Null Pointer Exceptions

Problems, Current Approaches, and Ongoing Efforts

https://CheckerFramework.org/

Twitter: @CheckerFrmwrk

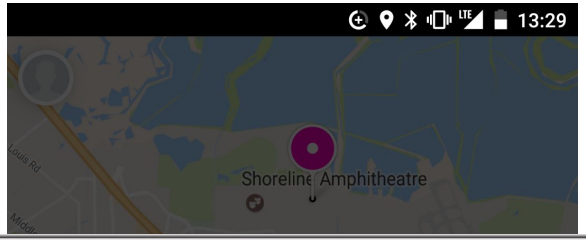
Live demo: https://CheckerFramework.org/live/

Werner Dietl, University of Waterloo

https://ece.uwaterloo.ca/~wdietl/

UNIVERSITY OF WATERLOO

Motivation



TREND MICRO InterScan™ Web Security Virtual Appliance

Log Off | --------Help---

Search

- System Status
- Dashboard
- + Application Control
- − HTTP
  - + HTTPS Decryption
  - + Advanced Threat Protection
  - + HTTP Inspection
  - + Data Loss Prevention
  - + Applets and ActiveX
  - − URL Filtering
    - Policies
    - Settings
- Reports
- + Updates
- Notifications
- + Administration

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:432)
        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)
```

ter.java:73)
77)

java.lang.NullPointerException

```
        org.apache.jsp.urlf_005fsection_005fpolicy_005frule_jsp._jspService(urlf_005fsection_005fpolicy_005frule_jsp.java:742)
        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:388)
        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.NullPointerException

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 Nullness Checker
- How to use advanced features
- Alternatives and ongoing efforts

This talk focuses on nullness.

A talk yesterday 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);
```


Null pointer exception

Where is the defect?

