Preventing Null Pointer Exceptions at Compile Time

The Checker Framework

`http://CheckerFramework.org/`

Twitter: @CheckerFrmwrk

Live demo: `http://CheckerFramework.org/live/`

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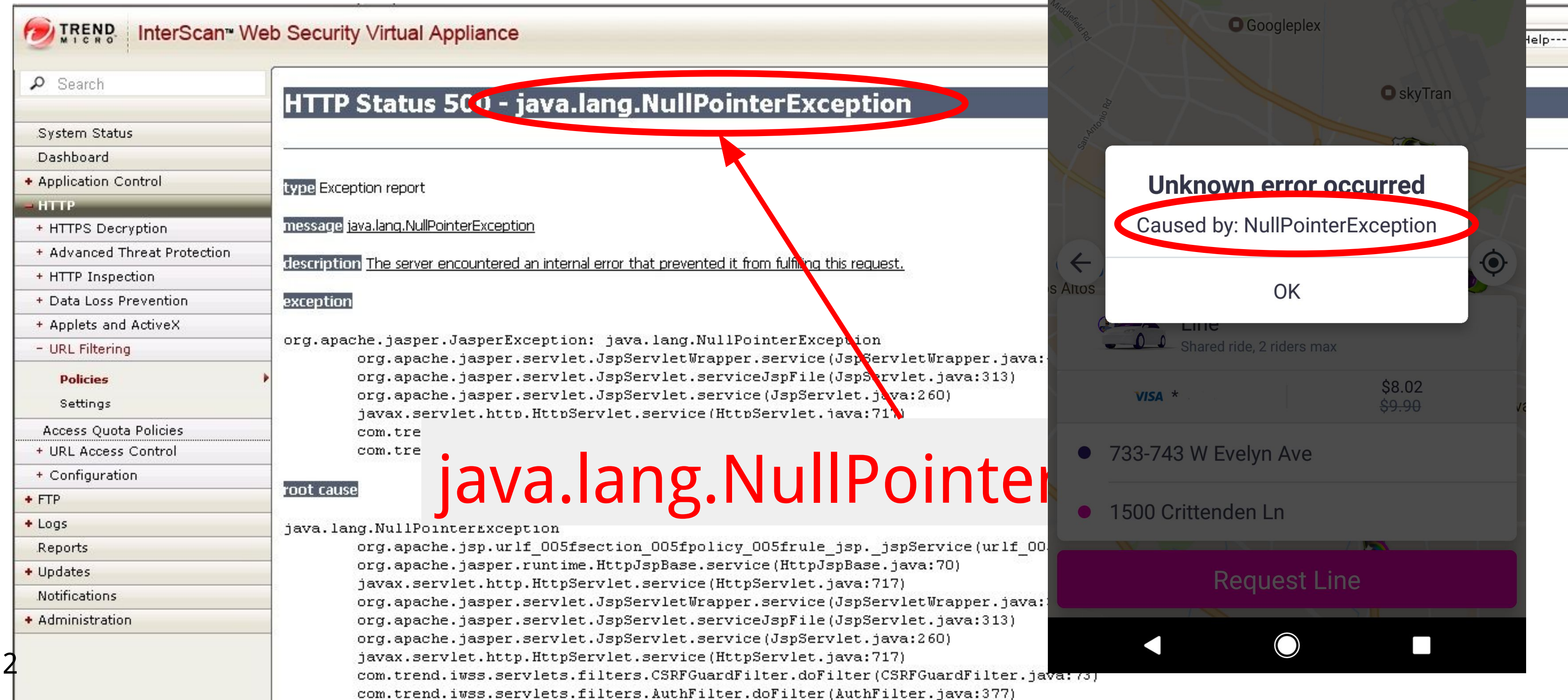
Motivation



HTTP Status 500 - java.lang.NullPointerException

type Exception report

message java.lang.NullPointerException

description The server encountered an internal error that prevented it from fulfilling this request.

