The Checker Framework: pluggable static analysis for Java

http://CheckerFramework.org/

@CheckerFrmwrk on Twitter
CheckerFramework on Facebook & Google+

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Joint work with Michael D. Ernst and many others.

Outline

- Pluggable type-checking
- Architecture overview
  - Java 8 syntax for Type Annotations
  - Dataflow Framework
  - Checker Framework
- Our experience
  - Case Studies
  - SPARTA: Android Security
  - VeriGames: Crowd-sourced Verification Games
- Writing your own type system

Java's type system is too weak

Type checking prevents many errors

```
int i = “hello”; // error
```

Type checking doesn't prevent enough errors

```
System.console().readLine();
Collections.emptyList().add(“one”);
dbStatement.executeQuery(userData);
```

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Type checking c ors

NullPointerException

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Java's type system is too weak

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```
System
Collections.emptyList().add(“one”);
dbStatement.executeQuery(userData);
```

UnsupportedOperationException

Java's type system is too weak

Type checking prevents many errors

```
int i = “hello”; // error
```

Type checking doesn't prevent enough errors

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

Collections

dbStatement.executeQuery(userData);
```

SQL Injection Attacks!

Static types: not expressive enough

Null pointer exceptions

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

Many other properties can't be expressed

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);
```

Where is the error?

Solution 1: Restrict use

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

Solution 2: Restrict implementation

```
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
- Reduce number of run-time checks

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

Extended type systems

- Null pointer exceptions (ICSE SEIP'11)
- Energy consumption (PLDI'11)
- Unwanted side effects (OOPSLA'04, '05, '12, ECOOP'08, ESEC/FSE’07)
- Unstructured heaps (ECOOP'07, '11, '12)
- Malformed input (FTfJP'12)
- UI actions not on event thread (ECOOP'13)
- Information leakage (CCS’14)

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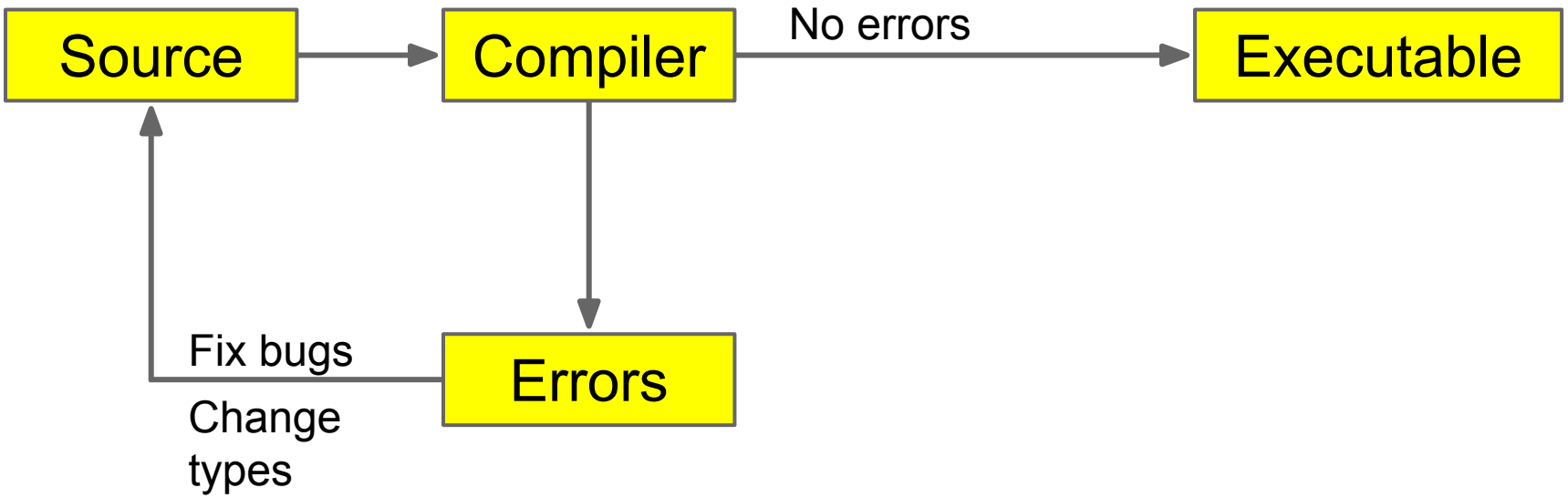
The Checker Framework

