Preventing Null Pointer Exceptions at Compile Time

http://CheckerFramework.org/

Twitter: @CheckerFrmwrk

Live demo: http://eisop.uwaterloo.ca/live

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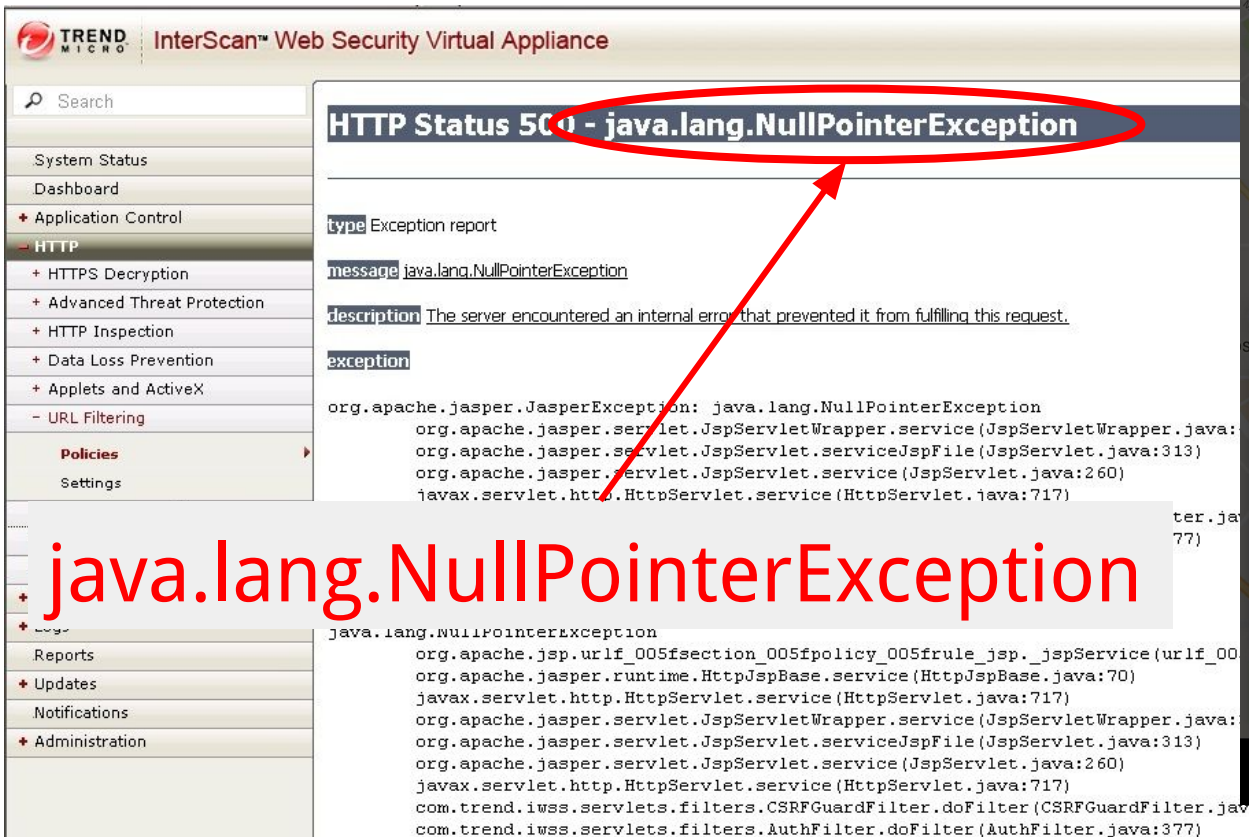
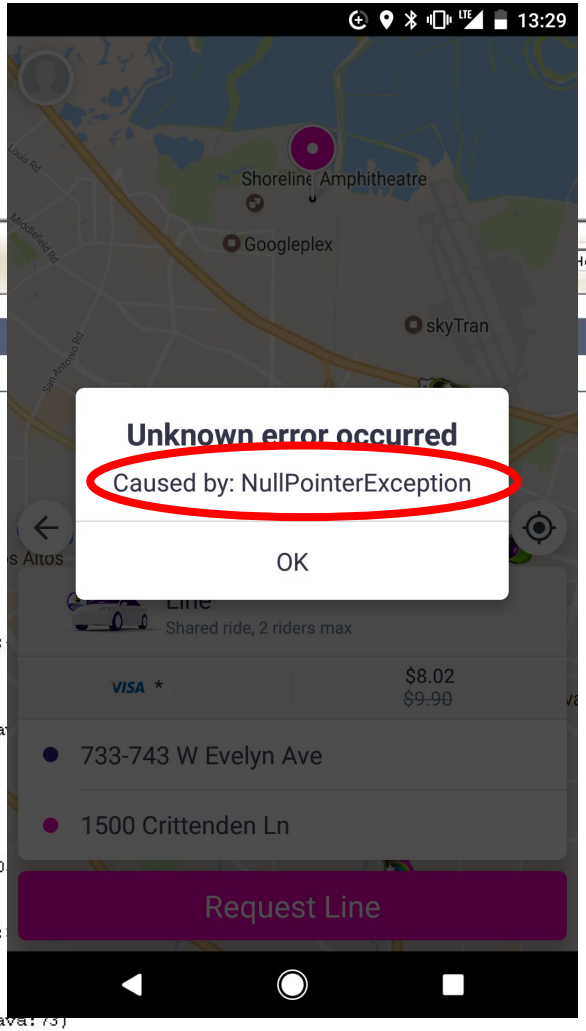
Motivation



