

Preventing Errors Before They Happen

The Checker Framework



<http://CheckerFramework.org/>

Twitter: @CheckerFrmwrk

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

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Motivation

The screenshot shows the Trend Micro InterScan Web Security Virtual Appliance interface. The left sidebar contains a navigation menu with options like System Status, Dashboard, Application Control, HTTP, HTTPS Decryption, Advanced Threat Protection, HTTP Inspection, Data Loss Prevention, Applets and ActiveX, URL Filtering, Policies, Settings, Access Quota Policies, URL Access Control, Configuration, FTP, Logs, Reports, Updates, Notifications, and Administration. The main content area displays an "HTTP Status 500 - java.lang.NullPointerException" error report. The title "HTTP Status 500 - java.lang.NullPointerException" is circled in red. A red arrow points from the text "java.lang.NullPointerException" at the bottom of the page to the circled title. The error report includes fields for 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), and root cause (java.lang.NullPointerException).

HTTP Status 500 - java.lang.NullPointerException

type Exception report

message `java.lang.NullPointerException`

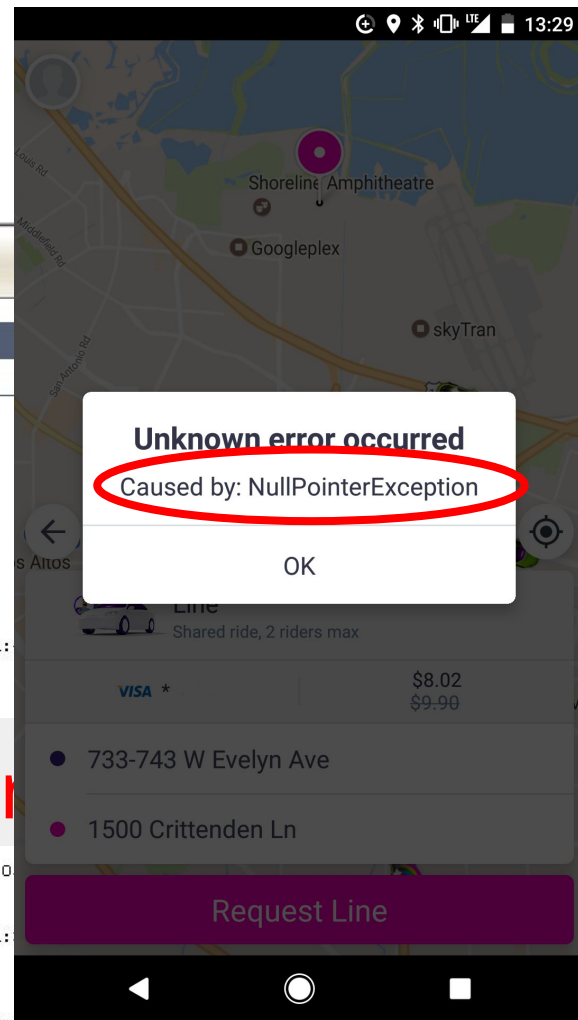
description The server encountered an internal error that prevented it from fulfilling this request.

exception

```
org.apache.jasper.JasperException: java.lang.NullPointerException
    org.apache.jasper.servlet.JspServletWrapper.service(JspServletWrapper.java:70)
    org.apache.jasper.servlet.JspServlet.service(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)
```

root cause

```
java.lang.NullPointerException
    org.apache.jsp.urlf_005fsection_005fpolicy_005frule_jsp._jspService(urlf_005fsection_005fpolicy_005frule_jsp._jspService(urlf_005fsection_005fpolicy_005frule_jsp.java:70)
    javax.servlet.http.HttpServlet.service(HttpServlet.java:717)
    org.apache.jasper.servlet.JspServletWrapper.service(JspServletWrapper.java:70)
    org.apache.jasper.servlet.JspServlet.service(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)
```



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
- Creating a custom 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();
```

