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(54) **RETAINING DAFNY SPECIFICATIONS**

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(51) **Int. Cl.**

G06F 11/36	(2006.01)
G06F 8/35	(2018.01)
G06F 8/41	(2018.01)
G06F 9/445	(2018.01)

(52) **U.S. Cl.**
CPC ***G06F 11/3628*** (2013.01); ***G06F 8/35*** (2013.01); ***G06F 8/447*** (2013.01); ***G06F 9/44589*** (2013.01)

(58) **Field of Classification Search**
None
See application file for complete search history.

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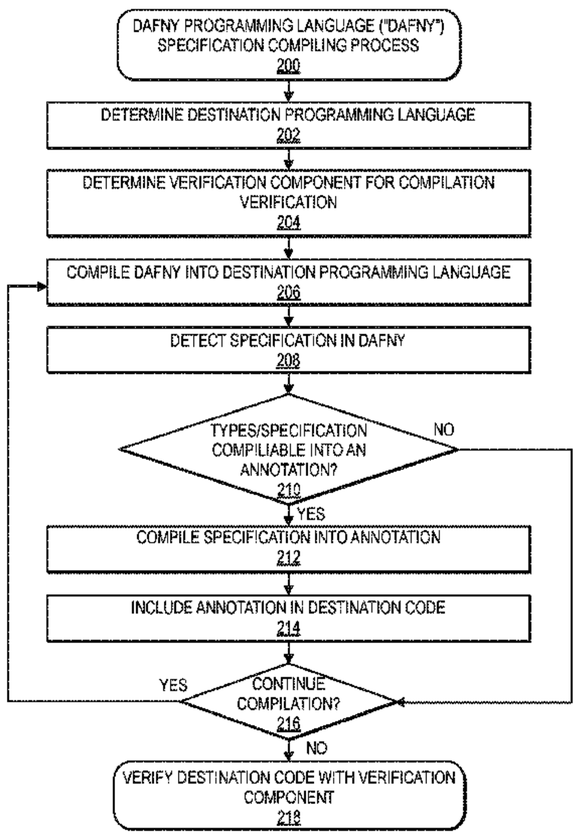
(57) **ABSTRACT**

Disclosed are systems and methods that determine specification portions of Dafny code and transform those specifications into one or more annotations, expressions, comments, and/or assertions that are included in a destination code written in a destination language as part of a compilation of the Dafny code into the destination code. The annotations, expressions, comments, and/or assertions in the destination code may be utilized by a verification component, such as a Checker Framework, to detect errors that are introduced into the destination code by the compiler as part of the compilation or to verify the absence of errors in the destination code.

23 Claims, 6 Drawing Sheets



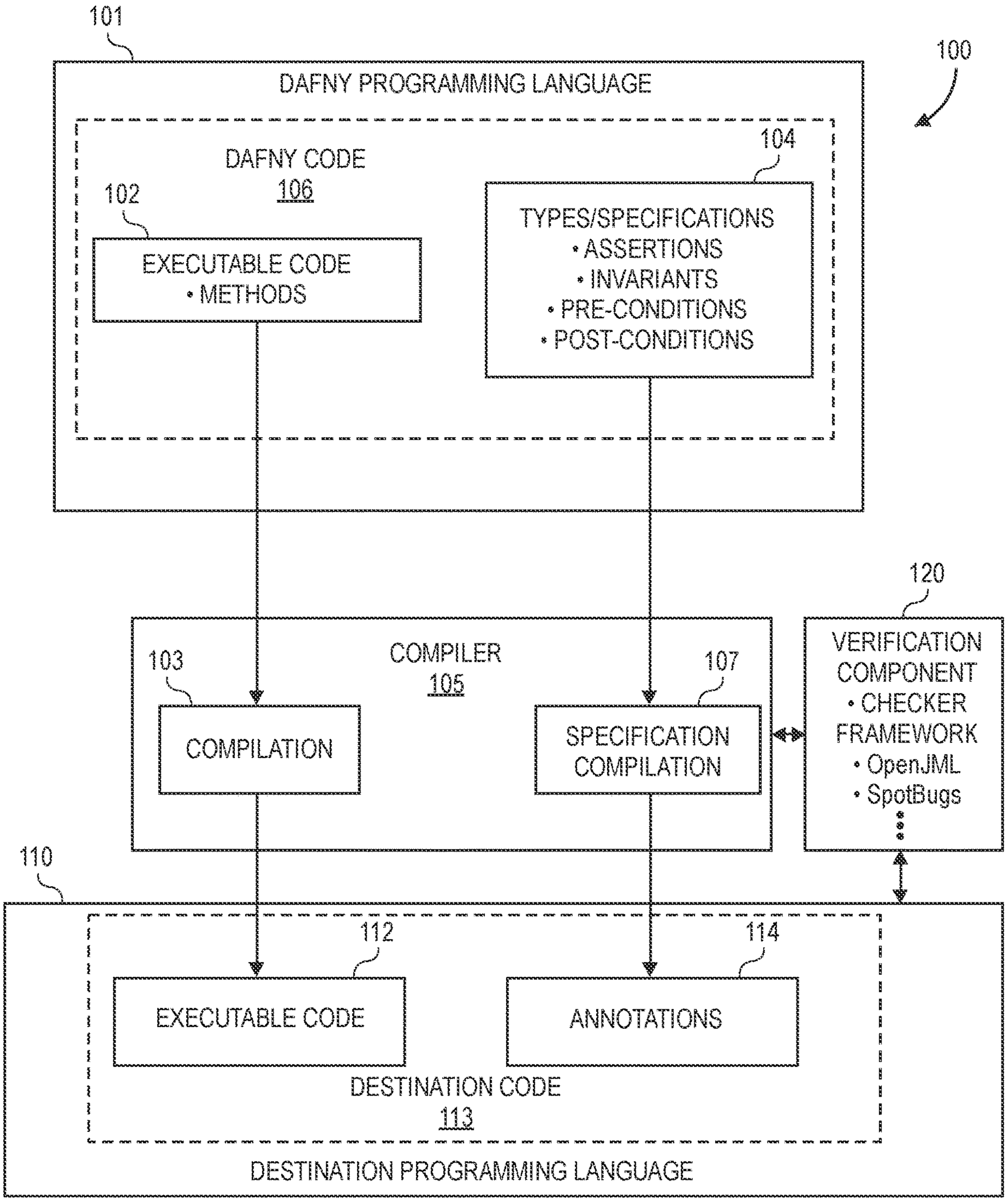

101
100
DAFNY PROGRAMMING LANGUAGE
DAFNY CODE
106
102
EXECUTABLE CODE
• METHODS
104
TYPES/SPECIFICATIONS
• ASSERTIONS
• INVARIANTS
• PRE-CONDITIONS
• POST-CONDITIONS
120
VERIFICATION COMPONENT
• CHECKER FRAMEWORK
• OpenJML
• SpotBugs
COMPILER
105
103
COMPILATION
107
SPECIFICATION COMPILATION
110
112
EXECUTABLE CODE
114
ANNOTATIONS
DESTINATION CODE
113
DESTINATION PROGRAMMING LANGUAGE

