

# Verifying imperative programs with Dafny

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February 24, 2025

## **Abstract**

The goal of this work is to show how to formally reason about imperative programming constructs such as assignments, loops, arrays and especially about dynamically allocated objects. To be able to achieve that, basic Dafny constructs will be shown, such as functions, methods, pre- and postconditions. The discussion thereafter will move towards recursion and termination as well as inductive datatypes. Having learned from those chapters, loop invariants and their usage will be explored. Because analyzing objects in the heap is more challenging, searching and modifying arrays will be covered. The final chapter will include a detailed discussion about Dafny's dynamic frames and their significance.

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# 1 Introduction

## 1.1 Why Dafny?

When software engineers encounter the field of formal methods and verification, this usually happens in an academic setting, where proof techniques are learned and done by hand. Moreover, actually taking advantage of those methods in practice involves a steep learning curve and lots of time. This unfortunately leads to less acceptance of verification techniques in an industry where fast time to market is essential Reid et al. (2020). Dafny promises to solve those problems. As a programming language designed to support specifications and proofs, it comes with an automated verifier that integrates seamlessly into most modern IDEs <sup>1</sup> making rigorous verification part of the software development process, thus reducing costly late-stage bugs that may be missed by testing. The language was designed by Rustan Leino in 2009 and its current version at the time of this writing is 4.9.0 from 31. October 2024.

## 1.2 Dafny's build system

The main idea in such verification-aware programming languages is that code is divided into two parts - the specification part and the implementation part Leino (2023). The built-in verifier in Dafny acts as an extended type checker and constantly proves that the provided implementation actually meets the behavior stated in the specification part of the given function, method or class. This is done by transforming the code into an intermediary that a tool called Boogie can understand. The correctness of the Boogie program implies the correctness of the Dafny program. Boogie then generates first-order verification rules that are passed to the Z3 SMT solver. Any violations of these conditions are passed back as verification errors Herbert et al. (2012). This process is visualized in Figure 1.

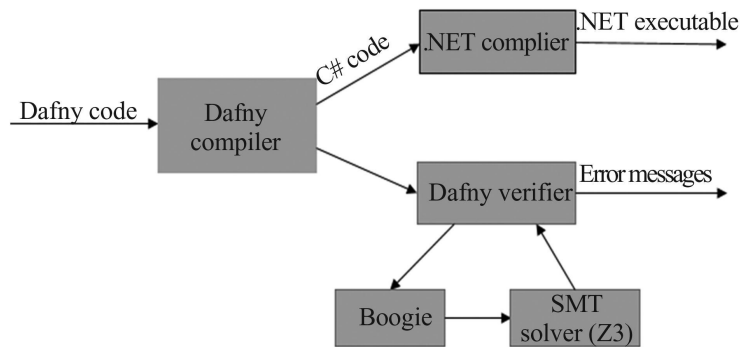


Figure 1: The Dafny build system as shown in Herbert et al. (2012)

<sup>1</sup>Integrated Development Environments (IDEs)

## 2 Building Blocks of Dafny

This work assumes the reader is familiarized with the fundamentals of program-semantics such as Floyd logic and Hoare triples, as they build the reasoning framework of Dafny and help to understand it more effectively.

### 2.1 Methods

As in other programming languages, a *method* is a block of code that prescribes some behavior. For instance, Listing 1 shows the declaration of a method called `Triple`.

```

1 method Triple(x: int) returns (r: int)
2   ensures Average(x) == 3 * x {
3     var y := 3 * x;
4     r := x + y;
5   }
```

Listing 1: A simple method in Dafny.

This method takes an *in-parameter* `x` of type integer and returns an *out-parameter* `r`, also of type integer. The **ensures** keyword is used to specify the method’s *postcondition*. A postcondition expresses a property that must hold after every invocation of the method through all possible return points. Postconditions are part of the method’s specification and appear before the body block Herbert et al. (2012). The body of a method is a list of statements that give the method’s implementation. In Dafny, methods can have any number of in- and out-parameters. Inside the method, the out-parameters are like local variables and can be assigned and read. When the method ends, whatever values were assigned to the out-parameters will be returned to the caller. The in-parameters however cannot be re-assigned Leino (2023).

### 2.2 Functions

Functions in Dafny are very mathematical in nature, because they are deterministic. Any two invocations of a function with the same arguments will result in the same value. Listing 2 shows how a simple function named `Average` looks like.

```

1 function Average(a: int, b: int): int
2   requires 0 <= a && 0 <= b {
3     (a + b) / 2
4   }
```

Listing 2: A simple function in Dafny.

Whereas a method is declared to have some number of out-parameters, a function instead declares a result type, and while a method body is a statement, the body of a function is an expression Leino (2023). Another important difference between functions and methods is, that functions are *transparent*. This means that their implementation is directly visible to the caller. That’s the reason why functions can also be used to describe pre- and postconditions like on line 2 in Listing 1. Methods on the other hand are *opaque*, so callers fully rely on the postcondition to reason about their return values.

### 3 Section about quotations

In this section, an example for a literal quotation is given.

*“A persona is a rich picture of an imaginary person who represents your core user group.”* (?)

Sometimes you might want to make use of the authors name within the text. Before, we used the command `citep{}`, which creates the brackets around author name and year. You can also use the `cite` command like this:

? defined the concept of persona as follows:

*“A persona is a rich picture of an imaginary person who represents your core user group.”* (?)

You may notice, that this increases the readability of the text.

According to APA format<sup>2</sup> there are some rules, when and how to include page numbers, when referring to literature.

*“Include page numbers for any citations in the text of your paper that include direct quotations or refer to a specific part of the work you are referencing. Direct quotations must include a page number as part of the citation. The quoted material should be followed by a citation in parentheses that gives the author’s name, the year in which the work was published, and the page number from which the quoted material appears.”* (?)

Check out the example and recommendations of ? on [http://www.ehow.com/how\\_5689799\\_cite-numbers-apa-format.html](http://www.ehow.com/how_5689799_cite-numbers-apa-format.html). In L<sup>A</sup>T<sub>E</sub>X you can include the pages very easy. For example:

?, p. 86 stated:

*“We hope that our preliminary attempts to begin answering the question will convince the reader, not necessarily that our views are correct, but that the question was and is well worth asking”* (?, p. 86)

Note that in the first reference, we used `citet[]{}{}` in order to have brackets just around year and page number; later we used `citep[]{}{}`.

### 4 Section about references within the document

If you want to refer to you own chapters, figures, tables or the like, you can make use of the `ref{}{}` command, for example:

- section 3 on page 5

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<sup>2</sup>American Psychological Association (APA)

### 4.1 Subsection within Foundations

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### 4.2 Another subsection within Foundations

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## 5 Methodology

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## 6 Results

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## 7 Conclusion

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## References

- Herbert, L., Leino, K. R. M., and Quaresma, J. (2012). *Using Dafny, an Automatic Program Verifier*, pages 156–181. Springer Berlin Heidelberg, Berlin, Heidelberg.
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