```
Collections.emptyList().add("one");
```



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();
```

```
Collections.emptyList().add("one");
```



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](#)



Java's type system is too weak

Type checking prevents many errors

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

Type checking doesn't prevent enough errors

```
System UnsupportedOperationException
```

```
Collections.emptyList().add("one");
```



Some errors are silent

```
Date date = new Date();  
myMap.put(date, "now");  
date.setSeconds(0);    // round to minute  
myMap.get(date);
```



Some errors are silent

```
Date date = new Date();  
myMap.put(date, "now");  
date.setSeconds(0);    // round to minute  
myMap.get(date);
```

Corrupted map



Some errors are silent

```
dbStatement.executeQuery(userInput);
```



Some errors are silent

```
dbStatement.executeQuery(userInput);
```

SQL injection attack

Initialization, data formatting, equality tests, ...



SQL injection attack

Goal: don't execute user input as a SQL command

```
private String wrapQuery(String s) {  
    return "SELECT * FROM User WHERE userId='" + s + "'";  
}
```

If a user inputs his name as: ' or 'x'='x
the SQL query is: ... WHERE userID=' ' or 'x'='x'

To prevent errors: sanitize user data before use



Vulnerable code

```
void op(String in) {  
    ...  
    executeQuery(in);  
}  
  
...  
op(userInput);
```



Vulnerable code

```
void op(String in) {  
    ...  
    executeQuery(in);  
}  
  
...  
op(userInput);
```

Where is the defect?



Vulnerable code

```
void op(String in) {  
    ...  
    executeQuery(in);  
}  
...  
op(userInput);
```

Where is the defect?



Vulnerable code

```
void op(String in) {
```

```
...
```

```
    executeQuery(in);
```

```
}
```

```
...
```

```
op(userInput);
```

Where is the defect?

Can't decide without specification!



Specification 1: untainted parameter

```
void op(@Untainted String in) {  
    ...  
    executeQuery(in);  
}  
  
...  
op(userInput);
```



Specification 1: untainted parameter

```
void op(@Untainted String in) {  
    ...  
    executeQuery(in);  
}  
  
...  
op(userInput); // error
```



Specification 2: tainted parameter

```
void op(@Tainted String in) {  
    ...  
    executeQuery(in);  
}  
  
...  
op(userInput);
```



Specification 2: tainted parameter

```
void op(@Tainted String in) {  
    ...  
    executeQuery(in);           // error  
}  
  
...  
op(userInput);
```



Preventing SQL injection

Goal: don't execute user input as a SQL command

```
private String wrapQuery(String s) {  
    return "SELECT * FROM User WHERE userId='" + s + "'";  
}
```

If a user inputs his name as: ' or 'x'='x
the SQL query is: ... WHERE userID=' ' or 'x'='x'

@Tainted = might be untrusted user input

@Untainted = sanitized, safe to use



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)

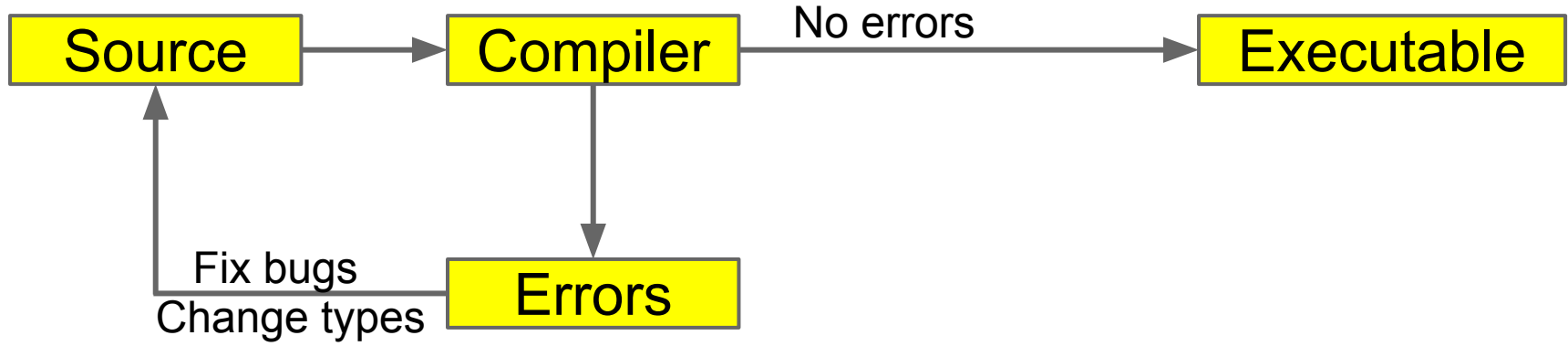
```
% javac -processor NullnessChecker MyFile.java
```