java.lang.NullPointerException



Outline

- Solution: Pluggable type-checking
- Tool: Checker Framework
- Features and how to use them
- Advanced mechanisms

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();
```

Java's type system is too weak

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int i = "hello";
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Type checking doesn't prevent enough errors

NullPointerException

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

Prevent null pointer exceptions

Goal: the program only dereferences non-null references

Types of data:

`@NonNull`	reference is never null
`@Nullable`	reference may be null

Null pointer exception

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

Null pointer exception

Where is the defect?

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

Can’t decide without specification!

Specification 1: non-null parameter

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

Specification 1: non-null parameter

```
String op(@NonNull Data in) {
  return "transform: " + in.getF();
}
…
String s = op(null);      // error
```

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();
}                                  // error
…
String s = op(null);
```

Nullness demo

- Detect errors
- Guarantee the absence of errors

- Flow-sensitive type refinement

Solution: Pluggable Type Checking

1. Design a type system to solve a specific problem
2. Write type qualifiers in code (or, use type inference)

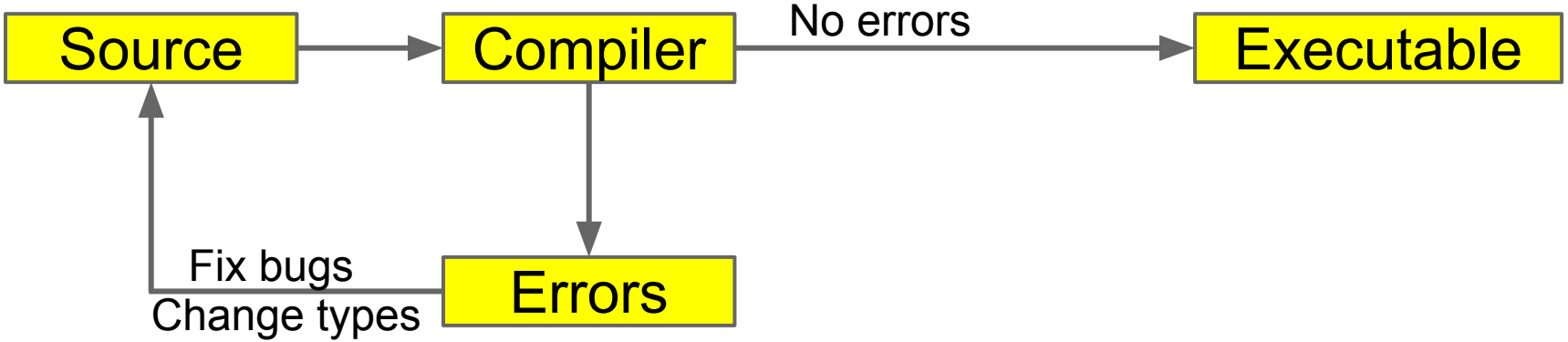
```
@Nullable Date date = ...;
date.setSeconds(0);  // compile-time error
```