A framework for pluggable type checkers
“Plugs” into the OpenJDK compiler

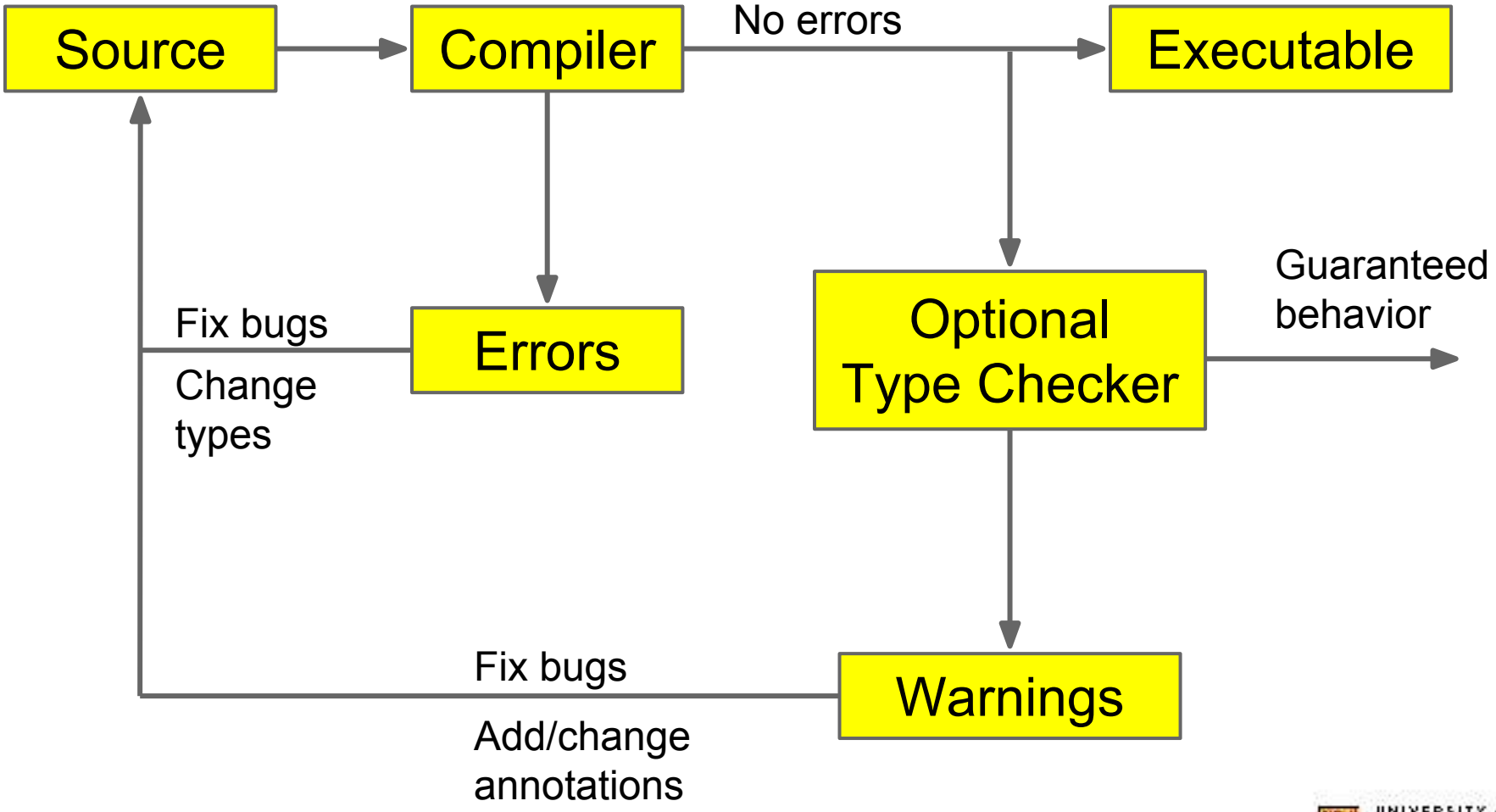
```
javac -processor MyChecker ...
```

