

More Programming Than Programming: Teaching Formal Methods in a Software Engineering Programme

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Abstract. Formal methods for software correctness are critical to the future of software engineering — and so must be an essential part of software engineering education. Unfortunately, formal methods are often resisted by students due to perceived difficulty, mathematicity, and practical irrelevance. We redeveloped our software correctness course by taking a programming intensive approach, using the solver-aided language Dafny to provide instant formative feedback via automated assessment. Our redeveloped course increased student retention and resulted in the best evaluation for the course for at least ten years.

Keywords: Formal Methods · Software Engineering · Education · Dafny.

1 Introduction

In the last 20 years, formal methods for software verification have moved from an esoteric research topic [38] to a set of increasingly practical tools, and from doctoral study to undergraduate degrees. Victoria University of Wellington’s Computer Science and Software Engineering programmes include a course, SWEN324 “Software Correctness” that teaches software verification. We often call this course “Programming Made Hard” because 100 students repeat the assignments they completed years ago in introductory programming courses, but now must specify those programs’ behaviour and verify that their implementations meet those specifications. In 2020 we redesigned SWEN324 using the solver-aided Dafny language, supported by Leino’s Dafny textbook [36]; we are just finishing teaching the 2021 version of the course at time of writing. Students and teaching staff found the use of Dafny very positive: the 2020 course offering received the highest overall evaluation for at least ten years.

Although very positive overall, students found Dafny difficult to learn and to use, and our informal observations as teachers are that many of these difficulties stem from “accidental” complexity introduced by the Dafny tool. This accidental complexity obscures the “essential” complexity of learning the fundamentals of software verification, and then applying those techniques to verifying simple programs [9]. In this paper we reflect on our experience teaching SWEN324, focusing particularly on our course design and issues with formal tooling.

2 Background

Formal verification of software systems has been a significant research topic for in computer science for 50 years or more [28]. Tools such as Dafny, SAW, SPIN are increasingly mature enough to support industrial application [23, 47] but the main barrier to adoption remains a lack of software engineers trained in their use [20]. To address this problem, there have been a number of studies on the usability of formal methods, and tools that support formal verification. Beckert and Grebing [6] for example used the Cognitive Dimensions framework [22] to evaluate the usability of the KeY proof tool; Grebing and Ulbrich [21] followed this up with a user study.

Tools have also been (re)designed to better support programmers in the task of verifying their programs. Whereas the Dafny tool, although interactive, requires programmers to verify their whole program statically, Gradual Dafny [18] allows programmers to choose between static (“assert”) and dynamic (run time “assume”) verification for each invariant. Other gradual verification approaches have shown similar promise at partial verification, but with choices embodied in the tools themselves [3, 45, 5, 48]. Coming at the problem from the other side, Müller & Ruskiewicz [41] demonstrated how standard program debuggers could be used to debug verification failures, by generating a modified program that reproduced the failure when run, and Christakis [12] integrated concolic testing tools and lower level solver debuggers into Dafny’s IDE.

More recently, some of the most interesting recent program verification work has been using the Rust language [8]. Eschewing garbage collection, Rust has an ownership types system that is used to manage memory allocation, object lifetimes, and permissible inter-object references. Program verification tools such as Prusti [4] and RustBelt [29] leverage ownership information to support verification without needing memory structures to be described separately.

Finally, as formal methods’ industrial use has increased, so has their relevance to education [15, 17, 30, 10]; Zhumagambetov [50] offers a relatively recent systematic literature review. Aceto and Ingolfsdottir [1], for example, have described a recent course at the University of Reykjavik, where students can participate in a three week intensive formal methods course at first year. Yatapanage [49] describes a recent second year course taught at De Montfort University that applied formal methods to concurrent programming — although the paper’s title highlights most students’ concerns when approaching this topic “*Students Who Hate Maths and Struggle with Programming*”. Kamburjan and Gratz [30] showed how a custom interactive proof tool can generate a positive effect on student engagement; Körner and Krings[32] describe how pedagogical changes to inquiry-based learning can support the user of formal tools. In some ways closest to the approach we present here, Ettinger describes how Dafny has been used for six years at Ben-Gurion University to support teaching refinement-style “correct-by-construction” programming [16], and Blazy describes a similar course based on Why3 [7]. Gudemann describes how verification tools can even support similar learning strategies even in applied computer science courses taught using C [24].

3 SWEN324 Software Correctness

Formal methods have been taught as part of Computer Science and Software Engineering programmers at VUW since 1984. Unfortunately, formal methods are often resisted by students due to perceived difficulty, mathematicity, and practical irrelevance — and SWEN324 had similar problems. In 2021 we had the opportunity to redevelop the course, as a companion to a relatively new course SWEN326 “Safety Critical Systems”, that focused on correct software engineering in a wider context, including software processes, testing, and abstract modelling (based on Alloy). This meant that we were able to refocus SWEN324 specifically on formal methods for software correctness based on program proof.