```
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);
```

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)

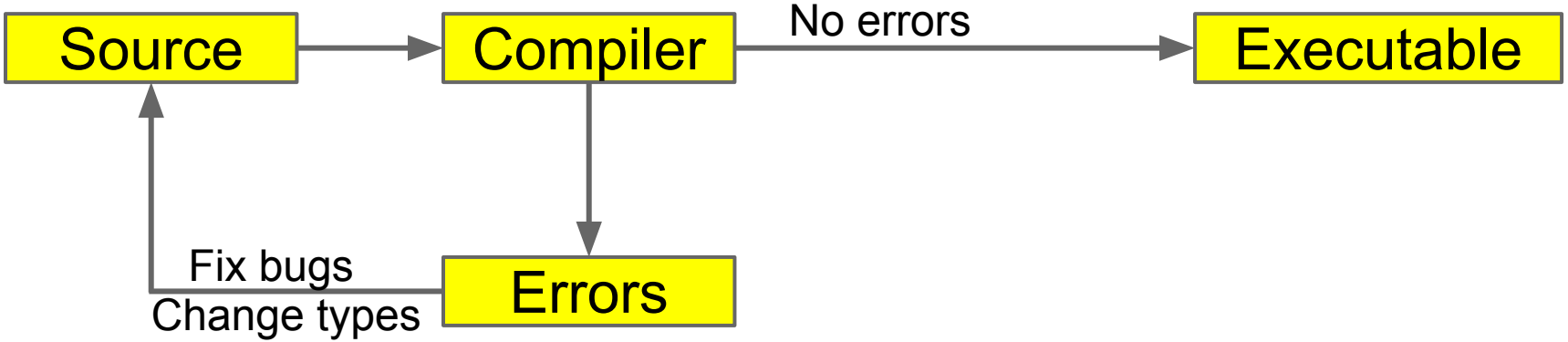
```
void foo (@Nullable Date date) {
  date.setSeconds(0); // compile-time error
```

3. Type checker warns about violations (bugs)

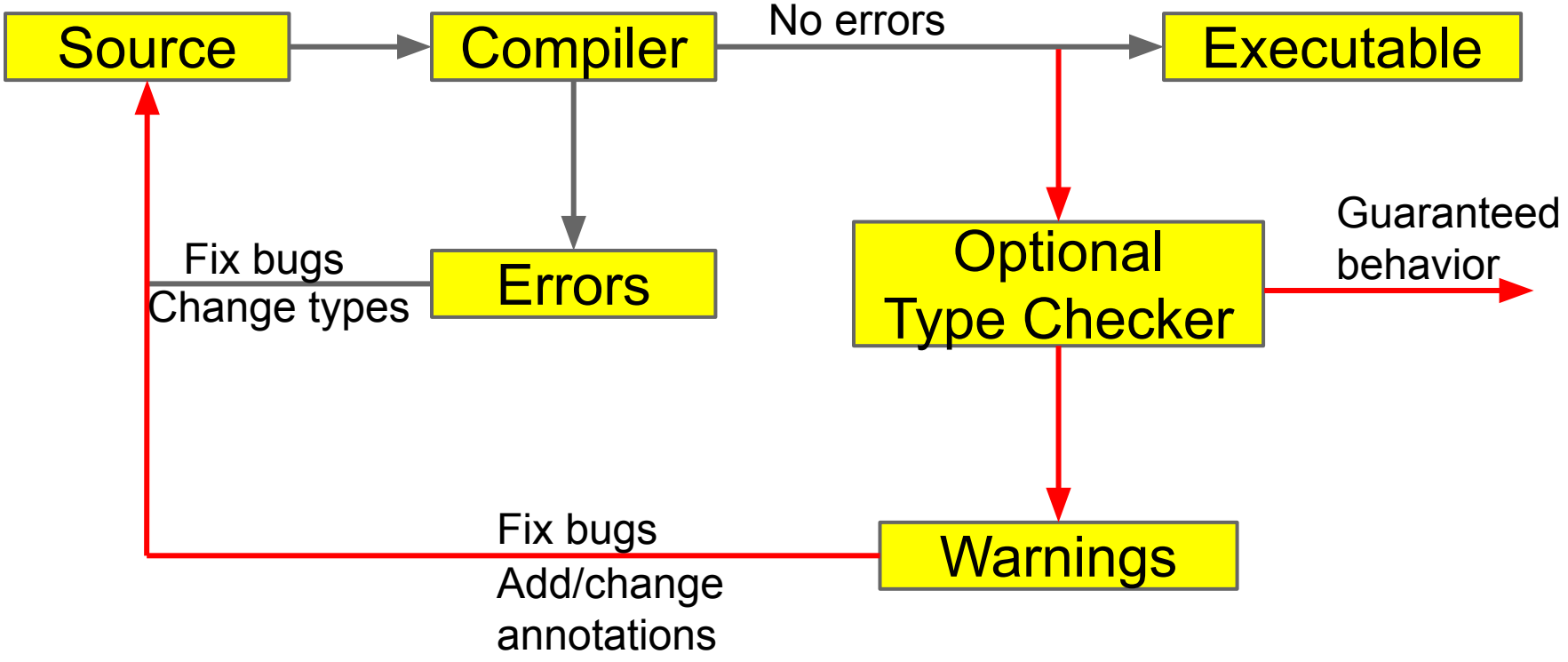
```
% javac -processor NullnessChecker MyFile.java