Eclipse plug-in, Ant and Maven integration

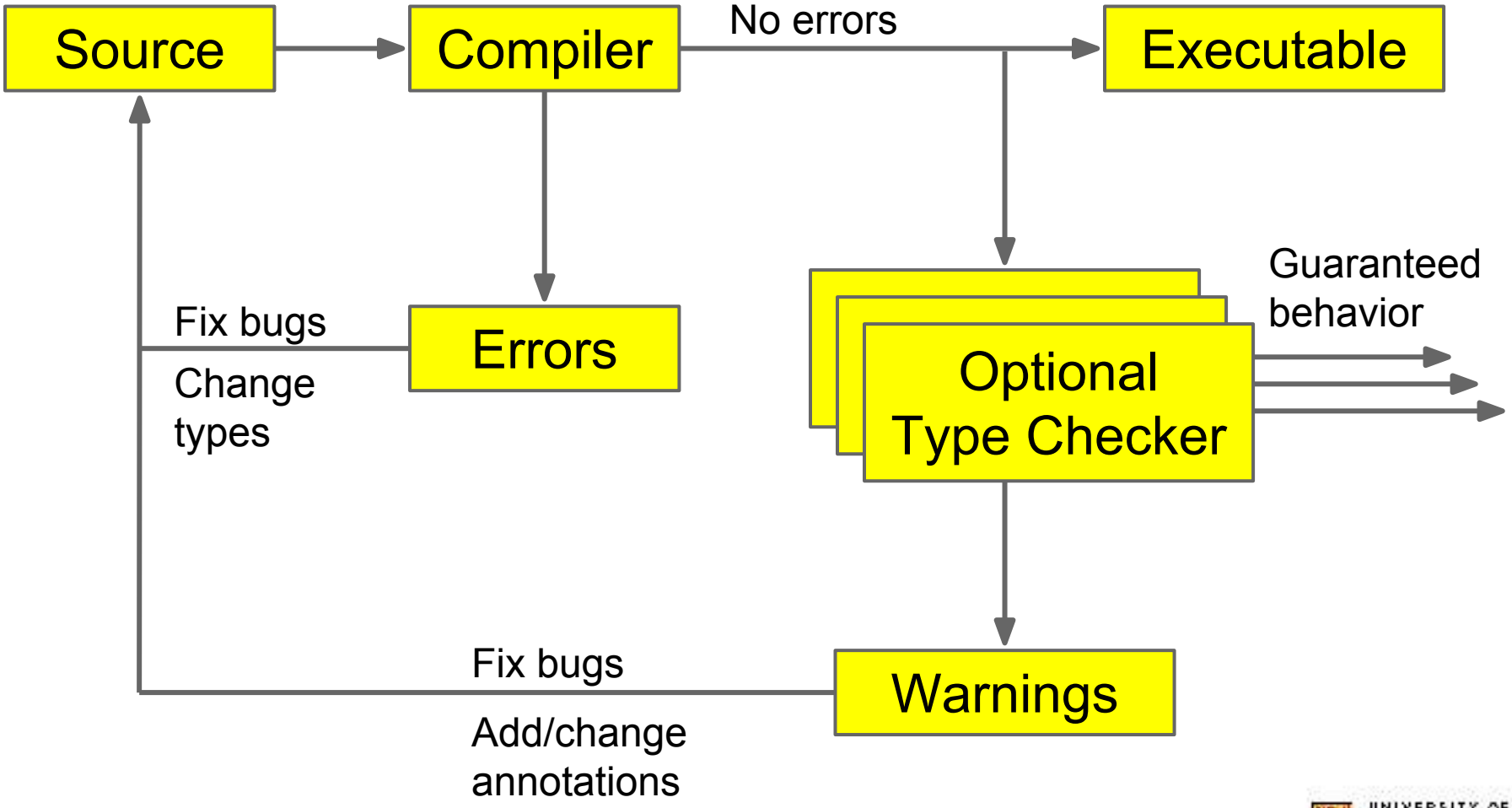
Type Checking



Optional Type Checking



Optional Type Checking



What bugs can you detect & prevent?