Traditional Formal Course: We initially considered staying with a relatively straightforward, “traditional” formal methods course, introducing students to propositional and predicate logic, then working up through weakest preconditions to Hoare logics and their application in describing and reasoning about software systems, culminating in pencil-and-paper proofs. After some debate, it was decided that this was not appropriate for several reasons. In particular, our students have already taken compulsory courses including Boolean algebra and logic (as mathematics) and discrete logic (as physics) during first year: we do not want students to regard this as “another maths or physics course” — our earlier experience with such courses suggested that such a course would not be popular [42]. On the other hand, our programme is heavily based around programming, with all engineering majors requiring a full first year computer science programme, and software engineering majors keen to take practical elective courses to develop programming skill and experience [42, 43].

Abstract Formal Modelling: We also considered taking an approach based on abstract formal modelling. High-level tools, such as TLA+ [33], Alloy Alloy [27] or SPIN [26], support reasoning and mechanised checking of systems’ properties, based on abstract models of those systems, rather than actual programming and source code. It is clear that these kinds of abstract formal models can play an important role in software engineering projects, at least in project’s the early stages, supporting design validation before a single line of code has been written. Indeed, we had earlier taught a first-year course (SWEN102) that attempted to give a gentle introduction to formal methods within a more general context of software modelling, beginning with UML and moving through to Alloy [42]. The idea was to present formal and informal approaches as different points in a spectrum of approaches to describing software systems, rather than being totally different subjects. We also wanted to ensure that students see software modelling as a useful way of understanding systems, rather than just an exercise in learning new notations, so we felt it was important that any formal notation we used be supported by tools which allowed students to explore the consequences of the models they created. This course was mostly successful on its own terms: even first year students were generally capable of domain modelling using Alloy, of translating functional requirements into Alloy properties, and then able to analyse the Alloy models to demonstrate that the requisite properties held (or explain why they did not).

Unfortunately, our SWEN102 course was never widely popular: for better or for worse, our cohort, privilege programming, over pretty much every other software engineering activity or practice. For the SWEN102 approach to work, we first had to successfully “sell” modelling, and then second to “sell” the advantage of formal models over informal ones — where students simply did not see the relevance of the models to the programming / software engineering tasks the expected to undertake. On the other hand: SWEN102 demonstrated that even our early undergraduate students were capable of learning formal tools, constructing formal models, and handling propositional and predicate logic.

Formalism as Programming: For this reason, we decided to base our SWEN324 course redesign on the reverse of the traditional approach. Rather than progressing bottom up from propositional logic to predicate logic, Hoare logic, and eventually perhaps experimenting with a practical tool, we aimed to progress top down: starting with programming language based tool, and then using that high-level tool as a context in which we can present and teach the key concepts of software correctness — while offering the majority of students an experience that feels like programming, rather than like doing mathematics.

The latest version of this course — SWEN324 “Software Correctness” — adopted the Dafny programming language and associated toolset, based on the Z3 solver and the Visual Studio Code. Dafny provides what Leino has called “auto-active” verification [37] in which verification is seamlessly incorporated into development practices and the toolchain. It may be clearer to think of this approach as *implicit* verification where programmers annotate their programs with preconditions, postconditions, variants, invariants, as in Eiffel [40], and do not interact directly with formal models or e.g. proof trees. This is in contrast to *explicit* verification technologies such as Coq [44, 11] where programmers must interact with solvers by directly building proofs and proof trees, potentially even extracting programs from those proofs. Dafny’s implicit approach still offers many guarantees: Dafny attempts to prove programs totally correct by default, so recursive methods and loops often require programmers to give variants to prove termination, and loops in particular generally require invariants to prove correctness. Array and pointer accesses typically require invariants, assertions, or preconditions to ensure all accesses are within bounds and variables are initialised and non-null. This means that Dafny programmers (and thus students) interact with Dafny’s underlying prover indirectly, at arm’s length, in terms of definitions in their programs and constructs in the Dafny language, rather than having to learn explicit representations of proof.

Choice of Dafny: Dafny was selected for a number of pragmatic reasons: it is well supported by a team in Amazon’s Automated Reasoning Group led by Rustan Leino, has substantial publicly available on-boarding and tutorial material, including a full book by Leino [36], an online playground at Rise4Fun, documentation available online, and a developing academic community — and, frankly, because what little experience the course staff had with suitable tools seemed most transferable to Dafny. Based on our earlier experience, we hoped Dafny would offer a number of advantages over Alloy, or more sophisticated tools like Coq [44] or Why3 [7]. First, Dafny offers a concrete, ASCII-compliant syntax — being restricted to ASCII means students should feel some

familiarity with the notation: students would not need to learn how to type, let alone pronounce, relatively esoteric characters such as α , δ , or o (little were we to know how familiar alpha, delta, and omicron would become). Dafny’s syntax and semantics being based on C# and Java should also be familiar. Students can use the development toolsets they already know, such as VS Code, Eclipse, Git — particularly important for students who need tools such as screen readers, magnifiers, or voice control to complete their work.