FIG. 1

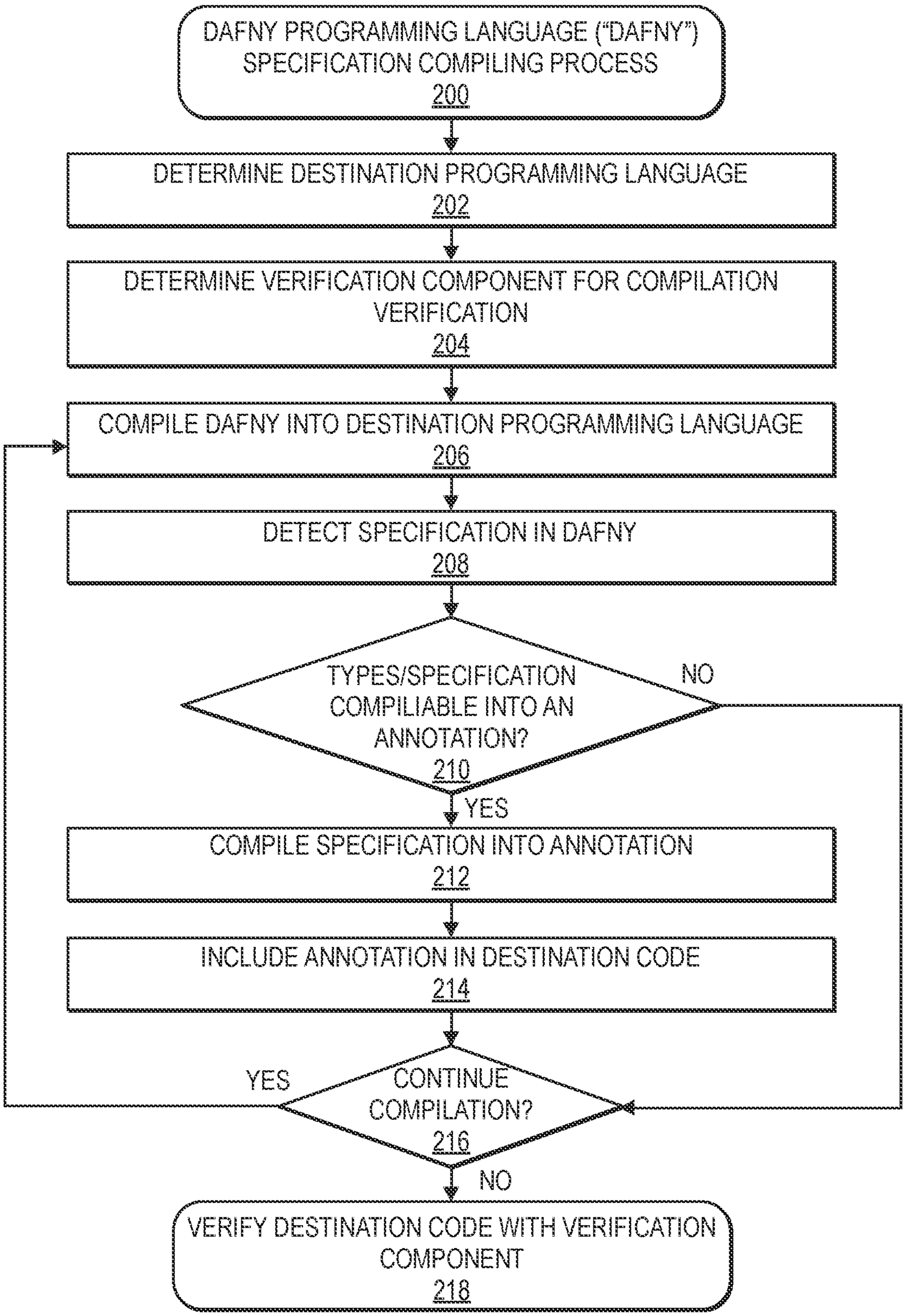

DAFNY PROGRAMMING LANGUAGE ("DAFNY") SPECIFICATION COMPILING PROCESS
200
DETERMINE DESTINATION PROGRAMMING LANGUAGE
202
DETERMINE VERIFICATION COMPONENT FOR COMPILATION VERIFICATION
204
COMPILE DAFNY INTO DESTINATION PROGRAMMING LANGUAGE
206
DETECT SPECIFICATION IN DAFNY
208
TYPES/SPECIFICATION COMPILIABLE INTO AN ANNOTATION?
210
NO
YES
COMPILE SPECIFICATION INTO ANNOTATION
212
INCLUDE ANNOTATION IN DESTINATION CODE
214
CONTINUE COMPILATION?
216
YES
NO
VERIFY DESTINATION CODE WITH VERIFICATION COMPONENT
218

FIG. 2

310

DAFNY CODE

```
module Option {
  datatype T<U> = Some(x: U) | None
}
// Model of a java.util.Map
module {:extern} Map {
  import opened Option
  datatype T = Map(x: map<string, Option.T<string>>){
    function method {:extern} get(key: string): Option.T<string>
  }
}
// Model of a java.lang.String
module {:extern} String {
  function method {:extern} toUpperCase(s: string): string
}
module Test {
  import opened Map
  import opened Option
  import opened String
  method foo(input: Map.T) {
    var v := input.get("abc");
    match v {
      case Some(val) => print String.toUpperCase(val);
      case None => print "Got null from input at \"abc\" ";
      }
    }
  }
}
```

