

```
void print(@ReadOnly Object x) {  
    List<@NonNull String> lst;  
    ...  
}
```

# Practical pluggable types via the Checker Framework

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# Problem 1: Java's type checking

- Type checking prevents many bugs

```
int i = "hello"; // type error
```

- Type checking doesn't prevent **enough** bugs

```
java.lang.NullPointerException
```

```
at checkers.util.GraphQualifierHierarchy.isSubtype(GraphQualifierHierarchy.java:21)
at checkers.types.QualifierHierarchy.isSubtype(QualifierHierarchy.java:70)
at checkers.types.TypeHierarchy.isSubtypeImpl(TypeHierarchy.java:100)
at checkers.types.TypeHierarchy.isSubtype(TypeHierarchy.java:64)
at checkers.basetype.BaseTypeChecker.isSubtype(BaseTypeChecker.java:305)
at checkers.basetype.BaseTypeVisitor.commonAssignmentCheck(BaseTypeVisitor.java:48)
at checkers.basetype.BaseTypeVisitor.commonAssignmentCheck(BaseTypeVisitor.java:46)
at checkers.basetype.BaseTypeVisitor.checkArguments(BaseTypeVisitor.java:597)
at checkers.basetype.BaseTypeVisitor.visitMethodInvocation(BaseTypeVisitor.java:27)
at com.sun.tools.javac.tree.JCTree$JCMMethodInvocation.accept(JCTree.java:1315)
at com.sun.source.util.TreePathScanner.scan(TreePathScanner.java:67)
at checkers.basetype.BaseTypeVisitor.scan(BaseTypeVisitor.java:110)
at com.sun.source.util.TreeScanner.visitExpressionStatement(TreeScanner.java:239)
at com.sun.tools.javac.tree.JCTree$JCExpressionStatement.accept(JCTree.java:1155)
at com.sun.source.util.TreePathScanner.scan(TreePathScanner.java:67)
at checkers.basetype.BaseTypeVisitor.scan(BaseTypeVisitor.java:110)
at com.sun.source.util.TreeScanner.scanAndReduce(TreeScanner.java:80)
```

# Problem 1: Java's type checking

- Type checking prevents many bugs

```
int i = "hello";    // type error
```

- Type checking doesn't prevent **enough** bugs
  - Null dereferences
  - Incorrect equality tests
  - Incorrect mutation
  - SQL injection
  - Privacy violations
  - Misformatted data
  - ...

# Solution: Pluggable type systems

- Design a type system to solve a specific problem
- Write type qualifiers in your code (or, type inference)  
`@NonNull Date d = ...;`  
`d.getMonth(); // no possible NPE`
- Type checker warns about violations (bugs)

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

```
MyFile.java:149: dereference of possibly-null reference bb2  
    if (vars1.containsAll(bb2.vars))  
                        ^
```

# Problem 2:

## Implementing pluggable types

- Modify a compiler: hard
- Previous frameworks: too weak
- Alternatives to case studies:
  - Soundness proof for core calculus
  - Toy examples
- Hampers **understanding** and **use** of type systems
- A type system is valuable **only if** it helps developers to find and prevent errors
  - Case studies are necessary



# Example:

## Type systems for immutability

```
println(@ReadOnly Object x) { ... }  
  
@ReadOnly Object[] getSigners() { ... }  
  
Map<@Immutable Date, Object> cache;
```

- Formalisms, proofs, etc.
- Crucial insight from case studies
  - Javari type system [Birka 2004]: 160 KLOC
  - IGJ type system [Zibin 2007]: 106 KLOC
- Larger case studies have revealed even more

# Solution: The Checker Framework

- Enables creation of **pluggable types** for Java
- **Expressive**
  - Can create realistic type systems
- **Concise**
  - Most checks are built in
  - Declarative syntax for common cases
- **Scalable**
  - Large programs
  - Full Java language
  - Java toolchain
- Aids **programmers** and **type system designers**

# Contributions

- **Syntax** for type qualifiers in Java
- **Checker Framework** for writing type checkers
- **5 checkers** written using the framework
- **Case studies** enabled by the infrastructure
- **Insights** about the type systems