Second, because Dafny is well supported by a toolset, we are able to rely on Dafny itself to provide students rapid formative feedback — simply by requiring students to submit their solutions via the Dafny verifier. In a very real sense, we are able to leverage the “essential difficulty” of formal verification of correctness — that no only must students implement a correct program, but they must also convince the Dafny prover that their implementation is correct — to aid the students in that task. In simple cases, where students’ focus on implementing programs, we can directly supply students with the Dafny specifications and the tool itself will provide feedback: either their program verifies against the specification, or it does not. Where students’ focus is on writing specifications, we can allow students to verify their solutions against hidden “oracle” specifications, and again Dafny can check that the students’ specifications capture important properties described by the oracles, or more straightforwardly, that the students’ specifications and the oracles are mutually consistent [19].

Finally, because Dafny is relatively mature, there is a fair amount of material available online, which students are able to access as necessary. We were also able to use a draft version of Leino’s *Program Proofs* textbook [36].

Continuous Automated Feedback: The ability for Dafny to provide feedback, and that this course was targeted at third-year students — experienced both in programming and in tertiary study — lead us to make this automated feedback a central feature of the course. Again based on our department’s practice in teaching programming — with which our students are very familiar! — we provide that feedback in two ways.

First, our “lectures” are centred around a weekly series of small “mastery” questions about Dafny and verification, served from a simple website. This is similar to the existing Dafny Rise4Fun website, but simpler: we discuss this further in the next section. The weekly questions are released at the start of each week, and students may discuss the questions, may work in groups, ask for answers, and make any number of attempts at answering them — but are expected to answer the vast bulk of these questions correctly. The time in “lectures” allows students to discuss any of the questions with the class, lead by the course staff — in practice, the website lets us know which questions students are currently finding difficult, and so we use that to guide choices. Because of the very liberal rules around answering the mastery questions, we can work out the solution to any weekly question in class, and even demonstrate the correct answer and show it verifying: if students choose to pay little attention and just copy the provided answer, so be it.

Second, we also incorporate automated feedback into larger summative individual assignments (again, we provide examples in the next section). Students can submit answers to the assignments as many times as necessary: by running each submission through the Dafny verifier, students then get immediate feedback about their submis-

sion. This feedback is quite terse (just the number of assertions verified, or not verified) because it is not intended to replace students’ use of IDEs or to substitute for their own attempts at verification — rather it is so students can judge their progress through the course, and in particular, to know when they have completed each part of each assignment. We are careful to ensure that every important concept required by the summative assignments are covered by weekly questions before the assignment is due. Thus, while we can discuss the summative assignments only in broad outline, we can (and do) refer students to the relevant weekly questions which we can discuss in as much detail and at as much length as necessary.

Course Design: As with all VUW engineering courses, SWEN324 is offered in one twelve week semester, generally split into two six-week half-semester. Figure 1 shows the ideal course plan (for COVID reasons, an extra week’s break was substituted at week 9 in 2020 and week 3 in 2021). There are four main topics in the course: learning Dafny as a programming language; writing Dafny (method) specifications; verifying those specifications against Dafny programs; and handling objects with mutable state.

Week	Topic	Assignment
1.	Introduction — overview, industrial use [25, 13]	A1 Programming (10%)
2.	Programming — pre- and post-conditions	
3.	Data — inductive data types, pattern matching	
4.	Recursion — totality, termination	
5.	Structural Recursion — over inductive types	
6.	Iteration — loops, variants	
	Midterm break	A2 Specifying Programs (15%)
	Midterm break	
7.	Loops – loop invariants and variants	A3 Verifying Programs (15%)
8.	Recursion vs Iteration — tail recursion	
9.	Recursion vs Iteration — specs. vs. programs	
10.	Objects — mutable structures and validity	A4 Reasoning about Systems (40%)
11.	Ownership — ownership of representation	
12.	Proofs — Dafny “assert” vs “calc”	
15.		

Fig. 1. SWEN324 course plan.

Course Content: The resulting course covers most of the content Leino’s *Programs Proofs* [36], although it does not explicitly address the foundational material. In more detail: we address essentially all the “core” features of Dafny circa 2020, i.e. Dafny version 2.3.0. This included Dafny methods and classes (imperative, and mutable); functions and inductive datatypes (immutable, finitary); pre and postconditions; predicates (Boolean functions); assumptions and assertions; compiled vs ghost code, well-founded recursion and explicit termination measures, pattern matching, destructors; built-in collections (arrays, sets, maps); loops, invariants, and variants; recursive specifications of iterative programs (including transformations between general recursion, tail recursion, and iteration); and representation invariants for dynamic data structures.