3. Type checker warns about violations (bugs)

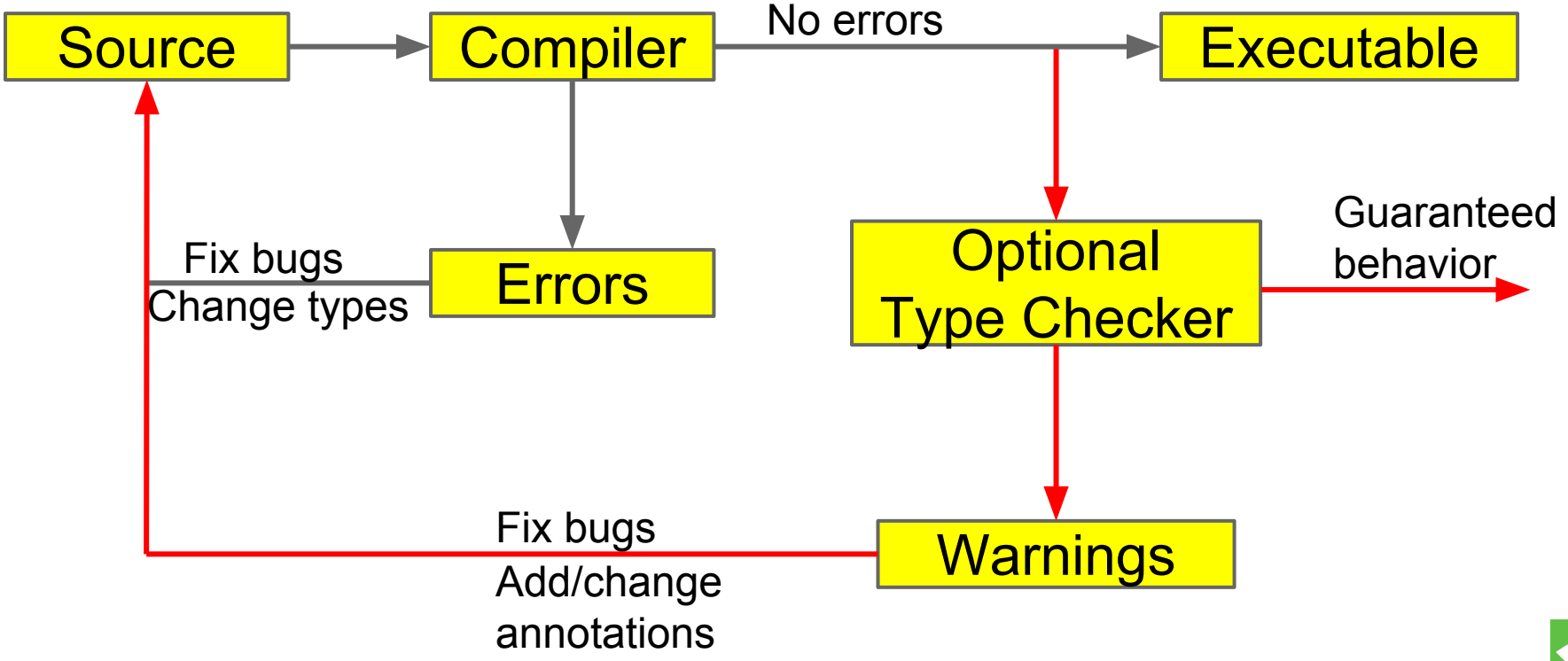
```
% javac -processor NullnessChecker MyFile.java

MyFile.java:149: dereference of possibly-null reference bb2
      allVars = bb2.vars;
                ^
```