The property you care about:	The annotation you write:
Null dereferences	`@NonNull`
Mutation and side-effects	`@Immutable`
Concurrency: locking	`@GuardedBy`
Security: encryption,	`@Encrypted`
tainting	`@Untainted`
Aliasing	`@Linear`
Equality tests	`@Interned`
Strings: localization,	`@Localized`
Regular expression syntax	`@Regex`
Signature format	`@FullyQualified`
Enumerations	`@Fenum`
Typestate (e.g., open/closed files)	`@State`

Users can write their own checkers!

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Checker Framework experience

Type checkers reveal important latent defects

Ran on >3 million LOC of real-world open-source code as of early 2011

Found hundreds of user-visible failures

Annotation overhead is low

Mean 2.6 annotations per kLOC

    20 annotations per kLOC for Nullness Checker

[Dietl et al. ICSE'11]

Formalizations

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

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

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

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

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

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

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

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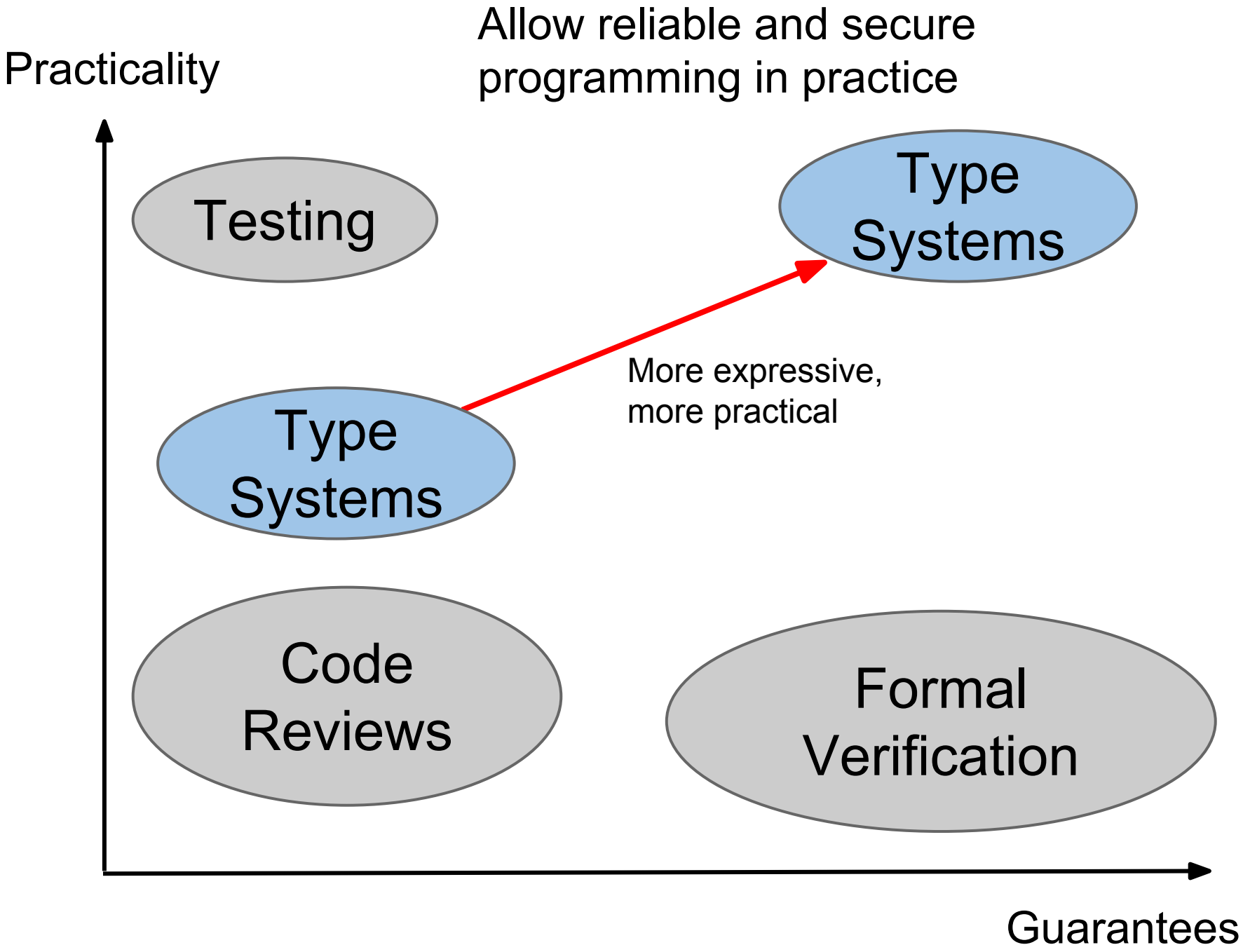
Allow reliable and secure programming in practice
Practicality
Testing
Type Systems
More expressive, more practical
Type Systems
Code Reviews
Formal Verification
Guarantees