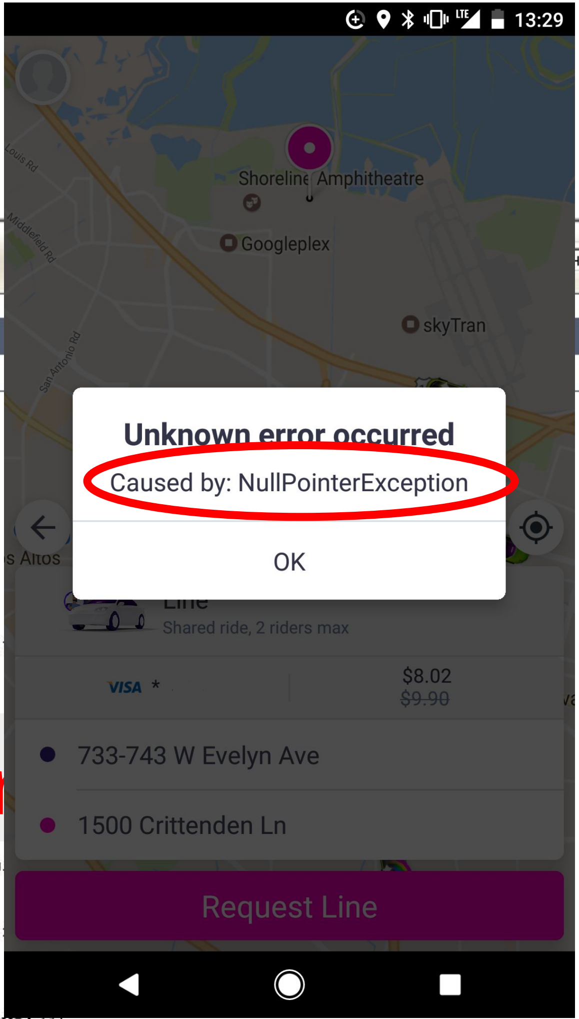
exception

```
org.apache.jasper.JasperException: java.lang.NullPointerException
        org.apache.jasper.servlet.JspServletWrapper.service(JspServletWrapper.java:
        org.apache.jasper.servlet.JspServlet.serviceJspFile(JspServlet.java:313)
        org.apache.jasper.servlet.JspServlet.service(JspServlet.java:260)
        javax.servlet.http.HttpServlet.service(HttpServlet.java:717)
        com.tre
        com.tre
```

root cause

```
java.lang.NullPointerException
        org.apache.jsp.urlf_005fsection_005fpolicy_005frule_jsp._jspService(urlf_00
        org.apache.jasper.runtime.HttpJspBase.service(HttpJspBase.java:70)
        javax.servlet.http.HttpServlet.service(HttpServlet.java:717)
        org.apache.jasper.servlet.JspServletWrapper.service(JspServletWrapper.java:
        org.apache.jasper.servlet.JspServlet.serviceJspFile(JspServlet.java:313)
        org.apache.jasper.servlet.JspServlet.service(JspServlet.java:260)
        javax.servlet.http.HttpServlet.service(HttpServlet.java:717)
        com.trend.iwss.servlets.filters.CSRFGuardFilter.doFilter(CSRFGuardFilter.java:73)
        com.trend.iwss.servlets.filters.AuthFilter.doFilter(AuthFilter.java:377)
```

java.lang.NullPointer



Unknown error occurred

Caused by: NullPointerException

OK

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 caused 25% of all medical device recalls

Outline

- Verification approach: Pluggable type-checking
- Tool: Checker Framework
- How to use it
- Advanced features

This talk focuses on nullness.

A talk earlier today focussed on writing your own type system.

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

Type checking prevents many errors

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

Type checking doesn't prevent enough errors

```
NullPointerException
```

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

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();
```

Nullness Checker demo Fixed

✓

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();
  }
  …
  String s = op(null);
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Null pointer exception

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Null pointer exception

Where is the defect?

```
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);
```

✓

Solution: Pluggable Type Checking

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

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

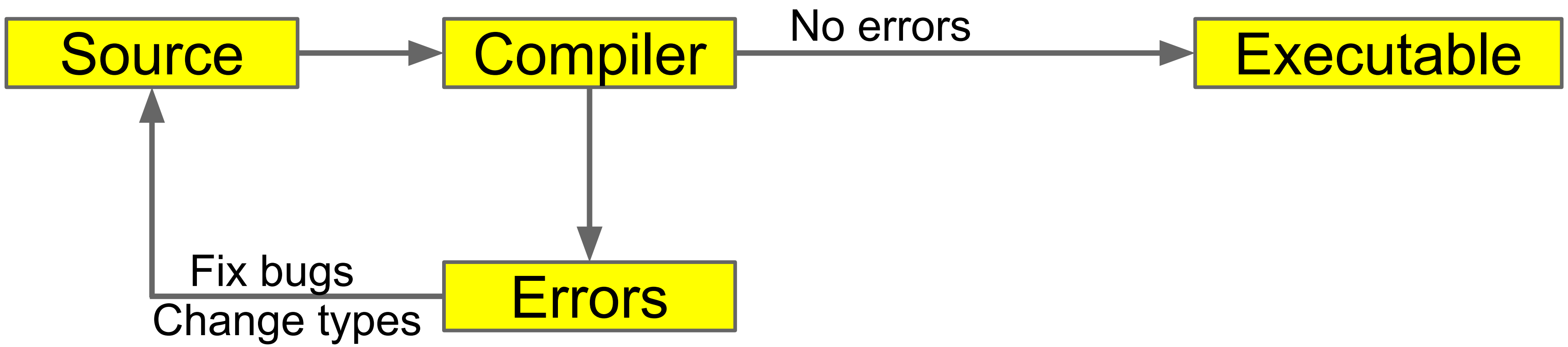
3. Type checker warns about violations (bugs)