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

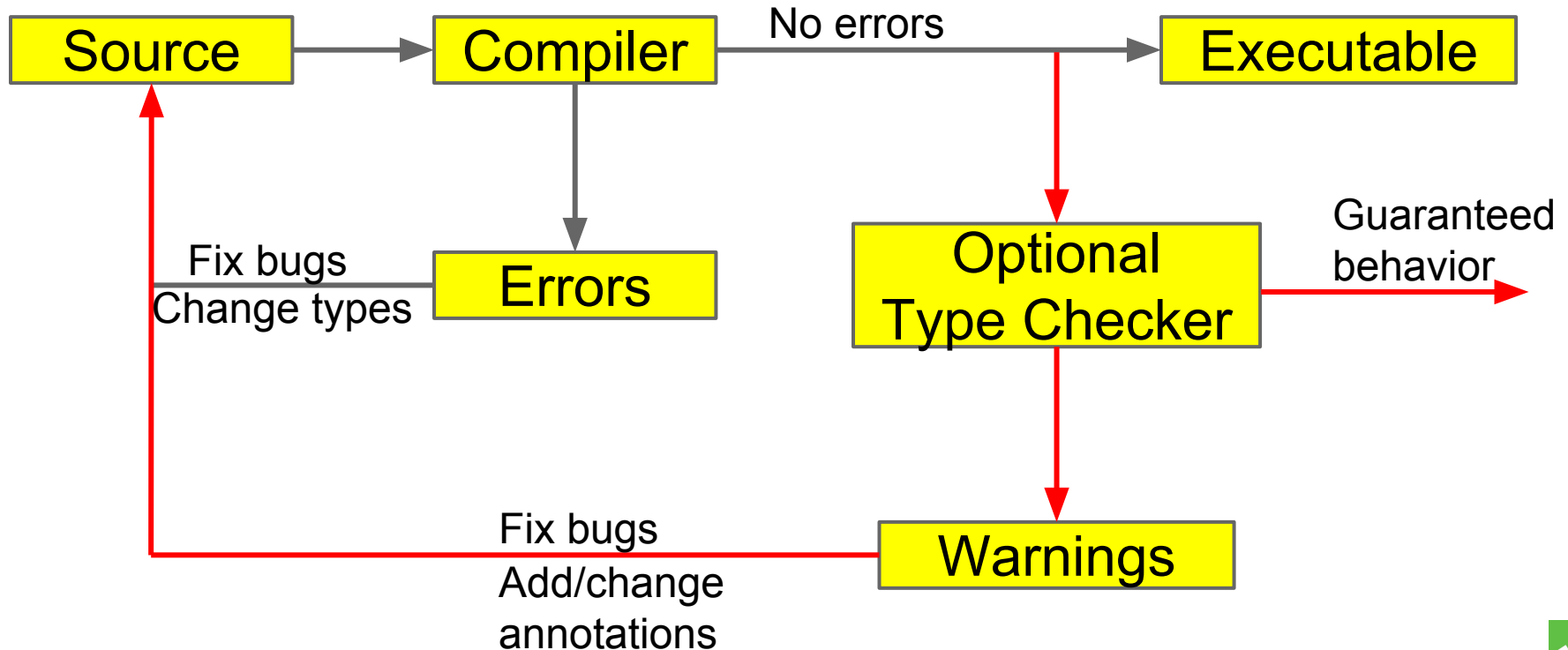
^



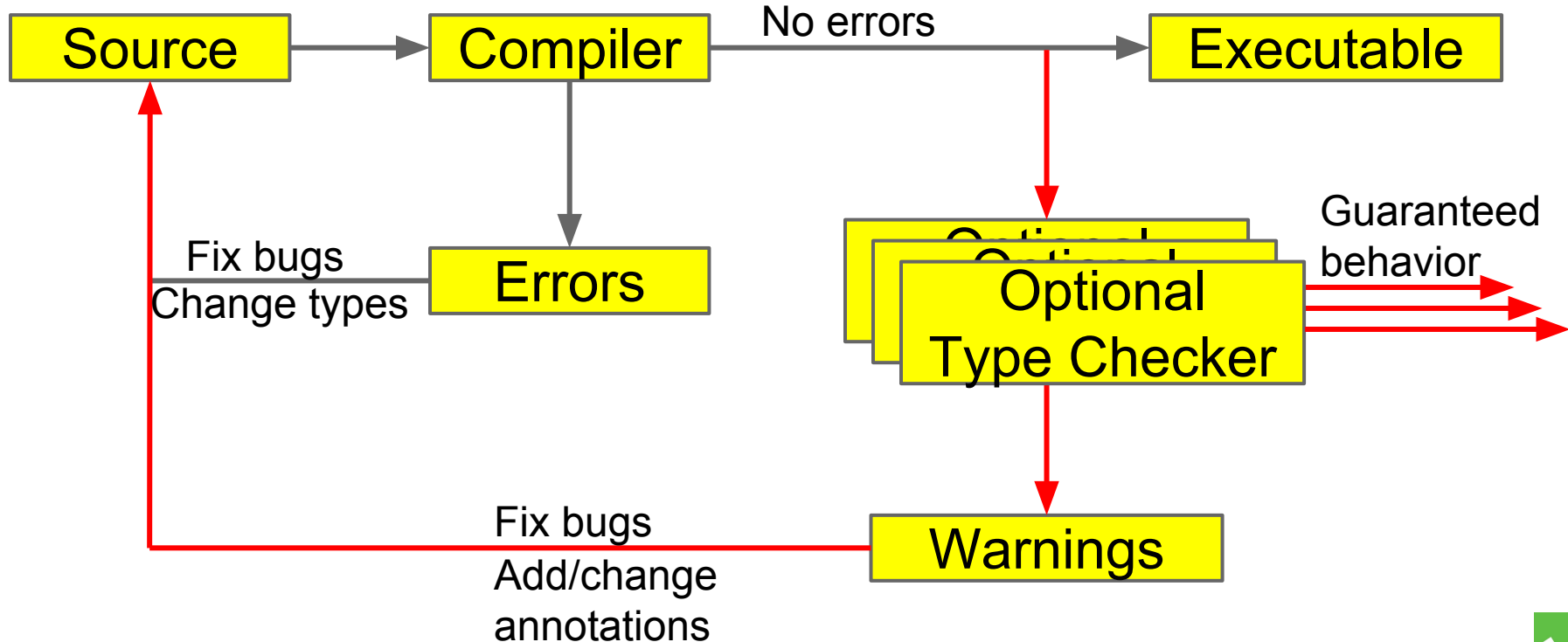
Type Checking



Optional Type Checking



Optional Type Checking



Prevent null pointer exceptions

Type system that statically guarantees that:
the program only dereferences
known 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();  
}  
...
```

Can't decide without specification!

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



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);
```



