Code verification

CSE 403
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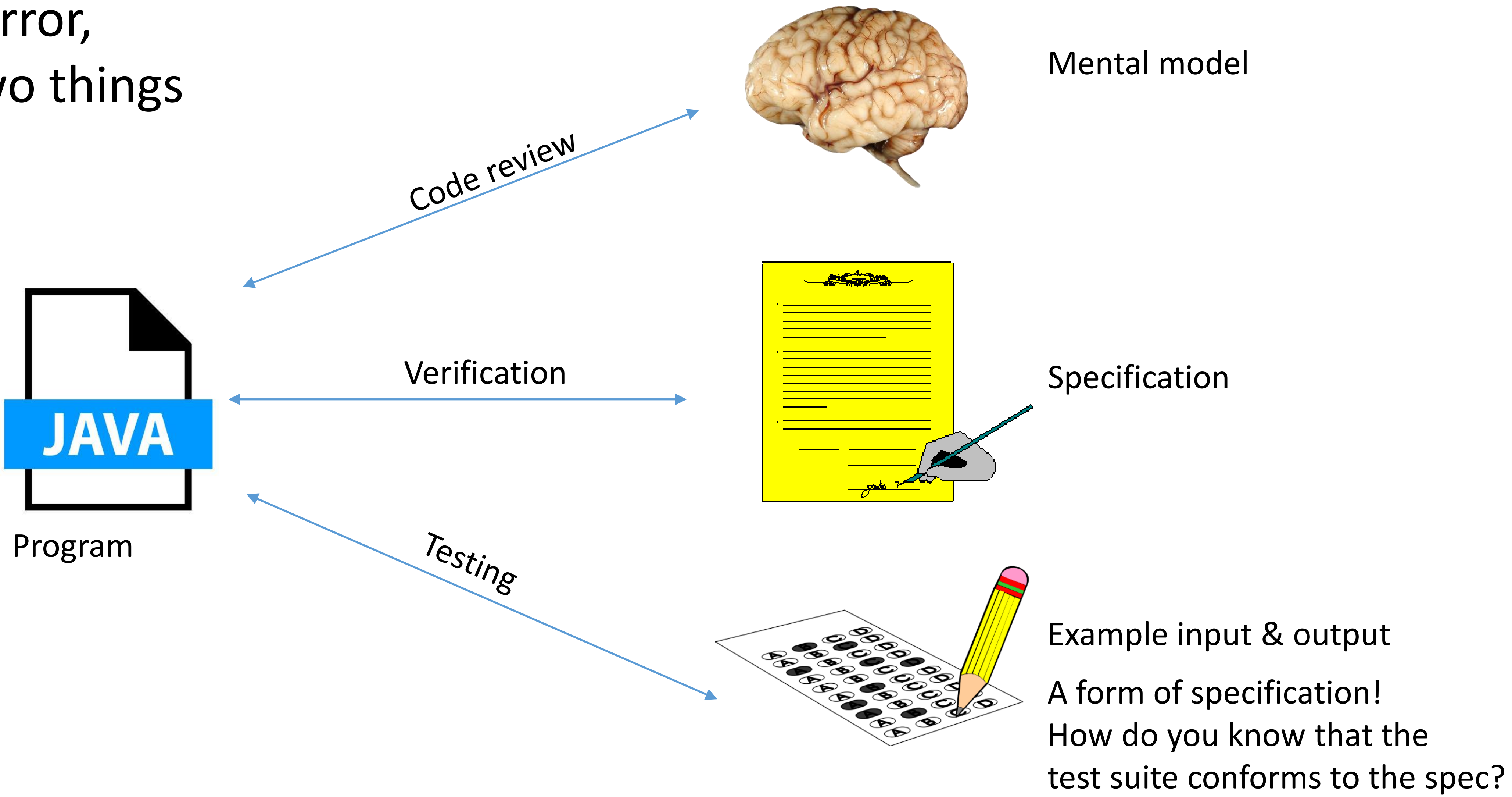
Specification and verification

