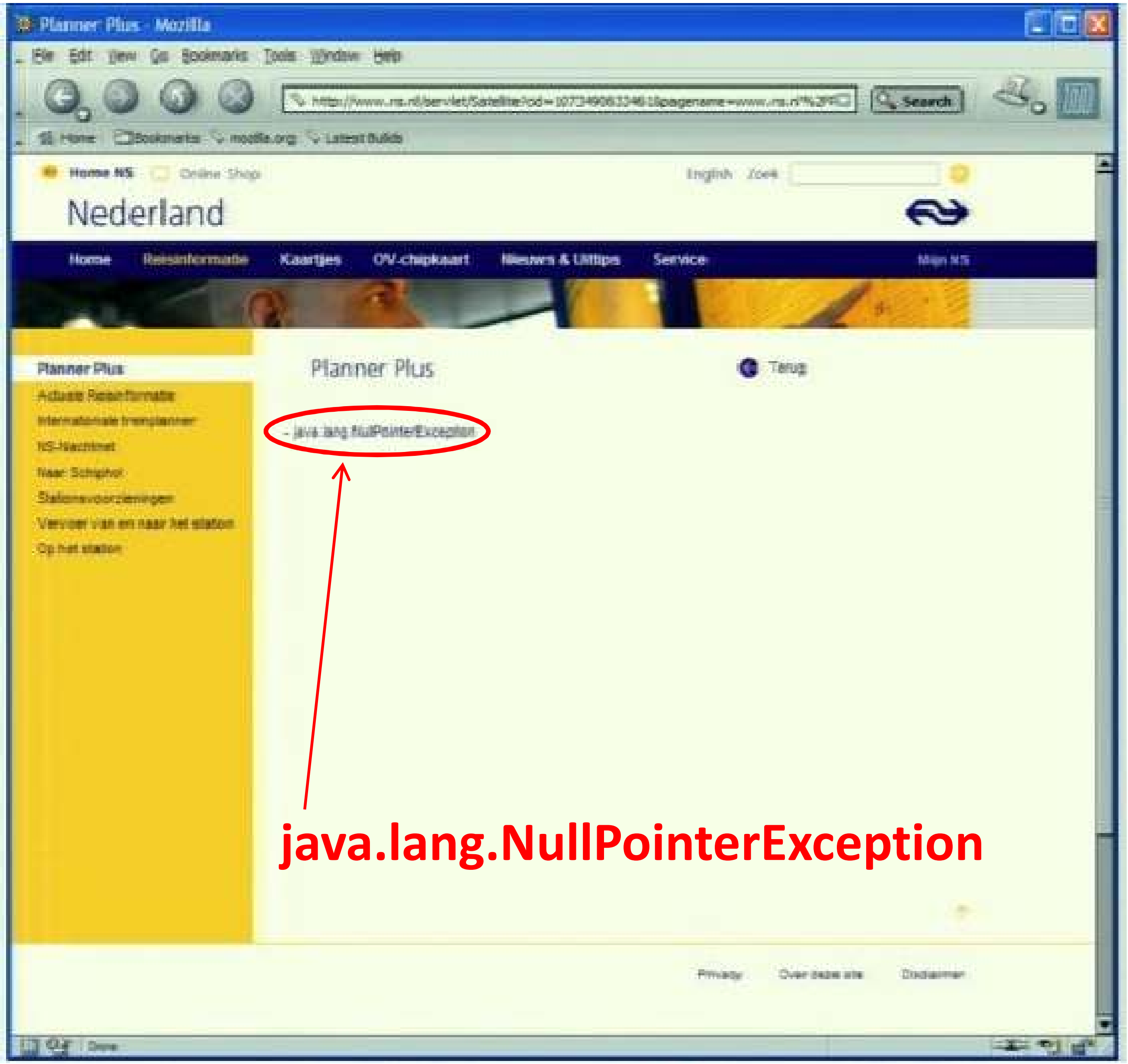
```
print(@Readonly Object x) {
  List<@NonNull String> lst;
  …
}
```

