreneurial Engineering Network (KEEN) [17]. Embracing failure as a learning opportunity has also been shown to be a key observable behavior of students who are developing EM [18]. Integration of EM has resulted in strong outcomes in engineering education [19, 20]. These outcomes include increased motivation [21], improved student professional development, and better preparation for real-world problem solving impacting their communities, corporations, and nations [22].

Recognizing these benefits, the mechanical engineering program at Ohio Northern University has implemented several MBL courses. Due to the successful outcomes of these courses, there was a desire to embed MBL into the electrical and computer engineering programs. This paper outlines the development of a mastery-based embedded systems course for upper level electrical and computer engineering students aimed to introduce productive failure into the ECE curriculum.

This work details the course design and student performance. The paper also reports on developing student failure tolerance, and presents lessons learned from the initial offering of the course.

Course Design

This work focuses on the redesign of Embedded Real-Time Applications from a standard course structure to an MBL scheme. This course is a required class for all electrical engineering and computer engineering students at Ohio Northern University, who typically take the course in their third year, fall semester. The course also serves as an elective for computer science and mechanical engineering students pursuing a concentration in Robotics. The course is required to cover standard embedded systems content with a focus on mobile robotics, and so employs the Texas Instruments Robotics System Learning Kit with a TI MSP432 LaunchPad with an ARM Cortex™-M Processor, and accompanying textbook [23]. Table 1 shows the course outcomes for this course.

In the development of the MBL model, we adopted several best practices from literature with some modifications [4]. The best practices applied to this course are summarized below:

1. *Each mastery skill should evaluate one well-defined skill* [4]
   This ensures that students are actually tested on the skill itself. Quizzes were designed to

Table 1: Course outcomes

	Outcome	Category
1	Apply knowledge of microcontroller architecture-including registers, memory, I/O, and instruction sets-to configure and troubleshoot embedded system components	Embedded Systems
2	Develop software for basic robotic navigation with a finite state machine	Embedded Systems
3	Interface robotic sensors with a microcontroller	Embedded Systems
4	Implement timers, interrupts, and pulse-width modulation on an embedded system	Embedded Systems
5	Interface DC motors with hardware and software drivers	Embedded Systems
6	Implement robotic system and sensor integration	Robotics
7	Demonstrate basic principles of robotic odometry	Robotics
8	Implement system control with PID feedback	Robotics
9	Demonstrate principles of embedded system communication using standard protocols	Embedded Systems
10	Develop a project schedule and monitor progress as tasks are completed and objectives are met	Project Management
11	Utilize an entrepreneurial mindset (curiosity, connections, and creating value) and creativity to apply new knowledge	Entrepreneurial Mindset

test on one specific skill, and lab experiences or project milestones included rubrics which specified specific requirements to meet the skill.

2. *Lecture materials should match the mastery assessments* [4]
   Applying this practice, quizzes over specific skills were not available to students until the relevant materials were covered in lecture.
3. *Example problem sets should be available for the students* [4]
   In many cases, Monday was a typical lecture while Wednesday was a flipped-classroom pedagogy in which students watched a video in advance of class and worked through practice/example problems in class either independently or in small groups. In addition, after each quiz was administered, an example solution for the first quiz version was posted in the online Learning Management System. There was no homework assigned in

the course, and these problem sets and quiz solutions served in place of these assignments.

4. *Regular opportunities for feedback should be provided* [4]
   Quizzes were, in general, administered on Fridays. Quizzes were returned the following class meeting (Monday), allowing students several days to digest the results, ask questions, and attend office hours. In addition, students were given a 'bingo sheet' (see Appendix A) for tracking their progress, and the instructor provided four bingo sheet check-ins across the course of the semester. Passed skills were 'checked off' on the bingo sheet, giving students the feeling of success when they mastered a skill.
5. *Students should be limited on the number of skills they can test or retest per quizzing opportunity* [4]
   Students were limited to test 3 skills per quizzing opportunity. This allowed students to focus on fewer skills at a time and reduced overhead for the faculty managing the course.

