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Ten Years of Badge-Based/Mastery Learning for Computer Architecture—Lessons Learned

Dr. Peter Jamieson, Miami University

Dr. Jamieson is an Associate Professor in the Electrical and Computer Engineering department at Miami University. His research focuses on Education, Games, and FPGAs.

Ten Years of Badge-Based/Mastery Learning for Computer Architecture - Lessons Learned

Abstract

Ten years ago, we chose to implement a badge-based version of a computer architecture course. We presented a research paper [1] on this approach with the concern that the modality would result in a flattened grade distribution where most students would receive high grades. Our early results showed this was not the case, and in retrospect, the concern was not relevant. In this paper, we provide lessons learned over the 10 years we have taught the course in a badge-based format providing information on interventions we implemented in an attempt to make the course better for students.

For the last ten years of running a computer architecture in a badge-based format, we will provide the current structure of the course including a badge-stream that focuses on security. We will also present the statistics from the course including student grades, badge completion statistics, and anecdotal observations from the student reviews including student comments. Overall, we believe this approach to teaching computer architecture is successful in helping students who want to learn the topic with a focus on their interests. There also is a clear divide among students who like the badge-based approach versus those who would prefer a more traditional and less-student-centered teaching model. The results of this work provide a longitudinal experience of using badge-based teaching for computer architecture, and we believe the approach is sound understanding that the limitation of the model is how large it can be scaled to.

1 Introduction

Ten years ago, we implemented a badge-based computer architecture course for 2nd-year undergraduate students at Miami University pursuing a Computer Engineering major. Around then, we also presented a paper [1] that compared a computer architecture course implemented as a traditional lecture and as a badge-based course to see if the grade distribution would be significantly different. Our comparison showed that the grade distributions were similar for both lecture and badge-based course structures.

A badge-based course provides the learner with a set of badges that can be worked on and demonstrated (assessed) to provide evidence of mastery of a specific set of skills. The idea of getting badges aligns with mastery-based teaching or specification grading where the learner demonstrates a capability and achieves the “badge”, “masters” the topic, or “meets” the specification. In our computer architecture course, badges are divided into three categories that include: core, intermediate, and advanced. Three core badges must be completed to get a letter grade of "C" in the course. Completion of additional badges directly maps a student's letter grade to higher values in the course. The motivation behind badge-based learning for this course is to allow people with high interest in particular topics to delve deeper into the material while still providing less interested students with a basic understanding of the topic. Badge-based learning is assessed via deliverables that the instructor views and discusses with the student. These assessment sessions can be redone if that student does not satisfactorily demonstrate mastery of the badge topic. This assessment differs from tests and assignments, which are one-off assessment points that can go poorly independent of a student's learned skills.

This work focuses on evaluating the badge-based computer architecture over the decade we have run it. In particular, we will provide summative statistics for the course in terms of student grades, completed badge distribution, and provide anecdotal discussion of student evaluations. We will also provide insight into changes we have made throughout the running of this course to increase student success and provide our evaluation of whether these interventions provided any significant changes or benefits to the students. Finally, we will discuss our conclusion of the qualities of badge-based learning as a classroom model for learning.

The remainder of this paper is organized as follows: Section 2 provides a brief review of badge-based course literature. Section 3 describes the badge-based course in terms of the badges, assessment, and deliverables including the changes we made to the overall structure of the course. Section 4 provides summative results of the course in a longitudinal review over the time it has been run. Section 5 discusses our experience with a badge-based course, and the modifications we have tried, and Section 6 concludes the paper.

2 Background

Badge-based learning hinges on ideas of project-based learning [2], experiential learning [3], and formative assessment [4], [5] among others. Since we last reviewed badge-based learning in 2014 [1], badge-based learning has continued to be a topic of research, and we list several studies ([6], [7], [8], [9]), innovations ([10]), and articles ([11], [12], [13]) that have emerged. More recently, the idea of badges has shifted into the space of micro-credentials [14] [15], and the main researchers that have focused on badge-based learning come from gamification research and design [16], [17], [18]. The idea of badges still, is a gamification method for education that may lack clear benefits [19].

The idea of a merit-based badge evolved from the British army, and today badges are common among organizations such as Girl/Boy Guides/Scouts among many other groups. The base idea of a merit badge is that the badge is awarded once an individual completes a set of tasks, and in an educational setting these tasks demonstrate mastery of a particular topic or skill. The digital badge, which is a new term, is a badge that is awarded and stored online as opposed to made, given, and displayed on a uniform. Gibson *et. al.* article [13] provides a good introduction to the emergence of the badge as a micro-credential.