There are only two chapters of material from *Program Proofs* that we intentionally overlook. Chapter 2 presents the mathematical foundations of Dafny’s program logic, based on Hoare Logic and Weakest Preconditions. Where necessary, we discuss Dafny’s semantics informally: we have not needed to refer the formal definitions. Chapter 5 presents the notion of proof and Dafny’s constructs (function lemmas, `calc` blocks) that can support programmers in making explicit proofs. Perhaps more surprisingly we have not needed this material either. Because Dafny is an *implicit* verification system, students do not need to build proof objects, and they are not even able to see what proofs Dafny’s solver many have constructed!

Course Assessment: The overall assessment of the course is shown in Figure 2. A significant fraction of the assessment supports the formative mastery questions, with the balance taken up by four summative assignments, one for each part, and a reflective essay. Each part of the course is addressed by around 25 weekly formative mastery questions. Students who complete all the mastery questions and the first assignment are well on the way to obtaining a bare pass; students who are hoping for an “excellent” grade must complete most of the assignments correctly.

Weekly Overview Questions (Dafny, open)	20%
Assignment A1: Programming (Dafny, individual)	10%
Assignment A2: Specifying (Dafny, individual)	15%
Assignment A3: Verifying (Dafny, individual)	15%
Assignment A4: Reasoning (20% Dafny, 20% essay, individual)	40%

Fig. 2. SWEN304 Assessment Items.

These assessment weights also guide students time. VUW courses of this size (15 points) are rated at 150 hours over the whole trimester — nominally 10 hours per week over 15 weeks — 12 lecture weeks and a three-week assessment period at the end. Allowing approx. 25 hours (2 hours per week) to attend lectures, and another 25 hours for background reading, installing software, navigating Git, etc, that leaves 100 hours of assessed work. The assessment percentages offer a rough guide to the amount of time students should aim to spend on each piece of work.

Course Objectives: The resulting course objectives are that, by the end of the course, students should be able to:

1. Explain what it means for a system to be correct, what engineering techniques we can use to increase confidence in correctness, and why this is important.
2. Use formal structures such as sets, functions, relations and sequences to model software systems.
3. Use formal notations to specify desired properties of software systems, such as assertions, pre- and postconditions, variants, and invariants.
4. Use formal tools to check that systems correctly implement their desired properties.
5. Use formal reasoning to explain why a particular system is correct with respect to a specification.

The first objective is primarily tested by the essay: the other objectives by the assignments and mastery questions.

4 Assessment

To quote Tom Angelo [2], “*most students are going to try to ‘study to the test.’*”. What is assessed is what we can expect students to (try to) learn. This is why we have restructured SWEN324 around questions and assignments with automated feedback, rather e.g. than traditional lecture content. In this section we present examples of the assessment items we designed for SWEN324, to demonstrate the kind of problems students are able to solve during the course.

4.1 Weekly Overview Questions

As discussed above, 20% of the assessment in SWEN324 is in the form of formative weekly questions. Students can choose to answer any question at any time, and make repeated attempts to answer each question. The point is formative, to support learning, rather than summative evaluation — although the system records when each student successfully answers each question. Students can repeat completed questions (e.g. to experiment with alternative solutions) — the question stays listed as completed.

Figure 3 shows the rudimentary web system that presents these questions to students. The left-hand pane shows some Dafny code including a place-holder “[???”; this placeholder is replaced by whatever students type in to the right-hand pane. This system was originally built by our colleague Marco Servetto to help students revise their Java knowledge, and is well integrated with the other systems which we use in the school: we have re-purposed this tool for Dafny.

The question in Figure 3 (titled “First Past the Post”) is addressing a basic definition of Boolean algebra: what is Dafny’s Boolean “exclusive-or” operator. This question shows the advantage of the placeholder mechanism: potential solutions are necessarily restricted to fit within the syntactic context of the placeholder. The solution to this question is Dafny’s “!=” operator.

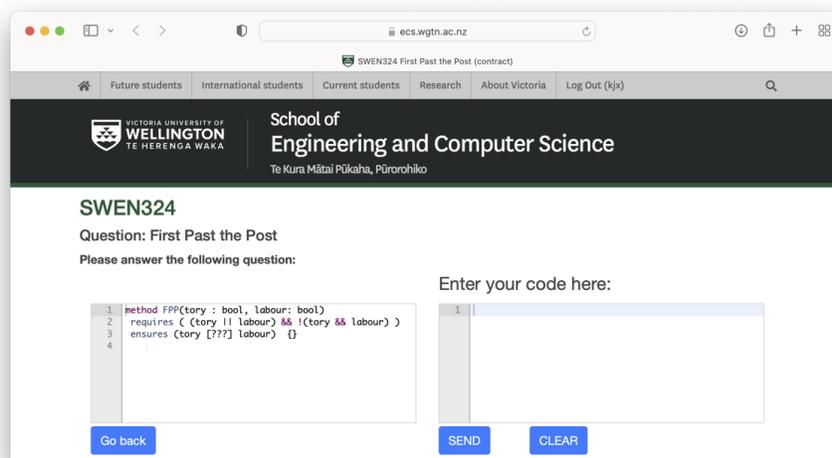


Fig. 3. Web interface for weekly questions.

