Improving Software Quality with Static Analysis and Annotations for Software Defect Detection

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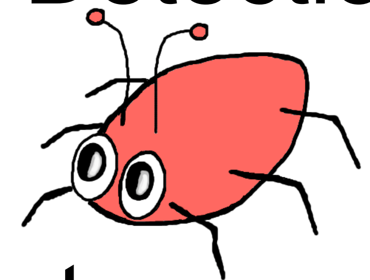
About Me

- Professor at Univ. of Maryland since 1988, doing research in programming languages, algorithms, software engineering
- Technical Lead on JSR-133 (Memory model), JSR-305 (Annotations for Software Defect Detection)
- Founder of the FindBugs™ project
  - Open source static analysis tool for defect detection in the Java™ Programming Language



- Technical advisory board of FORTIFY SOFTWARE

Static Analysis

- Analyzes your program without executing it
- Doesn't depend on having good test cases
  - or even any test cases
- Generally, doesn't know what your software is supposed to do
  - Looks for violations of reasonable programming
    - Shouldn't throw NPE
    - Shouldn't allow SQL injection
- Not a replacement for testing
  - Very good at finding problems on untested paths
  - But many defects can't be found with static analysis

Common Wisdom about Bugs and Static Analysis

- Programmers are smart
- Smart people don’t make dumb mistakes
- We have good techniques (e.g., unit testing, pair programming, code inspections) for finding bugs early
- So, bugs remaining in production code must be subtle, and finding them must require sophisticated static analysis techniques
  - I tried lint and it sucked: lots of warnings, few real issues

Can You Find The Bug?

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```
if (listeners == null)
    listeners.remove(listener);
```

- JDK1.6.0, b105, sun.awt.x11.XMSelection
  - lines 243-244

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Why Do Bugs Occur?

- Nobody is perfect
- Common types of errors:
  - Misunderstood language features, API methods
  - Typos (using wrong boolean operator, forgetting parentheses or brackets, etc.)
  - Misunderstood class or method invariants
- Everyone makes syntax errors, but the compiler catches them
  - What about bugs one step removed from a syntax error?

Bug Categories

Selected categories for today's discussion

- Correctness - the code seems to be clearly doing something the developer did not intend
- Bad practice - the code violates good practice

Bug Patterns

- Some big, broad and common patterns
  - Dereferencing a null pointer
  - An impossible checked cast
  - Methods whose return value should not be ignored
- Lots of small, specific bug patterns, that together find lots of bugs
  - Every Programming Puzzler
  - Every chapter in *Effective Java*
  - Many postings to http://thedailywtf.com/

Analysis Techniques

Whatever you need to find the bugs

- Local pattern matching
  - If you invoke **`String.toLowerCase()`**, don't ignore the return value
- Intraprocedural dataflow analysis
  - Null pointer, type cast errors
- Interprocedural method summaries
  - This method always dereferences its parameter
- Context sensitive interprocedural analysis
  - Interprocedural flow of untrusted data
    - SQL injection, cross site scripting

... Students are good bug generators

- Student came to office hours, was having trouble with his constructor:

```
/** Construct a WebSpider */
public WebSpider() {
        WebSpider w = new WebSpider();
    }
```

- A second student had the same bug
- Wrote a detector, found 3 other students with same bug

Infinite recursive loop

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Double Check Against JDK1.6.0-b13

- Found 5 infinite recursive loops
- Including one written by Joshua Bloch

```
public String foundType() {
    return this.foundType();
}
```

- Smart people make dumb mistakes
  - 27 across all versions of JDK, 40+ in Google's Java code
- Embrace and fix your dumb mistakes

Finding Null Pointer Bugs with FindBugs

- FindBugs looks for a statement or branch that, if executed, guarantees a null pointer exception
- Either a null pointer exception could be thrown, or the program contains a statement/branch that can't be executed

- Could look for exceptions that only occur on a path
  - e.g., if the condition on line 29 is true and the condition on line 38 is false, then a NPE will be thrown
  - but would need to worry about whether that path is feasible

Null Pointer Bugs Found by FindBugs

JDK1.6.0-b105

- 109 statements/branches that, if executed, guarantee NPE
  - We judge at least 54 of them to be serious bugs that could generate a NPE on valid input
- Most of the others were deemed to be unreachable branches or statements, or reachable only with erroneous input
  - Only one case where the analysis was wrong

Examples of null pointer bugs

simple ones

//com.sun.corba.se.impl.naming.cosnaming.NamingContextImpl