320 301 321 302 303

FIG. 3

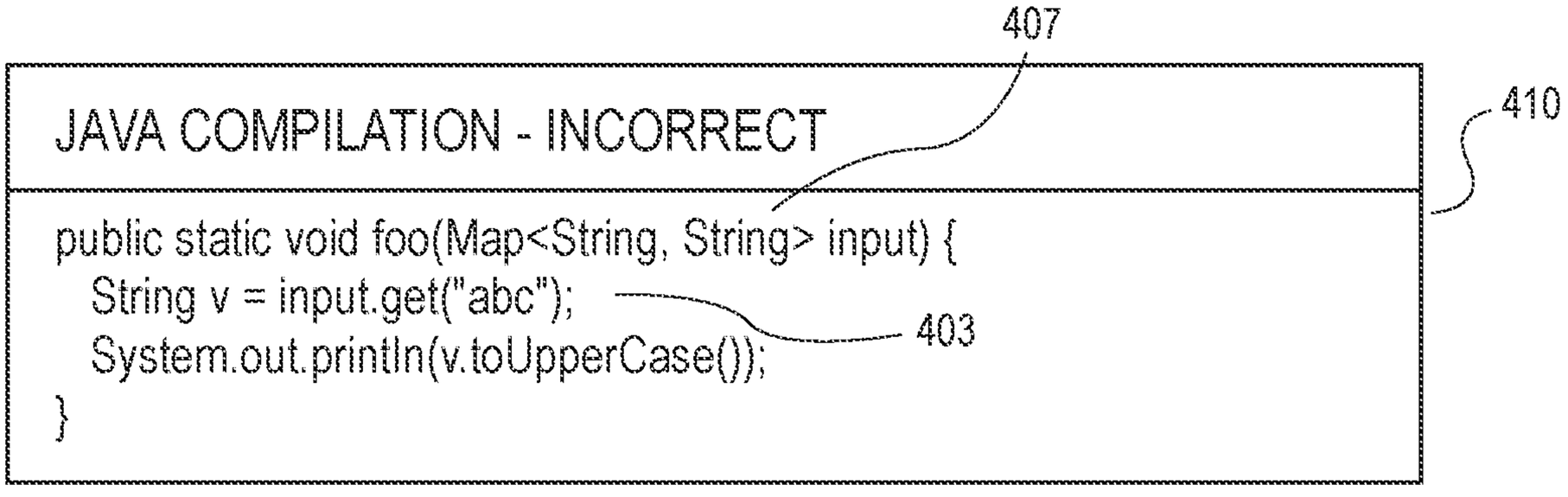


FIG. 4

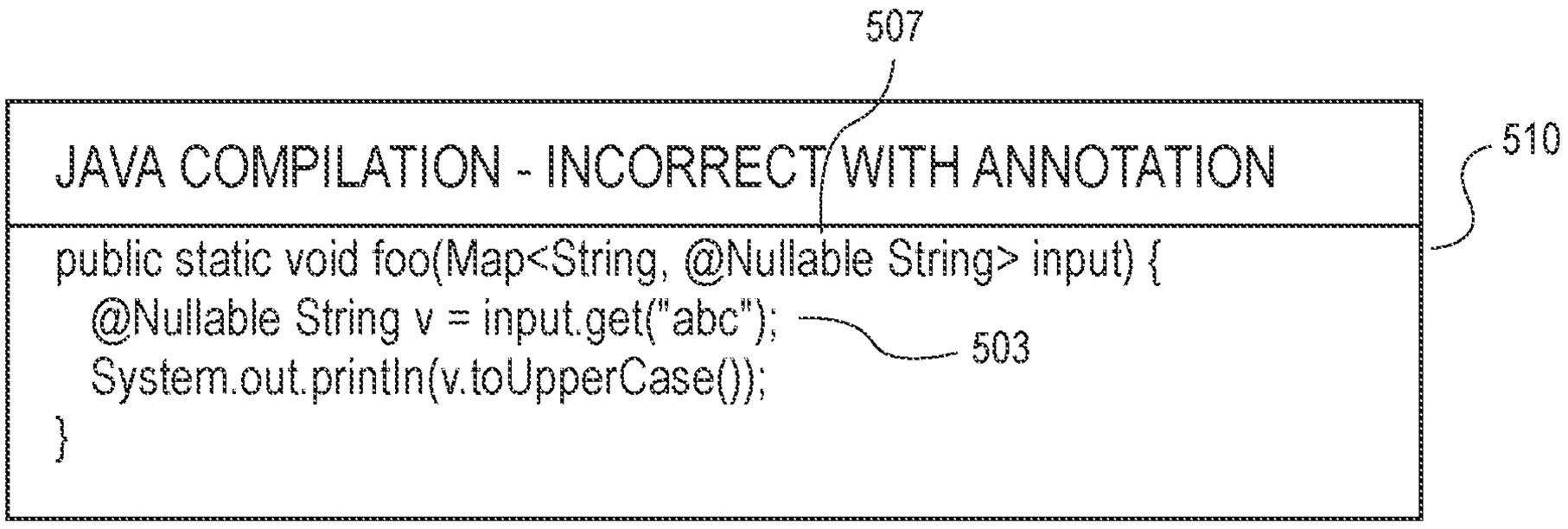


FIG. 5

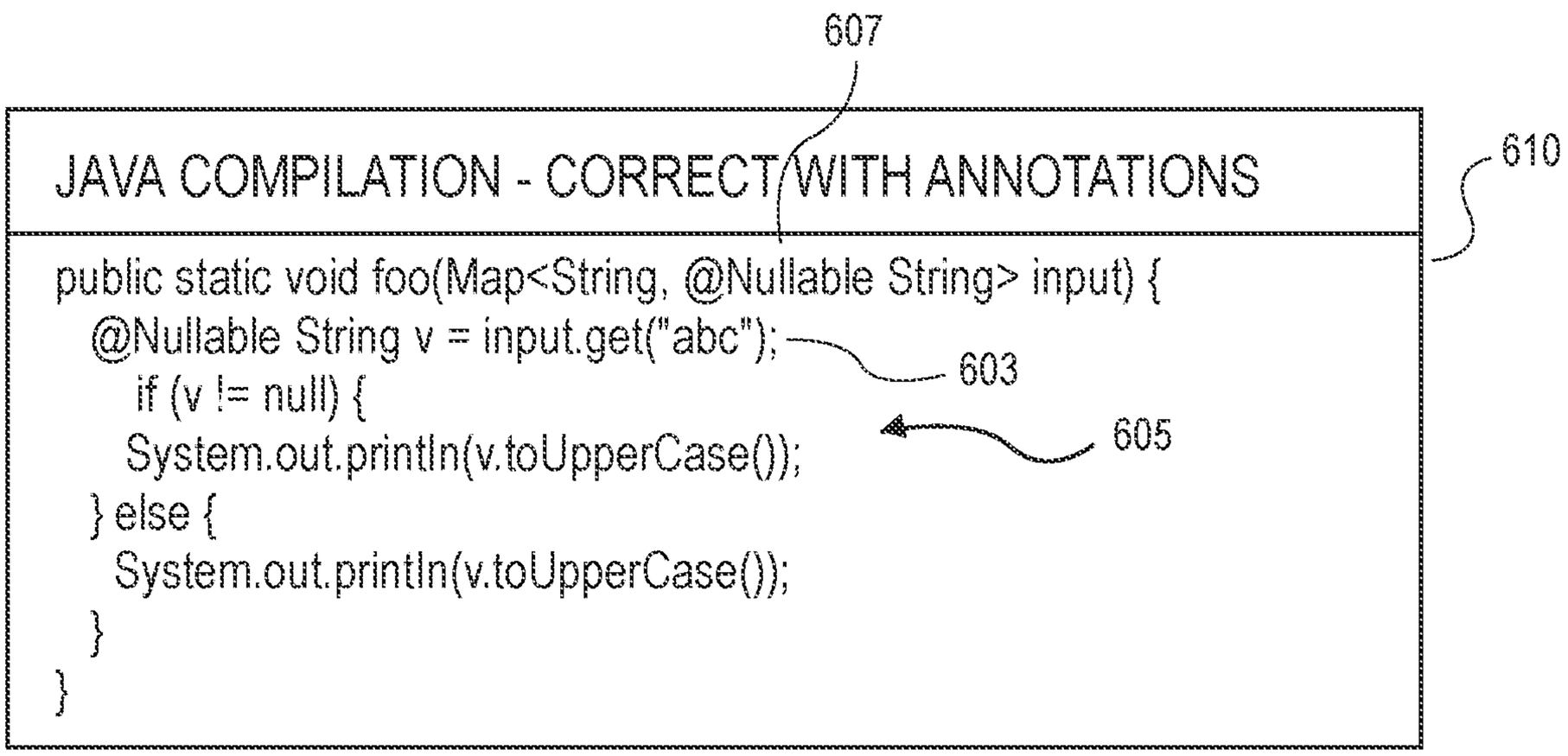


FIG. 6

710

DAFNY CODE

720

```
method getValueMethod(key: string, context: map<string, bool>) returns (reg: bool)
  requires key in context
{
  return context[key];
}
```

701

FIG. 7

810

JAVA COMPILATION - WITHOUT ANNOTATION

```
static boolean getValue(String key, Map<String, Boolean> context) {
    return context.get(key);
}
```

803

FIG. 8

910

JAVA COMPILATION - WITH ANNOTATION

```
static boolean getValue(String key, Map<String, Boolean> context) {
    assert context.get(key) != null : "@AssumeAssertion(nullness)";
    return context.get(key);
}
```

903

905-1

905-2

FIG. 9

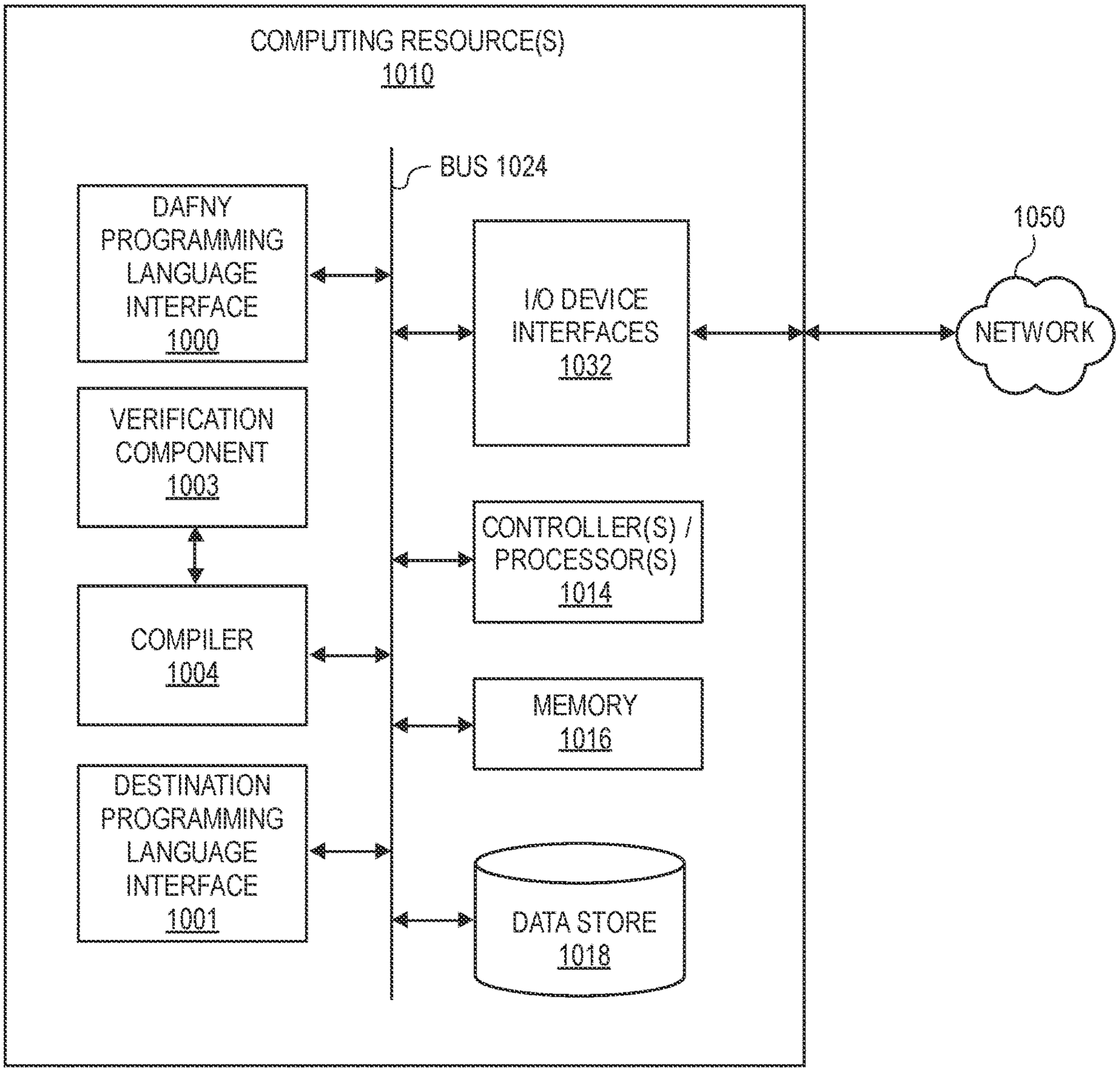

COMPUTING RESOURCE(S)
1010
BUS 1024
DAFNY PROGRAMMING LANGUAGE INTERFACE
1000
VERIFICATION COMPONENT
1003
COMPILER
1004
DESTINATION PROGRAMMING LANGUAGE INTERFACE
1001
I/O DEVICE INTERFACES
1032
CONTROLLER(S) / PROCESSOR(S)
1014
MEMORY
1016
DATA STORE
1018
1050
NETWORK

FIG. 10

RETAINING DAFNY SPECIFICATIONS

BACKGROUND

Dafny is a computer programming language with a built-in static program verifier. Developing programs in Dafny allows developers to prove the absence of errors, such as null-pointer errors, out-of-bound exceptions, and non-terminating loops. For example, developers can include specifications in the Dafny code that state one or more assertions, invariants, pre-conditions, and/or post-conditions. However, when compiling Dafny code into a code written in the destination program language, such as Java, the information indicated in the specifications is lost. As a result, there is currently no way to ensure that the compiler, in compiling the Dafny code into code written in the destination program language, has not introduced an error into the code written in the destination programming language.