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  - Java 8 syntax for Type Annotations
  - Dataflow Framework
  - Checker Framework
- Our experience
  - Case Studies
  - SPARTA: Android Security
  - VeriGames: Crowd-sourced Verification Games
- Writing your own type system

Project overview

Java 8 type annotation feature

jsr308-langtools extensions

annotation-tools

checker-framework

- javacutils
- dataflow
- stubparser
- framework
- checker: 18 default type systems

checker-framework-inference

Project overview

Java 8 type annotation feature

jsr308-langtools extensions

annotation-tools

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- javacutils
- **dataflow**
- stubparser
- **framework**
- checker: 18 default type systems

checker-framework-inference

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, …

Explicit method receivers

```
class MyClass {
  int foo(@TParam String p) {…}
  int foo(@TRecv MyClass this,
          @TParam String p) {…}
```

No impact on method binding and overloading

Constructor return & receiver types

Every constructor has a return type

```
class MyClass {
  @TReturn MyClass(@TParam String p) {...}
```

Inner class constructors also have a receiver

```
class Outer {
  class Inner {
    @TReturn Inner(@TRecv Outer Outer.this,
                   @TParam String p) {...}
```

Array annotations

A read-only array of non-empty arrays of English strings:

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

CF has invariant arrays:

- `@NonNull String[]` is unrelated to `@Nullable String[]`

Compare to Java's unsound covariant arrays:

- `String[]` is a subtype of `Object[]`

CF: Java 6 & 7 Compatibility

Annotations in comments

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

Voodoo comments for arbitrary source code

```
/*>>> import myquals.TRecv; */
...
  int foo(/*>>> @TRecv MyClass this,*/
          @TParam String p) {…}
```

CF: Annotating external libraries stub files and annotated JDK

Allows annotating external libraries

- As separate text file (stub file)

  checker-framework/checker/src/…/jdk.astub

- Within its .jar file (from annotated partial source code)

  checker-framework/checker/jdk/...

Dataflow Framework

Initially for flow-sensitive type refinement

Now a project of its own right

1. Translate AST to CFG
   Standard multipass visitor over AST
2. Perform dataflow analysis over CFG with user-provided
   a. Abstract value — What are we tracking?
   b. Transfer functions — What do operations do?
   c. Store — What are intermediate results?
3. Allow queries about result