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

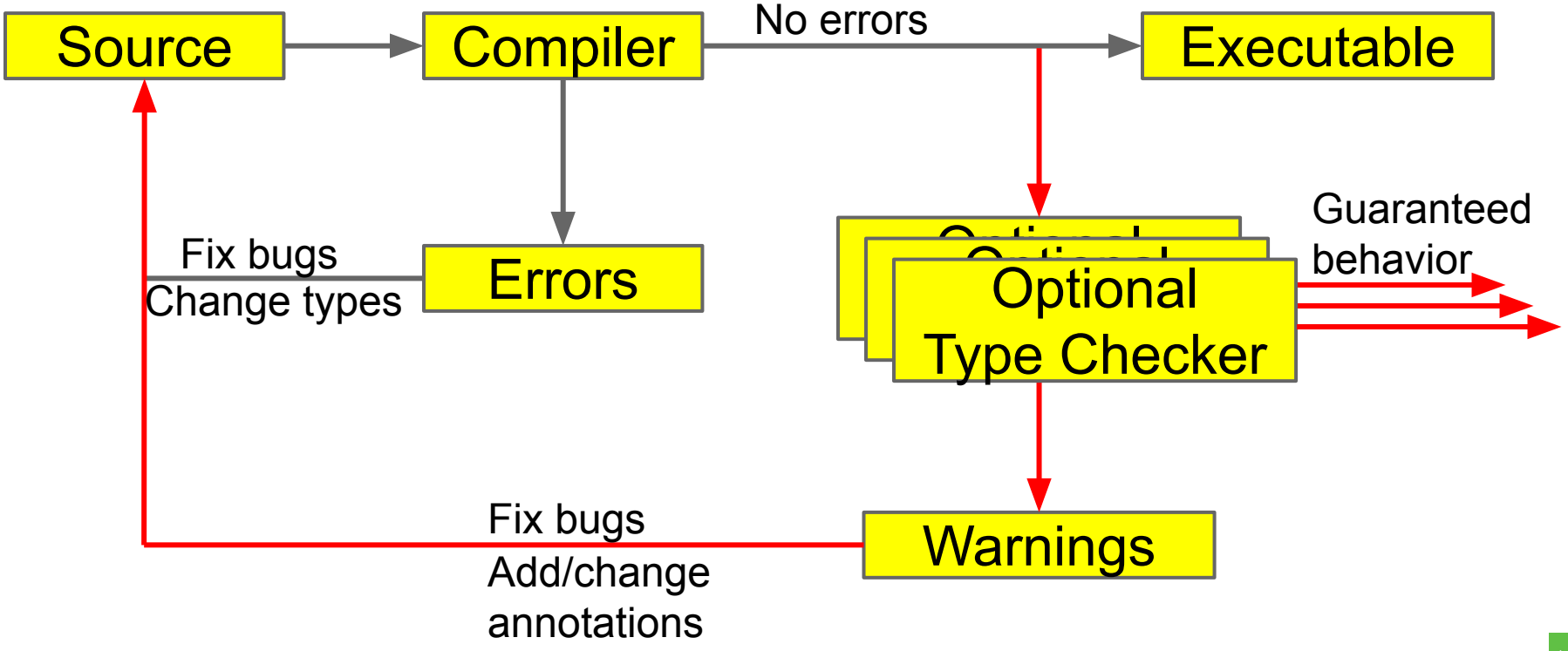

Type Checking



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 ...
```

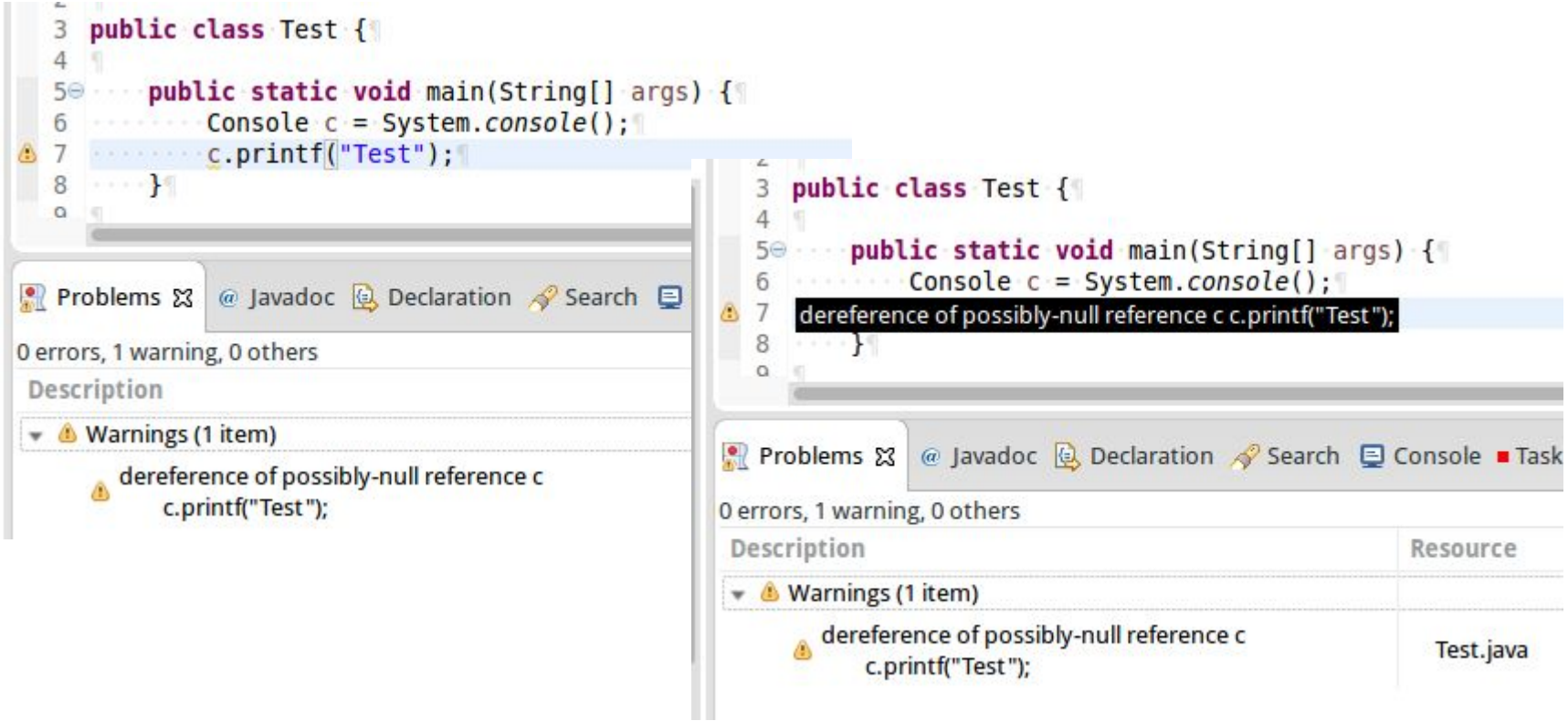
Standard error format allows tool integration

Ant, Maven, Gradle integration