BRIEF DESCRIPTION OF THE FIGURES

FIG. **1** is a block diagram of an environment for compiling code written in a Dafny programming language to code written in a destination programming language, with Dafny specifications being compiled into annotations in the destination programming language, in accordance with disclosed implementations.

FIG. **2** is an example Dafny programming language specification compiling process, in accordance with disclosed implementations.

FIG. **3** is an example code written in the Dafny programming language.

FIG. **4** is an example code in a destination programming language resultant from an incorrect compilation of the Dafny code of FIG. **3**.

FIG. **5** is an example code in the destination programming language with annotations compiled from types of the Dafny code of FIG. **3**, in accordance with disclosed implementations.

FIG. **6** is another example code in the destination programming language with annotations compiled from the types of the Dafny code of FIG. **3**, in accordance with the disclosed implementations.

FIG. **7** is another example code written in the Dafny programming language.

FIG. **8** is an example code in a destination programming language resultant from a traditional compilation of the Dafny code of FIG. **7**.

FIG. **9** is another example code in the destination programming language with annotations compiled from the specifications of the Dafny code of FIG. **7**, in accordance with the disclosed implementations.

FIG. **10** is a block diagram of an example computing resource, in accordance with disclosed implementations.

DETAILED DESCRIPTION

Disclosed are systems and methods that determine specification portions of Dafny code ("Dafny code") and compile those specifications into annotations, expressions, comments, and/or assertions that are included in a code written in a destination language ("destination code") as part of a compilation of the Dafny code into the destination code. A "specification" of the Dafny code that may be compiled into annotations, assertions, comments, and/or expressions in a destination programming language may include types, specifications, and/or any other portion of Dafny code that

is not compilable into executable code in the destination programming language. Accordingly, a specification may include a pre-condition, a post-condition, an invariant, an assertion, or a type. The annotations, assertions, comments, and/or expressions in the destination code may be utilized by a verification component, such as a Checker Framework, Open Java Modeling Component ("OpenJML"), a SpotBugs component, etc., to detect errors that are introduced into the destination code by the compiler as part of the compilation or verify the absence of errors in the destination code.

While the discussion herein refers to the compilation of Dafny specifications into annotations in a destination programming language, it will be understood the disclosed implementations may also be utilized to compile Dafny specifications into assertions, expressions, comments, or any combination of annotations, assertions, comments, and expressions in a destination programming language. The use of annotations throughout the specification is to simplify discussions and is not to be considered as limiting.

As discussed further below, annotations provide extra information about types, such as knowing whether or not the type can be nullable to prevent null-pointer error, or determining all possible values of a variable to prevent out-of-bound exceptions. These annotations provide idiomatic code that includes more information and readability to the generated destination code when viewed by a human developer and also provide an automated way for a verification component to verify the destination code. For example, the annotations may be used by a verification component to verify whether a null-pointer error exists in the destination code, whether a constant value error exists in the destination code, whether an arithmetic overflow error exists in the destination code, whether an out-of-bounds error exists in the destination code, whether unsafe signedness operations exist in the destination code, whether unsafe downcasting operations exist in the destination code, whether security errors exist in the destination code, whether an invalid regular expressions exist in the destination code, etc.

FIG. **1** is a block diagram of an environment **100** for compiling Dafny code **106** written in the Dafny programming language **101** to a destination code **113** written in a destination programming language **110**, with Dafny specifications **104** being compiled into annotations **114**, in accordance with disclosed implementations.

Like many programming languages, Dafny code **106** includes methods, variables, types, loops, if statements, arrays, integers, etc. A method is a piece of imperative, executable code **102** and the body of the method is code contained within braces. As with all code, the body includes a series of statements, such as imperative assignments, if statements, loops, etc. While such methods are common among programming languages, Dafny diverges from other languages with the use of types/specifications **104**, collectively referred to herein as specifications. Specifications provide a developer the ability to specify, in a more natural language, the intent of a method with a combination of assertions, invariants, pre-conditions, and post-conditions. Dafny uses those specifications to verify that the method executes as intended by the developer.

Rather than discard specifications **104** included in the Dafny code **106** when compiling the Dafny code **106** into a destination code **113** written in a destination programing language **110**, as is done by existing compilers, the disclosed implementations identify the specifications **104** and convert those specifications **104** into annotations **114** that are included in the destination code **113** and usable by a verification component **120** to verify the destination code **113**.

For example, and in accordance with the disclosed implementations, when compiling **103** Dafny code **106**, using a compiler **105**, into destination code **113** written in a destination programming language **110**, such as Java, rather than discarding the specifications **104** included in the Dafny code **106**, additional analysis may be performed. In some implementations, the compiler **105** may be extended to include a specification compilation component **107** that detects the specification(s) **104** included in the Dafny code **106** and compiles those specifications **104** into annotations **114** that may be included in the destination code **113** along with the executable code **112**. For example, the specification compilation component **107** may understand the Dafny programming language **101**, the destination programming language **110**, and a verification component **120**, such as a Checker Framework, OpenJML, SpotBugs, etc., that interfaces with the compiler **105** to verify the resultant destination code. Utilizing that understanding of the Dafny programming language **101**, the destination programming language **110**, and the verification component **120**, the specification compilation component **107**, as discussed further below, may identify specifications in the Dafny programming language **101** and compile those specifications into annotations **114**, expressions and/or assertions, that are included in the destination code **113** and that are usable by the verification component **120**.

While the example illustrated in FIG. **1** indicates that the specification compilation component **107** that compiles the specification(s) **104** from the Dafny code **106** to annotations **114** in the destination code **113** is an extension of the compiler **105**, in other implementations the specification compilation component **107** may be separate and/or independent of the compiler **105**. For example, the compiler **105** may process the executable code within the Dafny code **106** to generate the executable code **112** within the destination code **113** and the specification compilation component **107** may further process the Dafny code **106** to identify and compile specifications **104** of the Dafny code **106** into annotations **114** that are included in the destination code **113**.

By retaining information included in the specification(s) **104** of the Dafny code **106** as annotations **114** in the destination code **113**, the verification component **120** is able to utilize those annotations to determine, at compile time, the presence of an error in the destination code **113** that was introduced by the compiler **105** or verify the absence of the error from the destination code **113**. As a result, the disclosed implementations provide a technical improvement of improving the operation of a computing system by enabling the ability to verify the accuracy of compiled code that is compiled from the Dafny programming language **101** to a destination programming language **110** at compile time so that the destination code **113** does not fail at runtime.

