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Mastery Learning-Like Teaching with Achievements

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This paper describes the design of a second-year, 20 ECTS credit course on imperative and object-oriented programming. The key design rhetoric is encouraging students to assume responsibility for their own learning, and, to this end, elements from mastery learning and other teaching strategies are used in concert to construct an achievement-based system where students are put in charge of how and when they are examined. In addition to describing the elements of the course design, the paper reports on experiences from teaching in this format, and how the format has evolved over time.

1 INTRODUCTION

Four years ago at Uppsala University, we changed the 2nd year 20 ECTS credit course\(^1\) that introduces imperative and object-oriented programming, with focus on coding and tools. With the new course design, we hoped to change the way students approach learning and also force students to assume more responsibility for their studies. This paper summarises the outcomes of this undertaking: it explains the key course design elements, how the course design has changed from its initial implementation to its current format, lessons learned from the process, and a biased, qualitative self-evaluation.

First and foremost, it is important to understand the setting in which this takes place: Sweden, a country where university education is “free” in the sense that there are no tuition fees and students are given a basic allowance and state-sponsored loans for studying. The course in question, Programming Methodology for Imperative and Object-Oriented Programming, has 120–140 students yearly and is a mandatory 2nd-year course on both the traditional computer science bachelor programme and the five-year engineering programme in information technology. Before this course, students have been taught functional programming (lately with Haskell), basic data structures, program construction principles, and basic computer architecture including a little assembly language. Each batch of students can be divided into 3 roughly equi-sized groups — those who are already programmers (programming extracurricularly), those who learned imperative programming in upper-secondary school, and those who have only studied programming at the university. The course runs for a full semester at 66% speed (≈ 530 working hours for each student); students take one other course in parallel first half of the semester, and another in the second half. These courses vary with degree program but are usually math-oriented.

In our experience of programming courses (not just limited to Uppsala or Sweden), student assessment usually comes in the shape of a number of implementation-based assignments. These assignments are often cleverly designed so that concepts just taught in lectures can be successfully employed to solve the problems at hand. A student is thought to have mastered the key concepts if she is able to provide a “working implementations” of the assignments that pass some key tests.

We find this practice problematic for several reasons:

\(^1\)An ECTS credit is a standard EU credit unit. 20 ECTS credits corresponds to ≈533 hours of work.

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a) it rewards students’ ability to pattern match recent lecture content onto a problem which has little bearing on “real-world” programming, and rewards the ability to solve programs the way the teacher intended rather than using independent thinking;
b) as students commonly collaborate, there is no real check that a student has worked on all parts of a program and thus actively reflected on all goals of the assignment;
c) because the problem of implementing a program that performs X is so much more concrete than grasping abstract topics like “encapsulation”, the former tends to overshadow the latter. Many predominantly qualitative aspects of software, like e.g., maintainability, are hard to understand without living with code for a very long time and suffering from own mistakes/choices.

We set out to develop a course that helps students reflect on skills and actively think about what they are doing, and where we could be reasonably sure that all students were actively engaging not only with the practice of programming, but also with more general concepts that go beyond the “random” set of concepts that surface in the parts of a program a particular student happens to write. At the same time, we wanted to cater equally to the above-mentioned groups of students, allow experienced programmers to quickly dive into more complicated matters, and leverage the fact that they are mostly self-serving in a way that would help us direct more resources to those with less programming experience. Also, in particular, we wanted to make the students actively make decisions about their learning, as well as what to learn when, rather than just sit down and “be taught”. In the process, we developed a system we came to call “Achievement Unlocked”, which is similar to mastery learning (Bloom 1968; Guskey 2010), although we had not heard about that at the time. Our main source of inspiration was constructive alignment (Biggs 1996). In this paper we report on the use of Achievement Unlocked in this one particular course. In future papers, we hope to explore the key ideas more deeply, connect them to existing theories like mastery learning, and discuss their application to teaching advanced software design.

Outline. Section 2 describes the course structure, the achievement system, and how students demonstrate mastery, plus the interplay with e.g., lectures, assignments, our version of a closed-book exam, and how to give a final grade to each student. Section 3 reports on our self-evaluation, based to a large extent on feedback from students and teaching assistants. Finally, Section 4 concludes.

2 COURSE STRUCTURE

As this course fits in two larger degree programmes, it must serve many masters, and has thus been subject to “feature creep” in its formal course goals over the years. In addition to learning how to program in imperative and object-oriented languages, students are expected to learn about programming methodologies and tools, as well as basic software engineering, in particular agile software development processes. Additionally, soft skills such as oral presentation and report writing should be taught, as well as professional ethics (to a limited extent). An overview of the achievements, a sample achievement description and the course outline with syllabus, timings and deadlines can be found in Appendix.