Detecting and preventing null pointer errors with pluggable type-checking

CSE 331
University of Washington

Motivation


Planner Plus - Mozilla
File Edit View Go Bookmarks Tools Window Help
Home NS
Online Shop
English
Zoek
Nederland
Home
Reisinformatie
Kaartjes
OV-chipkaart
Nieuws & Uittips
Service
Planner Plus
Terug
- java.lang.NullPointerException
java.lang.NullPointerException
Privacy
Over deze site
Disclaimer

Java's type checking is too weak

- Type checking prevents many bugs

```
int i = "hello";     // type mismatch
myString.getDate(); // method not found
```

- Type checking doesn't prevent enough bugs

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

$\Rightarrow$ NullPointerException

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

$\Rightarrow$ UnsupportedOperationException

Some errors are silent

```
Date date = new Date(0);
myMap.put(date, "Java epoch");
date.setYear(70);
myMap.put(date, "Linux epoch");
```

$\Rightarrow$ Corrupted map

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

$\Rightarrow$ SQL injection attack

Initialization, data formatting, equality tests, …

Problem: Your code has bugs

- Who discovers the problems?

  - If you are very lucky, testing discovers (some of) them
  - If you are unlucky, your customer discovers them
  - If you are very unlucky, hackers discover them
  - If you are smart, the compiler discovers them
- It's better to be smart than lucky

Type indicates legal operations

- Type checking prevents many bugs

```
int i = "hello";
myString.getDate();
```

- Goal: avoid NullPointerException
- Idea: use types to indicate legality
- Consider references (pointers) as an ADT
  - Operation: dereferencing

    `x.field`, `x.method()`

Types for null pointer prevention

Replace **`Object`** by two new types

- **`NonNullObject`**

  Dereference is permitted

  ```
  NonNullObject nn;
  nn.field
  nn.method()
  ```

- **`PossiblyNullObject`**

  Dereference is forbidden

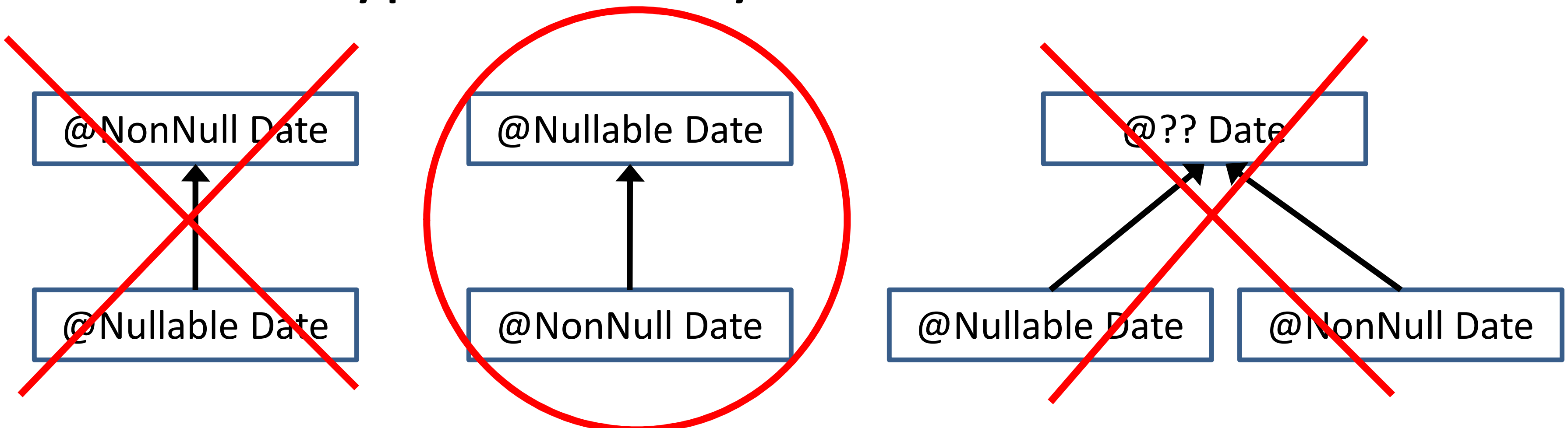
  ```
  PossiblyNullObject pn;
  pn.field        // compile-time error
  pn.method()     // compile-time error
  ```

Problems:

- Can you use PossiblyNullObject for anything?
- Must rewrite all your Java applications and libraries

Types for null-pointer-prevention

- Which type hierarchy is best?