```
if (name != null || name.length > 0)
```

//com.sun.xml.internal.ws.wsdl.parser.RuntimeWSDLParser

```
if (part == null | part.equals(""))
```

// sun.awt.x11.ScrollPanePeer

```
if (g != null)
  paintScrollBars(g,colors);
g.dispose();
```

Redundant Check For Null

Also known as a reverse null dereference error

- Checking a value to see if it is null
  - When it can't possibly be null

// java.awt.image.LoopupOp, lines 236-247

```
public final WritableRaster filter(
       Raster src, WritableRaster dst) {
    int dstLength = dst.getNumBands();
    // Create a new destination Raster,
   // if needed
    if (dst == null)
     dst = createCompatibleDestRaster(src);
```

Redundant Check For Null

Is it a bug or a redundant check?

- Check the JavaDoc for the method
- Performs a lookup operation on a `Raster`.
  - If the destination `Raster` is `null`,
  - a new `Raster` will be created.
- Is this case, a bug
  - particularly look for those cases where we know it can't be null because there would have been a NPE if it were null

Bad Method Invocation

- Methods whose return value shouldn't be ignored
  - Strings are immutable, so functions like **`trim()`** and **`toLowerCase()`** return new String
- Dumb/useless methods
  - Invoking **`toString`** or equals on an array
- Lots of specific rules about particular API methods
  - Hard to memorize, easy to get wrong

Examples of bad method calls

// com.sun.rowset.CachedRowSetImpl

```
if (type == Types.DECIMAL || type == Types.NUMERIC)
      ((java.math.BigDecimal)x).setScale(scale);
```

// com.sun.xml.internal.txw2.output.XMLWriter

```
try { ... }
catch (IOException e) {
  new SAXException("Server side Exception:" + e);
  }
```

Type Analysis

- Impossible checked casts
- Useless calls
  - equals takes an `Object` as a parameter
    - but comparing a `String` to `StringBuffer` with `equals(...)` is pointless, and almost certainly not what was intended
  - `Map<K,V>.get` also takes an `Object` as a parameter
    - supplying an object with the wrong type as a parameter to `get` doesn't generate a compile time error
    - just a `get` that always returns null

Lots of Little Bug Patterns

- checking if `d == Double.NaN`
- Bit shifting an `int` by a value greater than 31 bits
- Every Puzzler this year
  - more than half for most years

When Bad Code Isn't A Bug

- Static analysis tools will sometimes find ugly, nasty code
  - that can't cause your application to misbehave
- Cleaning this up is a good thing
  - makes the code easier to understand and maintain
- But for ugly code already in production
  - sometimes you just don't want to touch it
- We've found more cases like this than we expected

When Bad Code Isn't A Bug

bad code that does what it was intended to do

```
// com.sun.jndi.dns.DnsName, lines 345-347
 if (n instanceof CompositeName) {
    // force ClassCastException
    n = (DnsName) n;
    }
```

```
// sun.jdbc.odbc.JdbcOdbcObject, lines 85-91
if ((b[offset] < 32) || (b[offset] > 128)) {
  asciiLine += ".";
}
```

When Bad Code Isn't A Bug

Code that shouldn't go wrong

```
// com.sun.corba.se.impl.dynamicany.DynAnyComplexImpl
String expectedMemberName = null;
try {
    expectedMemberName
      = expectedTypeCode.member_name(i);
} catch (BadKind badKind) { // impossible
} catch (Bounds bounds) { // impossible
}
if ( !(expectedMemberName.equals(memberName) ... ))
  {
```

When Bad Code Isn't A Bug

When you are already doomed

// com.sun.org.apache.xml.internal.security.encryption.XMLCiper
// lines 2224-2228