# Syntax for type qualifiers

- Java 7: annotate any use of a type

```
List<@NonNull String> myStrings;  
  
myGraph = (@Immutable Graph) tmpGraph;  
  
class UnmodifiableList<T>  
    implements @ReadOnly List<@ReadOnly T> {}
```

- Backward-compatible: compile with any Java compiler

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

# Tool integration

- IDE support: javac, Eclipse, Netbeans
  - IntelliJ planned
- Annotated JDK
- Type inference: 3 tools
- Building type checkers:
  - ETH Zurich, MIT, Radboud U., U. of Buenos Aires, U. of California at Los Angeles, U. of Saarland, U. of Washington, U. of Wisconsin – Milwaukee, Washington State U., ...
- Integrating with other tools:
  - IBM, INRIA, JetBrains, MIT, Oxford, Sun, Victoria University of Wellington, ...

# Outline

- Syntax for type qualifiers in Java
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# A complete, useful type checker

```
@TypeQualifier
@SubtypeOf(Unqualified.class)
public @interface Encrypted { }
```

To use it:

1. Write `@Encrypted` in your program

```
void send(@Encrypted String message) { ... }
```

2. Compile your program

```
javac -processor BasicChecker -Aquals=Encrypted  
MyProgram.java
```

# Built-in features

- Arbitrary type qualifier hierarchy
- Subtyping: inheritance, overriding, assignment
- Polymorphism
  - Types (Java generics)
  - Type qualifiers
- Type qualifier inference (flow-sensitivity)
- Implicit and default qualifiers
- ...

# Defining a type system

**@TypeQualifier**

```
public @interface NonNull { }
```

# Defining a type system

1. Type qualifier hierarchy
2. Type introduction rules
3. Other type rules

**@TypeQualifier**

```
public @interface NonNull { }
```

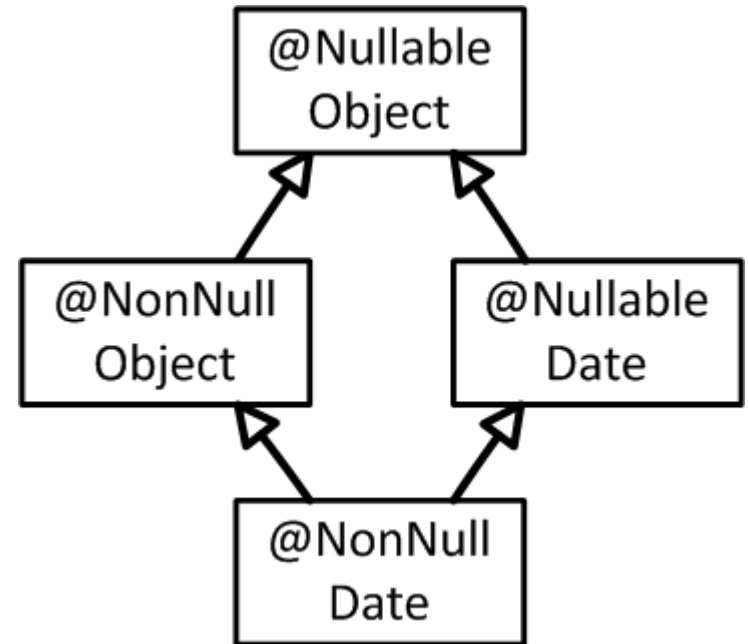
# Defining a type system

1. Type qualifier hierarchy
2. Type introduction rules
3. Other type rules

`@TypeQualifier`

`@SubtypeOf( Nullable.class )`

```
public @interface NonNull { }
```





# Defining a type system

1. Type qualifier hierarchy
2. **Type introduction rules**
3. Other type rules

```
new Date()  
"hello " + getName()  
Boolean.TRUE
```

```
@TypeQualifier
```

```
@SubtypeOf( Nullable.class )
```

```
@ImplicitFor(trees={ NEW_CLASS,  
                     PLUS,  
                     BOOLEAN_LITERAL, ... } )
```

```
public @interface NonNull { }
```

# Defining a type system

1. Type qualifier hierarchy
2. Type introduction rules
3. Other type rules

```
synchronized(expr) {  
    ...  
}
```

Warn if expr  
may be null

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

# Type refinement

```
Date d1, d2, d3;    // may be null
d1 = new Date();
d1.getMonth();     // OK: d1 is non-null
assert d2 != null;
d2.getMonth();     // OK
if (d3 != null) {
    d3.getMonth(); // OK
}
```