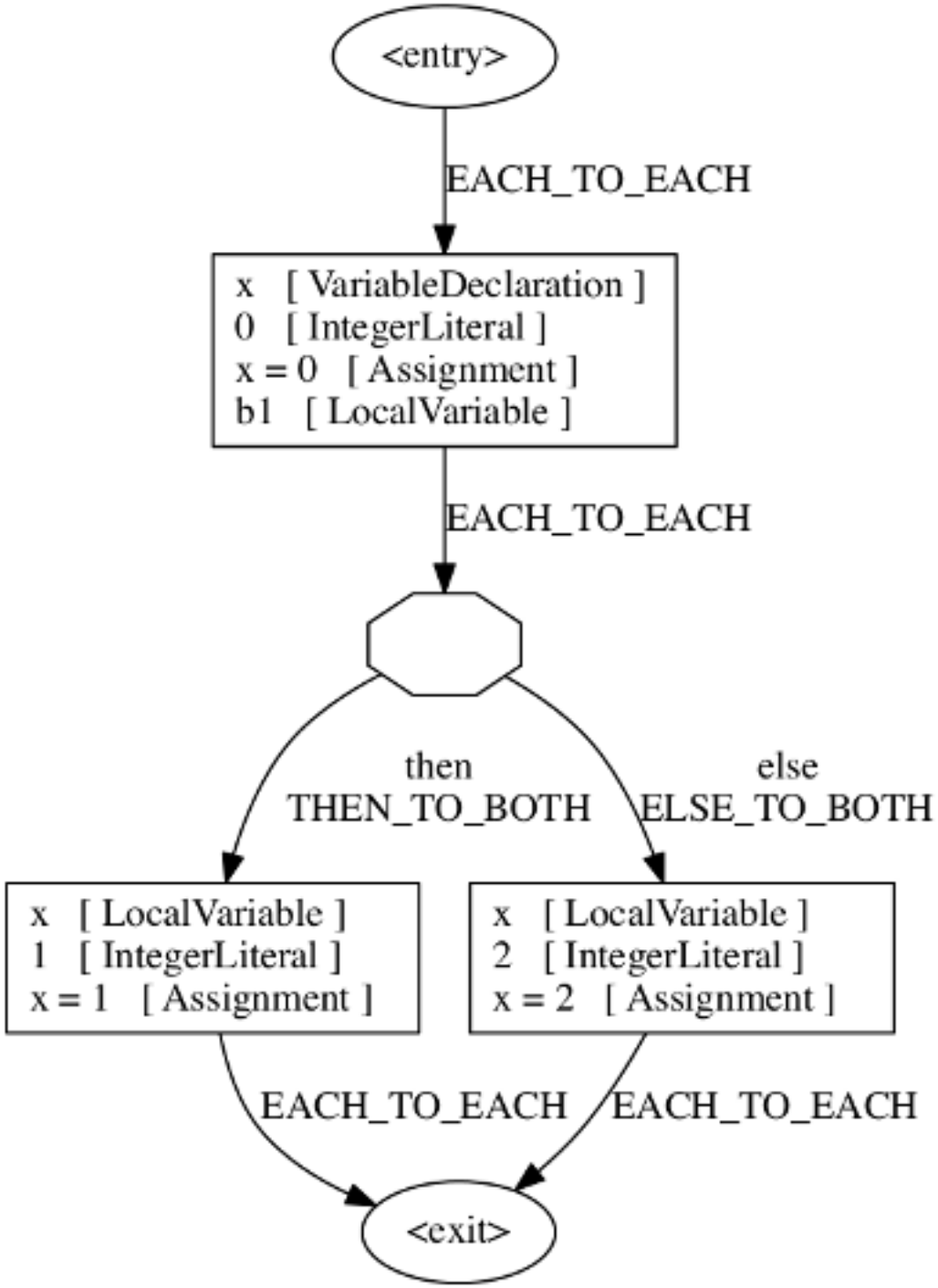
Control Flow Graph

CFG is a graph of basic blocks

- Conditional basic blocks to model conditional control flow
- Exceptional edges

Use type Node for all Java operations and expressions, e.g.,

- StringLiteralNode, FieldAccessNode, etc.
- Make up the content of basic blocks



Properties of the CFG

- Explicit representation of implicit Java constructs
  - Unboxing, implicit type conversions, etc.
  - Analyses do not need to worry about these things
  - All control flow explicitly modeled (e.g. exceptions on field access)
- High-level constructs
  - Close to source language
- Different from other approaches
  - Not three-address-form
  - Analysis is not performed over the AST

Checker Framework - “Framework”

- Full type systems: inheritance, overriding, ...
- Generics (type polymorphism)
  - Also qualifier polymorphism
- Flow-sensitive type qualifier inference
  - Infers types for local variables
  - reusable component
- Qualifier defaults
- Pre-/Post-conditions
- Warning suppression
- Testing infrastructure

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Evaluations

- Checkers reveal important latent bugs
  - Ran on >3 million LOC of real-world code
  - Found 40 user-visible bugs, hundreds of mistakes
- Annotation overhead is low
  - Mean 2.6 annotations per kLOC
- Learning their usage is easy
  - Used successfully by first-year CS majors
- Building checkers is easy
  - New users developed 3 new realistic checkers

SPARTA: Static Program Analysis for Reliable Trusted Apps

Security type system for Android apps
Guarantees no leakage of private information