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, internning, locking, ... -->
  <dependency>
    <groupId>org.checkerframework</groupId>
    <artifactId>checker-qual</artifactId>
    <version>1.9.7</version>
  </dependency>
</dependencies>
```

Eclipse, IntelliJ, NetBeans integration

```
3 public class Test {  
4  
5     public static void main(String[] args) {  
6         Console c = System.console();  
7         c.printf("Test");  
8     }  
9 }
```

Problems @ Javadoc Declaration Search

0 errors, 1 warning, 0 others

Description

▼ Warnings (1 item)

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

```
3 public class Test {  
4  
5     public static void main(String[] args) {  
6         Console c = System.console();  
7         dereference of possibly-null reference c c.printf("Test");  
8     }  
9 }
```

Problems @ Javadoc Declaration Search Console

0 errors, 1 warning, 0 others

Description

Resource

▼ Warnings (1 item)

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

Test.java



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



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

Check

Examples:

Nullness: [NullnessExample](#) | [NullnessExampleWithWarnings](#)

MapKey: [MapKeyExampleWithWarnings](#)

Interning: [InterningExample](#) | [InterningExampleWithWarnings](#)

Lock: [GuardedByExampleWithWarnings](#) | [HoldingExampleWithWarnings](#) | [EnsuresLockHeldExample](#) | [Loc](#)



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!



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.



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

<h1>Formalizations</h1>		$h \in \text{Heap}$	$= \text{Addr} \rightarrow \text{Obj}$
		$\iota \in \text{Addr}$	$= \text{Set of Addresses} \cup \{\text{null}_a\}$
		$o \in \text{Obj}$	$= {}^r\text{Type, Fields}$
$P \in \text{Program}$	$::= \text{Class, ClassId, Expr}$	${}^rT \in {}^r\text{Type}$	$= \text{OwnerAddr ClassId} \langle \overline{{}^r\text{Type}} \rangle$
$\text{Cls} \in \text{Class}$	$::= \text{class ClassId} \langle \overline{\text{TVarId}} \rangle$	$\text{Fs} \in \text{Fields}$	$= \text{FieldId} \rightarrow \text{Addr}$
	$\text{extends ClassId} \langle \overline{{}^s\text{Type}} \rangle$	$\iota \in \text{OwnerAddr}$	$= \text{Addr} \cup \{\text{any}_a\}$
	$\{ \text{FieldId } {}^s\text{Type}; \text{Met} \}$	${}^r\Gamma \in {}^r\text{Env}$	$= \overline{\text{TVarId } {}^r\text{Type}; \text{ParId Addr}}$
${}^sT \in {}^s\text{Type}$	$::= {}^s\text{NType} \mid \text{TVarId}$		$h, {}^r\Gamma, e_0 \rightsquigarrow h', \iota_0$
${}^sN \in {}^s\text{NType}$	$::= \text{OM ClassId} \langle \overline{{}^s\text{Type}} \rangle$		$\iota_0 \neq \text{null}_a$
$u \in \text{OM}$	$::=$	$h, {}^r\Gamma, e_0 \rightsquigarrow h_0, \iota_0$	$\iota = h'(\iota_0) \downarrow_2 (f)$
$\text{mt} \in \text{Meth}$	$::=$	$\iota_0 \neq \text{null}_a$	$\text{OS-Read} \frac{}{h, {}^r\Gamma, e_0.f \rightsquigarrow h', \iota}$
$\text{MethSig} ::=$		$h_0, {}^r\Gamma, e_2 \rightsquigarrow h_2, \iota$	
$w \in \text{Purity}$	$::=$	$h' = h_2[\iota_0.f := \iota]$	
$e \in \text{Expr}$	$::= \text{OS-Upd} \frac{}{h, {}^r\Gamma, e_0.f = e_2 \rightsquigarrow h',}$		
	$\text{Expr.MethId} \langle \overline{{}^s\text{Type}} \rangle (\text{Expr}) \mid$		$\Gamma \vdash e_0 : N_0 \quad N_0 = u_0 \ C_0 \langle _ \rangle$
	$\text{new } {}^s\text{Type} \mid ({}^s\text{Type}) \text{ Expr}$		$T_1 = fType(C_0, f)$
${}^s\Gamma \in {}^s\text{Env}$	$::= \overline{\text{TVarId } {}^s\text{NType}; \text{ParId } {}^s\text{Type}}$		$\Gamma \vdash e_2 : N_0 \triangleright T_1$
		$\text{GT-Read} \frac{\Gamma \vdash e_0 : N_0 \quad N_0 = _}{\Gamma \vdash e_0.f : N_0 \triangleright fType(C_0, f)}$	$\text{GT-Upd} \frac{u_0 \neq \text{any} \quad rp(u_0, T_1)}{\Gamma \vdash e_0.f = e_2 : N_0 \triangleright T_1}$
$h \vdash {}^r\Gamma : {}^s\Gamma$			
$h \vdash \iota_1 : \text{dyn}({}^sN, h, \iota_1)$			
$h \vdash \iota_2 : \text{dyn}({}^sT, \iota_1, h(\iota_1) \downarrow_1)$			
${}^sN = u_N \ C_N \langle _ \rangle$			
$u_N = \text{this}_u \Rightarrow {}^r\Gamma(\text{this})$			
$\text{free}({}^sT) \subseteq \text{dom}(C_N)$			
$\text{DYN} \frac{}{\text{dyn}({}^sT, \iota, {}^rT, (\overline{X} \ ^rT'; _) = {}^sT[\iota'/\text{this}, \iota'/\text{peer}, \iota/\text{rep}, \text{any}_a/\text{any}_n, {}^rT/\overline{X}, {}^rT'/\overline{X'}]}$			

Practicality

Testing

Built-in Type
Systems



Pluggable
Type Systems

Formal
Verification

Guarantees 49

Demo: regular expression errors

@Regex = valid regular expression

OK: "colou?r"

NOT: "1) first point"

@Regex(2) = has 2+ capturing groups

OK: "((Linked)?Hash)?Map"

OK: "(http|ftp)://([^/]+)(/.*)?"

NOT: "(brown|beige)"



Regular Expression Example