- A subtype has fewer values
- A subtype has more operations
- A subtype is substitutable
- A subtype preserves supertype properties

Type qualifiers

- **Java 8**: annotations on types

```
@Untainted String query;
List<@NonNull String> strings;
myGraph = (@Immutable Graph) tmpGraph;
class UnmodifiableList<T>
  implements @Readonly List<@Readonly T> {}
```

- **Backward-compatible**: compile with any Java compiler

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

Compile-time checking

1. Write type qualifiers in code

```
@NonNull Date date1 = new Date();
@Nullable Date date2 = null;
```

2. Type checker warns about violations (bugs)

```
date1.setTime(70);     // OK
date2.setTime(70);     // compile-time error
```

Benefits of type qualifiers

- **Find bugs** in programs
- Guarantee the **absence of errors**
- **Improve documentation**
- Improve code structure & maintainability
- Aid compilers, optimizers, and analysis tools
- Reduce number of assertions and run-time checks

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

Pluggable type-checking demo

- Detect errors
- Guarantee the absence of errors
- Verify the correctness of optimizations

What bugs can you find & prevent?

	The annotation you write:
• Null dereferences	**`@NonNull`**
• Mutation and side-effects	**`@Immutable`**
• Concurrency: locking	**`@GuardedBy`**
• Security: encryption, tainting	**`@Encrypted`** **`@Untainted`**
• Aliasing	**`@Linear`**
• Equality tests	**`@Interned`**
• Strings: localization, regular expression syntax	**`@Localized`** **`@Regex`**
• Typestate (e.g., open/closed files	**`@State`**
• You can write your own checker!	

Using a checker

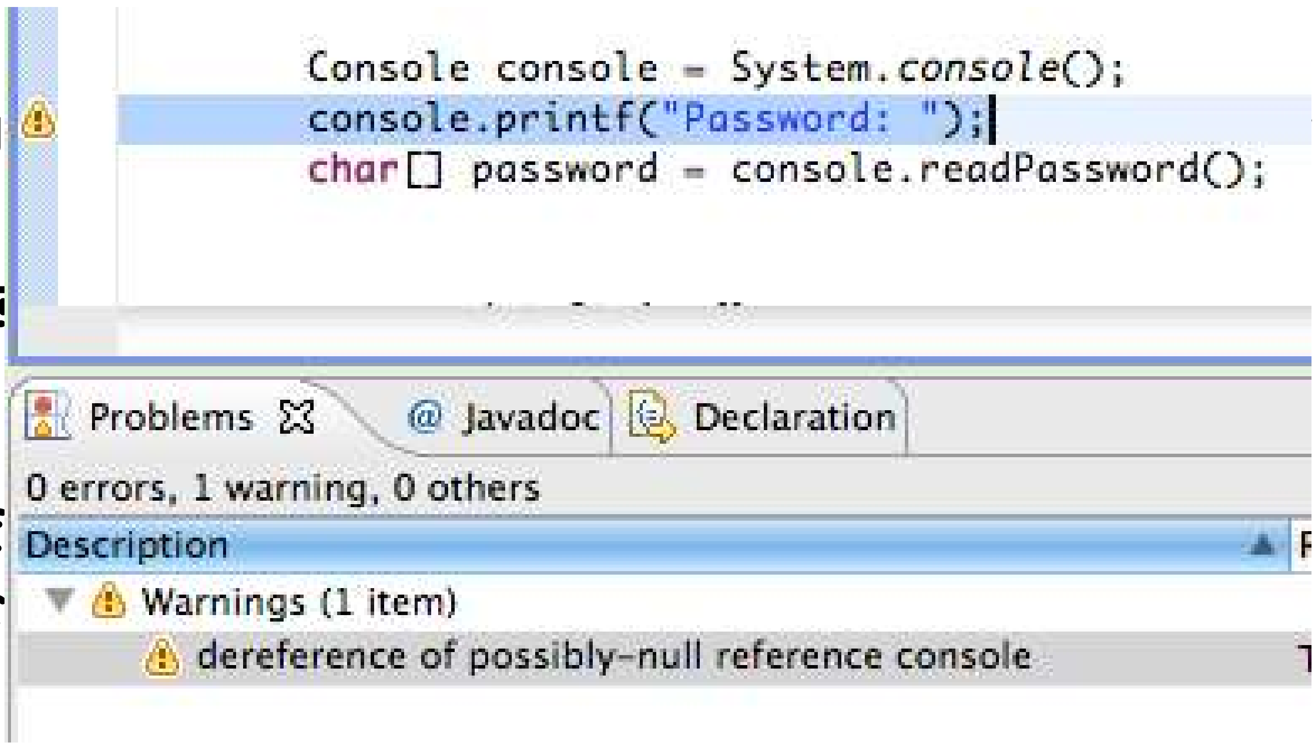
- Run in IDE or on command line
- Works as a compiler plug-in (annotation processor)
- Uses familiar error messages