Type-checks as if annotations/casts were present  
“Local flow-sensitive type qualifier inference”

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# Sample type checkers

- Basic checker (subtyping)
- Null dereferences (@NonNull)
- Errors in equality testing (@Interned)
- Reference immutability (Javari)
- Reference & object immutability (IGJ)

< 500 LOC per checker

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# Case studies

- Annotated existing Java programs
- Found bugs in every codebase
  - Verified by a human and fixed
- As of summer 2007: 360 KLOC
  - Now: > 1 MLOC
  - Scales to > 200 KLOC

# Checkers are easy to use

- Natural part of workflow
- Feels like Java
- Few false positives
  - Easy to understand and fix



# Annotations are not too verbose

- Examples:
  - Nullness: 1 per 75 lines
  - Interning: 124 in 220 KLOC revealed 11 bugs
- Careful choice of defaults
- Type refinement
- Possible to annotate part of program
- Fewer annotations in new code

# Comparison: other Nullness tools

	Null pointer errors		False warnings	Annotations written
	Found	Missed		
Checker Framework	8	0	4	35
FindBugs	0	8	1	0
Jlint	0	8	8	0
PMD	0	8	0	0

- Checking a 4KLOC program
- The other tools find bugs besides null dereferences

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# Lessons learned

- Type systems
  - Interning
  - Nullness
  - Javari
  - IGJ
- Polymorphism
- Framework design
- Others: supertype qualifiers, simple type systems, inference, syntax, language integration, toolchain, ...

# Interning type system

- New approach to finding equality errors
  - Purely type system
  - Fully backward compatible
  - Permits both interned and uninterned instances

# Nullness type system

- New default: non-null except locals (NNEL)

- Signatures: non-null

- Locals: nullable

- Inspired by practical use

- Exploits flow sensitivity

- Applicable to other type systems

Default	# annotations	Ratio
@Nullable	382	11
@NonNull	80	2.3
NNEL	35	1.0

- Nullness differs from other type systems

- More application invariants

- Run-time checks

- Needs flow-sensitivity

# Javari type system

- Enhancements:

- Permit covariant method parameters

```
class Super { void mymethod(Object x); }
```

```
class Sub   { void mymethod(@ReadOnly Object x); }
```

- Improved type parameter inference

- Improved treatment of fields

# IGJ type system

- Need class, object, and reference immutability
- IGJ weakness: visitor pattern and callbacks
- In SVNKit:
  - Getters have side effects
  - Setters have no side effects



# Polymorphism

- Multiple varieties:
  - Type polymorphism (Java generics including wildcards)
  - Qualifier polymorphism (different context sensitivity)
  - Containing-object context (deep immutability)
- Qualifier polymorphism: one qualifier is enough
  - Linear-time inference (with flow- & context-sensitivity)
- Polymorphism dominated all other problems
  - Type system, design, and implementation challenges
  - Evaluation **cannot** ignore generics

# Framework design

- Checker and compiler are decoupled
- All type rules are written in Java
  - Integrated declarative and procedural mechanisms
- Procedural code is necessary
  - Don't automate the type systems of yesterday
- Representation of annotated types
- Framework is good for more than type checking

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# Related work

- JavaCOP [Andreae 2006]
  - Pattern-matching syntax, requires Java helper methods
  - No Java generics, not scalable, no realistic evaluation yet
- JQual [Greenfieldboyce 2007]:
  - Inference framework, same basic rules as [Tschantz 2006]
  - No Java generics, limited expressiveness, no checker, not precise, not sound
- JavaCOP and JQual authors attempted to implement Javari
  - Only 1 out of 5 keywords, incorrect method overriding
- JastAdd [Ekman 2007]
  - Extensible compiler framework
  - Not concise

# Contributions

- Checker Framework for creating type checkers
  - Robust, scalable, easy to use
  - Demos available
  - <http://pag.csail.mit.edu/jsr308>
- For **programmers**: prevents errors
- For **type system designers**:
  - Enables construction & evaluation of type systems
  - Yields insight into type systems