```
public static void main(String[] args) {  
    String regex = args[0];  
    String content = args[1];  
    Pattern pat = Pattern.compile(regex);  
    Matcher mat = pat.matcher(content);  
    if (mat.matches()) {  
        System.out.println("Group: " + mat.group(1));  
    }  
}
```



Regular Expression Example

```
public static void main(String[] args) {  
    String regex  
    String content  
    Pattern pat = Pattern.compile(regex);  
    Matcher mat = pat.matcher(content);  
    if (mat.matches())  
        System.out.println("Group: " + mat.group(1));  
}
```

PatternSyntaxException

IndexOutOfBoundsException



Fixing the Errors

`Pattern.compile` only on valid regex

`Matcher.group(i)` only if $> i$ groups

...

```
if (!RegexUtil.isRegex(regex, 1)) {  
    System.out.println("Invalid: " + regex);  
    System.exit(1);  
}
```



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 @NotEmpty [] 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)



Checker Framework facilities

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



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?

What operations are legal and illegal?



Example: Nullness Checker

What runtime exceptions to prevent?

NullPointerException

What properties of data should always hold?

What operations are legal and illegal?



Example: Nullness Checker

What runtime exceptions to prevent?

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What properties of data should always hold?

@NonNull references always non-null

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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?

What operations are legal and illegal?



Example: Regex Checker

What runtime exceptions to prevent?

PatternSyntaxException,
IndexOutOfBoundsException

What properties of data should always hold?

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?



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,



New type system

What runtime exceptions to prevent?

1

What properties of data should always hold?

2

What operations are legal and illegal?

3



New type system

What runtime exceptions to prevent?

1

What properties of data should always hold?

2

What operations are legal and illegal?

3



New type system

What runtime exceptions to prevent?

1

What properties of data should always hold?

2

What operations are legal and illegal?

3



New type system

What runtime exceptions to prevent?

1

What properties of data should always hold?

2

What operations are legal and illegal?

3



New type system

What runtime exceptions to prevent?

1

What properties of data should always hold?

2

What operations are legal and illegal?

3



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 {}
```