% j File.java

MyF

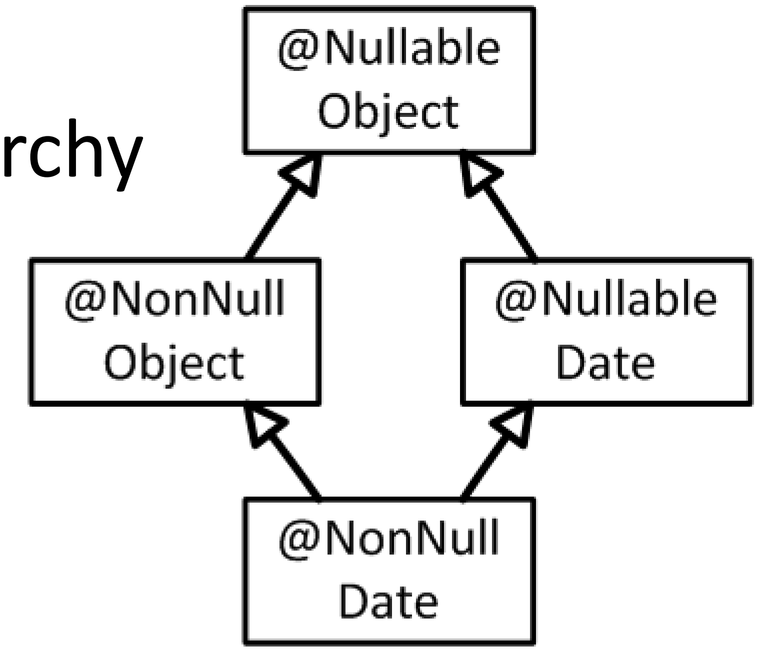
f

r



What is checked

- Proper use of the type hierarchy
  – assignments
  – method calls and returns
  – overriding



- Proper use of methods and operations
  – No dereferences of possibly-null values

What the checker guarantees

- Program satisfies type property
  - no bugs (of particular varieties)
  - no wrong annotations
- Caveat 1: only for code that is checked
  - Native methods
  - 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

Static and dynamic typing

- Static typing
  - Compiler guarantees that some errors cannot happen
    - The set of errors depends on the language
    - Other errors are still possible!
  - Examples: C, C++, Objective C, Java, C#, ML, Haskell
- Dynamic typing
  - The run-time system keeps track of types, and throws errors
  - Examples: Lisp, Scheme, Perl, PHP, Python, Ruby, JavaScript
- No type system
  - Example: Assembly

Why we ♥ static typing

- Documentation
- Correctness/reliability
- Refactoring
- Speed

Why we ♥ dynamic typing
(= Why we  static typing)