2.1 The Achievement System

The course is centered around a relatively large set of achievements, around 70, which are derived from the formal course goals and checked against the ACM/IEEE Curriculum for Computer Science (2013). Each achievement belongs to a certain grade level—3, 4 or 5—and to pass with a certain grade, a student must pass 100% of the achievements belonging to that grade, and those below. Some achievements only exist on the basic grade level (3) whereas others exist at increasing depth.
across all grade level. An example of the former is “writing documentation”\(^2\). An example of the latter is profiling, where running a profiler, producing profiling output and using it to explain a program’s performance is at grade level 3, using profiling output to improve and demonstrate the performance improvement is at level 4, and level 5 includes reducing memory footprint.

Achievements are skills that students must demonstrate “mastery of” at least once during the course in order to pass the course. Importantly, achievements are not tied to any specific assignments or dates. Instead, students are required to **map the achievements** to activities during the course (for example, programs they write as part of mandatory assignments) and may **attempt to demonstrate** mastery when they so choose. Section 2.4 discusses demonstration in further detail.

Because any achievement can be demonstrated at any time, students are free to attempt to demonstrate mastery when they feel they have “grokked” something, not at an externally-controlled moment in time. Some students demonstrate piecemeal interleaved with assignment work, others first complete an assignment and then make fewer but more comprehensive demonstrations. Students are strongly encouraged to make demonstrations that tell a coherent story. A student that realises the connection between “identity and equality” and “aliasing” will be able to demonstrate both of these achievements together, and in less time than it would take to demonstrate them both separately.

### 2.2 Influencing Student Behaviour Through Resource Limitation

While there are abundant opportunities to demonstrate, the number of lab sessions with demonstration slots are limited, as are the number of achievements that can be demonstrated in an attempt and even successfully demonstrated in a session. This is an integral part of the course design. Making the demonstration attempts a limited resource increases their value, and discourages “waste” in the sense of attempting to pass by brute force (because students invariably learn something from failed demonstration attempts). The last two times the course was given, there have been around 30 slots for presenting, and a maximal number of 4 achievements per demonstration.\(^3\) This encourages **clustering of achievements** to form larger presentations. Students unable to form synthesis are at a disadvantage as they will not be able to cluster achievements as effectively. This is on purpose as the ability to form synthesis is something that we wish to have reflected in a student’s grade. Students say that the emphasis on clustering forces them to work with the subject continuously throughout the course (from course evaluation and interviews).

To discourage students abandoning good practices after successfully demonstrating mastery, we randomly select achievements from a student’s collection of passed achievements for re-examination. The re-check is intended to be superficial, and mostly serve as a means of jogging students’ memory and keeping knowledge fresh. A successful demonstration cannot be “lost” if a re-check fails, but the student will be re-checked again until the re-check succeeds. This way, re-checks can pile up, effectively blocking students from making progress with other demonstrations.

### 2.3 Achievement Choice & Specification

The actual selection of achievements seem not to be crucial to the course design and we have tweaked both the number, distribution and content of the achievements over the last years. Our course focuses on imperative and object-oriented programming, and emphasises methodology and

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\(^2\)Not because there is not enough depth in the subject, but because of prioritising other subjects.

\(^3\)About 60 of the 70 achievements are demonstrated in lab sessions. Thus, a student could theoretically successfully demonstrate enough achievements to pass the course twice with the highest grade, or fail 50% of all attempts and still pass with highest grade, within the allowed number of demonstration attempts.
tools, which is reflected in the achievements. For example, we have achievements related to using version control, using the Unix shell, build management and source code editing.

As part of the goal of forcing students to work with achievements is to force them to make their own plans and map achievements to activities in the course, we have experimented with presenting the achievements in list form, where achievements belonging together were grouped, but without highlighting this or giving names to the groups. This seems to overwhelm some students who panic at the sheer volume, and who quickly filter out achievements connected to higher grades simply to make the list more manageable. Our current design is to give each group a name and present the achievements in this group together. It seems that the grouping of assignments in named groups is more important than the actual groups, likely because it makes the set of achievements less daunting for the students.

As the course material is currently only available in Swedish, we provide a list of the groups of achievements used in 2016, and a rough outline of the achievements in each group in the Appendix, together with an example achievement.