```
% javac -processor NullnessChecker MyFile.java

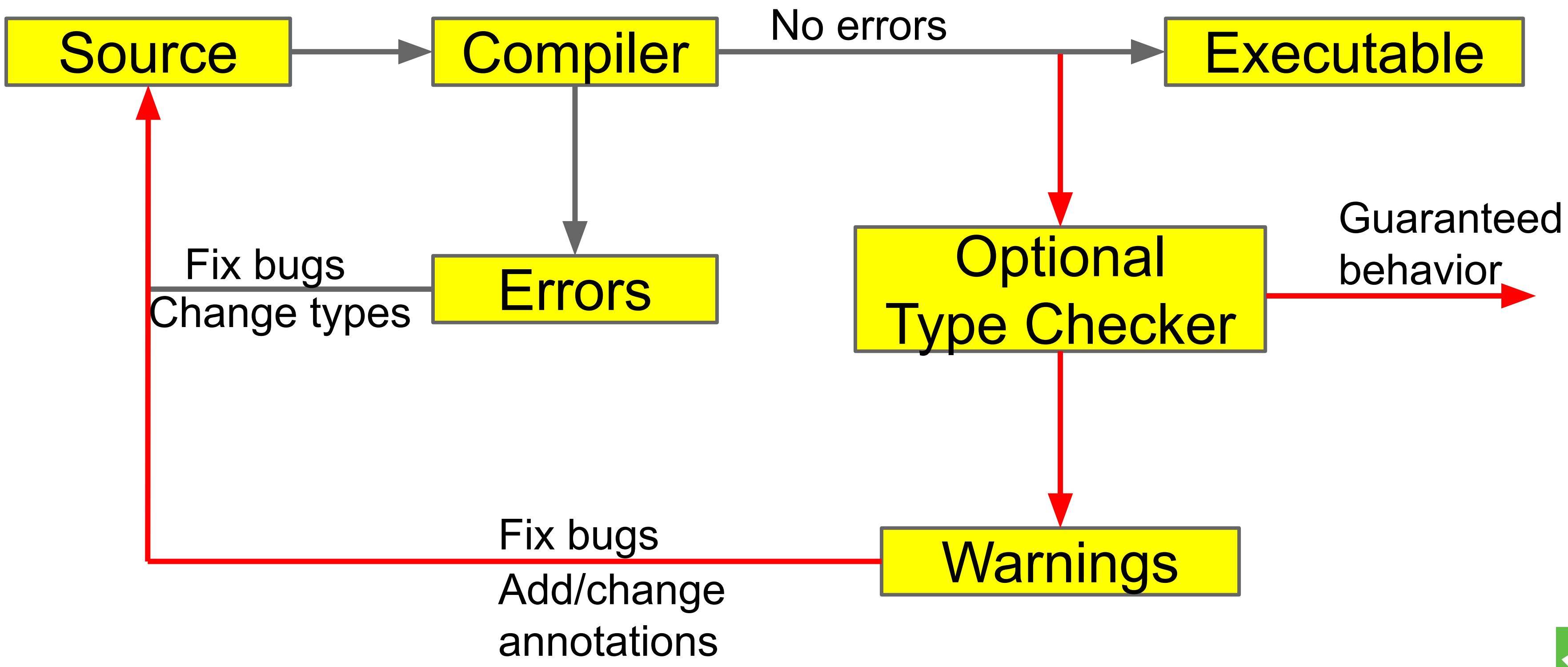
MyFile.java:149: dereference of possibly-null reference bb2
      allVars = bb2.vars;
                ^
```

✓

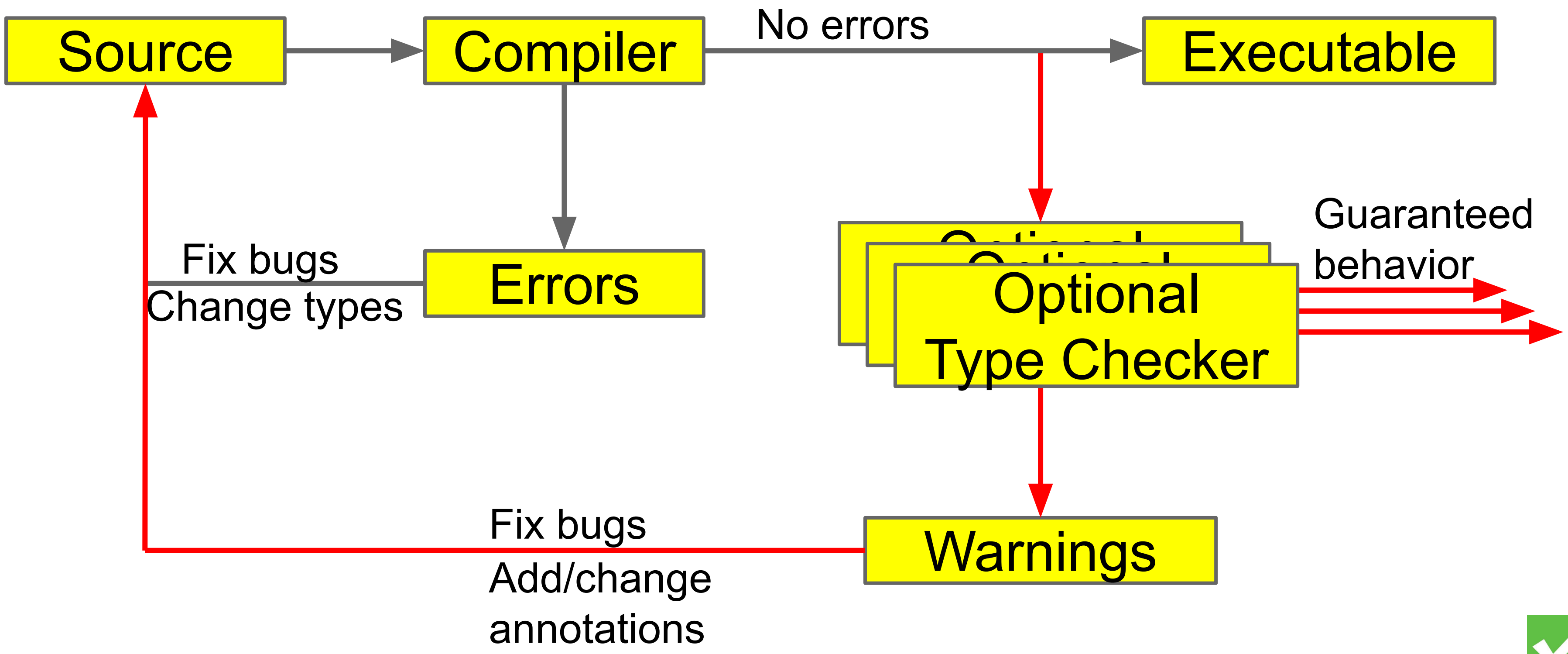
Type Checking



Optional Type Checking



Optional Type Checking



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)

The Checker Framework

A framework for pluggable type checkers

“Plugs” into the OpenJDK or OracleJDK compiler