Figure 4 shows the course-wide overview of the summary questions, showing how many students have completed each question. This proved very used in tracking students' progress through the course overall, and in choosing lecture topics (i.e. which questions we will discuss and then answer in lectures). Generally we aim to pick questions where that top 10-20% of students have answered successfully (we can lure them into the discussion of their solutions) but the bulk of the class has not (so that they are interested in learning how to solve those questions). This also allows us to choose not to revisit questions that the vast majority of the class has already answered, even if some stragglers have not — rather than taking up everyone's class time with well understood topics. Rather, we can direct stragglers e.g. to the recordings of the lectures where we have answered those questions, or arrange to provide individual support.

Name	Total Completed	Completed On time	Completed Late
The answer to the ultimate question of life, the universe, and everything.	59	44	15
The answer to the ultimate question of life, the universe, and everything (again).	59	42	17
The ZX81 is the world's greatest home computer.	58	41	17
The ZX Spectrum is colourful.	57	36	21
Black Espresso (set)	54	36	18
Americano (programming)	55	32	23
Mocha (set)	54	32	22
White Espresso (Dafny problem)	55	31	24
Fluffy (define a Method)	55	30	25
Going Down	53	30	23
Addition Addition Addition	53	30	23
Gaudete	53	30	23

Fig. 4. Overview of student progress.

It is worth reiterating that these questions are at least as important as resources or content or prompts for lecture sessions, as questions that students must answer by themselves. Fairly early on, for example, there is a relatively simple question that most students get wrong:

```
//complete the following method which returns the "real"
//sum and product of its two real arguments
method SumAndDifference(a : real, b : real) [???]

//Hint: https://www.youtube.com/watch?v=kqFPDrDWAHs
```

The point of this question is that the question title (“We’ll look at them together then we’ll take them apart”) and method name (“SumAndDifference”) are inconsistent with the comment on the method (“//.. "real" sum and product”). This inconsistency was originally introduced in error, however we kept it because of the valuable in-class discussion it engendered, about how comments can be misleading, as can method names, or alternatively tests or specifications can be incorrect. As it happens,

here the comment is wrong: the automated test indeed requires sum and difference not sum and product.

The “First Past the Post” question illustrates how we use Dafny to revise Boolean algebra. The questions get rather more sophisticated as the course progresses. For example, the “Very Logical, Mr Spock” question also tests Boolean algebra, but requires students to understand how a method’s control flow and assignments are summarised by postconditions (“ensures”):

```
method logical(a : bool, b : bool, c : bool) returns (t : bool)
  ensures [???]
{
  t := false;
  if (b) {
    if (a) { t := true; } } else { t := false; }
  if (c) { t := a; }
}
```

The “How many leaves” question requires students to write a recursive function to calculate the size of a tree:

```
datatype Tree = Leaf | Node(left: Tree, right: Tree)
function method Size(t: Tree): nat
[???]

method Main() {
  var tl:Tree := Leaf;
  var tc:Tree := Node(Node(Leaf, Leaf),Leaf);
  assert Size(tl) = 1;
  assert Size(tc) = 3;
  print "└─",Size(tl),"└─",Size(tc), "\n";
}
```

The “Hopalong” question requires students to define a termination measure, as Dafny programs are total by default:

```
//insert a decreases clause so Dafny can prove termination
function hopalong(q: int, x : int, y : int, z : int) : int
[???]
{
  var modulo := (x + y + z) % 3;
  q + if (y ≤ 0) ∨ (z ≤ 0) ∨ (x ≤ 0) then 0 else
  if (modulo = 0) then (hopalong(q+1, x + 3, y - 1, z + 2))
  else if (modulo = 1) then (hopalong(q+3, x - 3, y , z - 1))
  else (hopalong(q+5, x + 2, y, z - 10))
}
```

Our final example is an excerpt of the last of the weekly questions — the full example presents 90 lines of code to students; another 30 lines of code for method implementations are omitted. This question is rather more complex, requiring students to

implement both the “Valid()” predicate to describe the class invariant of a complex mutable object, and to manipulate the “Repr” ghost field that must track the auxiliary implementation objects owned by the stack:

```
datatype StackModel = Empty | Push(val : int, prev : StackModel)

class Stack {
  var values : array<int>
  var capacity : nat
  var size : nat

  ghost const Repr : set<object>

  //Define these two methods so that the hidden code below works
  // constructor(capacity_ : nat)
  // predicate Valid()
  [???]

  method push(i : int)
    requires Valid()
    ensures Valid()
    modifies Repr
    ensures capacity = old(capacity)
  /*omitted*/
```