To find an error,
compare two things



Comparing a program to a specification

- Every behavior exhibited by the program
  is permitted by the specification
- Dynamic analysis = run the program (e.g., testing)
- Static analysis = don't run the program (e.g., type checking)

- Problem: how to determine facts about all possible executions?
- Dynamic analysis:
- Static analysis:

Comparing a program to a specification

- Every behavior exhibited by the program
  is permitted by the specification
- Dynamic analysis = run the program (e.g., testing)
- Static analysis = don't run the program (e.g., type checking)

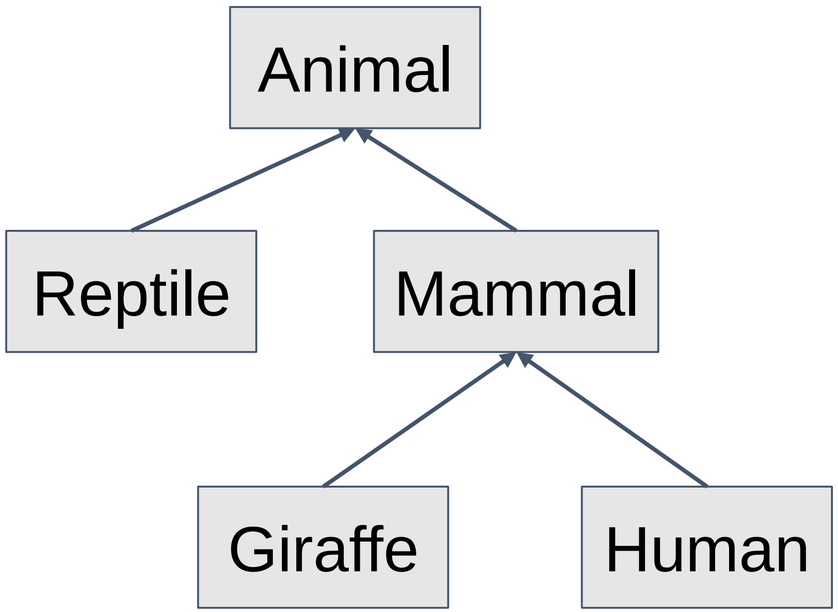
Problem: how to determine facts about all possible executions?

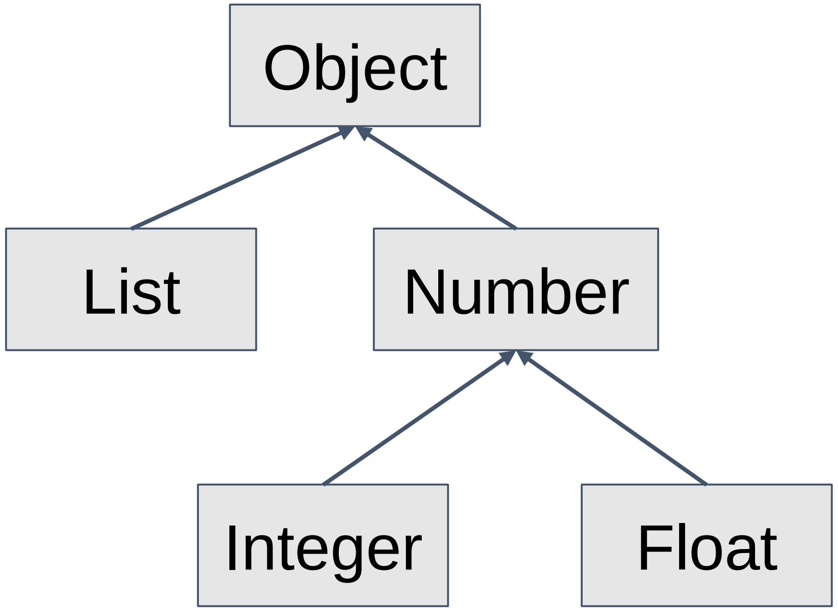
- Dynamic analysis: not possible
- Static analysis: estimate what the program might do at run time
  - Execution: consider *both* branches of a conditional
  - Values: consider the *set* of values a variable might contain

A type is a set of values

- A type is a set of values
  - `int` contains 0, 1, 2, …
  - `Integer` contains 0, 1, 2, …, null
  - `String` contains "Hello World", “UW CSE", "", null