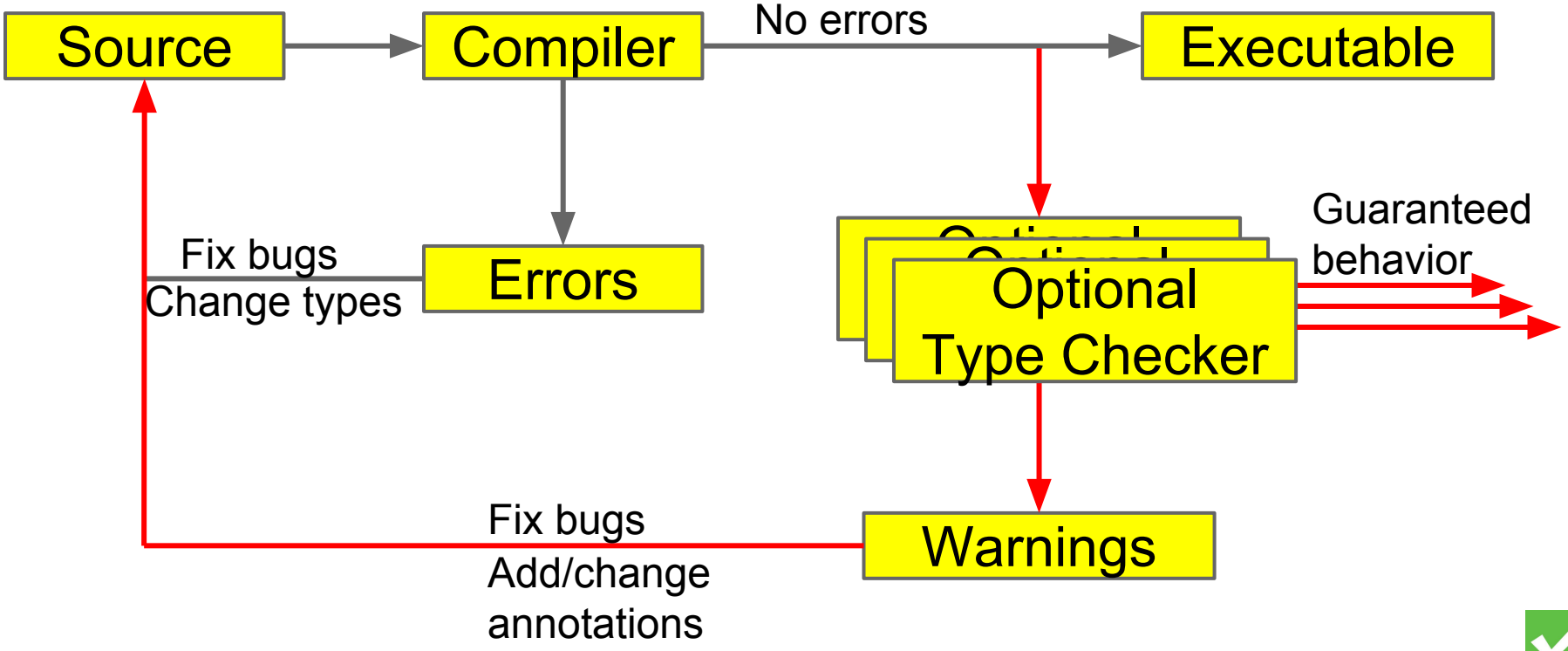
Type Checking



Optional Type Checking



Optional Type Checking



The Checker Framework

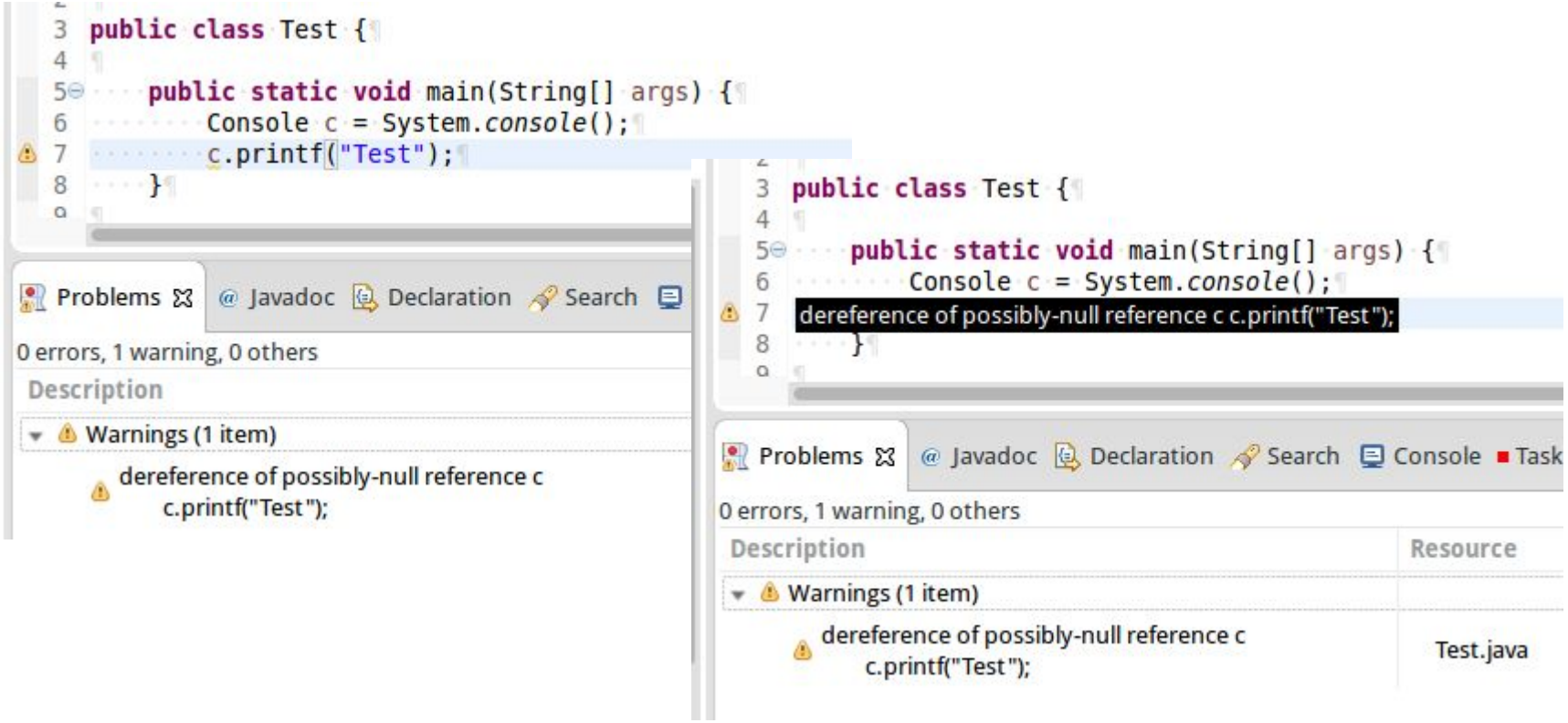
A framework for pluggable type checkers

“Plugs” into the OpenJDK or OracleJDK compiler

```
javac -processor MyChecker ...
```