As an MBL framework, assessment on each skill is pass/fail. Failed skills could be retried with different versions of the quizzes, and lab or project assignments could be resubmitted until the requirements were met. For quizzes, the grading schema was as follows:

- P: Pass, 100% correct
- P-: Pass, >85% correct
- R+: Retake, >70% correct
- R: Retake, 70% or less correct

In order to complete a skill, students were required to earn a P or P-. On the first attempt at any given skill, P- grades were not awarded. The first MBL quizzes became available at the end of week three, and new skills were introduced each week. Most A level skills were not introduced until the second half of the semester.

A total of 25 course competencies were developed, separated into three levels. Required Skills (R-Level) correspond to the bare minimum a student should be required to demonstrate in order to pass the course. All outcomes associated with ABET Assessment are represented in this tier- as we believe demonstrating these outcomes is essential to earning a passing grade. Completion of all R-Level skills and nothing else corresponds to a final grade of 'D' in the course. Proficiency Skills (P-Level) build on R-Level skills and demonstrate a higher level of knowledge and application of embedded systems, Completing several P-Level skills in addition to the R-Level skills corresponds to a 'C' in the course. The final level, Advanced Skills (A-Level) are an integration of R and P-Level with more advanced course content, such as interrupts, synchronous serial communication, odometry, and control. Completing more of these skills resulted in improved course grades. A full outline of the grading standards for the course is shown in Table 2.

Table 2: Grading standards for MBL Embedded Systems course

Final Grade	Description
F	Do not complete all R-Level Skills
D	Complete all R-Level Skills
C	Complete all R-Level Skills, plus *P-Level Skills and at least 2 more skills from P or A Level
B	Complete all R-Level Skills, plus *P-Level Skills, plus *A-Level Skills and at least 2 more skills from P or A Level
A	Complete all R-Level Skills, plus *P-Level Skills, plus *A-Level Skills and at least 6 more skills from P or A Level

Table 3: Required Level Skills

	Skill		Outcome
Tested	R1	Demonstrate ability to specify registers and memory addresses	1
	R2	Demonstrate the ability to write C code for embedded applications	1
	R3	Configure and use ports for input and output	1
	R4	Control DC motors	5
	R5	Demonstrate principles of embedded system communication using UART	9
Lab	R6	Develop an effective experiment with a clear procedure	3
	R7	Acquire experimental data correctly using appropriate instrumentation	3
	R8	Draw valid conclusions using engineering judgement from obtained experimental data	3
	R9	Control a robotic system applying PID control	8
Project	R10	Utilize an entrepreneurial mindset (curiosity, connections, and creating value) and creativity to apply new knowledge	11
	R11	Project R Level	6
	R12	Project specific software design using a structured Finite State Machine	2

Table 4: Proficiency Level Skills

		Skill	Outcome
Tested	P1	Use timers to measure time on an embedded system	4
	P2	Acquire and process data on an embedded system	3
	P3	Design software using a structured Finite State Machine	2
Project	*P4	Acceptable robot navigation	7
	*P5	Project P Level	10

Table 5: Advanced Level Skills

		Skill	Outcome
Tested	A1	Implement interrupts in embedded systems	4
	A2	Implement PWM on embedded systems	4
	A3	Implement feedback control with PID	8
	A4	Demonstrate basic principles of robot odometry	7
	A5	Demonstrate principles of embedded system communication using SPI	9
	A6	Demonstrate principles of embedded system communication using I2C	9
Project	*A7	System integration full navigation task	6
	*A8	Project A Level	10

The complete list of skills, by level are shown in Table 3, 4, and 5. The table also shows which corresponding course outcomes are tied to each skill. In total, 14 of the skills correspond to quizzes and 4 skills are assessed through lab requirements. The remaining 7 are associated with the semester-long robotics project, which has a similar structure to robotics projects in other literature [24].