- Some types have subset relationships





Type-checking is formal verification

- A type is a specification: what values are intended/expected
- The type-checker rejects the program
  if it cannot prove that the code meets the specification
- The type-checker does static analysis:
  - Consider all possible paths through the program
  - Consider sets of possible values for each variable
- Guarantee: the run-time value is in the set
  - The type is a trustworthy over-estimate
  - Virtual machine integrity
  - Detects/prevents programmer errors

Java's type system is too weak

Type checking prevents many errors

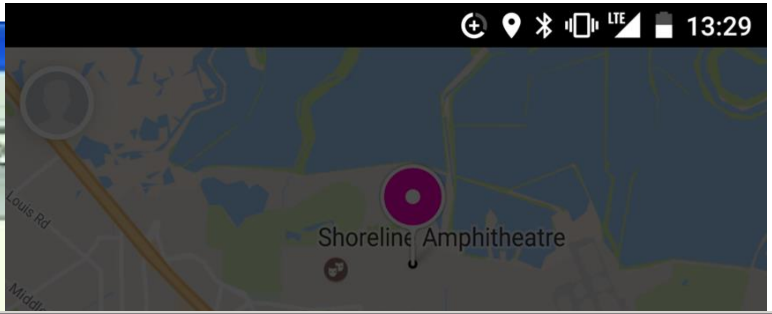
```
int i = "hello";
```

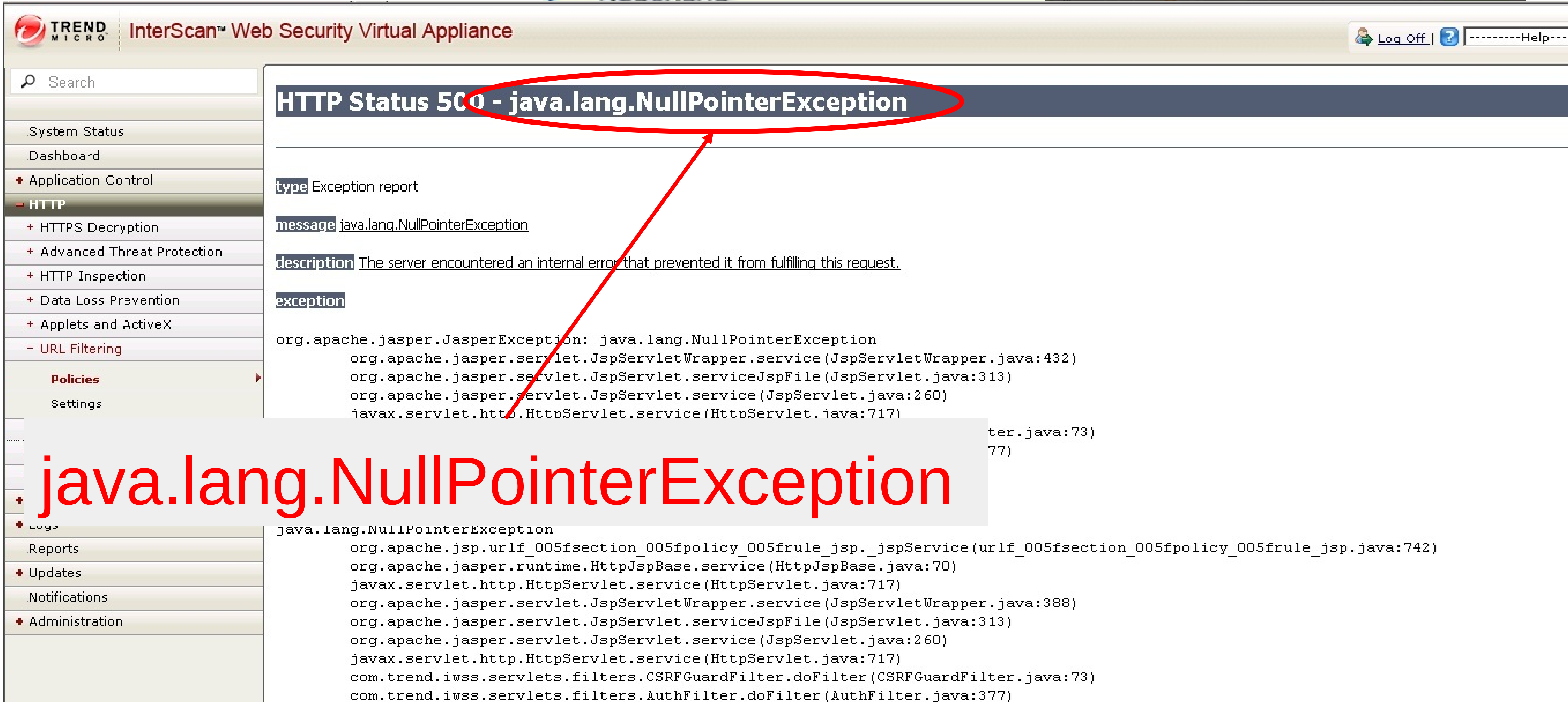
Type checking doesn't prevent enough errors

```
System.console().readLine();
```