FIG. **2** is an example Dafny programming language specification compilation process **200**, in accordance with disclosed implementations.

The example process **200** begins by determining a destination programming language to which the Dafny code is to be compiled, as in **202**. Any of a variety of programming languages may be the destination programming language. For example, the destination programming language may be, but is not limited to, Java, .NET, Go, JavaScript, C#, etc.

In addition to determining the destination programming language, the verification component that will be used to verify the compiled destination code is also determined, as in **204**. As is known, verification components, or compiler plug-ins, such as Checker Framework, OpenJML, SpotBugs, etc., may be used during programming at compile time to check code for errors or to verify the absence of errors. For example, Checker Framework may process annotations in Java code to determine if a null-pointer error exists in the code or to verify that a null-pointer error does not exist in the code, to determine if a constant value error exists in the code or to verify that a constant value error does not exist in the code, to determine if an arithmetic overflow error exists in the code or to verify that an arithmetic overflow error does not exist in the code, to determine if an out-of-bounds error exists in the code or to verify that an out-of-bounds error does not exist in the code, to determine if an unsafe signedness operation exists in the code or to verify that an unsafe signedness operation does not exist in the code, to determine if a security error exists in the code or to verify that a security error does not exist in the code, to determine if an invalid regular expression exists in the code or to verify that an invalid regular expression does not exist in the code, etc.

Dafny code may then be compiled into the destination programming language, as in **206**. As part of the compilation, the Dafny code is also processed to detect a specification included in the Dafny code, as in **208**. For example, the example process **200** may process the abstract syntax tree ("AST") of the Dafny code to determine portions of the Dafny code that are specifications. For example, the AST may be processed to identify particular terms (e.g., requires, ensures, invariant, etc.), symbols, phrases, etc., that correspond to or otherwise identify specifications in the Dafny code.

Upon detection of a specification included in the Dafny code, a determination is made as to whether the specification is compilable into an annotation that can be included in the destination code and usable by the verification component, as in **210**. In some examples, not all specifications may be compilable into an annotation, expression, comment, and/or assertion. In other implementations, all specifications of a Dafny code may be compiled into annotations, expressions, comments, and/or assertions.

If it is determined that the specification is compilable into an annotation, expression, comment, and/or assertion, the specification is compiled into an annotation, expression, comment, and/or assertion that can be utilized by the verification component to verify the destination code, as in **212**, and the annotation, expression, comment, and/or assertion is included into the destination code, as in **214**. For example, the annotation, expression, comment, and/or assertion may be included in the destination code at a position corresponding to the portion of the code that is to be verified by the verification component using the annotation, expression, comment, and/or assertion.

Upon generation and inclusion of the annotation, expression, comment, and/or assertion in the destination code, or if it is determined that the specification is not compilable into an annotation, expression, comment, and/or assertion that can be utilized by the verification component, a determination is made as to whether the example process is to continue compiling the Dafny code, as in **216**. If it is determined that compilation is to continue, the example process **200** returns to block **206** and continues. If compilation is not to continue, the compiled destination code is verified by the verification component, as in **218**. For example, the verification component may verify the destination code based on the annotations, expressions, comment, and/or assertions included in the destination code to determine if an error exists in the code that was introduced by the compiler as part of the compilation or to verify that an error does not exist in the destination code.

FIG. **3** is an example Dafny code **310** written in the Dafny programming language.

In the example Dafny code **310**, the code includes a module 'Test' **320** that includes a method **321** 'foo(input: Map.T)' with a body that defines a variable as 'var v:=input.get("abc")' and a 'match v' **301** case that includes two specifications, in this example types Some and None in the lines: 'case Some(val)=>print String.toUpperCase(val)' **302** and 'case None=>print "Got null from input at \"abc\""" **303**.

Because traditional compilers do not utilize the types **302**, **303** included in the Dafny code when compiling the Dafny code **310** into a destination programming language, such as Java, the resultant destination code cannot be automatically verified as accurate because it is possible that the compiler introduced an error in the compilation.

For example, and referring to FIG. **4**, illustrated is an example code **410** in a destination programming language, in this example Java, resultant from an incorrect compilation of the Dafny code **310** of FIG. **3** using a traditional compiler.

As illustrated in FIG. **4**, the compiler that was used to compile the Dafny code **310** to the java code **410** introduced an error because the compiler did not include code generation for 'match v' **301** case of the original Dafny code **310** illustrated in FIG. **3**. In the Java code **410** the argument type is indicated as 'String' **407** and is indicated as 'String v=input.get("abc")' **403** in the variable declaration. However, at runtime, the code illustrated in FIG. **4** could result in a null value for v, which would cause the program to fail when trying to call 'null.toUpperCase( )'. For example, in the Java code **410**, 'input.get("abc")' will return 'null' if the map contains the mapping "abc"→>'null' or if the mapping does not contain the key "abc" at all.

Because the specifications included in Dafny were not considered or otherwise utilized by the traditional compiler, there is no way to automatically verify or determine the null-pointer error in the destination code **410**.

In comparison, FIG. **5** illustrates an example code **510** in the destination programming language, in this example Java, with annotations generated from specifications of the Dafny code **310** of FIG. **3**, in accordance with disclosed implementations.

In the example illustrated and discussed with respect to FIG. **5**, even though the compiler utilized to compile the Dafny code **310** (FIG. **3**) to the destination code **510** still introduced the same error as the traditional compiler that compiled the Java code **410** illustrated in FIG. **4**, the additional processing performed in accordance with the disclosed implementations includes annotations of '@Nullable String' **507** rather than 'String' **407** (FIG. **4**) in the argument and '@Nullable String v=input.get("abc")' in the declaration **503** rather than 'String v=input.get("abc")' **403** (FIG. **4**).

With the addition of the annotations **507**, **503**, a verification component, such as the Checker Framework, can automatically process the java code **510** and determine that an error was introduced by the compiler during compilation of the Dafny code **410** to the Java code **510**. For example, the Checker Framework, upon processing the Java code **510** as part of compilation, would indicate that 'AT' in the Java code **510** may be 'null.' By including the annotations, the Checker Framework can automatically verify the code, or in this example detect an error at compile time so that the Java code **510** does not fail at runtime.

FIG. **6** is another example code **610** in the destination programming language, in this example Java code, with annotations generated from the specifications of the Dafny code of FIG. **3**, in accordance with the disclosed implementations.