Our course organization and the idea of badge-based learning for an entire course in many ways is similar to mastery learning [20] and tangentially to specifications grading [21]. We, for the sake of this paper, will continue to call our approach badge-based learning, but as practitioners as opposed to theorists, we understand that our approach might be categorized better.

3 Badge-based Course Organization

At BLINDED University, computer architecture is taught in the second year of a computer engineering degree and covers basic computer architecture and associated assembly languages. This material typically uses textbooks such as Patt and Patel's, "Introduction to Computing Systems - from bits & gates to C & beyond" [22], Patterson and Hennessy's, "Computer Organization and Design - The Hardware/Software Interface" [23].

The prerequisites for the computer architecture course include an introduction to programming and data structures, meaning all the students have been exposed to programming languages (JAVA programming in our case), and the students have completed an introduction to digital system design with HDL design. This allows our badge-based computer architecture course to have less focus on topics such as number conversions/representations, binary arithmetic, and digital circuits used in computer architecture, and the course can focus on how such systems are built and optimized.

Some of the outcomes of our computer architecture course are listed here specifying that the student will have the ability to:

1. describe the operations performed by the CPU.
2. enumerate the registers in a CPU and describe their uses.
3. convert unsigned integers between the following representations: decimal, binary, octal, and hexadecimal.
4. represent signed integers using one's and two's complement representations.
5. perform addition and subtraction of signed integers represented in two's complement representation.
6. describe the salient aspects of the stored program concept.
7. describe the key components of a CPU and their functionality.
8. describe commonly used instructions, their formats, operands required, and encoding to opcodes.
9. illustrate the relationship between mnemonics and machine language translation.
10. use selected assembler directives for assembly language programming.
11. describe the various memory addressing modes used by the instructions with example usage.
12. describe the concept of CPI and quantitatively compare the performance of various architectural solutions.
13. explain the concept and use of microprogramming
14. describe the process of linking and loading programs.
15. describe the various phases of assembly.
16. develop assembly language programs, debug assembly programs, and trace the operation of assembly language programs.
17. describe the four stages in a traditional pipeline