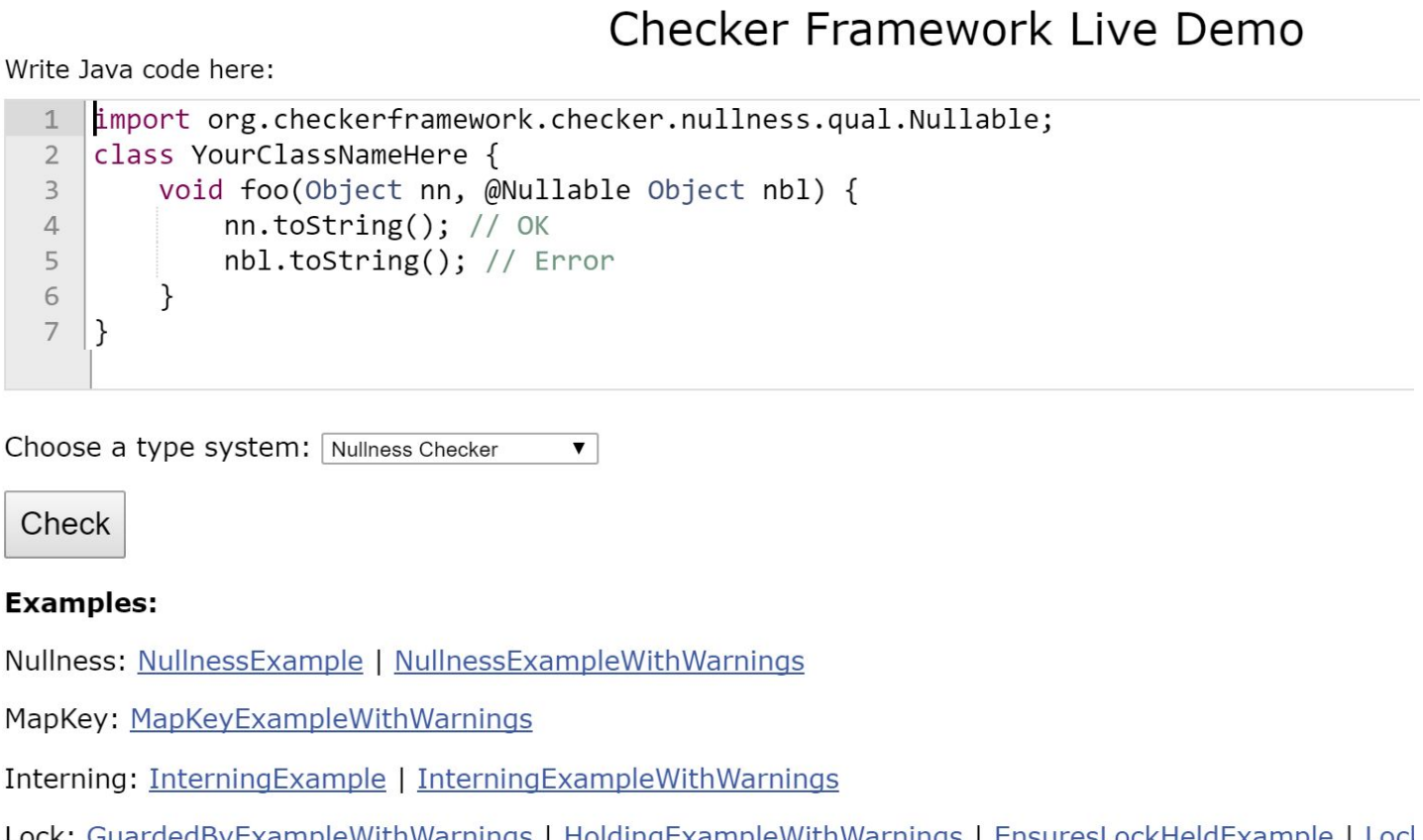
```
<presetdef name="jsr308.javac">
  <javac fork="yes"
    executable="${checkerframework}/checker/bin/${cfJavac}" >
    <!-- JSR-308-related compiler arguments -->
    <compilerarg value="-version"/>
    <compilerarg value="-implicit:class"/>
  </javac>
</presetdef>
```