In comparison to the code illustrated in FIG. **4** and FIG. **5**, the code **610** illustrated in FIG. **6** is a proper compilation of the Dafny code **310** (FIG. **3**) into the Java programming language with the inclusion of annotations, in accordance with the disclosed implementations. Like the code **510** (FIG. **5**), the Java code **610** includes the annotations of '@Nullable String' **607** in the argument and '@Nullable String v=input.get("abc")' in the declaration **603**. In addition, the executable portion of the Java code **605** is a correct compilation of the Dafny code **310**. In such an example, the annotations introduced by the disclosed implementations are still beneficial because the verification component, such as Checker Framework, can still process the code **610**, based on the annotations **607**, **603**, and verify that the code **610** does not include errors.

FIG. **7** is another example code **710** written in the Dafny programming language.

In this example, the code **710** includes a pre-condition specification **701** "requires key in context," for the method **720** specifying that the method will only be run if the pre-condition specification **701** holds.

FIG. **8** is an example code **810** in the destination programming language, in this example Java, using a traditional compiler to compile the example code **710** (FIG. **7**) into the destination programming language.

As illustrated in FIG. **8**, using a traditional compiler, the pre-condition specification **701** (FIG. **7**) is not considered by the compiler and the resultant destination code **810** does not consider the pre-condition specification. For example, a traditional compiler may compile the method **720** in FIG. **7** to "static boolean getValue(String key, Map<String, Boolean>context) {return context.get(key)" **803**. Because the pre-condition specification **701** was not compiled or considered, there is no way to verify that the pre-condition will hold and the example portion **803** of destination code **810** may fail at runtime.

In comparison, FIG. **9** illustrates another example code **910** in the destination programming language, in this example Java, with an assertion **905-1** and an annotation **905-2** generated from the pre-condition specification **701** of the Dafny code **710** of FIG. **7**, in accordance with the disclosed implementations.

As illustrated in FIG. **9**, the compilation of the pre-condition specification **701** (FIG. **7**) by the disclosed implementations results in an assertion **905-1** of "assert context.get(key) !=null:" and the annotation **905-2** of @AssumeAsssertion(nullness)," both of which may be utilized by a verification component to verify that the destination code **910** does not include any errors introduced by the compiler or to determine that the destination code **910** includes an error introduced by the compiler.

FIG. **10** is a block diagram conceptually illustrating example components of computing resource(s) **1010**, such as a laptop, desktop, server, or any other type of computing resource, whether local, remote, physical, or virtual, that may be utilized with the disclosed implementations. In some implementations, the disclosed implementations may be implemented across one or more computing resources **1010**.

The computing resource(s) **1010** may include one or more controllers/processors **1014**, that may each include a central processing unit (CPU) for processing data and computer-readable instructions, and a memory **1016** for storing data and instructions. The memory **1016** may individually include volatile random-access memory (RAM), non-vola-

tile read only memory (ROM), non-volatile magnetoresistive random-access memory (MRAM) and/or other types of memory. The computing resource(s) may also include a data storage component **1018**, for storing data, code, executable code, data sets, mappings, libraries, etc. Each data storage component may individually include one or more non-volatile storage types such as magnetic storage, optical storage, solid-state storage, etc. The computing resource(s) **1010** may also be connected to removable or external non-volatile memory and/or storage (such as a removable memory card, memory key drive, networked storage, etc.), internal, and/or external networks **1050** (e.g., the Internet, cellular networks, satellite networks) through respective input/output device interfaces **1032**.

Computer instructions for operating the computing resource(s) **1010** and its various components may be executed by the respective computing resource's controller(s)/processor(s) **1014**, using the memory **1016** as temporary "working" storage. Computer instructions may be stored in a non-transitory manner in non-volatile memory **1016**, storage **1018**, and/or an external device(s). Alternatively, some or all of the executable instructions may be embedded in hardware or firmware on the respective device in addition to, or instead of software.

The computing resource(s) **1010** includes input/output device interfaces **1032**. A variety of components may be connected through the input/output device interfaces. Additionally, the computing resource(s) **1010** may include an address/data bus **1024** for conveying data among components of the respective computing resource. Each component within a computing resource **1010** may also be directly connected to other components in addition to (or instead of) being connected to other components across the bus **1024**.

The computing resources may include a Dafny programming language interface **1000** and/or a destination programming language interface **1001** to allow a programmer accessing the computing resource(s) **1010** to program in the respective language and/or access code written in Dafny and/or a destination programming language. Likewise, the computing resource(s) **1010** may include a compiler **1004** that may compile Dafny code into destination code written in the destination programming language and transform specifications in the Dafny code to annotations in the destination code that may be used by a verification component **1003** to determine any errors in the destination code or verify that the destination code does not include any errors. As noted above, in other implementations, transformation of the specifications in the Dafny code to annotations in the destination code may be performed by a transformation component that is separate from the compiler **1001**.

Finally, as discussed herein, the verification component **1003** may interact with the compiler and process the destination code at compile time to identify, based on the annotations included in the destination code, any errors in the destination code or to verify that the destination code is absent of errors.

The components of the computing resource(s) **1010**, as illustrated in FIG. **10**, are exemplary, and may be located as a stand-alone device or may be included, in whole or in part, as a component of a larger device or system.

The above aspects of the present disclosure are meant to be illustrative. They were chosen to explain the principles and application of the disclosure and are not intended to be exhaustive or to limit the disclosure. Many modifications and variations of the disclosed aspects may be apparent to those of skill in the art. Persons having ordinary skill in the field of computers, and computer programming should recognize that components and process steps described herein may be interchangeable with other components or steps, or combinations of components or steps, and still achieve the benefits and advantages of the present disclosure. Moreover, it should be apparent to one skilled in the art that the disclosure may be practiced without some, or all of the specific details and steps disclosed herein.

Moreover, with respect to the one or more methods or processes of the present disclosure shown or described herein, including but not limited to the flow charts shown in FIG. **2**, orders in which such methods or processes are presented are not intended to be construed as any limitation on the claimed inventions, and any number of the method or process steps or boxes described herein can be omitted as optional or combined in any order and/or in parallel to implement the methods or processes described herein. Also, the drawings herein are not drawn to scale.

Aspects of the disclosed system may be implemented as a computer method or as an article of manufacture such as a memory device or non-transitory computer readable storage medium. The computer readable storage medium may be readable by a computer and may comprise instructions for causing a computer or other device to perform processes described in the present disclosure. The computer readable storage media may be implemented by a volatile computer memory, non-volatile computer memory, hard drive, solid-state memory, flash drive, removable disk, and/or other media. In addition, components of one or more of the modules and engines may be implemented in firmware or hardware.

Disjunctive language such as the phrase "at least one of X, Y, or Z," or "at least one of X, Y and Z," unless specifically stated otherwise, is otherwise understood with the context as used in general to present that an item, term, etc., may be any of X, Y, or Z, or any combination thereof (e.g., X, Y, and/or Z). Thus, such disjunctive language is not generally intended to, and should not, imply that certain implementations require at least one of X, at least one of Y, or at least one of Z to each be present.