`NullPointerException`

Motivation





java.lang.NullPointerException

Null pointer exception

Where is the defect? (Whose fault: implementer or client?)

```
String op(Data in) {
  return "transform: " + in.getF();
}
```

Library

```
String s = op(null);
```

Client

Null pointer exception

Where is the defect? (Whose fault: implementer or client?)

```
String op(Data in) {
  return "transform: " + in.getF();
}
```

Can't decide without a specification!

```
String s = op(null);
```

Specification 1: non-null parameter

```java
@NonNull Data in;
```

Type qualifier — Java basetype

Type

```java
String op(@NonNull Data in) {
  return "transform: " + in.getF();
}
```

```java
String s = op(null);
```

Specification 1: non-null parameter

```
String op(@NonNull Data in) {
  return "transform: " + in.getF();
}
```

```
@NonNull Data in;
```

Type qualifier — Java basetype — Type

```
String s = op(null);
```

Defect

Specification 2: nullable parameter

```
String op(@Nullable Data in) {
  return "transform: " + in.getF();
}

String s = op(null);
```

Specification 2: nullable parameter

```
String op(@Nullable Data in) {
  return "transform: " + in.getF();
}
```

Defect

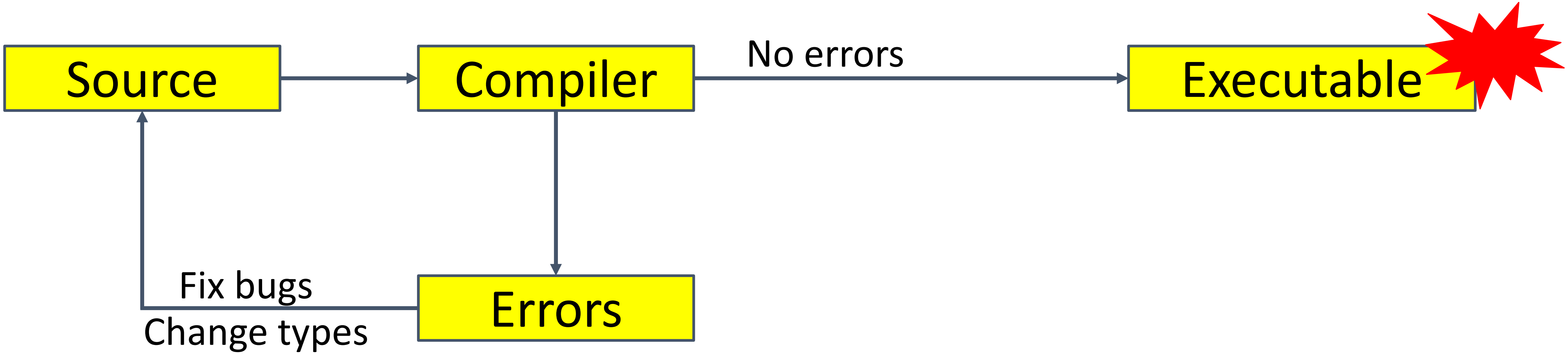
```
String s = op(null);
```

Nullness Checker demo

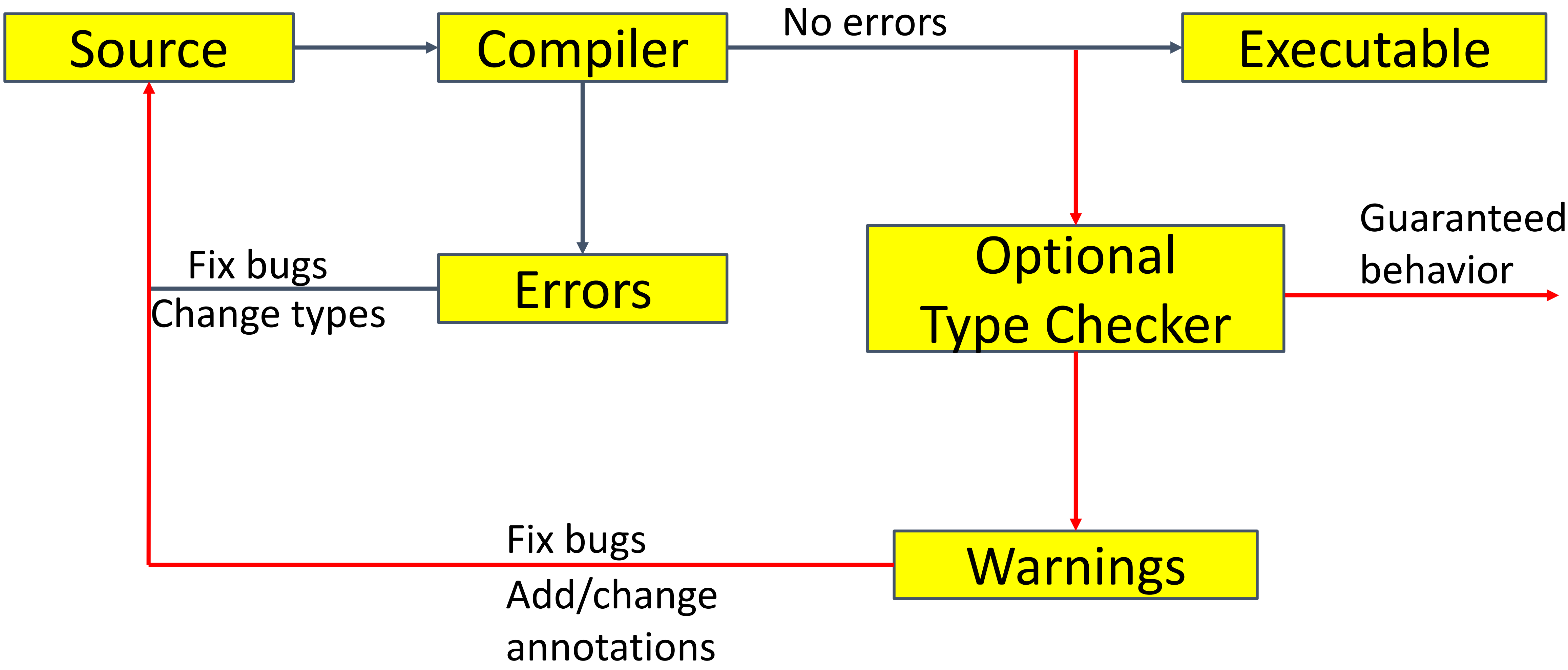
- Programs to verify:
  - The Nullness Checker
  - JUnit 4.3

- Features:
  - Detect errors
  - Guarantee the absence of errors
  - Flow-sensitive type refinement