Standard error format allows tool integration

Eclipse, IntelliJ, NetBeans plug-ins



Ant, Maven, Gradle integration

```
<presetdef name="jsr308.javac">
  <javac fork="yes"
    executable="${checkerframework}/checker/bin/${cfJavac}" >
    <!-- JSR-308-related compiler arguments -->
    <compilerarg value="-version"/>
    <compilerarg value="-implicit:class"/>
  </javac>
</presetdef>
```

```
<dependencies>
  ... existing <dependency> items ...
  <!-- annotations from the Checker Framework:
          nullness, interning, locking, ... -->
    <dependency>
      <groupId>org.checkerframework</groupId>
      <artifactId>checker-qual</artifactId>
      <version>1.9.7</version>
    </dependency>
</dependencies>
```

Live demo: http://eisop.uwaterloo.ca/live/

Checker Framework Live Demo

Write Java code here:

```
1  import org.checkerframework.checker.nullness.qual.Nullable;
2  class YourClassNameHere {
3      void foo(Object nn, @Nullable Object nbl) {
4          nn.toString(); // OK
5          nbl.toString(); // Error
6      }
7  }
```

Choose a type system: Nullness Checker ▼

Check

Examples:

Nullness: NullnessExample | NullnessExampleWithWarnings

MapKey: MapKeyExampleWithWarnings

Interning: InterningExample | InterningExampleWithWarnings

Lock: GuardedByExampleWithWarnings | HoldingExampleWithWarnings | EnsuresLockHeldExample | Locl

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)

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.

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)

What a checker guarantees

The program satisfies the type property. There are:

- no bugs (of particular varieties)
- no wrong annotations

- Caveat 1: only for code that is checked
  - Native methods (handles reflection!)
  - Code compiled without the pluggable type checker
  - Suppressed warnings
    - Indicates what code a human should analyze

  Checking part of a program is still useful
- Caveat 2: The checker itself might contain an error

Formalizations

$$
\begin{array}{rcll}
\mathtt{P} & \in & \text{Program} & ::= \ \overline{\mathtt{Class}},\ \mathtt{ClassId},\ \mathtt{Expr} \\
\mathtt{Cls} & \in & \text{Class} & ::= \ \mathtt{class\ ClassId}\langle\overline{\mathtt{TVarId}}\rangle \\
 & & & \quad \mathtt{extends\ ClassId}\langle\overline{{}^{\mathtt{s}}\mathtt{Type}}\rangle \\
 & & & \quad \{\ \overline{\mathtt{FieldId}\ {}^{\mathtt{s}}\mathtt{Type};}\ \overline{\mathtt{Met}} \\
{}^{\mathtt{s}}\mathtt{T} & \in & {}^{\mathtt{s}}\text{Type} & ::= \ {}^{\mathtt{s}}\mathtt{NType} \mid \mathtt{TVarId} \\
{}^{\mathtt{s}}\mathtt{N} & \in & {}^{\mathtt{s}}\text{NType} & ::= \ \mathtt{OM\ ClassId}\langle\overline{{}^{\mathtt{s}}\mathtt{Type}}\rangle \\
\mathtt{u} & \in & \text{OM} & ::= \\
\mathtt{mt} & \in & \text{Meth} & ::= \\
 & & \mathtt{MethSig} & ::= \\
\mathtt{w} & \in & \text{Purity} & ::= \\
\mathtt{e} & \in & \text{Expr} & ::= \\
 & & & \quad \mathtt{Expr.MethId}\langle{}^{\mathtt{s}}\mathtt{Type}\rangle\mathtt{(Expr)} \mid \\
 & & & \quad \mathtt{new}\ {}^{\mathtt{s}}\mathtt{Type} \mid \mathtt{(}{}^{\mathtt{s}}\mathtt{Type}\mathtt{)\ Expr} \\
{}^{\mathtt{s}}\Gamma & \in & {}^{\mathtt{s}}\text{Env} & ::= \ \overline{\mathtt{TVarId}\ {}^{\mathtt{s}}\mathtt{NType};}\ \overline{\mathtt{ParId}\ {}^{\mathtt{s}}\mathtt{Type}}
\end{array}
$$

$$
\begin{array}{rcll}
\mathtt{h} & \in & \text{Heap} & = \ \mathtt{Addr} \to \mathtt{Obj} \\
\iota & \in & \text{Addr} & = \ \text{Set of Addresses} \cup \{\mathtt{null}_a\} \\
\mathtt{o} & \in & \text{Obj} & = \ {}^{\mathtt{r}}\mathtt{Type},\ \mathtt{Fields} \\
{}^{\mathtt{r}}\mathtt{T} & \in & {}^{\mathtt{r}}\text{Type} & = \ \mathtt{OwnerAddr\ ClassId}\langle\overline{{}^{\mathtt{r}}\mathtt{Type}}\rangle \\
\mathtt{Fs} & \in & \text{Fields} & = \ \mathtt{FieldId} \to \mathtt{Addr} \\
\iota & \in & \text{OwnerAddr} & = \ \mathtt{Addr} \cup \{\mathtt{any}_a\} \\
{}^{\mathtt{r}}\Gamma & \in & {}^{\mathtt{r}}\text{Env} & = \ \overline{\mathtt{TVarId}\ {}^{\mathtt{r}}\mathtt{Type};}\ \overline{\mathtt{ParId\ Addr}}
\end{array}
$$