4.2 Assignments

The four Dafny assignments are very similar to the overview questions in spirit — but with two main differences: they are undertaken using whichever Dafny IDE students choose (usually Visual Studio Code); and students must upload complete Dafny files into the school’s standard submission system, rather than using a specialised web interface. Assignment questions are significantly larger than weekly questions. Whereas the overview questions typically aim to teach one single verification concept or Dafny construct, the assignments typically require students to combine techniques and link concepts together. To guide students’ work, we again ensure rapid feedback by reporting the results of Dafny attempting to verify each submission, and we allow students to submit work any number of times. Space does not permit us to include full details of assignment questions here — however some of the more interesting questions included:

1. Add annotations to the code of a vector sum (A1) or small sorting network (A1).
2. Print out the text of the song “Ten Green Bottles” (exactly as supplied, 1743 characters) but with a program shorter than 750 characters (A1).
3. Calculate the income tax payable by an individual New Zealander (A1).
4. Calculate with Carolingian duodecimal currency or interval arithmetic (A2).
5. Verify functional implementations of sets, lists, and maps (A2,A3).
6. Test if a string is a Palindrome (A4).
7. Implement search trees (A3), tries (A3), or balanced trees (A4).
8. Implement an object-oriented mutable map (A4).

These questions obviously get harder as they go along. The first questions either ask students to annotate existing code, or write code without specifications to introduce students to the language. Even here, however, apparently simple programs such as “Ten Green Bottles” (which we do not verify against any external specifications) still require significant verification effort to be accepted by Dafny — at least four or five lines of annotation out of a 25-line solution. Dafny needs to prove termination, and that all array accesses are in bounds, and this necessitates preconditions constraining arguments on all subsidiary methods and functions. The final assignment questions are as complex as the final data structure examples from *Program Proofs*.

4.3 Essay

A reflective essay provides the last 20% of the course. This is the final assessment component that students complete — although due to VUW’s regulations, it is due together with the fourth Dafny assignment, as late as possible in the term. The core rubric for the essay is straightforward: to write no more than 750 words reflecting on students’ “experience with verified programming in Dafny to ensure software correctness”, in the style of a blog post aimed to communicate to other students, developers, or software engineers. Students are invited to select a problem (typically from the final assignment, but “in case of emergency” they may choose any programming problem) and then explain how they used Dafny to specify, implement, and verify their chosen problem; to discuss which features of Dafny made this easier (or harder); and if they had to do it again, what they would do differently and why.

This essay fulfills two important purposes in the course design. Towards higher marks, a VUW “A-” grade is 80%: a student who completes all the assignments perfectly but chose not to attempt the essay would get that grade. The essay thus enables us to distinguish the truly outstanding “A+” students from the merely excellent “A” or “A-” students. At the other end of the grade distribution, reasonable attempts at the weekly questions and the first two assignments should yield 40%: an essay that demonstrates merely “adequate evidence of learning” is then sufficient to pass the course.

5 Experience with Dafny

Mathematics may still be taught via pencil and paper (or \LaTeX) but these days teaching programming is impossible without a toolchain: a language implementation, a development environment, and the other accoutrements students expect. Our course design teaches verification as a specially intense kind of programming (“More programming than programming is our motto” [46]) — this requires a toolchain that is reliable, scalable, and supported enough to cope with daily use by hundreds of students. Luckily, we found the current versions Dafny were certainly good enough for our purposes: we were able to spend the vast majority of our efforts in teaching the practices and principles of verification, rather than working around problems and bugs in the tools. While we encountered roughly one serious bug during each course offering so far, the Dafny project team resolved them assiduously. Our overall experience with Dafny was very positive.

Probably the biggest issue we encountered was just finding the resources – notably staff time and effort — to support rapid feedback via automated marking of the weekly questions and the assignments. The problem was not so much the necessary infrastructure, which is essentially a one-off cost, but the advance preparation needed for automated marking of every assignment. Basically, marking must be complete before an assignment can be released, rendering it no longer possible to write underspecified assignments which point students in a general direction, wait until the assignment deadline, and then take as much time as necessary *after the students have submitted their work* to work out the marks, the desired solutions, or even *whether solutions are possible*. All this work must now be completed beforehand.

That said, we did strike three more technical issues that could be addressed via changes to Dafny’s design:

Program Testing: We encourage students to start by testing their implementations, because it is easier to verify code that is correct than it is to verify incorrect code :-). Dafny’s tight integration of proving and programming unfortunately means that programs cannot easily be tested until they are fully verified. We observed students continually “commenting out” assertions and preconditions to be able to test their programs, and then undoing those comments to undertake verification. There are four related problems here.

First, Dafny’s requirements to prove all memory accesses safe, and that all programs terminate, often mean even simple programs have to be heavily annotated just to compile. A method to swap two array elements will require array reads and writes to be in bounds; the obvious (and best practice) solution is to define method preconditions which ensure method arguments are in bounds: but now all callers of the method must themselves do enough to meet those preconditions.

Second, while annotations, assumptions, and non-totality declarations etc. can be used to remove the need for some of these checks, they still require students to annotate their programs explicitly, i.e. so students always have to deal with the checks even if just to tell Dafny to ignore them!