To simplify the course structure, we try to fit everything inside the achievement system, even though that sometimes goes against the idea of achievements. Thus, we represent each completed assignment as an achievement, as well as the final project. This does not seem to be confusing to students, but possibly comes at a cost of making the achievements idea less pure. At the end of the course, there are often students who have demonstrated all achievements except one or more complete assignments. To us, this highlights the importance of decoupling skill demonstration from finished artefact implementation. By giving specific assignments, we ensure that students write substantial amounts of code in the course, and that some parts of the code survive long enough that the pain of bad choices, bad naming, etc. can be learned from.

2.4 Demonstrating Mastery

With few exceptions, all demonstrations take the form of oral examination in front of a computer terminal with one examiner and two students working in a pair. There are several reasons for pairing students together: the students outnumber the examiners, reducing stress and taking pressure off the situation; if a student gets stuck, the partner can take over or help out; it is easier to create a meaningful discussion with more than two people—for example, the examiner can ask the other student whether she agrees or disagrees with a statement that the first student made, or if she can propose a different way of doing something than what the first student just explained. Examining two students at a time also cuts the total number of demonstrations in half, saving examiner time.

Checks are individual, meaning that both students must demonstrate mastery. A mostly passive student will not pass a check even with a brilliant partner. It is clearly stated that the responsibility for making sure that both students actively participate is on the students, and not on the examiner. This encourages students to prepare the demonstration and discuss who says what, which in our experience makes presentations run faster, have higher quality, and increase student reflection.

The choice of oral examination serves several purposes. Explaining interactively is time-efficient, both for the student and examiner, and feedback is given immediately when the demonstration is still fresh in the student's mind. Technical communication is an important soft-skill that is trained automatically in this setting, and students are both encouraged and helped to improve their ability to communicate about software development. Nevertheless, some students complain, saying that they are not interaction-oriented and much prefer to explain themselves in writing. We explain to

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4Throughout the course, the average student writes a total of 4–5,000 lines of code, not including introduction labs, extensions of assignments to address a certain achievement, or the course project.
them that communication and interaction are key skills, and do not provide any alternative means for them to demonstrate.

2.4.1 Demonstration Process. Demonstrations take place in designated computer labs and (for students with laptops) lecture halls, during 4 hour lab sessions, which are scheduled twice weekly throughout the semester. Students request to demonstrate through a web page where they choose which achievements they wish to demonstrate. An achievement for re-check is added automatically by the system, using the history of passed demonstrations. Re-checks are disabled early in the course, until students have passed a sufficiently large number of assignments. On average 7–8 TAs serve 100 students in each session. (About 3 senior TAs and 10–12 junior TAs are attached to the course.)

After requesting to demonstrate, students wait (ideally while continuing to work). A feed of pending requests to demonstrate is shown on a screen to the examiners, who claim demonstrations before dispatching to where the students are located. We follow no special rules for claiming demonstrations: sometimes it makes sense to have the same examiner claim a student’s second attempt, other times it makes sense to hand over to someone else. To increase throughput, it sometimes makes sense to have one examiner claim several demonstrations in the same room. As the achievements a students wishes to demonstrate is visible in the feed, examiners can avoid achievements they feel uncertain about, request help from a more senior examiner, etc.

Students are notified that their request has been picked up and by whom. At all times, students can see how many requests are waiting and how many are in front of their request, if any. Students are not allowed to have more than one pending request or make requests before lab sessions start.

When the examiner arrives, the students must pitch their demonstration, which means:

1. Stating the achievements they wish to demonstrate
2. Explaining why/how it makes sense to demonstrate them together
3. Explaining what evidence they will use in the demonstration

If the examiner is not satisfied with 1 or 2, she will explain why and should reject the request (in practice, this has not been strictly enforced as we want to avoid discouraging students from trying to pitch a demonstration). By evidence in 3, we mean artefacts developed in the course that will form the basis of the demonstration. For example, “we profiled the binary search tree that we developed in Assignment 2”. The key idea with evidence is that students must relate the achievements to the programming assignments (and programming project) of the course. In the course’s initial instalment, we naively allowed any code to be used in demonstrations prompting students to search for code rather than write their own, or spending lots of time trying to write a minimal program that could be used to demonstrate a maximal number of achievements. While there are merits to both these approaches, we are seeking to teach how to write imperative and object-oriented code, which is why we added the requirement of evidence in the form of assignments from the course.

Examiners will often ask questions to force students to go "off-script", e.g., ask what would happen if X was changed for Y, or change some lines of code, or introduce a bug etc.