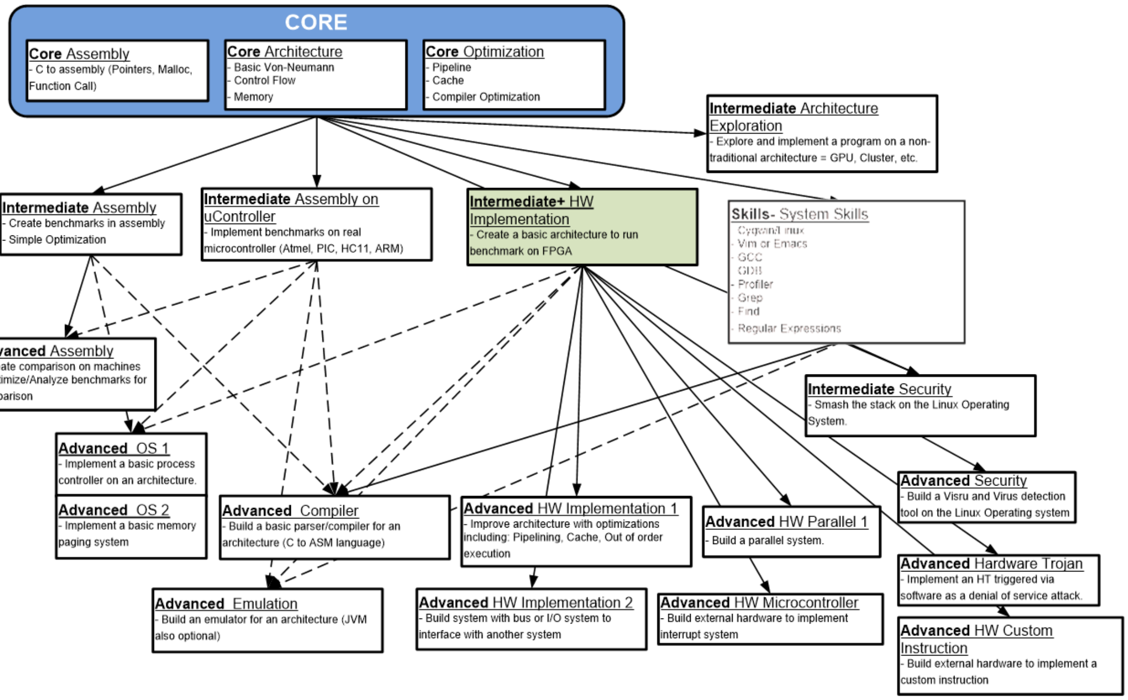
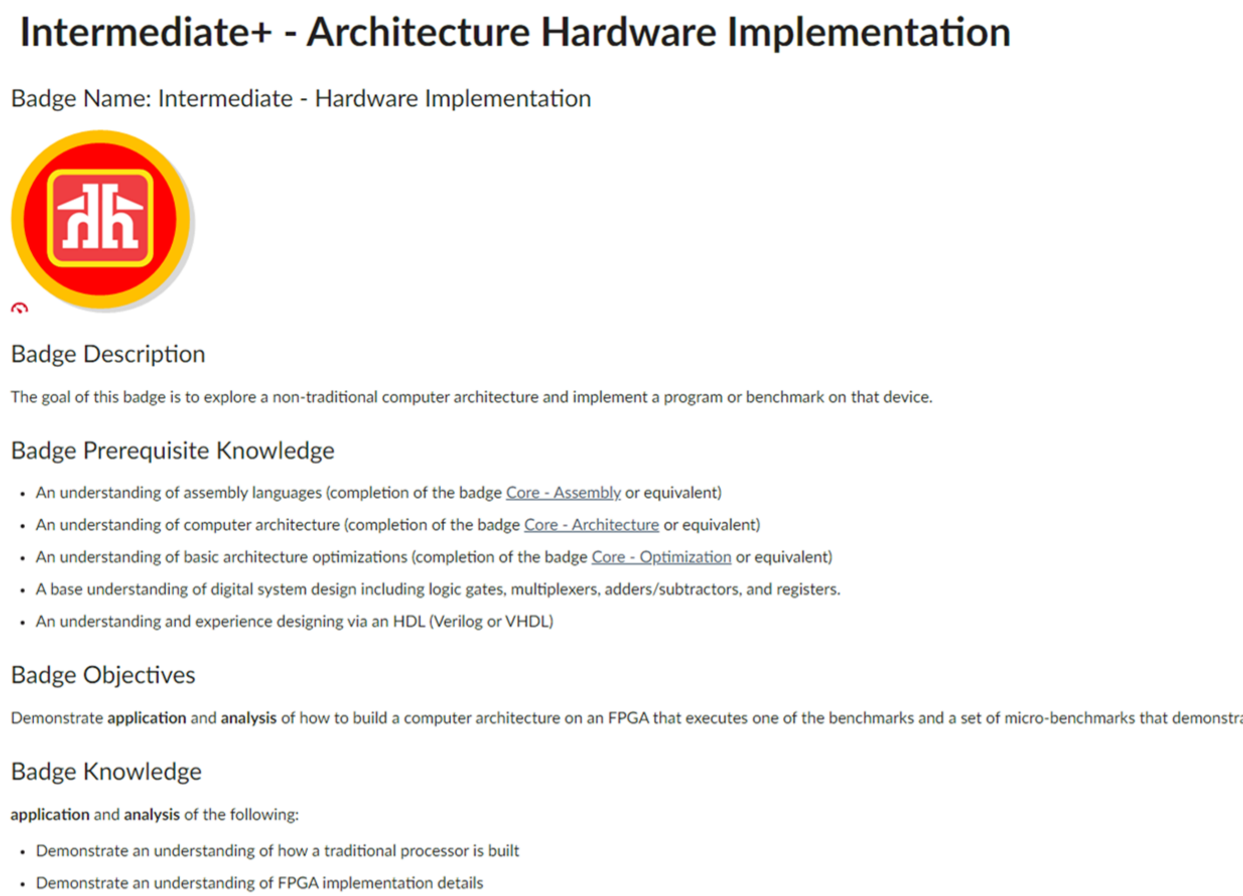


Figure 1: The pre and co-requisites for the badges in computer organization.