```
<dependencies>
  ... existing <dependency> items ...
  <!-- annotations from the Checker Framework:
          nullness, interning, locking, ... -->
    <dependency>
      <groupId>org.checkerframework</groupId>
      <artifactId>checker-qual</artifactId>
      <version>3.22.0</version>
    </dependency>
</dependencies>
```

Eclipse, IntelliJ, NetBeans integration



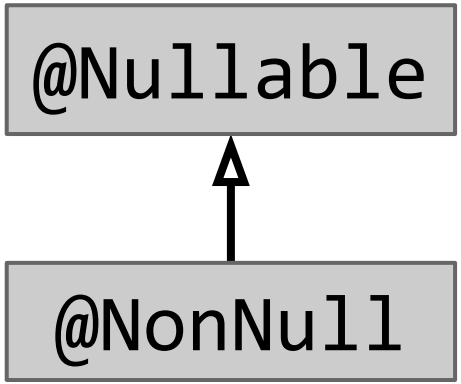
Live demo: http://CheckerFramework.org/live/



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!

Type rules

To prevent null pointer exceptions:

- `expr.field`
  `expr.getValue()`
  receiver must be non-null
- `synchronized (expr) { … }`
  monitor must be non-null
- …

Flow-sensitive type refinement

After an operation, give an expression a more specific type

```
@Nullable Object x;
if (x != null) {
   ...
}
...
```

x is @NonNull here

x is @Nullable again