If the examiner finds the answer to 1–3 satisfactory, she will hand over the running of the demonstration to the students. Different examiners approach this task differently. Some will interrupt and ask questions. Some delay all questions to the end. What approach students prefer seems highly subjective, with a slight preference for more interactive examiners.

Only the achievements explicitly stated at the beginning of the demonstration can be passed in the demonstration. If a student in the process of demonstrating happens to “meet the requirements” for some other achievement, this will be ignored. Further we will not even tell the student. Our philosophy is that you can only know what you know you know, meaning that accidentally
demonstrating procedural abstraction not knowing that that is what you are doing counts as nothing.

Each achievement will be marked as either pass, fail or fail with push-back. A student that fails to demonstrate an achievement is free to try again at her leisure. The limited attempts plus the waiting time discourages students from brute forcing their way to a pass by making continuous attempts, accumulating feedback from the previous examiners to present to the next. A fail with push-back indicates that the student has misunderstood something deeply, prompting us to block any re-attempt for the rest of the lab session to encourage spending some more time understanding that achievement. There are no special limits on the number of attempts to demonstrate one particular achievement. Failures with or without push-back are not counted towards any grade.

An examiner’s decision is final, and the examiner does not have to motivate failing a presentation. However, we ask examiners to explain and motivate both passing and failing grades on demonstrations to reinforce learning, build confidence, and to help students transition from a failed demonstration to a passing one.

2.4.2 Demonstrations & Plagiarism. Because the focus of a demonstration is the skill in relation to the evidence, we feel that plagiarism is not really a problem. We encourage students to discuss solutions, look at code written by fellow students, and collaborate. Because demonstration commonly involves examiners pointing at code, and asking questions about it, or altering the code as part of the discussion, students that lack a deep understanding of the code have a hard time passing. Ultimately, the student is demonstrating some abilities, not whether he or she wrote a particular piece of code or not.

2.5 Lectures
The course uses traditional lectures. Many lectures have a corresponding screen cast which covers similar content in a different way, often with a focus on code, most of the time showing an editor and a terminal and not slides. Several lectures are given through “live coding” where the lecturer switches between drawing on a whiteboard and projecting an editor and terminal and incrementally constructing a program from scratch. Each lecture is mapped to a set of achievements, to help students (predominantly those without much prior programming experience) make plans for what to demonstrate. Following constructive alignment, mapping lectures to achievements has been very helpful for lecture design—what should be covered in this lecture, what can be cut in the event of running out of time, etc.

2.5.1 Discussion. Initially, students fear demonstrating mastery because they are not used to the process, and find it difficult to understand beforehand. To this end, we encourage students to attempt presentations early on, not with the goal of passing, but with the goal of understanding and practising how to give a demonstration. This concept is eye-opening to many, and is easily explained in terms of sacrificing an abundant resource (lots of demonstration slots remaining) in exchange for knowledge that will be useful throughout the entire course. Usually, once the initial resistance is broken down, students have no problem requesting demonstrations.

One goal of reducing expected learning outcomes to much smaller achievements was to reduce the expertise and amount of teacher training required to be an examiner for demonstrations (especially judging quality more than pass/fail). The teaching staff on this course is predominantly made up of junior TAs (bachelor or master students) and senior TAs (PhD students). Because each achievement demonstration is pass/fail (and push-back), we feel that it is easy to deliver reasonably consistent quality both on judgement and feedback. In combination with each student
going through at least 40–70 demonstrations, unfairness due to examiner inconsistencies is not a problem in practice.

The focus on oral presentations put orally-skilled students at an advantage, but this is mitigated by the evidence requirement and the probing when examiners change code or introduce bugs. We experience considerable improvement in presentation quality from many students who initially are afraid, block, or otherwise are uneasy when forced to talk in-front of others. We try to motivate the use of oral examination by relating it to technical job interviews, and, according to the course evaluation, by the end of the course most students are happy with doing oral presentations.

2.6 Working with Phases and Sprints

We divide the course into three phases, one devoted to imperative programming (currently in C), one to object-oriented programming (currently in Java), and one devoted to a programming project. The first two phases are further subdivided into two sprints each, subdivision of the third phase is controlled by the students themselves. Each sprint is two weeks and has one assignment. At the end of each sprint is the soft deadline for the assignment. The soft deadline marks the time when an assignment should be finished for the student to be perfectly on-time. At the end of the following sprint is the hard deadline, which is the final deadline for handing in the assignment. Failure to meet a hard deadline means that the student is derailing and is subsequently called to a face-to-face meeting with the goal of adjusting the plan for finishing the course. Again, there is no punishment or points deducted, but students work hard to meet soft deadlines and very hard not to break hard deadlines. In fact, the idea of using deadlines as a tool to help with planning was suggested by students after the first instalment of the course (which had no deadlines).