The badge-based course consists of a student demonstrating their increasing understanding of computer architecture by completing badges. The structure of these badges is shown in Figure 1 where three core or basic badges are at the top of the diagram, intermediate badges are under them, and advanced badges are along the base. In this figure, solid lines connecting badges are recommended prerequisites for pursuing higher-level badges, and the dotted lines are used for related badges (as in you should be familiar with one of the dotted lines before pursuing the targeted badge). The green box, "Intermediate+ HW", highlights that this badge is special in terms of it being worth more than the intermediate badges. The faded out "Skills- System Skills" badge is no longer a badge in the course as Linux skills are now taught to the students in another course, but the badge box is included to guide students on how those skills are needed elsewhere. All students start by completing the core badges and then proceeding along their chosen path.

Each of the badge details is maintained on a course WIKI, and Figure 2 shows a sample badge for the "Intermediate+ HW". Note that there is a circular badge with an orange border and red center in the upper left corner, this is the digital badge that we created and is displayed on a student's wiki page to show what they have attained. Once a student has prepared the badge, they will bring the badge deliverables to the instructor and a discussion will occur to verify that the material is sufficiently mastered and understood. If the student has mastered the badge material, then the badge will be added to the student set of completed badges such as in Figure 3, which is an example of a student badge after the course in 2023 (3 core badges, 1 Intermediate+ HW, and a Master Builder badge).

Class time in a course such as this, is spent working on badges with the bonus that the instructor



Intermediate+ - Architecture Hardware Implementation

Badge Name: Intermediate - Hardware Implementation

Badge Description

The goal of this badge is to explore a non-traditional computer architecture and implement a program or benchmark on that device.

Badge Prerequisite Knowledge

- An understanding of assembly languages (completion of the badge Core - Assembly or equivalent)
- An understanding of computer architecture (completion of the badge Core - Architecture or equivalent)
- An understanding of basic architecture optimizations (completion of the badge Core - Optimization or equivalent)
- A base understanding of digital system design including logic gates, multiplexers, adders/subtractors, and registers.
- An understanding and experience designing via an HDL (Verilog or VHDL)

Badge Objectives

Demonstrate **application** and **analysis** of how to build a computer architecture on an FPGA that executes one of the benchmarks and a set of micro-benchmarks that demonstra

Badge Knowledge

application and **analysis** of the following:

- Demonstrate an understanding of how a traditional processor is built
- Demonstrate an understanding of FPGA implementation details

Figure 2: Sample screenshot of one of the badge descriptions hosted on Canvas.

Table 1: A table showing the mapping between obtained badges and the student's final letter grade.

Letter Grade	# Core Badges	# Intermediate Badges	# Advanced Badges	Additional Comments
F	0	-	-	-
D-	0-3	-	-	Base badges partially assessed
D	1	-	-	-
C	3	-	-	-
B	3	1	-	-
B+	3	2	-	-
A-	3	3	-	-
A	3	1	1	-
A+	3	1	1	Exceptional advanced work

is available to answer questions. The instructor also evaluates each badge during class time or office hours. The remaining logistical question is how are the badges related to course grades. To

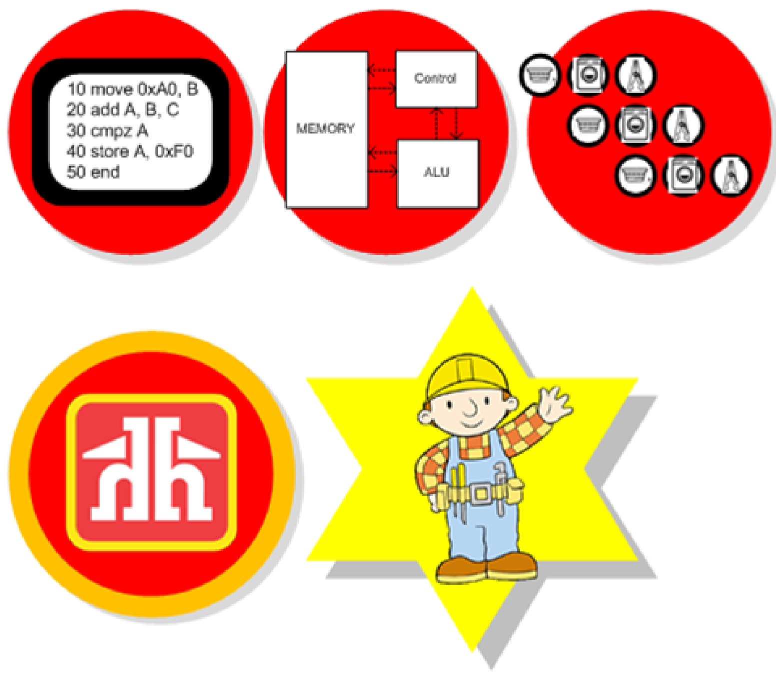


Figure 3: A sample of badges completed by one student in 2023 where they completed the core, completed intermediate+ HW and received the Master Builder badge.