```
javac -processor MyChecker …
```

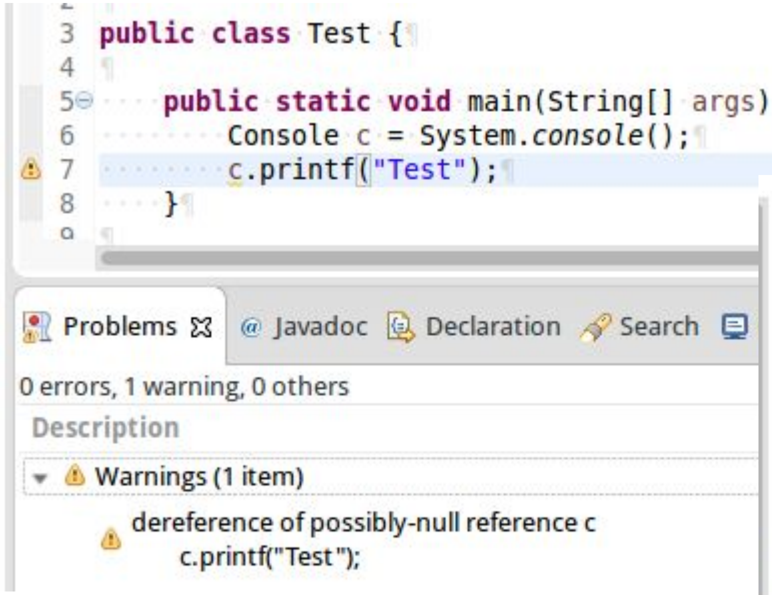
Standard error format allows tool integration

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>2.5.0</version>
    </dependency>
</dependencies>
```

Eclipse, IntelliJ, NetBeans integration



```
public class Test {

    public static void main(String[] args) {
        Console c = System.console();
        c.printf("Test");
    }

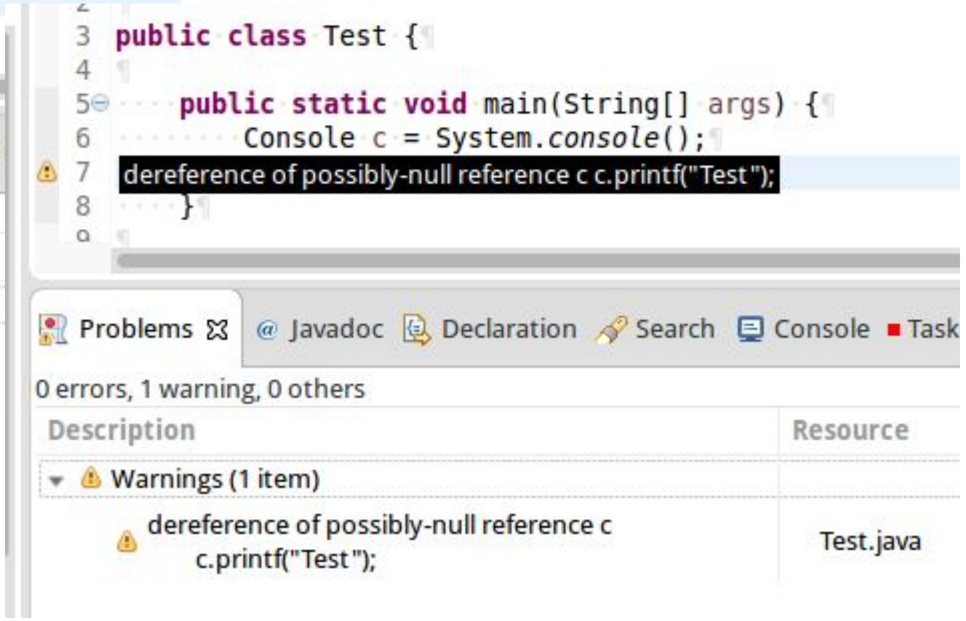
```

0 errors, 1 warning, 0 others

Description

Warnings (1 item)