As the course progresses, the number of assignments to choose from in each sprint increases, reflecting our expectancy of student’s increasing maturity and ability to branch out.

To reduce the administrative burden, we keep track of assignments as achievements, meaning “Successful demonstration of the Assignment of Phase 1, Sprint 1” is an achievement. For each sprint, students are asked to plan for a number of achievements to demonstrate, in a way similar to story points (see e.g., Cohn (2004)). We plot progress as remaining number of achievements to desired grade and visualise this as a burndown chart. We have experimented with several ways of visualising student progress, most of which led to increased stress. Burndown charts tell a rich story, allow plotting trends, exploring possibility of getting several grades at the same time, and show periods of high/low activity etc. Figure 1 shows an example of burndown charts generated by students using a provided on-line spreadsheet template. At the end of each sprint, students meet a TA in groups of ≈10 to discuss their progress, compare burndown charts and trade insights about assignments, achievements, demonstrations, etc. These meetings serve as a forcing function for updating the burndown chart and also force students to openly discuss their (lack of) progress and make plans. While some students are stressed by always chasing the ideal burndown, they are also very happy about always knowing what are the possible attainable grades and adjust their desired grade up and down depending on a wide variety of reasons.

The division of the course into discrete units of time is important to make progression through the course visible, especially given that students are not required to make demonstrations at any specific time. Judging from experiments that we have made with more/fewer/longer/shorter sprints, this is a quite flexible part of the design and finding a good balance between a sense of urgency and student stress is key.
2.7 The Coding Exam

The only guaranteed individual marking on the course is called the coding exam, in which students use lab computers to solve relatively simple programming problems without access to the Internet in limited time. Cutting students off from the Internet breaks the workflow of many students who are used to getting unstuck by searching and visiting websites like Stack Overflow, or discussing with a partner. We see that students must be encouraged explicitly and repeatedly to practise solving problems alone and—importantly—off-line, regardless of their programming skills.

While passing the coding exam is mandatory, it is strictly a pass/fail examination and does not affect the final grade—its only purpose is to present an obstacle that students will never be able to get past without actually learning how to program (to some limited degree). In our experience, many students have such low confidence in their programming ability that they will avoid touching the keyboard unless forced to. These students pair up with other more confident students and let them sit in the driver position throughout the course, and will learn many concepts shallowly as is inevitable without any actual coding. We are completely open with the students that the coding exam is an artificial obstacle that is there to scare the students that would otherwise never leave the passenger seat to take place in front of the keyboard.

Because the coding exam is done on lab computers, students have access to the editors and IDEs that they use in the rest of the course, and important tools like gdb and valgrind. We also provide test cases that can be run easily from the command prompt, allowing students to test their solutions. Ability to compile and run test is a double-edged sword, however, as some students go into panic mode when faced with hard error messages, and get stuck on preliminaries such as forgetting what are the arguments to `main` in C rather than focus on the parts that the exam wanted to test.

To some extent, the code exam can be corrected automatically by just running a set of tests on the hand-ins. Students passing the code exam gets no other feedback than a passing grade. Hand-ins for which the tests fail will be manually inspected and the code handed back to the student annotated with a given a list of errors and bad smells in the code, which corresponds to numbers in a lengthy code exam report posted on the course web page.\(^5\) Because of automatic testing, results sans feedback can usually be given within 24 hours of the code exam. Only functional correctness determines pass/fail. This is partly to reduce stress and help students to focus, but also because code quality comes up in almost all other parts in the course.

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2.8 Final Grade

A student’s final grade is decided solely by the number of achievements successfully demonstrated. The achievements are stratified after grade levels to match qualitative assessment that could perhaps have been made using more comprehensive grading of handed-in assignments, and in that sense “quantifying quality.” We do not allow, for example, substituting one achievement on level 5 for another on level 4, etc. The achievements match the learning outcomes decided by (in our case) higher powers, and when read in that light, it does not make sense to substitute, for example, procedural abstraction for knowledge of garbage collection. Students initially baulk at the concept of getting 100% (of anything) to get a corresponding grade, possibly because of how other courses allow “points trading.”