- More concise code
  - Type inference is possible
- No false positive warnings

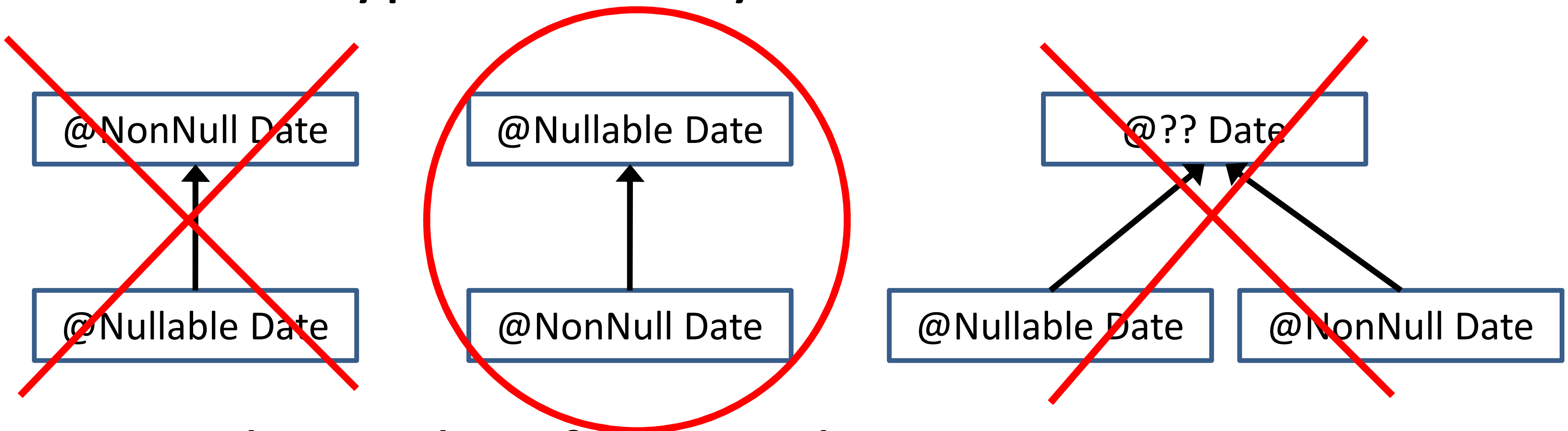
  Every static type system rejects some correct programs

```
@NonNull String lineSep
      = System.getProperty("line.separator");
```

- More flexible code
  - Add fields at run time
  - Change class of an object
- Ability to run tests at any time
  - Feedback is important for quality code
  - Programmer knows whether
    static or dynamic feedback is best

Nullness subtyping relationship

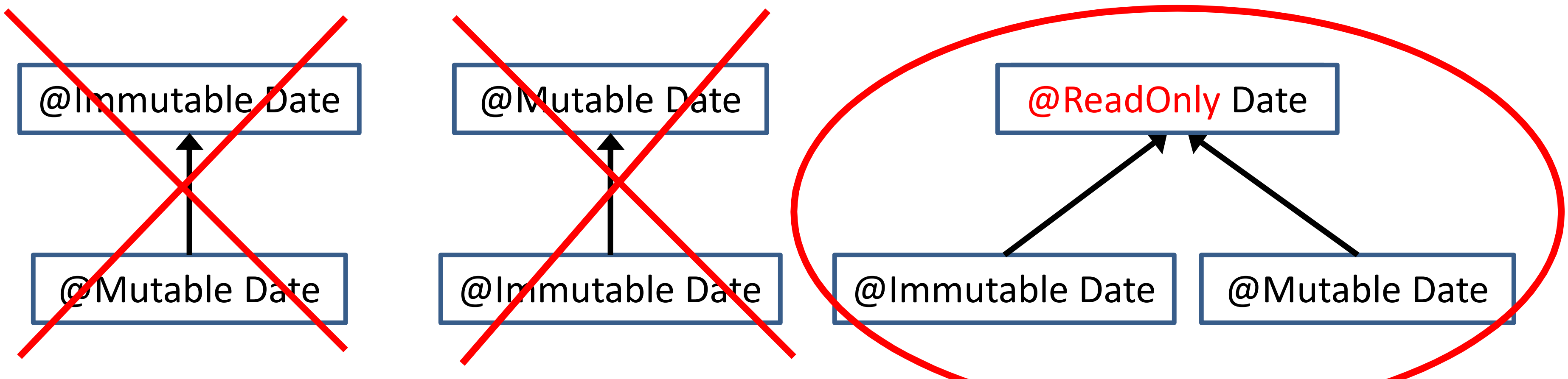
- Which type hierarchy is best?