Third, while Dafny does support command line options to e.g. ignore verification and compile and run programs directly, verification is an all-or-nothing, static affair: either verification is attempted for the whole program, or all specification and verification constructs are ignored.

Fourth (and finally) the options to control verification are buried in the command line, and are not surfaced in the Visual Studio Code IDE.

Following the example of Gradual Dafny [18] and Gradual Verification [3, 5, 48] more generally should make testing easier. Ideally students would be able to run programs in a “test mode” where Dafny checks as many assertions, assumptions, and pre- and postconditions as possible dynamically. Students could then express a series of unit tests as Dafny assertions: if the program verifies, well and good; but if not, they would still have the option of running the program and using print statements or host debuggers to interrogate program state. Recent Dafny releases [34] now support an `expect` statement that does Gradual Dafny style dynamic checking: implementing this option

may be as simple as translating Dafny’s verification condition as `expects` rather than `asserts`.

Verification Debugging: Much of the work of verifying Dafny programs involves students annotating their code — adding `require` and `ensure` clauses and assertions until the verifier has enough information to discharge its proof obligations. Students find this hard because it is not obvious what Dafny “knows” at any given program point: which assertions Dafny is able to prove, which assertions Dafny is able to refute, and which assertions Dafny is unable to answer (i.e. where the prover times out). We also observed cases where Dafny is unable to verify an assertion because it does not have enough information about variable values — this is particularly prevalent in code where e.g. students have forgotten to write method postconditions, or have not realised a particular postcondition is necessary. This manifests as Dafny being unable to verify an assertion about a method’s return value, and simultaneously unable to verify the negation of that same assertion. Even good students find this situation intensely frustrating. Ideally Dafny would be able to give programmers more information about what it knows, e.g. by querying its underlying solver [12].

Mutable Object Structure: Dafny is one of the few tools that can verify programs built from composite structures of mutable objects using class invariants and representation sets. In practice, this requires either explicit definitions of “`Valid`” and “`Repr`” attributes [36] which are verbose and complex, or implicit definitions generated via the “`autocontracts`” attribute [35] which are concise but opaque. Few students were able to use either mechanism effectively. Perhaps by building on work verifying Rust programs, such as Prusti [4] and RustBelt [29], it should be possible to add ownership annotations to fields and parameters, to check those annotations as with Rust’s borrow checker [39, 14, 31] and thus extend the implicit definitions already generated by `autocontracts`.

We also encountered a number of pragmatic issues that arose with Dafny, but which appear to be consequences of Dafny’s design choices, and as such are less amenable to technical fixes.

Idiosyncrasies: Dafny’s syntax is sometimes idiosyncratic, which students found hard to follow. To give just one example, here are a method and function to add two numbers:

```
method addM (a : int, b : int) returns (c : int) { c := a + b; }
function method addF (a : int, b : int) : int { a + b }
```

The syntax for declaring the return values are different (`returns` vs `:`); the syntax for actually returning the results are different; a final semicolon is mandatory in the method and forbidden in the function. Adding insult to injury, methods and functions then perform very differently in the verifier:

```
0   var m := addM(x,y);
1   var f := addF(x,y);
2   assert m = x + y; //Fails to verify
3   assert f = x + y; //Verifies
```

Dafny verifies the assertion on line 4, because functions are incorporated into the verification context. Dafny fails to verify the assertion on line 3, however, because methods are always abstracted by their postconditions, and the declaration of `addM` omits postconditions. There are reasons for these choices, but they do make the language more difficult to learn.

Implicit vs. Explicit Verification: We have described as taking an implicit (aka “auto-active” [37]) approach to verification. Our students, or Dafny programmers in general, do not construct proofs explicitly, in some verification domain that reflects on the base domain of the program: rather they work in an extended programming language domain. That is, students focus on programs, and program verification, but not on the foundations of logic, programming languages, and critically, not on proof. Our teaching practice builds on this implicit approach: students definitely need an implicit understanding of the underlying formal concepts — because they will be incapable of completing any work without that understanding — but we present those concepts completely within the programming approach: we don’t discuss the semantics of programming languages, weakest preconditions, the kind of inferences Dafny’s underlying solver is making, let alone how it works. We approach software verification in the same way that most software engineering courses approach statically-typed languages: students can understand the benefits, and use the type systems, but could not give a type-theoretic explanation for why their programs don’t compile.

Arguably the biggest weakness of this implicit approach is that it sidesteps the question of proof. Dafny does not illustrate proofs of programs (other than symbolic dumps designed for debugging Dafny). As a result, we do not expose students to formal proofs, and in fact students never need to understand what a proof is.

We do teach that Dafny assertions can be used as “hints” to the verifier checker; we also show how Dafny (ghost) functions can be used within specifications or assertions to embody lemmas that Dafny cannot find itself. In the latter part of the course, questions require (ghost) data and methods to model the state of imperative objects. We mention Dafny’s `calc` statement that supports line-by-line reasoning only in passing.