3 (SELF-)EVALUATION

In this section, we report on feedback from students (based on the 2016 non-mandatory course evaluation which asked 53 questions and was filled out by 80 students), teaching assistants as well as our own reflections. We concentrate on feedback on the achievement system and not on the course on a whole. Feedback from teaching assistants has not been collected through any systematic means.

3.1 Feedback from Students

In the 2016 course instalment, we felt that we had finally understood how to explain the achievement system to students: by introducing it as a set of checkboxes that they had to tick off at some point that made sense to them during the course. Students commented very positively on the achievement system in the course evaluation, and suggestions for change were generally in the form of (perceived) improvements such as “merge these achievements”, “provide more suggestions for clustering of achievements” or “clarify achievement X to make it more clear”. Almost 3/4 of the students report that they grouped achievements together for demonstration based on how the achievements fit together. Almost 2/3 of students think that the setup with constant small checks helped them avoid procrastinating, though a little less than 1/3 disagree. Notably, 45% of students think that their stress-level increased due to the large number of checks.

90% of the students felt that it was always clear to them what grades were attainable (66% strongly, 24% less strong). 75% of the students felt that the achievement system has helped them absorb the contents of the course. Students generally perceive being more responsible for driving their own studies (e.g., clustering achievements, planning etc.) as something good.

1/3 of the students think that the oral examination has greatly influenced their ability to explain, motivate and communicate. Another 51% agree but to a lesser extent. There is a strong preference for immediate oral feedback over delayed feedback in written form.

40% of the students do not think that they would have gotten more out of the course by doing fewer oral checks, though 26% think that they would have gotten a little more out of it. 18% think they would have gotten a lot more out of it. Notably, oral checks get the most complaints due to the time students spend queuing, waiting to demonstrate. Invariably in the last years, illness or other unfortunate circumstances have caused a shortage of examiners a few times each semester, causing waiting times to inflate and students to complain. In 2016, the average waiting time was 53 minutes between asking to demonstrate and having the grade entered into the system (so this includes demonstration time). To our mind, this is relatively short, but there are also many demonstrations. Some students say that “waiting time is not a problem, since there is always something to work on

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6A system identifying achievements that make sense to allow substitution can of course be constructed, but would add more complexity for questionable gain.
while waiting.” Some students spend the time waiting in the queue *waiting*, which seems wasteful. In future work, we wish to understand this behaviour — is it because a looming demonstration is stressful, because a pending demonstration is an alibi to take a break, because of fear of swapping out a rehearsed demonstration, etc.

### 3.2 Feedback from Teaching Assistants

An effect of allowing students to demonstrate any achievement at any time is that teaching assistants need to be prepared to assess a mastery demonstration about any part of the course material at any time. This is very different from other courses where students typically all work with the same assignment at the same time. Senior TAs and more experienced junior TAs see this as something positive with the course, as the work becomes more stimulating and less monotonic. Junior TAs are sometimes instead stressed by this, especially early on in the course, because they feel like they have to be able to answer any question about the course. To mitigate this we encourage TAs to ask each other for help, and to sit in and listen to each other’s mastery assessments in order to learn from each other. Throughout the course we also have semi-regular lunch meetings together with the TAs to discuss what works well and not, as well as trading “assessment strategies” for different achievements. TAs that have taken the course themselves are typically more comfortable with the assessment situation as they have experienced it from the other side.

Many TAs are stressed when there is high pressure on the demonstration request list and long waiting times in the lab rooms. In these situations, TAs sometimes have a hard time balancing the quality and quantity of assessments; giving more detailed feedback means that other students have to wait even longer for their chance to demonstrate.

### 3.3 Our Own Reflections

The main negative aspect of switching to the achievement-based system is that a lot of time that was previously spent casually chatting with students during lab sessions is now spent taking demonstrations. This leaves less time for interested students to discuss with teaching assistants, and less time to form stronger connections with students. It is also likely that students spend less time programming, and more time reflecting, rehearsing, and demonstrating.

In our opinion, students learn *more* and are more aware of what they learn. Students are able to discuss concepts like abstraction, modularity, inheritance, etc. at a much higher level and relate these concepts to their own code. To a greater extent than before, students also form opinions about concepts and constructs, rather than just accepting them as decreed. To an overwhelming extent, students now think of themselves as the active agents in their learning, in contrast to previous years when students were expecting to *be taught*. To a larger extent than before, students are aware of their own strengths and weaknesses, and ability to plan and execute plans. The ability to reflect on their own learning was also observed by Matthias Hauswirth, a professor from Lugano visited the course for a day in 2016 and carried out interviews with several students.