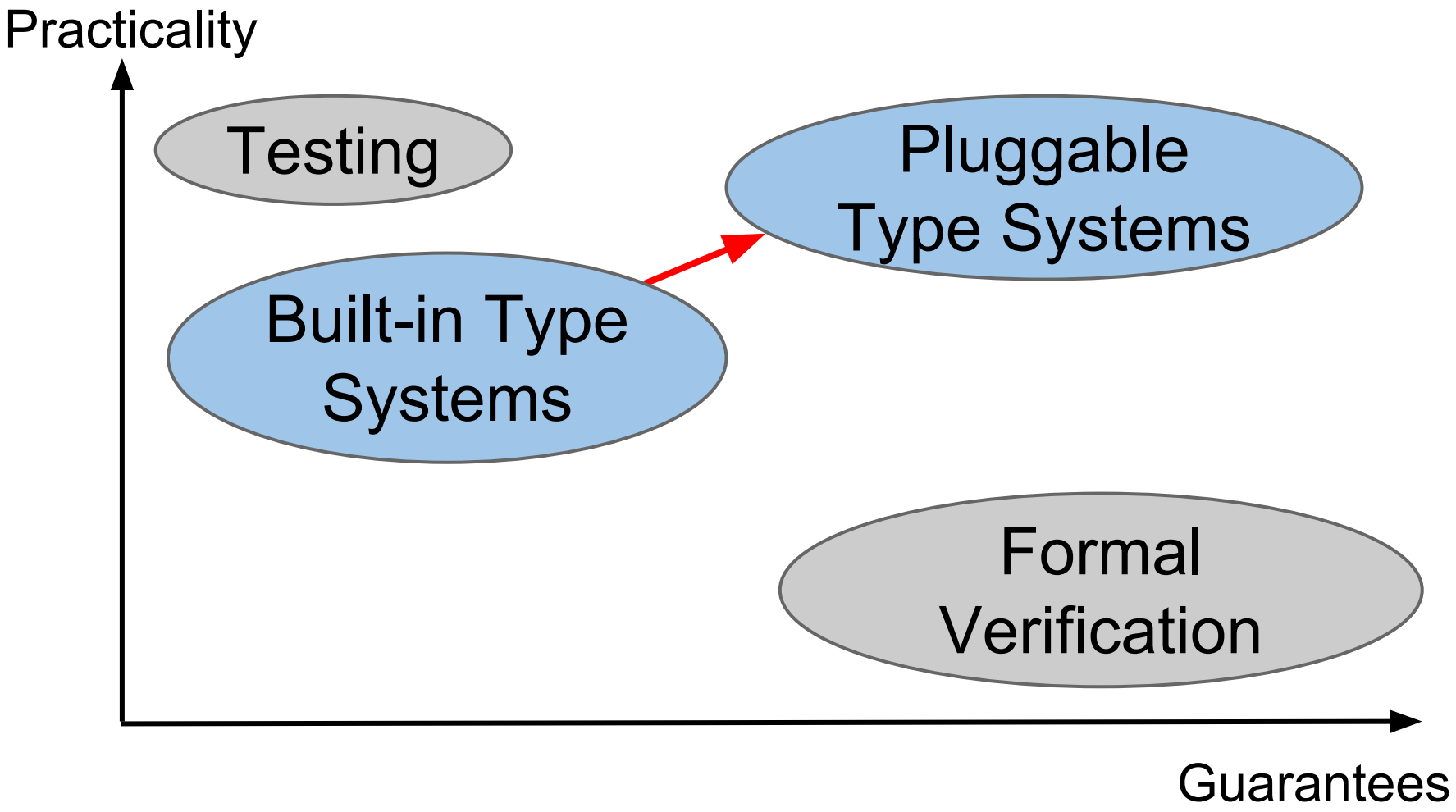
$$
\text{OS-Upd}\ \frac{\begin{array}{c}\mathtt{h}, {}^{\mathtt{r}}\Gamma, \mathtt{e}_0 \rightsquigarrow \mathtt{h}_0, \iota_0 \\ \iota_0 \neq \mathtt{null}_a \\ \mathtt{h}_0, {}^{\mathtt{r}}\Gamma, \mathtt{e}_2 \rightsquigarrow \mathtt{h}_2, \iota \\ \mathtt{h}' = \mathtt{h}_2[\iota_0.\mathtt{f} := \iota]\end{array}}{\mathtt{h}, {}^{\mathtt{r}}\Gamma, \mathtt{e}_0.\mathtt{f}{=}\mathtt{e}_2 \rightsquigarrow \mathtt{h}',}
$$