Encrypted Checker Demo

Let's build it!



Testing infrastructure

jtreg-based testing as in OpenJDK

Lightweight tests with in-line expected errors:

```
String s = "%+s%";  
//:: error: (format.string.invalid)  
f.format(s, "illegal");
```



Defining a type system

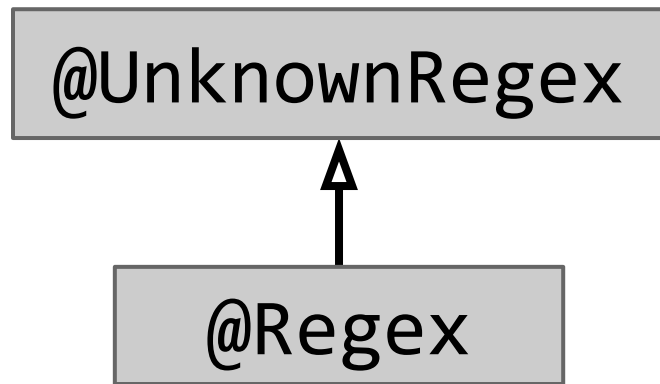
1. Qualifier hierarchy
 - defines subtyping
2. Type introduction rules
 - types for expressions
3. Type rules
 - checker-specific errors
4. Flow-refinement
 - better types than the programmer wrote



Defining a type system

1. Qualifier hierarchy
 - subtyping, assignments

```
@SubtypeOf(UnknownRegex.class)  
public @interface Regex {
```



Defining a type system

- 2. Type introduction rules
 - types for expressions

```
Data d = new Data();
```

```
@ImplicitFor( trees = {  
    Tree.Kind.NEW_CLASS,  
    Tree.Kind.NEW_ARRAY, ... })
```

```
@DefaultQualifierInHierarchy
```

```
@DefaultForUnannotatedCode({  
    DL.PARAMETERS, DL.LOWER_BOUNDS })
```



Defining a type system

3. Type rules

- checker-specific errors

```
synchronized(xxx) {  
}
```

```
void visitSynchronized(SynchronizedTree node) {  
    ExpressionTree expr = node.getExpression();  
    AnnotatedTypeMirror type =  
        getAnnotatedType(expr);  
    if (!type.hasAnnotation(NONNULL))  
        checker.report(Result.failure(...), expr);  
}
```



Defining a type system

4. Flow-refinement

- better types than the programmer wrote

```
if (x != null) {  
    x.f = ...; // valid
```

```
if (ElementUtils.matchesElement(method,  
    IS_REGEX_METHOD_NAME,  
    String.class, int.class)) {  
    ...  
}
```



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!



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



Checker Framework Community

Open source project:

<https://github.com/type-tools/checker-framework>

- Monthly release cycle
- >13,000 commits, 75 authors
- Welcoming & responsive community
- Google Summer-of-Code participant



Checker Framework plans

More type systems:

- Immutability
- Index-out-of-bounds
- `Optional<T>` type
- Determinism
- Signed vs. unsigned numbers

Type inference

Combined static & dynamic enforcement



Pluggable type-checking improves code

Checker Framework for creating type checkers

- Featureful, effective, easy to use, scalable

Prevent bugs at compile time

Create custom type-checkers

Improve your code!

<http://CheckerFramework.org/>