achieve this we use a mapping from badges to grades that is provided at the beginning of the semester in the syllabus. Table 1 shows how the badges are mapped to letter grades, and this is done for administration and economic purposes of the university. In terms of educational benefits, the authors do not believe letter grades have any benefit in the learning process but understand the relationship between them and the assessment of learning.

4 Results Over the Last Ten Years

We will present two pieces of data in this work. These are cumulative results noting the course was run to various class sizes over the last eleven years (missing one year due to the instructor's academic leave and two years were run in an online version during Covid-19). We will present the grade distribution and the cumulative badges successfully demonstrated over the teaching of the course.

Table 2 shows the grades all 190 students received in the course. In our previous work [1], we were worried that our modified course structure that focuses on mastery-based teaching would result in a significant increase in grade distribution. That work showed that this was not the case, and our grade distribution seems reasonable, noting that a mastery-type approach is tasked with evaluating students on a curve.

Table 3 shows the number of badges awarded divided into core, intermediate, and advanced. The major change to the course was the removal of the "System Skills" badge in 2017; this resulted in

Table 2: Shows the cumulative letter grades over the time period the course has been offered.

Letter	# Total Students
A	44
B	70
C	49
D	23
F	4
Total	190

Table 3: Shows the badges acquired by students since we've run the course .

Badge	# Total Students Attaining
Core - Assembly	182
Core - Architecture	165
Core - Optimization	151
Intermediate - System Skills (available until 2016)	42
Intermediate - Assembly	45
Intermediate+ - HW	20
Intermediate - Security	27
Advanced - Assembly	9
Advanced - OS 1	1
Advanced - Compiler	7
Advanced - Emulation	1
Advanced - HW Implementation 1	2
Advanced - HW Implementation 2	1
Advanced - HW Parallel	6
Advanced - Security (Virus)	6

the number of students getting a letter grade of A or B shifting from 80% to 50%. From our perspective, this result is fine since using Linux is not tightly related to computer architecture. Also, the Covid-19 transition impacted students resulting in poorer grades; however, the university policy was pass/fail during this time so a letter grade of "D-" was sufficient to complete the course.

Another interesting observation from this data is that the Advanced badges: assembly, parallel hardware, security, and compilers are all roughly equally interesting to motivated students. The hardest of these, from the instructor's perspective, is building a simple back-end of a compiler, but many students gravitate to this badge due to their skillset which includes programming.

5 Discussion

Our previous work for this space proposed the badge-based course for computer architecture presented the structure of the course and a small experiment to test how the new course modality compared gradewize to the previous lecture-based course [1]. Now, having run the course in the new modality for ten years, we will discuss what we have experienced and learned.

The first question other instructors have when we discuss this course modality is how scalable is it. The largest number of students we have had for this course was 29 students completing the course (2 dropped before the drop deadline). At this size, we were still easily able to teach the course and provide students with the time needed to assess their badges and provide consultation on various ideas in the course. From our perspective, the course is manageable to a size of 40, but we haven't had a chance to prove this in any meaningful setting.

Table 4: Significant changes made to the course.

Year	Significant Change
2013	Created initial course with new modality
2015	Transitioned the course to "Canvas" course management
2015	Made lectures to help students achieve "C" with core badges
2017	Removed the "Intermediate - System Skills" badge
2017	Shifted to implementing RISC-V systems [24]
2019	Shifted to Online for Covid-19
2020	Created inverted teaching modules for Core badges
2020	Provided an assignment that tested Core badges
2022	Added a microcontroller advanced badge [25]

Table 4 shows the significant changes made to the course. The first relevant change was the removal of "Intermediate - System Skills" which we showed in the previous section resulting in a harder course to achieve a letter grade of "B". In 2020, the redesign of the course with online inverted classes was an extension of the 2015 attempt to capture students and help them complete the course at a "C" level. Much like our previous experience with lecture-based teaching of computer architecture, it is very difficult to bring some students' performance away from a "D" or lower. These students have not found their intrinsic motivation towards the subject and are hard to help.