Part of DARPA's
Automated Program Analysis
for Cybersecurity (APAC)
program

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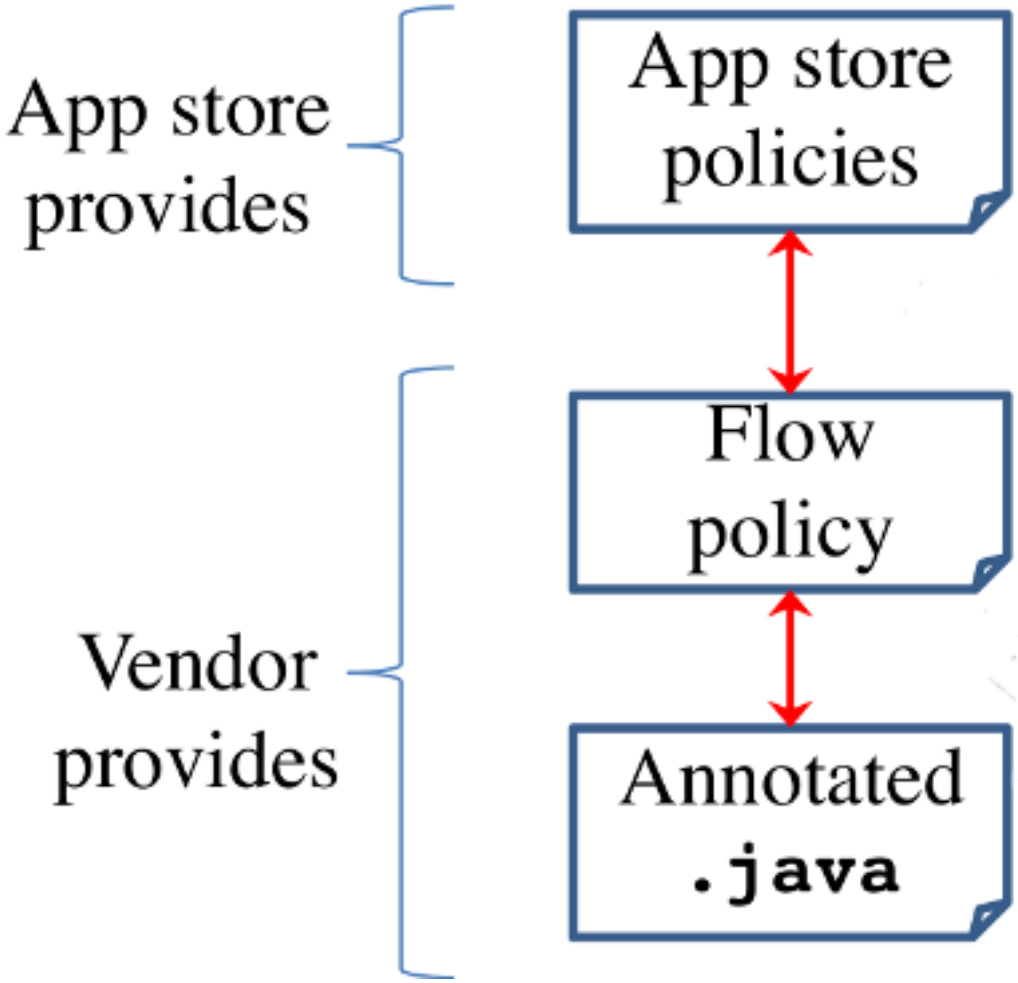
Collaborative Verification



SPARTA: Static Program Analysis for Reliable Trusted Apps

- Software vendor and the app store auditor collaborate on verification task
- Flow-sensitive, context-sensitive information-flow type system
- Red Team provided 72 apps (576 kLOC)
- Detected 96% of information flow malware and 82% of all malware

See ”Collaborative Verification of Information Flow for a High-Assurance App Store” paper at CCS’14

Crowd-sourced verification

Make software verification easy and fun

Make the game accessible to everyone

Harness the power of the crowd

Goal: Verify software while waiting

`http://verigames.com/`

FTfJP'12 paper

Building checkers is easy

Example: Ensure encrypted communication

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

Building checkers 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
   - checker-specific flow properties

Testing Infrastructure

jtreg-based testing as in OpenJDK

Light-weight tests with in-line expected errors:

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

Conclusions

Java 8 syntax for type annotations

Dataflow Framework

Checker Framework for creating type checkers

- Featureful, effective, easy to use, scalable

Prevent bugs at compile time

Create custom type-checkers

Learn more, or download at:

`http://CheckerFramework.org/`