Unless otherwise explicitly stated, articles such as "a" or "an" should generally be interpreted to include one or more described items. Accordingly, phrases such as "a device configured to" or "a device operable to" are intended to include one or more recited devices. Such one or more recited devices can also be collectively configured to carry out the stated recitations. For example, "a processor configured to carry out recitations A, B and C" can include a first processor configured to carry out recitation A working in conjunction with a second processor configured to carry out recitations B and C.

Language of degree used herein, such as the terms "about," "approximately," "generally," "nearly" or "substantially" as used herein, represent a value, amount, or characteristic close to the stated value, amount, or characteristic that still performs a desired function or achieves a desired result. For example, the terms "about," "approximately," "generally," "nearly" or "substantially" may refer to an amount that is within less than 10% of, within less than 5% of, within less than 1% of, within less than 0.1% of, and within less than 0.01% of the stated amount.

Conditional language, such as, among others, "can," "could," "might," or "may," unless specifically stated otherwise, or otherwise understood within the context as used, is generally intended to convey in a permissive manner that certain implementations could include, or have the potential to include, but do not mandate or require, certain features, elements and/or steps. In a similar manner, terms such as

"include," "including" and "includes" are generally intended to mean "including, but not limited to." Thus, such conditional language is not generally intended to imply that features, elements and/or steps are in any way required for one or more implementations or that one or more implementations necessarily include logic for deciding, with or without user input or prompting, whether these features, elements and/or steps are included or are to be performed in any particular implementation.

Although the invention has been described and illustrated with respect to illustrative implementations thereof, the foregoing and various other additions and omissions may be made therein and thereto without departing from the spirit and scope of the present disclosure.

What is claimed is:

1. A method, comprising:

initiating, with a compiler, a compiling of a first code written in a Dafny programming language to a second code written in a Java programming language;

detecting, as part of the compiling, a specification included in the first code;

compiling the specification into at least one of an annotation that is understandable to a verification component, an expression that is understandable to the verification component, a comment that is understandable to the verification component, or an assertion that is understandable to the verification component;

including the at least one of the annotation, the expression, the comment, or the assertion in the second code; and

verifying, with the verification component, the second code, wherein the verification component utilizes the at least one of the annotation, the expression, the comment, or the assertion to verify at least a portion of the second code.

2. The method of claim **1**, wherein the verification component is at least one of a Checker Framework, an Open Java Modeling Component ("OpenJML"), or SpotBugs.

3. The method of claim **1**, wherein verifying includes at least one of:

detecting a presence of an error in the second code; or

verifying an absence of the error in the second code.

4. The method of claim **3**, wherein the error is at least one of a null-pointer error, a constant value error, an arithmetic overflow error, an out-of-bounds error, an unsafe signedness operation, an unsafe downcasting operation, a security error, or an invalid regular expression.

5. The method of claim **3**, wherein the error is introduced as part of the compilation of the first code written in the Dafny programming language into the second code written in the Java programming language.

6. A computing system, comprising:

one or more processors; and

a memory storing program instructions that, when executed by the one or more processors, cause the one or more processors to at least:

initiate, with a compiler, a compiling of a first code written in a Dafny programming language to a second code written in a destination programming language;

detect, as part of the compiling, a specification included in the first code;

compile the specification into at least one of an annotation that is understandable to a verification component, an expression that is understandable to the verification component, a comment that is understandable to the verification component, or an assertion that is understandable to the verification component;

include the at least one of the annotation, the expression, the comment, or the assertion in the second code; and

verify, with the verification component, the second code, wherein the verification component utilizes the at least one of the annotation, the expression, the comment, or the assertion to verify at least a portion of the second code.

7. The computing system of claim **6**, wherein the destination programming language is at least one of Java, .NET, Go, JavaScript, or C#.

8. The computing system of claim **6**, wherein the specification includes a portion of the first code written in the Dafny programming language that is not compilable into an executable code in the destination programming language.

9. The computing system of claim **6**, wherein the specification is at least one of a pre-condition, a post-condition, an invariant, an assertion, or a type.

10. The computing system of claim **6**, wherein the second code and the at least one of the annotation, the expression, the comment, or the assertion are idiomatic such that the second code and the at least one of the annotation, the expression, the comment, or the assertion can be read by a human or the verification component.

11. The computing system of claim **6**, wherein the program instructions, that when executed by the one or more processors to verify the second code, further include instructions, that when executed by the one or more processors, further cause the one or more processors to at least:

detect a presence of an error in the second code; or

verify an absence of the error in the second code.

12. The computing system of claim **11**, wherein the error is at least one of a null-pointer error, a constant value error, an arithmetic overflow error, an out-of-bounds error, an unsafe signedness operation, an unsafe downcasting operation, a security error, or an invalid regular expression.

13. The computing system of claim **11**, wherein the error is introduced as part of the compilation of the first code written in the Dafny programming language into the second code written in a Java programming language.

14. The computing system of claim **6**, wherein the verification component is at least one of a Checker Framework, an Open Java Modeling Component ("OpenJML"), or a SpotBugs component.

15. A computer-implemented method, comprising:

detecting, as part of a compiling of a first code from a first language into a second code written in a second language, a specification included in the first code;

compiling the specification into a first portion of the second code that is understandable to a verification component; and

verifying, with the verification component, the second code, wherein the verification component utilizes at least the first portion of the second code to verify whether at least a second portion of the second code includes an error.

16. The computer-implemented method of claim **15**, wherein:

the first portion is at least one of an annotation, an expression, a comment, or an assertion.

17. The computer-implemented method of claim **15**, further comprising:

initiating, with a compiler, the compiling of the first language into the second language;

wherein the first language is Dafny and the second language is Java.

18. The computer-implemented method of claim **15**, wherein the specification indicates at least one of a pre-condition, a post-condition, an invariant, an assertion, or a type.

19. The computer-implemented method of claim **15**, wherein the error is at least one of a null-pointer error, a constant value error, an arithmetic overflow error, an out-of-bounds error, an unsafe signedness operation, an unsafe downcasting operation, a security error, or an invalid regular expression.

20. The computer-implemented method of claim **15**, wherein the verification component is at least one of a Checker Framework, an Open Java Modeling Component ("OpenJML"), or a SpotBugs component.

21. A computer-implemented method, comprising:

compiling at least a portion of a first code written in a Dafny language into a second code written in a second language;

detecting, as part of the compiling, a first portion of the first code;

compiling the first portion into a second portion that is understandable to a verification component; and

verifying, with the verification component, the second code in the second language, wherein the verification component utilizes at least the second portion to verify at least a portion of the second code.

22. The computer-implemented method of claim **21**, further comprising:

including the second portion in the second code.

23. The computer-implemented method of claim **21**, wherein the first portion is a specification.

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