Evaluation

Evaluation of Student Performance

After each quiz day, the pass rates for each skill were tracked. These accumulated results were shared with students. This allowed students to see how the whole class was progressing, and provided an opportunity to encourage those who were unsuccessful in their first attempt, as they were not alone. This collective feeling could alleviate the ego threatening effect of failure.

Table 6 shows the skill pass rates across attempts, for the course section of 38 students which had 22 computer engineering (CpE), 14 electrical engineering (EE), 1 computer science (CS) and 1 mechanical engineering (ME) as primary majors. Of the students, 3 CpE students had EE as a secondary major, and one CpE had ME as a secondary major.

The maximum number of attempts for this course was 7, which meant that 7 unique versions of the same skill quiz were created. Quizzes became available at different points in the semester, as denoted within Table 6. In general, R-Level skills had the highest first and second attempt pass rates, and A-Level skills had the lowest.

Given the progression on R and P level skills, with enough attempts, most students were able to demonstrate mastery. By nature, the A-Level skills became available later in the semester, had fewer overall attempts, and were the least passed of all skills. The lower pass rates on A-Level skills may also be impacted by students choosing not to attempt them if they are satisfied with their grade progression in the course. The overall student performance resulted in a relatively high course GPA, with 22 “A” grades, 9 “B” grades, and 7 “C” grades awarded. Since assessments are pass-fail, this course design ensures that each student is able to demonstrate mastery of each required skill, as well as additional, more advanced skills.

Student Fault Tolerance

Students were asked to rate their agreement with the prompt “I feel that I am more tolerant to failure as a result of this course” on a 6 point Likert scale, with 1 representing Strongly Disagree and 6 representing Strongly Agree in the post-course survey. Of the 38 students, 29 responded to the survey. The results are shown in Table 7, which shows that 83% of the respondents indicated some level of agreement with the prompt, with 21% strongly agreeing that the course helped them develop failure tolerance.

Lessons Learned and Discussion

The design and implementation of an MBL Embedded Systems course presented in this work was at least moderately successful in the first attempt. All students were able to achieve a passing grade by demonstrating the minimum required skills. Although not covered in this paper, the project associated with the course required students to develop software and debug hardware to navigate an autonomous robotic platform around a playfield while avoiding obstacles and complete specific objectives. All but 1 group was able to successfully demonstrate these objectives above the minimum threshold for a course grade of “B”. This success suggests that students learned, and retained, enough in the course to implement the content in a practical application.

Table 6: Skill pass rate across attempts

	Level 1: Required Skills					Level 2: Proficiency Skills			Level 3: Advanced Skills					
	R1	R2	R3	R4	R5	P1	P2	P3	A1	A2	A3	A4	A5	A6
Week 1	18%													
Week 2	63%	47%												
Week 3	92%	71%	37%											
Week 4	95%	87%	63%											
Week 5	97%	95%	87%			47%								
Week 6	100%	97%	89%			71%	8%							
Week 7	100%	97%	97%	31%		84%	26%							
Week 8	100%	100%	100%	71%		87%	37%							
Week 9	100%	100%	100%	89%		89%	61%		8%	3%				
Week 10	100%	100%	100%	95%		95%	68%	24%	32%	21%				
Week 11	100%	100%	100%	97%		97%	71%	61%	37%	50%	3%	11%		
Week 12	100%	100%	100%	100%		97%	71%	68%	45%	53%	16%	18%		
Week 13	100%	100%	100%	100%	11%	97%	71%	79%	55%	58%	16%	37%	3%	
Week 14	100%	100%	100%	100%	82%	97%	71%	82%	61%	58%	24%	42%	5%	3%
Week 15	100%	100%	100%	100%	100%	97%	71%	82%	61%	58%	26%	53%	8%	11%

Table 7: Student response to failure tolerance prompt

Strongly Disagree	Disagree	Mostly Disagree	Mostly Agree	Agree	Strongly Agree
3%	10%	4%	45%	17%	21%