$$
\text{OS-Read}\ \frac{\begin{array}{c}\mathtt{h}, {}^{\mathtt{r}}\Gamma, \mathtt{e}_0 \rightsquigarrow \mathtt{h}', \iota_0 \\ \iota_0 \neq \mathtt{null}_a \\ \iota = \mathtt{h}'(\iota_0)\downarrow_2(\mathtt{f})\end{array}}{\mathtt{h}, {}^{\mathtt{r}}\Gamma, \mathtt{e}_0.\mathtt{f} \rightsquigarrow \mathtt{h}', \iota}
$$

$$
\text{GT-Read}\ \frac{\Gamma \vdash \mathtt{e}_0 : \mathtt{N}_0 \qquad \mathtt{N}_0 = \_\ \langle}{\Gamma \vdash \mathtt{e}_0.\mathtt{f} : \mathtt{N}_0 \rhd fType(\mathtt{C}_0, \mathtt{f})}
$$

$$
\text{GT-Upd}\ \frac{\begin{array}{c}\Gamma \vdash \mathtt{e}_0 : \mathtt{N}_0 \qquad \mathtt{N}_0 = \mathtt{u}_0\ \mathtt{C}_0\langle\_\rangle \\ \mathtt{T}_1 = fType(\mathtt{C}_0, \mathtt{f}) \\ \Gamma \vdash \mathtt{e}_2 : \mathtt{N}_0 \rhd \mathtt{T}_1 \\ \mathtt{u}_0 \neq \mathtt{any} \qquad rp(\mathtt{u}_0, \mathtt{T}_1)\end{array}}{\Gamma \vdash \mathtt{e}_0.\mathtt{f}{=}\mathtt{e}_2 : \mathtt{N}_0 \rhd \mathtt{T}_1}
$$

$$
\text{DYN}\ \frac{\begin{array}{l}\mathtt{h} \vdash {}^{\mathtt{r}}\Gamma : {}^{\mathtt{s}}\Gamma \\ \mathtt{h} \vdash \iota_1 : dyn({}^{\mathtt{s}}\mathtt{N}, \mathtt{h}, {}^{\mathtt{r}}\iota_1) \\ \mathtt{h} \vdash \iota_2 : dyn({}^{\mathtt{s}}\mathtt{T}, \iota_1, \mathtt{h}(\iota_1)\downarrow_1) \\ {}^{\mathtt{s}}\mathtt{N} = \mathtt{u}_N\ \mathtt{C}_N\langle\_\rangle \\ \mathtt{u}_N = \mathtt{this}_u \Rightarrow {}^{\mathtt{r}}\Gamma(\mathtt{this}) \\ free({}^{\mathtt{s}}\mathtt{T}) \subseteq dom(\mathtt{C}_N)\end{array}}{\left.\begin{array}{l}\\ \\ \\ \\ \\ \\ {}^{\mathtt{r}}\mathtt{T} = \iota'\ \_\langle\_\rangle \qquad \iota \vdash {}^{\mathtt{r}}\mathtt{T}\ {}^{\mathtt{r}}{<:}\ \iota'\ \mathtt{C}\langle\overline{{}^{\mathtt{r}}\mathtt{T}}\rangle \qquad \iota \vdash {}^{\mathtt{r}}\mathtt{T}\ {}^{\mathtt{r}}{<:}\ \iota'\ \mathtt{C}\langle\overline{{}^{\mathtt{r}}\mathtt{T}_a}\rangle \Rightarrow \iota \vdash \overline{{}^{\mathtt{r}}\mathtt{T}}\ {}^{\mathtt{r}}{<:}\ \overline{{}^{\mathtt{r}}\mathtt{T}_a} \\ \mathrm{dom}(\mathtt{C}) = \overline{\mathtt{X}} \qquad \mathrm{free}({}^{\mathtt{s}}\mathtt{T}) \subseteq \overline{\mathtt{X}} \circ \overline{\mathtt{X}'}\end{array}\right\} \implies \mathtt{h} \vdash \iota_2 : dyn({}^{\mathtt{s}}\mathtt{N} \rhd {}^{\mathtt{s}}\mathtt{T}, \mathtt{h}, {}^{\mathtt{r}}\Gamma)}{dyn({}^{\mathtt{s}}\mathtt{T}, \iota, {}^{\mathtt{r}}\mathtt{T}, (\overline{\mathtt{X}'\ {}^{\mathtt{r}}\mathtt{T}'}; \_)) = {}^{\mathtt{s}}\mathtt{T}[\iota'/\mathtt{this}, \iota'/\mathtt{peer}, \iota/\mathtt{rep}, \mathtt{any}_a/\mathtt{any}_u, \overline{{}^{\mathtt{r}}\mathtt{T}/\mathtt{X}}, \overline{{}^{\mathtt{r}}\mathtt{T}'/\mathtt{X}'}]}
$$


Practicality
Testing
Pluggable
Type Systems
Built-in Type
Systems
Formal
Verification
Guarantees

Since Java 5: declaration annotations

Only for declaration locations:

```
@Deprecated
class Foo {
   @Getter @Setter private String query;
   @SuppressWarnings("unchecked")
   void foo() { … }
}
```

But we couldn’t express

A non-null reference to my data

An interned String

A non-null List of English Strings

A non-empty array of English strings

With Java 8 type annotations we can!

