```
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$JCMethodInvocation.accept(JCTree.java:1315)
  at com.sun.source.util.TreePathScanner.scan(TreePathScanner.java:67)
  at checkers.basetype.BaseTypeVisitor.scan(BaseTypeVisitor.java:110)
  at com.sun.source.util.TreeScanner.visitExpressionStatement(TreeScanner.java:239)
  at com.sun.tools.javac.tree.JCTree$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, …

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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
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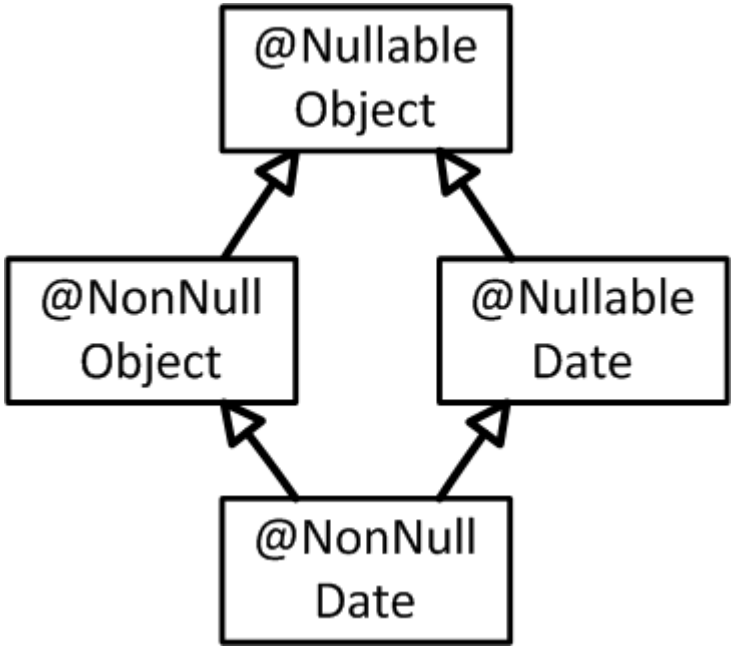
3. Other type rules




```
@TypeQualifier
@SubtypeOf( Nullable.class )
public @interface NonNull { }
```

Defining a type system

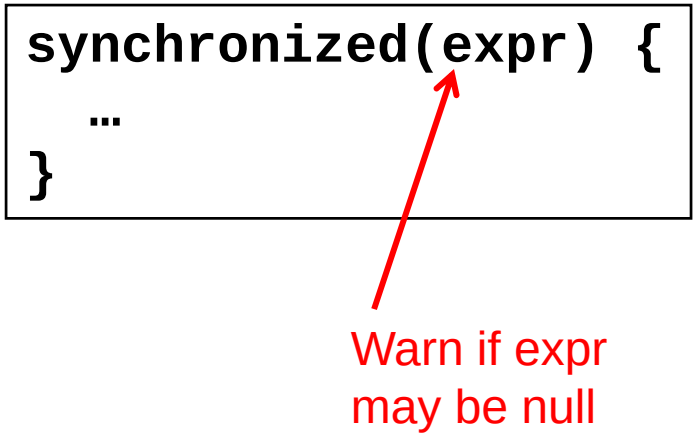
1. Type qualifier hierarchy
2. Type introduction rules
3. Other type rules

```
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




```
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	# anno-tations	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