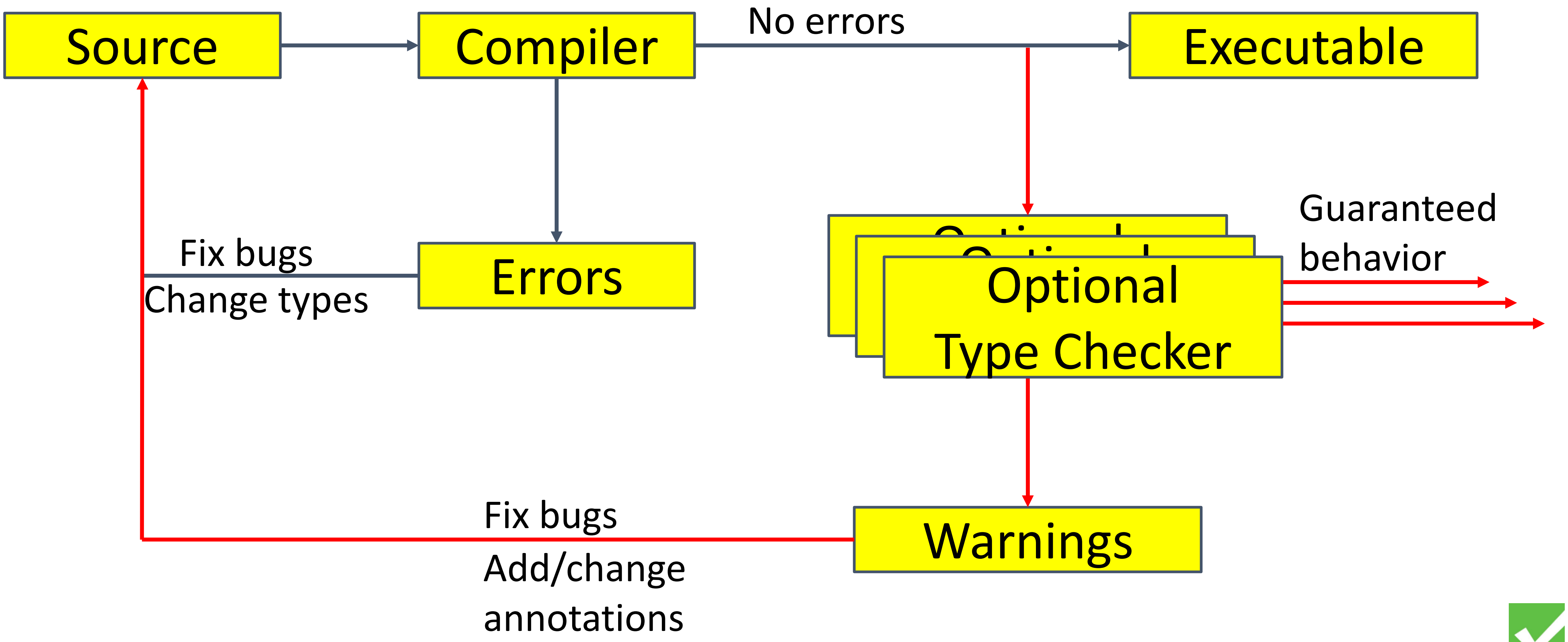
Type Checking



Optional Type Checking



Optional Type Checking



Benefits of type systems

- **Find bugs** in programs
    - Guarantee the **absence of errors**
- **Improve documentation**
    - Improve code structure & maintainability
- Aid compilers, optimizers, and analysis tools
    - E.g., could reduce number of run-time checks

- Possible negatives:
    - Must write the types (or use type inference)
    - False positives are possible (can be suppressed)

Comparison: other nullness tools

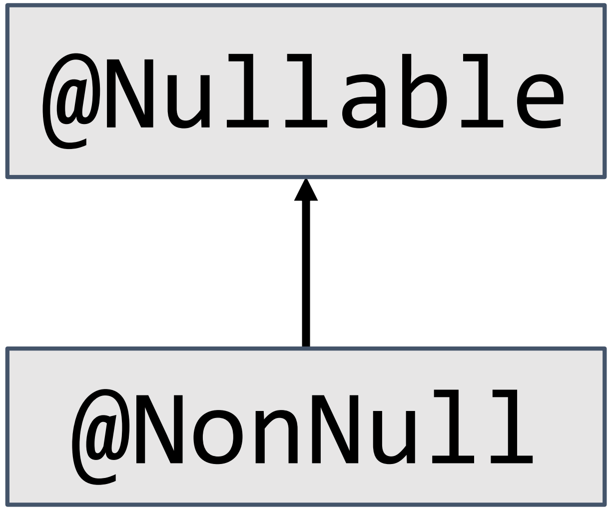
	Null pointer errors		False warnings	Annotations written
	Found	Missed		
Checker Framework	9	0	4	35
FindBugs	0	9	1	0
Jlint	0	9	8	0
PMD	0	9	0	0
Eclipse, in 2017	0	9	8	0
Intellij (@NotNull default), in 2017	0	9	1	0
	3	6	1	925 + 8