Generally, students appreciated the mastery-based approach to this course. Out of 36 responses to the course evaluations, 5 students directly highlighted mastery-based learning as a strength of the course, while an additional 12 mentioned that they thought the ability to retake quizzes was a strength. This is encouraging, as students were not prompted to discuss mastery-based learning at all in the course evaluations. One student stated that mastery based learning "*was very effective at encouraging me to continue working to learn something if I failed a skill while also not directly punishing me and my grade because I did not understand the material.*" Another student stated that "*it made me more motivated to try my best and pass the quizzes.*" Others commented on the reduced stress and focus on grades, with statements such as "*the failures didn't hang over my head and I was able to improve throughout the semester*", "*being able to repeat the quizzes removes the pressures of grades but really encourages learning*", and "*I liked how we were able to retake quizzes. It helped me actually learn the material and also reduced my stress outside of class.*"

While these comments indicated that quite a few students appreciated the mastery-based approach, not all students agreed. There were two respondents who felt the mastery-based system was a weakness of the course. One stated a key downside of mastery-based learning which is that they "*believe that failure can be good to encounter every so often to remind you to keep working hard but consistent and ever-present failure becomes simply annoying and makes me have a more apathetic attitude*", going on to state that "*at a certain point the bite of failure that makes it a potent learning tool becomes diluted when you are constantly failing things. Typically failure in other classes also means that it can be put behind you such as a bad exam but failure in the mastery style class means that it will come back to haunt you until it is passed.*" While there is a risk that students will focus only on short term memorization or become discouraged (as discussed in [16]), this did not appear to be a common response. The other respondent simply stated that they don't "*hate mastery classes*", they felt that they "*learn better using a standard class.*"

Several key lessons learned include:

1. Quiz generation, organization, and management is fairly time intensive. This must be considered when adopting MBL strategies
2. Outcomes should be stratified across mastery levels to differentiate students who meet requirements at a minimal, acceptable, or excellent level, which is helpful for course assessment

3. Students may choose to stop quizzing and focus on the final project when they are satisfied with their grade progression. This means that more advanced skills may not be quizzed for all students, so care should be taken to encourage students to learn and retain this content.

4. The project levels should do a better job of capturing the associated skills. For example, the A level project skill should require students to apply periodic interrupts, edge triggered interrupts, and/or other associated A level skills.

With these lessons in mind, we hope that this work has provided ample exploration of an MBL course design to implement in upper-level ECE courses. Additional information on this project can be found in a card on EngineeringUnleashed.com [25]. MBL prepares students for a flourishing life by helping them learn from their failures (and especially successes), deepen their learning, and develop into engineers that solve problems that matter for the world.

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Appendix A - Mastery Bingo Sheet

Required		**Proficiency**		**Advanced**	
R1*: Demonstrate ability to specify registers and memory addresses		P1: Use timers to measure time		A1: Implement interrupts on embedded systems	
R2*: Instruction Set (C Code)		P2: Acquire and process data on an embedded system		A2: Implement Pulse Width Modulation on embedded ssytems	
R3*: Digital I/O		P3: Design software using a structured FSM		A3: Implement PID Control	
R4*: Control DC Motors		P4*: Robotic Navigation Acceptable		A4: Demonstrate basic principles of robot odometry	
R5*: Serial Communications (UART)		P5*: Project P Level		A5: Serial Communications (SPI)	
R6*: Develop an effective experiment with a clear procedure				A6: Serial Communications (I2C)	
R7*: Acquire experimental data correctly using appropriate instrumentation				A7*: System Integration Full Navigation Task	
R8*: Draw valid conclusions using engineering judgement from obtained experimental data				A8*: Project A Level	
R9*: System Control (PID)					
R10*: Utilize an entrepreneurial mindet (curiosity, connections, and creating value) and creativity to apply new					

knowledge					
R11*: Project R Level					
R12*: FSM Software Design (Project Specific)					