dereference of possibly-null reference c
c.printf("Test");



```
public class Test {

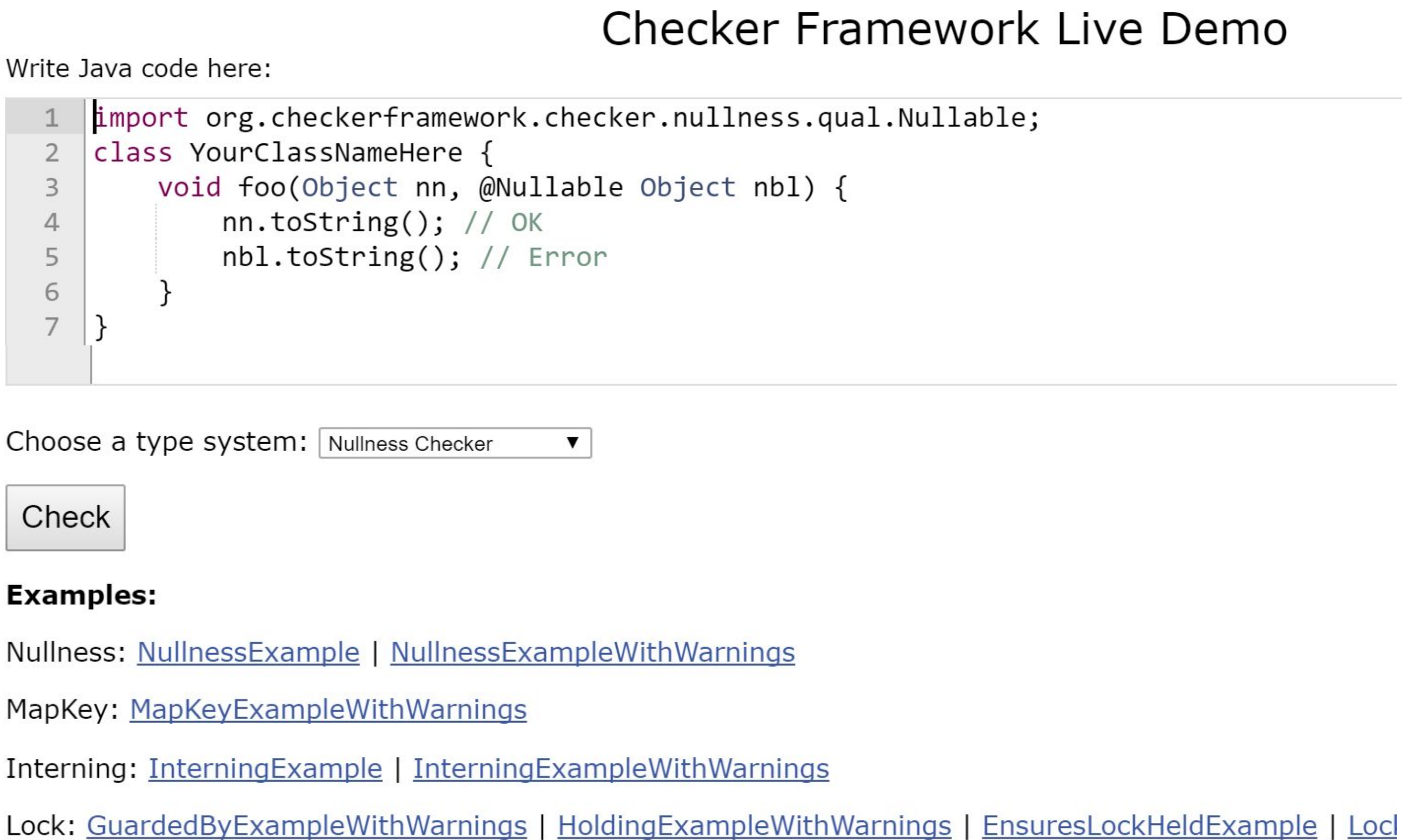
    public static void main(String[] args) {
        Console c = System.console();
dereference of possibly-null reference c c.printf("Test");
    }

```

0 errors, 1 warning, 0 others

Description	Resource
Warnings (1 item)	
dereference of possibly-null reference c c.printf("Test");	Test.java

Live demo: http://CheckerFramework.org/live/



Checker Framework Live Demo

Write Java code here:

```
import org.checkerframework.checker.nullness.qual.Nullable;
class YourClassNameHere {
    void foo(Object nn, @Nullable Object nbl) {
        nn.toString(); // OK
        nbl.toString(); // Error
    }
}
```

Choose a type system: Nullness Checker

Examples:

Nullness: NullnessExample | NullnessExampleWithWarnings

MapKey: MapKeyExampleWithWarnings

Interning: InterningExample | InterningExampleWithWarnings

Lock: GuardedByExampleWithWarnings | HoldingExampleWithWarnings | EnsuresLockHeldExample | Locl

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;
```

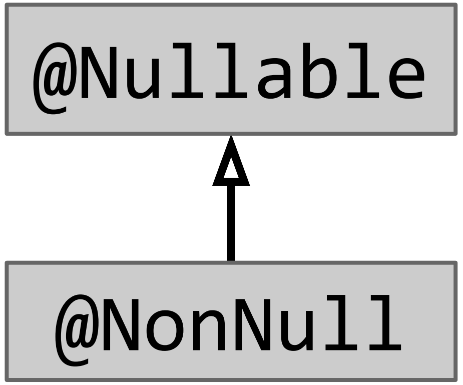
(Requires use of jsr308-langtools compiler.)

✓

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(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! … 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 a comment

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

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

✓

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)

Checker Framework facilities

- Full type systems: inheritance, overriding, ...
- Generics (type polymorphism)
  - Also qualifier polymorphism
- Qualifier defaults
- Pre-/post-conditions
- Warning suppression

Building a checker is easy

Example: Ensure encrypted communication