```
@Nullable Object y;
y = new SomeType();
...
y = unknownValue;
...
```

y is @NonNull here

y is @Nullable again

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)

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

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

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

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

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

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

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

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

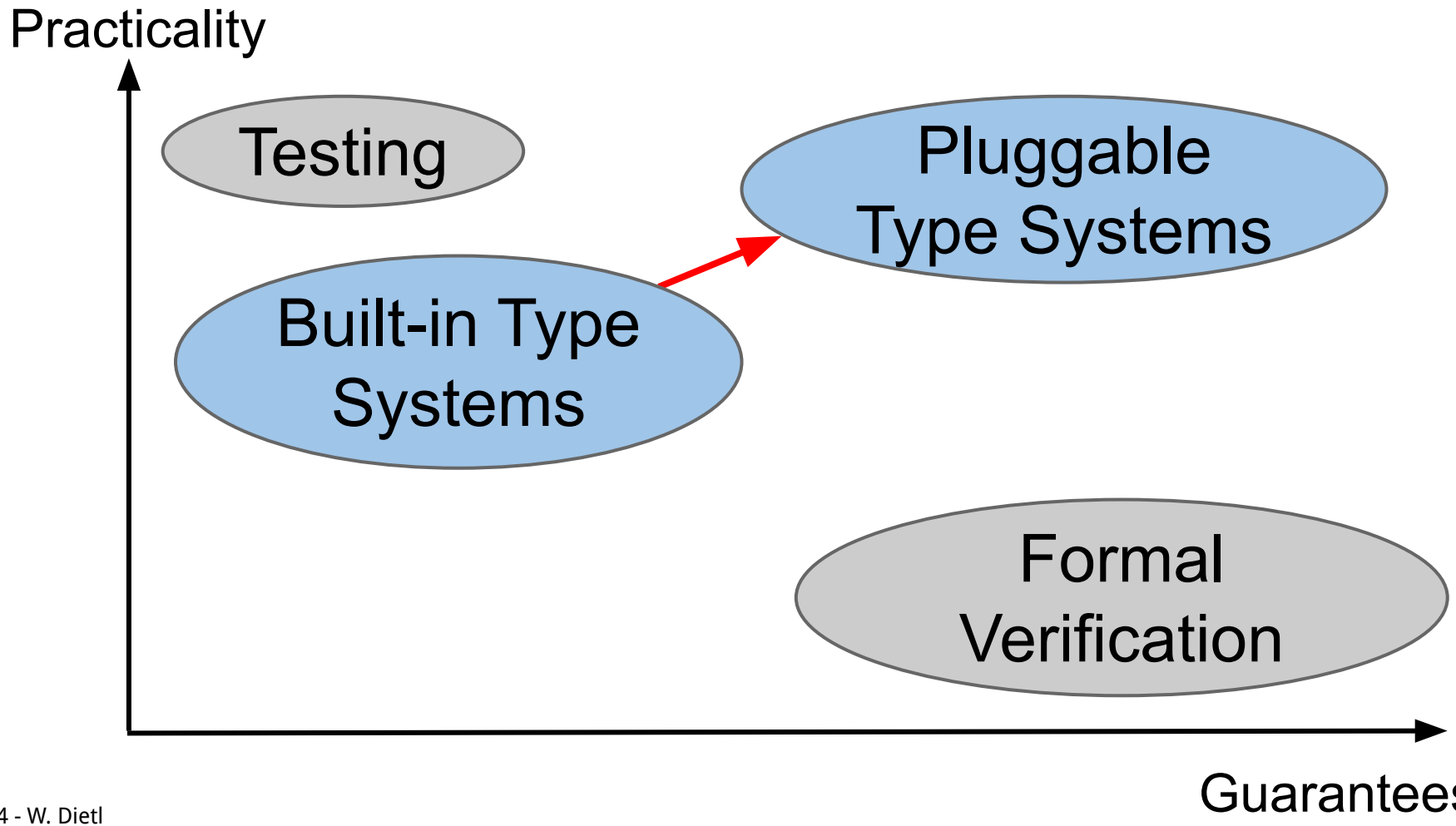
Verification

- **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.


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.

NullAway from Uber

https://github.com/uber/nullaway

- Fast
- Simplified generics - always non-null
- No contracts, but library models
- Uses the CF Dataflow Framework

Eradicate by Facebook/Meta

https://fbinfer.com/docs/checker-eradicate/

Kotlin Nullness

https://kotlinlang.org/docs/null-safety.html

- Nullness as part of the language
- Nicer syntax
- Contract annotations
- Platform types
- No Initialization Checker

Scala 3.0 Nullness

https://docs.scala-lang.org/scala3/reference/other-new-features/explicit-nulls.html

- Opt-in feature
- No Initialization Checker

JSpecify effort

http://jspecify.org/

- Collaboration between Google, JetBrains, Meta, SpotBugs, Uber, and many others
- Finally replace JSR 305
- Clear semantics and inter-op
- v0.2.0 released

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>`

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/`