During this time we have tried minor changes to the attendance policy to also help students who have a challenge with self-motivation. For example, we have imposed soft deadlines to help push students to do their work earlier in the semester to allow for time to pursue more challenging intermediate and advanced badges. None of these interventions seem to have helped students.

For instructors of this type of course, the challenge is to be able to guide students in several paths and to have a bank of questions to ask students to assess if students understand ideas in the core badges. Because so few students have gone down the paths of "Advanced - Emulation" or "Advanced - OS 1 or 2" we have collected material over the years as a resource for both student and instructor, but have much less experience guiding students in these pursuits. For example, Moya's thesis on emulation [26] is a nice introductory text on architecture emulation.

Overall, the opportunity to talk to students directly on topics to evaluate what they have learned seems to be a more valuable experience for both instructor and learner and has relations to the upgrading movement [27]. It is, however, a strange experience transitioning from lecture-based teaching to this modality as much of the time is spent doing nothing directly related to the class. This brings the existential question of "Am I teaching?". One way to alleviate this is to go around the classroom and ask each student how they are progressing on their current badge. This helps establish a "good" culture in the classroom that is informal and provides students with opportunities to ask questions and make connections with others in their class.

To push the culture more, we provide three badges for exemplary skills: Master Builder, Master Teacher, and Master Programmer. These badges are not awarded every year, and a Canvas page is maintained each year listing previous students who have achieved these badges.

The last question with this course modalitity is do students like this approach? From course reviews, there is a clear divide between students who like this approach and those who don't.

> The extremely hands-on approach to the course was new for me compared to the other classes that I have had that were lecture-heavy and with a single project, however, I felt that the badge-based set-up for this course forced me to be a true engineer and problem solve on my own which was a beneficial exercise.

The above quote is one of many samples of student comments on the course. From a written comment perspective, there are typically around 30% of the comments having a similar structure.

> For me personally, even though the professor is very well-versed and the course material is interesting, the badge style of learning really sucked for me personally. It felt poorly paced, entirely unguided, and rather stressful. I imagine this works for many students but it absolutely worsened my ability to learn the subject matter. It felt very frustrating to me to be paying a professor to teach me, and instead, he had me teach myself and ask him questions later. This style may have worked for other students but I will be avoiding classes in this format if at all possible in the future.

Contrasting the "good" comments, the above quote does appear in similar forms in the end-of-course reviews. These types of comments are rare in appearance coming at a rate of one or zero per year this course is taught, but this might be due to students completely checking out from the course due to their poor experience and not providing direct written feedback.

We note [28] (as do others), that student-centered learning is disliked by many students as the approach makes them work harder and they are unprepared. Even though the student-centered approach might improve learning, students, and humans, in general, evolved to avoid work. The above dislike of badge-based learning, we believe, is part of this sentiment.

6 Conclusions

In this work, we described our ten-year experience teaching a badge-based course on computer architecture. We provide results on the grades obtained and badges obtained in this course over the ten years. We also provide a discussion on what we have learned from this modality of teaching computer architecture that we will continue to use in the foreseeable future.

We believe that the badge-based approach to teaching computer architecture has made a significant improvement to what some students are learning compared to a slow progression for everyone in the lecture-based format. This is the case since badge-based learning allows interested learners to more deeply pursue aspects of computer architecture that they are interested in, which is not possible in the lecture-based approach.

For other instructors who would like to take a badge-based modality structure for teaching a course, we have the following recommendations based on our experiences:

- Depending on the number of badges that need to be assessed (ours is approximately four) and assessment takes approximately 15 minutes, you can judge roughly how many students this approach scales up to, noting that students can be assessed for the same badge multiple times.
- Artifact generation (building or producing something) is well suited for intermediate and advanced badges; however, these artifacts should be scaffolded well [29], which comes from the instructor having built the artifacts themselves.
- Including "Master" badges allows the instructor to reward and incentivize behaviors, and we believe improves the culture of the class.
- Conversation with students and knowing all their names is a fundamental step to creating a culture of community allowing students to help each other and create a community of practice [30].
- This choice of structure focuses teaching efforts on the higher and middle groups in the class, leaving those with little motivation to quickly finish the course not putting in a significant effort.

For us, our planned improvements to the course in its current state are to add Hardware Trojans attacking Processors as a second advanced security badge and to spend more time querying the class early in the semester to push students deeper into intermediate and advanced badges.

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