```
void send(@Encrypted String msg) {…}
@Encrypted String msg1 = ...;
send(msg1);   // OK
String msg2 = ....;
send(msg2);   // Warning!
```

✓

Building a checker is easy

Example: Ensure encrypted communication

```
void send(@Encrypted String msg) {…}
@Encrypted String msg1 = ...;
send(msg1);   // OK
String msg2 = ....;
send(msg2);   // Warning!
```

The complete checker:

```
@Target(ElementType.TYPE_USE)
@SubtypeOf(Unqualified.class)
public @interface Encrypted {}
```

✓

Defining a type system

1. Qualifier hierarchy
    - defines subtyping
2. Type introduction rules
    - types for expressions
3. Type rules
    - checker-specific errors
4. Flow-refinement
    - better types than the programmer wrote ✓

Dataflow Framework

Goal: Compute properties about expressions

- More accurate types than the user wrote
- Foundation for other static analyses
  - e.g. by Google error-prone and Uber NullAway

Dataflow Framework user provides

- What are we tracking?
- What do operations do?
- What are intermediate results?

Dataflow Framework does all the work!

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
Method 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

It’s easy to write your own type system!

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

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

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

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

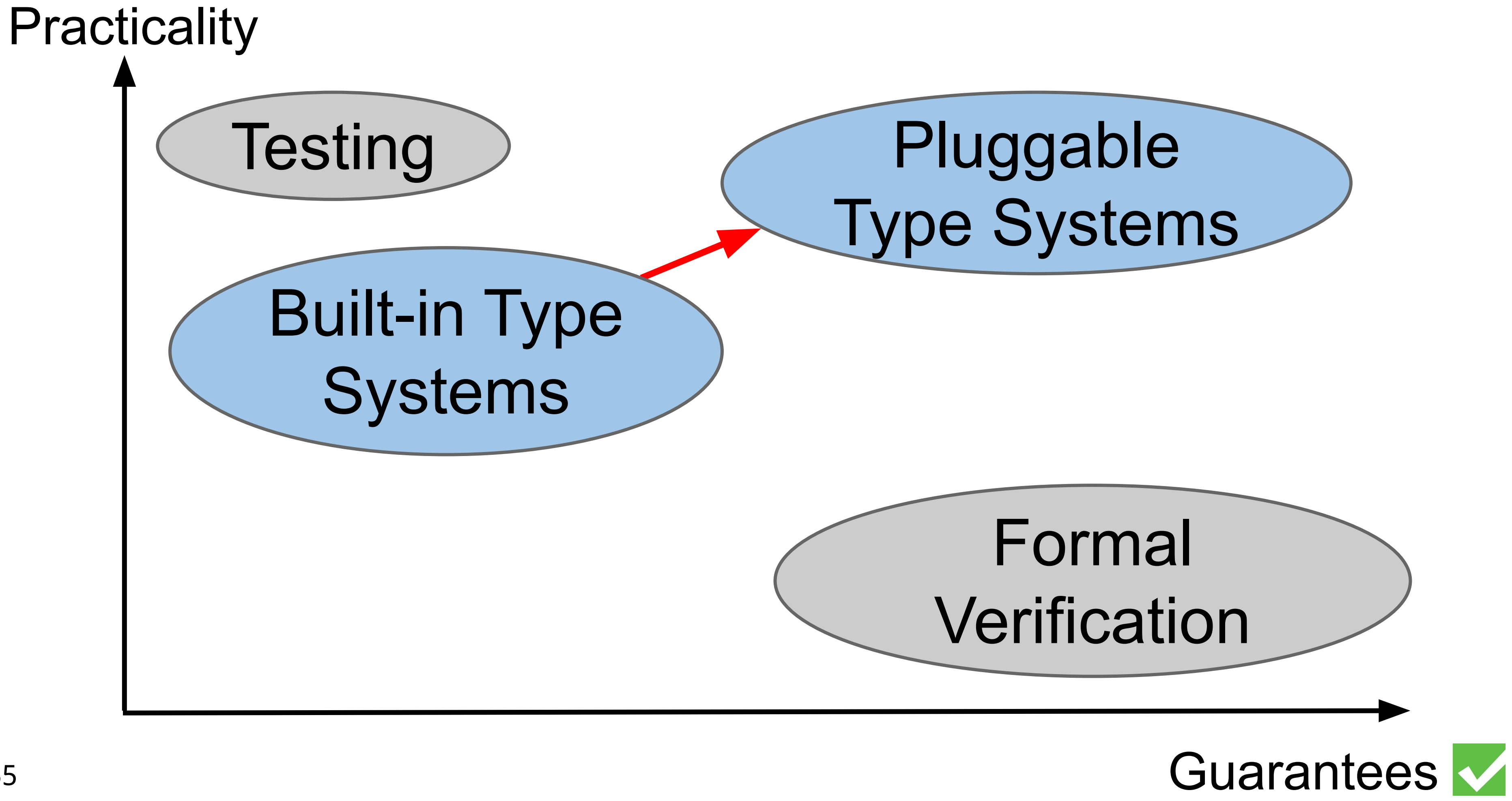
$$\text{OS-Read}\ \frac{\begin{array}{c}\mathtt{h}, {}^{r}\Gamma, \mathtt{e}_0 \leadsto \mathtt{h}', \iota_0 \\ \iota_0 \neq \mathtt{null}_a \\ \iota = \mathtt{h}'(\iota_0)\downarrow_2(\mathtt{f})\end{array}}{\mathtt{h}, {}^{r}\Gamma, \mathtt{e}_0.\mathtt{f} \leadsto \mathtt{h}', \iota}$$

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

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

$$\left.\begin{array}{l}
\mathtt{h} \vdash {}^{r}\Gamma : {}^{s}\Gamma \\