A non-null reference to my data

```
@NonNull Data mydata;
```

An interned String

```
@Interned String query;
```

A non-null List of English Strings

```
@NonNull List<@English String> msgs;
```

A non-empty array of English strings

```
@English String @NonEmpty [] a;
```

Java 8 extends annotation syntax

Annotations on all occurrences of types:

```
@Untainted String query;
List<@NonNull String> strings;
myGraph = (@Immutable Graph) tmp;
class UnmodifiableList<T>
  implements @Readonly List<T> {}
```

Stored in classfile

Handled by javac, javap, javadoc, …

Java 6 & 7 compatibility
(or avoid dependency on Checker Framework)

Annotations in comments:

```
List</*@NonNull*/ String> strings;
```

(Requires use of jsr308-langtools compiler.)

Annotating external libraries

When type-checking clients, need library spec.

Can write manually or automatically infer

Two syntaxes:

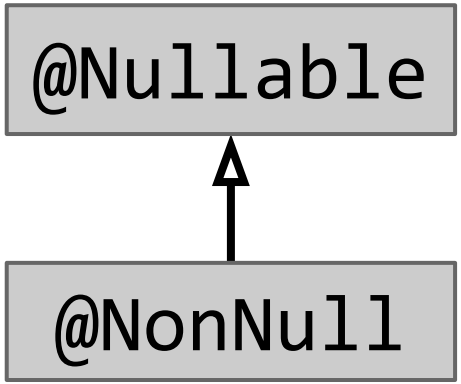
- As separate text file (stub file)
- Within its .jar file (from annotated partial source code)

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!

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();
}
```

3 ways to express persistence across side effects:

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

Side effects

`@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`

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

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 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`

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! ... unless

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

`@KeyFor` [rarely written, usually inferred]

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 Checker Framework false positives

```
@SuppressWarnings(“nullness”)
```

- Use smallest possible scope (e.g., local var)
- Write the rationale as comment

```
assert x != null : “@AssumeAssertion(nullness)”;
```

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

Optional checks

`-Alint=redundantNullComparison`

Warns if comparing a non-null value to null

`-Alint=uninitialized`

Warns if the constructor does not initialize all fields (even primitives that have a default)

Cost of software failures

$312 billion per year global cost of software bugs (2013)

$300 billion dealing with the Y2K problem

$440 million loss by Knight Capital Group Inc. in 30 minutes in August 2012

$650 million loss by NASA Mars missions in 1999; unit conversion bug

$500 million Ariane 5 maiden flight in 1996; 64 bit to 16 bit conversion bug

Software bugs can cost lives

1997: **225 deaths**: jet crash caused by radar software
1991: **28 deaths**: Patriot missile guidance system
2003: **11 deaths**: blackout
1985-2000: **>8 deaths**: Radiation therapy

2011: Software cause for 25% of all medical device recalls

Brainstorming new type checkers

What runtime exceptions to prevent?

What properties of data should always hold?

What operations are legal and illegal?

Type-system checkable properties:

- Dependency on values
- Not on program structure, timing, ...

Example: Nullness Checker

What runtime exceptions to prevent?

What properties of data should always hold?

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Example: Nullness Checker

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NullPointerException

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Example: Nullness Checker

What runtime exceptions to prevent?

NullPointerException

What properties of data should always hold?

@NonNull references always non-null

What operations are legal and illegal?

Dereferences only on @NonNull references

Example: Regex Checker

What runtime exceptions to prevent?

What properties of data should always hold?

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Example: Regex Checker

What runtime exceptions to prevent?

PatternSyntaxException,
IndexOutOfBoundsException

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Example: Regex Checker

What runtime exceptions to prevent?

PatternSyntaxException,
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What properties of data should always hold?

Whether a string is a regex and number of groups

What operations are legal and illegal?

Example: Regex Checker

What runtime exceptions to prevent?

PatternSyntaxException,
IndexOutOfBoundsException

What properties of data should always hold?

Whether a string is a regex and number of groups

What operations are legal and illegal?

Pattern.compile with non-@Regexp, 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.

Checker Framework Community

Open source project:

`https://github.com/typetools/checker-framework`

- Monthly release cycle
- 12,000 commits, 75 authors
- 40 issues closed since January 1, 2017
- Welcoming & responsive community

Pluggable type-checking improves code

Prevent NPEs with the Nullness Checker

- Featureful, effective, easy to use, scalable

Prevent bugs at compile time

Nullness is just one example type system

Get started today!

`http://CheckerFramework.org/`