Checking the Lookup program for file system searching (4kLOC)

Preventing null-pointer exceptions

Basic type system:

- **@Nullable** might be null
- **@NonNull** definitely not null



Default is @NonNull (opposite of Java's default)

- Requires fewer annotations
- Makes the dangerous case explicit

(Nearly) no annotations in method bodies!

Needed for some type arguments, as in **List<@Nullable String>**

Flow-sensitive type refinement

```
if (myField != null) {

  myField.hashCode();
}
```

No need to declare a new local variable

One check for `null` is not enough

```
if (myField != null) {
  method1();
  myField.hashCode();
}
```

```
if (method2() != null) {
  method2().hashCode();
}
```

3 ways to express persistence across side effects:

```
@SideEffectFree void method1() { … }
@MonotonicNonNull myField;
@EnsuresNonNull("myField") method1() {…}
```

Side effects (method, not type, annotations)

`@SideEffectFree`

Does not modify externally-visible state

`@Deterministic`

If called with == args again, gives == result

`@Pure`

Both side-effect-free and deterministic

The side-effect annotations are trusted, not checked

Lazy initialization and persistence across side effects

`@MonotonicNonNull` type annotation, written on a field type

Might be null or non-null

May only be (re-)assigned a non-null value

Purpose: avoid re-checking

Once non-null, always non-null

Example: Singleton pattern

Method pre- and post-conditions

Preconditions:

`@RequiresNonNull`

Postconditions:

`@EnsuresNonNull`

`@EnsuresNonNullIf`

```
@EnsuresNonNullIf(expression="#1", result=true)
public boolean equals(@Nullable Object obj) { ... }
```

Polymorphism over qualifiers

```
/** Interns a String, and handles null. */
@PolyNull String intern(@PolyNull String a) {
  if (a == null) {
    return null;
  }
  return a.intern();
}
```

Like defining two overloaded methods:

```
  @NonNull  String intern(@NonNull  String a) {…}
  @Nullable String intern(@Nullable String a) {…}
```

A non-null field might contain `null`!

```
@NonNull String name;
MyClass() {  // constructor
 … this.name.hashCode() …
}
```

Initialization

`@Initialized` (constructor has completed)

`@UnderInitialization(Frame.class)`

Its constructor is currently executing

`@UnknownInitialization(Frame.class)`

Might be initialized or under initialization

Map keys and `Map.get`

```
Map<String, @NonNull Integer> gifts;
… gifts.get("pipers piping").intValue() …
```

`Map.get` can return null!

The Nullness Checker must treat `anyMap.get()` as `@Nullable` … unless

- the value type is non-null, **and**
- the argument key appears in the map.

Expressed with **`@NonNull`**

Need a way to express this

@KeyFor denotes a set of values

`@KeyFor("myMap") String v;` means `v` is a key in `myMap`

If `myMap` = { "red": "valor", "blue": "mystic", "yellow": "instinct" }
then `@KeyFor("myMap")` denotes the set { "red", "blue", "yellow" }
v = "red" v = "blue" ~~v = "purple"~~ ~~v = "mystic"~~ ~~v = null~~

If `myMap` = { "bert": "tall", "ernie": "short" }
then `@KeyFor("myMap")` denotes the set { "bert", "ernie" }
v = "ernie" v = "bert" ~~v = "red"~~ ~~v = "mystic"~~ ~~v = null~~