\mathtt{h} \vdash \iota_1 : \mathit{dyn}({}^{s}\mathtt{N}, \mathtt{h}, {}^{r}\Gamma) \\
\mathtt{h} \vdash \iota_2 : \mathit{dyn}({}^{s}\mathtt{T}, \iota_1, \mathtt{h}(\iota_1)\downarrow_1) \\
{}^{s}\mathtt{N} = \mathtt{u}_N\ \mathtt{C}_N\mathtt{<\_>} \\
\mathtt{u}_N = \mathtt{this}_u \Rightarrow {}^{r}\Gamma(\mathtt{this}) \\
\mathit{free}({}^{s}\mathtt{T}) \subseteq \mathit{dom}(\mathtt{C}_N)
\end{array}\right\} \implies \mathtt{h} \vdash \iota_2 : \mathit{dyn}({}^{s}\mathtt{N} \rhd {}^{s}\mathtt{T}, \mathtt{h}, {}^{r}\Gamma)$$

$$\text{DYN}\ \frac{\begin{array}{c}{}^{r}\mathtt{T} = \iota'\ \mathtt{\_<\_>} \qquad \iota \vdash {}^{r}\mathtt{T}\ {}^{r}\mathtt{<:}\ \iota'\ \mathtt{C<}\overline{{}^{r}\mathtt{T}}\mathtt{>} \qquad \iota \vdash {}^{r}\mathtt{T}\ {}^{r}\mathtt{<:}\ \iota'\ \mathtt{C<}\overline{{}^{r}\mathtt{T}_a}\mathtt{>} \Rightarrow \iota \vdash \overline{{}^{r}\mathtt{T}}\ {}^{r}\mathtt{<:}\ \overline{{}^{r}\mathtt{T}_a} \\ \mathrm{dom}(\mathtt{C}) = \overline{\mathtt{X}} \qquad \mathrm{free}({}^{s}\mathtt{T}) \subseteq \overline{\mathtt{X}} \circ \overline{\mathtt{X}'}\end{array}}{\mathit{dyn}({}^{s}\mathtt{T}, \iota, {}^{r}\mathtt{T}, (\overline{\mathtt{X}'\ {}^{r}\mathtt{T}'};\_)) = {}^{s}\mathtt{T}[\iota'/\mathtt{this}, \iota'/\mathtt{peer}, \iota/\mathtt{rep}, \mathtt{any}_a/\mathtt{any}_u, \overline{{}^{r}\mathtt{T}/\mathtt{X}}, \overline{{}^{r}\mathtt{T}'/\mathtt{X}'}]}$$


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

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.

Tips

- 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 warning suppressions when possible
- Avoid raw types such as `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
- >14,400 commits, 75 authors
- Welcoming & responsive community
- Google Summer-of-Code participant

Pluggable type-checking improves code

Checker Framework for optional type checkers

- Featureful, effective, easy to use, scalable

Prevent null pointers at compile time

Improve your code!

`http://CheckerFramework.org/`