### 4 SUMMARY & CONCLUSION

Four years ago, we radically changed our course on imperative and object-oriented programming to a design where students are forced to take responsibility for their own learning. By reifying the formal course goals as a large number of small achievements to “unlock”, we give the students

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7In practice though, there are some natural constraints on which achievements are actually demonstrated. For example, achievements concerning object-oriented programming are typically not demonstrated until later in the course, and students often tend to demonstrate achievements that their peers have successfully demonstrated.

8Matthias Hauswirth, personal communication.
a quantifiable measurement of progress throughout the course. By separating the achievements from the mandatory assignments, the students themselves get to make the connection between the course concepts and their code.

In our experience, the students are able to explain and discuss course topics at a higher level than before, and after the third iteration of the course, we are at a point where a majority of students are at least as satisfied with the course as they were before the change. The course requires a large staff of teaching assistants to handle the oral examinations, but because the course produces students who are well-versed in the course contents, there is never a shortage of junior teaching assistants to employ. Scaling the course to accommodate a growing number of students in the future requires employing more teaching assistants to keep the waiting time in the lab sessions sufficiently low.

Because the course has changed in many ways (e.g., doubled in size) it is hard to say whether the course is more or less labour-intensive than before switching to achievements. It is budgeted the same way as all other courses at the department, and fits in that budget. A cost-neutral difference is that we seem to go through more TAs each working fewer hours than before. Our guess is that this is because TA work is now more intense as it is more oriented towards examination than before.

4.1 Lessons Learned

We end with some of the lessons we have learned while teaching this course.

Over the years, we have reduced the number of achievements slightly, mostly to make the list more manageable for students. Achievements that are hard to group with other achievements were the first to go. Related to this point, changes to the achievement system is a pain when dealing with old students, who did not pass the course (to some degree or at all) in a previous year. It is hard to translate the progress from one year to the other when the set of achievements are different. This problem can be alleviated by supporting partial grading. In our course we give 25% of all credits for completing 50% of the mandatory assignments (excluding the project) and ≈50% of the achievements needed for a passing grade (again, excluding achievements tied to the project). This way, students who fall far behind for some reason can aim to finish e.g., the assignments for the imperative phase and finish the object-oriented phase from the beginning the following year.

Due to the large number of demonstrations, computer support is crucial, both for handling the queue of demonstration requests and to keep track of the progress of each student. The large volume also means that errors will happen, meaning that the backend needs to support manual input of results. The fact that everything is recorded digitally is also a great source for data-mining. We can extract which achievements are currently the most popular, which achievements most students fail, statistics on waiting times etc. We can also report on the progress of the entire class to help students understand how their progress relates to the average progress of the class.

4.2 Final Remark

Achievement Unlocked is an interesting combination: it has elements of mastery learning (Bloom 1968), flipped class-room (Bergmann and Sams 2012) (in the sense of students doing lots of work at home and then come to discuss with teachers and TAs in lab sessions), gamification (with respect to resource management and unlocking of grades), and its design was heavily influenced by our belief in constructive alignment (Biggs 1996). As course designs go, it is complex, but purposely so—with the intent of forcing students to actively work with their learning process and reflect on study techniques, but reasonably scalable to the extent affordable junior assistants are available.

REFERENCES

Jonathan Bergmann and Aaron Sams. 2012. *Flip your classroom: Reach every student in every class every day*. International Society for Technology in Education.
A ACHIEVEMENTS AT A GLANCE

The list below gives a high-level overview of what the achievements in the course are and how they are grouped together. Remark that the grouping serves no other purpose than to help students abstract and thus reduce the perceived volume of skills to learn and demonstrate mastery of.

**Abstraction** Achievements in this group concern procedural and object-oriented abstraction, the importance of naming, and information hiding.

**Code Review** Informal code reviews, responding to code reviews, refactoring.

**Communication** Essay writing, giving a structured presentation, working as a teaching assistant.

The last achievement is on the highest grade-level and forces students to work as TAs during half a lab session where they work through the help list, and the students they are helping give them feedback. Part of the reason for having the helped students producing feedback is so that the helper must think actively about what the goals are of helping—not solving their problem, but helping them coming up with the solution themselves.

**Documentation** The single achievement in this group deals with writing interface documentation for other programmers to use.

**Encapsulation** Aliasing, name-based encapsulation, nested and inner classes, interplay of strong encapsulation and testing.