Assignments to `myMap` and v must maintain their relationship

Map key example

```
/** Computes predominators for each node in the graph. */
<T> Map<T, List<T>>
dominators(Map<T, List<@KeyFor("#1") T>> predecessors) {
  ...
  for (T node : predecessors.keySet()) {
    for (T pred : predecessors.get(node)) {   // no NPE
      ... predecessors.get(pred) ...          // no NPE
```

Suppressing warnings

Because of Nullness Checker false positives

```
if (x != null)
  // y has same nullness as x, which was just checked
  @SuppressWarnings("nullness")
  int z = y.field;
```

Write the rationale as a comment

Use smallest possible scope (e.g., local var)

```
assert x != null : "@AssumeAssertion(nullness): ...";
```

More: https://checkerframework.org/manual/#suppressing-warnings

Type-checking is modular

- Modular analysis = one procedure at a time
  - Contrast: whole-program analysis (slower, more precise)
- When analyzing a procedure, examines the specifications of callees
  - Never examines their implementation

```
void client() {
  Object k = callee();
  myMap.get(k).toString();
}
Object callee() {
  Object k = …;
  myMap.put(k, …);
  return k;
}
```

Possible Null-PointerException

```
void client() {
  Object k = callee();
  myMap.get(k).toString();
}
@KeyFor("myMap") Object callee() {
  Object k = …;
  myMap.put(k, …);
  return k;
}
```

Annotating external libraries

When type-checking clients, need library specification

The Nullness Checker comes with annotations for some libraries

For others, need to write specifications (or suppress warnings)

Two syntaxes:

- As separate text file (stub file)
- Within its .jar file (from annotated partial source code)

Checkers are usable

- Type-checking is familiar to programmers
- Modular: fast, incremental, partial programs
- Annotations are not too verbose
  - **@NonNull**: 1 per 75 lines
  - **@Interned**: 124 annotations in 220 KLOC revealed 11 bugs
  - **@Format**: 107 annotations in 2.8 MLOC revealed 104 bugs
  - Possible to annotate part of program
  - Fewer annotations in new code
- Few false positives
- First-year CS majors preferred using checkers to not
- **Practical**: in use in Silicon Valley, on Wall Street, etc.

Example type systems

Null dereferences (`@NonNull`)

- >200 errors in Google Collections, javac, ...

Equality tests (`@Interned`)

- >200 problems in Xerces, Lucene, ...

Concurrency / locking (`@GuardedBy`)

- >500 errors in BitcoinJ, Derby, Guava, Tomcat, ...

Fake enumerations / typedefs (`@Fenum`)

- problems in Swing, JabRef

String type systems

Regular expression syntax (`@Regex`)

56 errors in Apache, etc.; 200 annos required

printf format strings (`@Format`)

104 errors, only 107 annotations required

Signature format (`@FullyQualified`)

28 errors in OpenJDK, ASM, AFU

Compiler messages (`@CompilerMessageKey`)

8 wrong keys in Checker Framework

Security type systems

Command injection vulnerabilities (`@OsTrusted`)

5 missing validations in Hadoop

Information flow privacy (`@Source`)

SPARTA detected malware in Android apps

You can write your own checker!

Tips for pluggable type-checking

- Start small:
  - Start by type-checking part of your code
  - Only type-check properties that matter to you
- Use subclasses (not type qualifiers) if possible
- Write the spec first (and think of it as a spec)
- Avoid complex, unsound code
  - Avoid warning suppressions when possible
  - Avoid raw types like `List`; use `List<String>`

Verification

- **Goal**:
  prove that no bug exists
- **Specifications**:
  user provides
- **False negatives**:
  none
- **False positives**:
  user suppresses warnings
- **Downside**: user burden

Bug-finding

- **Goal**:
  find some bugs at low cost
- **Specifications**:
  infer likely specs
- **False negatives:**
  acceptable
- **False positives**:
  heuristics focus on most important bugs
- **Downside**: missed bugs

Neither is “better”; each is appropriate in certain circumstances.

Pluggable type-checking improves code

A type of formal verification:

- Write specifications
- Automatically check them

Featureful, effective, easy to use, scalable

Prevent bugs at compile time

Nullness is just one example type system

http://CheckerFramework.org/