- A subtype has fewer values
- A subtype has more operations
- A subtype is substitutable
- A subtype preserves supertype properties

Mutability subtyping relationship

- Which type hierarchy is best?



@Immutable: no one can do mutation

@Mutable: anyone can do mutation

@ReadOnly

- I can’t do mutation
- No guarantee about mutation from elsewhere

Advanced features

Avoiding the limitations of the conservative, static type-checker

Flow sensitivity

- Control <u>flow</u> determines the type

```
if (x==null) {
  ... // treat as nullable
} else {
  ... // treat as non-null
}
```

- Can refine the type to a subtype

More flow sensitivity

- Which calls type-check? Which calls ought to?

```
Object name;
name = new Object();
name.toLowerCase();
name = "HELLO";
name.toLowerCase();
name = new Object();
name.toLowerCase();
```

```
@Nullable String name;
name = null;
name.toLowerCase();
name = "HELLO";
name.toLowerCase();
name = null;
name.toLowerCase();
```

Flow sensitivity: permitted changes

Legal changes: change to a subtype

`@Nullable String name;`
`name = “hello”;`
`. . .` // treat **name** as non-null
	`@Nullable String name;`
	`name = otherNullable;`
	`. . .` // treat **name** as nullable

Illegal changes: change to a supertype

Violates the declaration

`String name;`
`name = new Object();`
`. . .` // treat **name** as `Object`
	`@NonNull String name;`
	`name = null;`
	`. . .` // treat **name** as nullable

Local type inference

Bottom line:

Rarely write annotations on local variables

Default for nullness checker:

Non-null except locals

Locals default to nullable (top of hierarchy)

Flow-sensitivity changes this as needed

The receiver is just another parameter

How many arguments does **`Object.equals`** take?

```
class MyClass {
  @Override
  public boolean equals(Object other) { … }
}
```

Two! Their names are **`this`** and **`other`**

Neither one is mutated by the method

- Java 8 syntax:

Optional syntax, for annotations

```
public boolean
equals(@Readonly MyClass this, @ReadOnly Object other) {…}
```

- Syntax in current tool:

Annotation on type of **`other`**

Annotation on type of **`this`**

```
public boolean equals(@ReadOnly Object other) @ReadOnly {…}
```

Find the potential null pointer error

```
class C {
  @Nullable Object currentObj;

  // If currentObj is non-null,
  // prints it and a timestamp
  void printCurrent() {
    if (currentObj != null) {
      System.out.println(this.getTimeStamp());
      System.out.println(currentObj.toString());
    }

  Object getTimeStamp() { … }
}
```

Lack of side effects

```
class C {
  @Nullable Object currentObj;

  // If currentObj is non-null,
  // prints it and a timestamp
  void printCurrent() {
    if (currentObj != null) {
      System.out.println(this.getTimeStamp());
      System.out.println(currentObj.toString());
    }
  @Pure
  Object getTimeStamp() { … }
}
```

Lazy initialization

```
class C {
  @LazyNonNull Object currentObj;

  // If currentObj is non-null,
  // prints it and a timestamp
  void printCurrent() {
    if (currentObj != null) {
      System.out.println(this.getTimeStamp());
      System.out.println(currentObj.toString());
    }

  Object getTimeStamp() { … }
}
```

Why doesn't this typecheck?

```
class C {
  @Nullable Object f;

  void m1() {
    setF();
    f.hashCode();
  }
  @AssertNonNullAfter("this.f")
  void setF() {
    this.f = new Object();
  }
}
```