**Generics** Dealing with generics both in Java and C, and designing with/for parametric polymorphism.

**Imperative Programming** Recursive vs. iterative solutions, tail recursion elimination.

**Inheritance** Object-oriented inheritance, overriding, overloading, subtype polymorphism, separation of concerns.

**Memory Management** Allocation on stack vs. heap, manual memory management, automatic memory management, manual vs. automatic memory management.

**Methodology** Defensive programming, exception handling, failure management and fault tolerance.

**Modularisation** Module boundaries and interfaces, coupling and cohesion, separation of concerns.

**Object, identity & structure** Identity vs. equality, value semantics, concrete vs. abstract classes.

**Planning** The single achievement in this group deals exclusively with planning and following-up, which is covered in Section 2.6.

**Pointers** Pointers and arrays in C, pointer-based linked structures, pointer semantics, indirection and pointers to pointers.

**Pragmatics** Compilers, interpreters, JITing, linking, and binding.

**Profiling & Optimisation** Profiling for performance and memory usage, optimising performance and memory usage guided by profiling results.

**Testing** Unit testing, test quality, static analysis, fuzzing.

**Tools** Debuggers, documentation tools, editors, build tools, working the terminal.
**Assignments**  This group collects the achievements mapping directly to assignments (e.g., Assignment in Phase 1, Sprint 1, etc.).

**Project**  This group collects the achievements that are part of the programming project at the end of the course. These are not demonstrated in the usual way, but we unify them with the other assignments for simplicity. Project achievements include using and evaluating the usefulness of pair programming, regression testing, working with pull requests and code reviews, coding standards, etc.

### A.1 Example Achievement: Implementing Generic Data Structures with Void Pointers

**Grade level: 3**

**Demonstrated: in lab sessions**

*Use void pointers in C programs in relevant ways to implement genericity, for example, a collection capable of storing any kind of data.*

Multiple copies of the same code with minor differences is undesirable. Consider for example two separate implementations of lists of integers and lists of floats where the second was created from the first. If a bug is found in one list, two sets of bug fixes must be carried out in equivalent ways to make sure the lists’ behaviour stays identical.

C supports pointers to data of unknown type (void pointers, `void *`) which can be used to build a general list (for example). Constructing a list where elements are void pointers allows the list to hold arbitrary data.

Void pointers is a common C idiom that is also used in many places in the standard C library to identify a memory location with unknown content. The compiler does not know what is at the location, nor the size of the object at the location.

Demonstrate your understanding of the void pointer idiom, and how the compiler’s lack of knowledge of the type of the object at an address influences programming. Start your demonstration by explaining the concept of genericity, how and when it is useful, and what you think about C’s support for genericity.

### B COURSE TIME-LINE

With few exceptions, each week has two 2-hour lectures and three scheduled 4-hour sessions for demonstration (and getting help).

**C Bootstrap (2 weeks)** (Broad but not deep): loops, recursion, basic I/O, functions, arrays, pointers, strings, modularisation and separate compilation, typedefs and basic data types, structs, unions, function pointers. What is good code?

All C assignments are made available at the end of the bootstrap. All Java assignments are made available in C Sprint 1 or early in C Sprint 2. Each sprint has one assignment and the soft deadline for the assignment is at the end of that sprint. Hard deadline at the end of following sprint.

There are five mandatory labs in the bootstrap. Soft deadline on the same day as the lab is scheduled. Hard deadline on the following lab.

**C Sprint 1 (3 weeks)** (Students build a small interactive program.) Recap from the bootstrap. Imperative vs. functional programming. Stack, heap and manual memory management. Pointers. Top-down and bottom-up design of programs. Layer design. Scripting and automation. Basic testing. What is a good programmer?

**C Sprint 2 (3 weeks)** (Students rebuild parts of the program in more dynamic ways, eg,

**Java Bootstrap (1 week)**  
Objects and classes. Basic Java. What parts of C carry over to Java.  
Automatic memory management. Execution environments (VMs, JITs, etc.)

**Java Sprint 1 (3 weeks)**  
Students choose between a classic OO simulation (cashiers and waiting lines in a store), or a very simple micro blogging application with a text-only interface that uses the network. (Lots of code is provided for the latter.)

**Java Sprint 2 (3 weeks)**  
Students choose between implementing a simple text-oriented MUD or a symbolic calculator. Both assignments focus on object structures, interfaces, inheritance and polymorphism.

**Project (4 weeks)**  
Basic Scrum.  
The project implements a basic automatic memory management system for simple C programs (a conservative Bartlett-style collector).