We consider this a trade-off worth making: the course stays focused on program verification, through a programming lens, and we use the time to allow students to complete more significant examples with more complex verification constructs, rather than teaching proof and necessarily working on smaller examples.

6 Evaluation

As part of VUW’s quality assurance process, we conducted a standard evaluation of SWEN324. Under the terms of that process, we can only report the quantitative results here. The quantitative questions employed a 5-point Likert scale (“Strongly Agree/ Agree/ Neither Agree nor Disagree/ Strongly Disagree” unless otherwise noted) and employ both objective and affective questions. We received 19 questionnaires from 88 students nominally enrolled in the course when the evaluations were conducted.

Based on the quantitative feedback, over 70% of students either agreed or strongly agreed that the course was well organised, and that its objectives were communicated

well. 70% of students considered the workload “about right”, although of the balance, 20% considered the workload “too much” or “far too much” while only 5% considered that that it was “too little”.

Considering quality measures, most students considered the course overall as “very good” (58%) or “excellent” (21%) — although one outlier did rank the course as “poor”. Apart from that outlier, all evaluated students agreed or strongly agreed that what they had learned in the course had been valuable, and over half that the course had stimulated interest in the subject “a great deal”. This results in a median overall score of 2.0 “very good”. Compared with other courses in the faculty, that is a slightly worse median (1.9), but perhaps more relevant are comparisons with earlier offerings of more traditional versions of the course. Over the last ten years, across many iterations of the course, these have ranged from 3.8 “Poor” to 2.3 (approaching “Good”) with most offerings around 2.6-2.7 — i.e. this version seems substantially better.

Finally, given the focus of our course design on online tools and automatic marking to provide rapid feedback, it is gratifying that 80% of students agreed or strongly agreed that the “online components of the course contributed to my learning”. Over 90% agreed or strongly agreed that “Assessment tasks have helped me to learn” and that “I received helpful feedback on my progress.” This is about as strong evidence for the benefits of the “programming style” approach we adopted in SWEN324, and the use of automated marking and feedback, that one is ever likely to receive.

Overall we consider the experiment of our redesign of SWEN324 a success. Following this programming-centric approach, almost all students were able to demonstrate enough engagement with practical software verification to pass the course, and those students who chose to put in the necessary time and effort were able to complete quite significant verification tasks. In spite of the “mastery” approach taken in much of the course, the final assignments and essays, were sufficient to ensure a good spread of grades across the course.

We are aware that the practical, pragmatic, programming focus of this approach has some trade-offs and costs. While students are able to program with Dafny, their knowledge of logic and indeed of formal methods and software verification is latent, i.e. implicit. For example, students would be able to propose preconditions for a given Dafny function (e.g. to avoid array bounds errors or invalid computation), and given interaction with a Dafny IDE, to write preconditions that Dafny could verify: many students could argue informally about why such preconditions were necessary. Because the knowledge is not explicit, they would not be able to present the formal rationale for those preconditions, to derive them from e.g. weakest preconditions, or to produce a formal proof that those preconditions would definitively rule out crashes at run time. We had hoped that these topics could be addressed in a follow-on fourth-year course, however it seems we will not have that opportunity.

The other costs were essentially resources: all students needed access to the Dafny tool at all times; technical support from tutors thus needed to be provided whenever possible. Automated marking (both weekly questions and assignments) was essential to maintaining that programming focus, and directly supported learning. Preparing the automated questions, and then validating them by verifying several different solutions also required significant time and effort, by both tutors and academic staff. Some of this

effort (e.g. weekly questions) could be amortised over multiple offerings of the course, but most institutions would need to refresh the main assignments for each course offering — at least in institutions without very strong honour code traditions that prevent sharing solutions across cohorts.

7 Conclusion

Getting code to work is one thing.

Proving it does what it's supposed to is something else.

Convincing Dafny you've proved it does what it's supposed to is something else entirely.

“Motto for a Software Correctness Course”

Thomas J. “Tad” Peckish (attrib.), twitter, Oct 4 2020

Formal methods are becoming more popular in software engineering practice, and accordingly more common in software engineering education course work. This shift has implications for how we teach: a course that aims to ensure every computer science or software engineering student has understanding of formal methods, and some basic exposure to formal tools, must necessarily be different to a course that (explicitly or implicitly) aims to prepare students for graduate work. We have described our experience in redeveloping our formal methods course to be for the many, not the few; by employing tool and strategies typically used to teach programming, rather than those of mathematics. So far, this approach has been fruitful: most students who enroll in the course are able to pass it; are able to actually complete some small problems using Dafny; and overall consider the course worthwhile. The key factors supporting this outcome were the Dafny tool, which is now sufficiently mature to be used at this scale, and the necessary time and effort to prepare weekly questions and assignments in advance to support feedback via automatic marking. We hope to continue with work, both to integrate formal methods ever more tightly into teaching programming, and to investigate how tools such as Dafny can best support this approach.

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