Possible NullPointerException

Postcondition

Type-checking is modular – reason from specs, not from implementation

Libraries you call must be annotated (much of the JDK is provided)

Why doesn’t this typecheck?

```
// Default: @NonNull
class C {
  Map<String, Date> m;
  String getDateString(String k) {
    return m.get(k).toString();
  }
}
```

Non-null map from non-null String to non-null Date

Non-null String

Possible NullPointerException

Map keys

```
// Default: @NonNull
class C {
  Map<String, Date> m;
  String getDateString(@KeyFor("m") String k) {
    return m.get(k).toString();
  }
}
```

`Map.get` returns null if the key is not in the map

Map is a formal parameter

```
class C {
  Date getDate(Map<String, Date> m,
               String k) {
    return m.get(k);
  }

  void useDate(Map<String, Date> m) {
    String s = "now",
    Date d = new Date();
    m.put(s, d);
    getDate(s);
  }
}
```

Naming a formal parameter

Use number, not name, for formal parameters. ☹

```
class C {
  Date getDate(Map<String, Date> m,
               @KeyFor("#0") String key) {
    return m.get(k);
  }

  void useDate(Map<String, Date> m) {
    String s = "now",
    Date d = new Date();
    m.put(s, d);
    getDate(s);
  }
}
```

How should identity be annotated?

```
String identity(String arg) {
  return arg;
}

void client() {                   // desired result:
  identity(“hello”).hashCode(); // OK; no warning
  identity(null).hashCode();    // compiler warning
}
```

How should identity be *written*?

These types are too specific:

```
String identity(String arg) {
  return arg;
}
```

We want to say:

```
ThatSameType identity(AnyType arg) {
  return arg;
}
```

In Java, this is expressed as:

```
<T> T identity(T arg) {
  return arg;
}
```

`identity` has many types:

- String $\rightarrow$ String
- Integer $\rightarrow$ Integer
- List<Date> $\rightarrow$ List<Date>

Java automatically chooses the best type at each call site

We also write this as: $\forall T.\ T \rightarrow T$

Java calls this a *generic method*

The standard term is *polymorphism*

Polymorphism over nullness

```
@PolyNull String identity(@PolyNull String arg) {
  return arg;
}

void client() {
  identity("hello").hashCode(); // OK; no warning
  identity(null).hashCode();    // compiler warning
}
```

@PolyNull is a hack that is necessary for non-generic methods

It is not necessary for generic methods:

```
// No annotations, but type-checks just like identity().
<T> T identity2(T arg) {
  return arg;
}
```

Safe but un-annotatable code

```
class Point {
  // rep invariant:  either rep1 or rep2 is non-null
  XAndY rep1;
  RhoAndTheta rep2;

  float magnitude() {
    if (rep1 != null) {
      return Math.sqrt(rep1.x * rep1.x
                       + rep1.y * rep1.y);
    } else {
      // We know rep2 is non-null at this point.
      return rep2.rho;
    }
  }
```

How to run the Nullness Checker

- **`ant check-nullness`**
- Run ant from within Eclipse
- Eclipse plug-in

More resources:

- Handout T8: Checker Framework for pluggable type-checking
- Checker Framework manual

Why run the Nullness Checker?

- In Winter 2011:
  - *Every* student discovered null pointer bugs
  - Students wished they had been using the Nullness Checker from the beginning of the quarter
- Slight extra credit
  - Applied *after* grades are decided

Summary of nullness annotations

`@Nullable`

`@NonNull` (rarely used)

  `@LazyNonNull`

Preconditions: **`@NonNullOnEntry`**

Postconditions:

  `@Pure`

  `@AssertNonNullAfter`

  `@AssertNonNullIfTrue`

  `@AssertNonNullIfFalse`

Initialization: **`@Raw`** (rarely used)

Maps: **`@KeyFor`**

Polymorphism: **`@PolyNull`** (rarely used)

Key ideas

- Any run-time error can be prevented at compile time
- A type system is a simple way of doing so
- A stronger type system forbids more code
  - This can be good or bad
- More practice understanding subtyping