```
if (null == element) {
  //complain
}
String algorithm = element.getAttributeNS(...);
```

Overall Correctness Results From FindBugs

Evaluating Static Analysis Defect Warnings On Production Software, ACM 2007 Workshop on Program Analysis for Software Tools and Engineering

- JDK1.6.0-b105
  - 379 correctness warnings
    - we judge that at least 213 of these are serious issues that should be fixed
- Google's Java codebase
  - over a 6 month period, using various versions of FindBugs
  - 1,127 warnings
  - 807 filed as bugs
  - 518 fixed in code

Results on Glassfish v2-b58 com.sun.** classes

- 211 medium/high priority correctness issues
- 122 null pointer issues
- 7 doomed calls to equals
- 1 bad switch fall through
- 4 uninitialized reads
- 3 self assignments
- 2 doomed calls to generic methods
- 26 invocations of toString on an array

Bad Practice

- A class that defines an equals method but inherits hashCode from Object
  - Violates contract that any two equal objects have the same hash code
- equals method doesn't handle null argument
- Serializable class without a serialVersionUID
- Exception caught and ignored
- Broken out from the correctness category

Fixing hashCode

- What if you want to define equals, but don't think your objects will ever get put into a HashMap?
- Suggestion:

```
public int hashCode() {
    assert false
     : "hashCode method not designed";
    return 42;
 }
```

Use of Unhashable Classes

- FindBugs previously reported all classes that defined equals but not hashCode as a correctness problem
  - but some developers didn't care
- Now reported as bad practice
  - but separately report use of such a class in a HashMap/HashTable as a correctness warning

Integrating Static Analysis

- Want to make it part of your development process
  - Just like running unit tests
- Have to tune the tool to report what you are interested in
  - Different situations have different needs
- Need a workflow for issues
  - Almost all tools will report some issues that, after reviewing, you decide not to fix
  - Need to have a way to manage such issues

Running Static Analysis

- "We've got it in our IDE, so we're done, right?"
  - no, it really needs to also be done automatically as part of your build process

- Are you scanning 2 million lines of code?
  - You probably don't want 20,000 issues to examine

Defect/Issue Workflow

- How do issues get reviewed/audited?
- Can you do team auditing and assign issues?
- Once you've reviewed an issue, does the system remember your evaluation when it analyzes that code again?
  - even if it is now reported on a different line number?
- Can you identify new issues
  - since last build?
  - since last release to customer/production?

Learning from mistakes

- With FindBugs, we've always started from bugs
- We need API experts to feed us API-specific bugs
  - Swing, EJB, J2ME, localization, Hibernate, ...
- When you get bit by a bug
  - writing a test case is good
  - considering whether it can be generalized into a bug pattern is better
  - You'd be surprised at the number of times you make a mistake so stupid “no one else could possible make the same mistake”
    - but they do

JSR-305: Annotations for Software Defect Detection

Status Report

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Why annotations?

- Static analysis can do a lot
  - can even analyze interprocedural paths
- Why do we need annotations?
  - they express design decisions that may be implicit, or described in documentation, but not easily available to tools

Where is the bug?

```
if (spec != null) fFragments.add(spec);
if (isComplete(spec)) fPreferences.add(spec);
```

Where is the bug?

```
if (spec != null) fFragments.add(spec);

if (isComplete(spec)) fPreferences.add(spec);
```

```
boolean isComplete(AnnotationPreference spec) {
    return spec.getColorPreferenceKey() != null
        && spec.getColorPreferenceValue() != null
        && spec.getTextPreferenceKey() != null
        && spec.getOverviewRulerPreferenceKey() != null;
}
```

Finding the bug

- Many bugs can only be identified, or only localized, if you know something about what the code is supposed to do
- Annotations are well suited to this...
    - e.g., @Nonnull

JSR-305

- At least two tools already have defined their own annotations:
  - FindBugs and IntelliJ
- No one wants to have to apply two sets of annotations to their code
  - come up with a common set of annotations that can be understood by multiple tools

JSR-305 target

- JSR-305 is intended to be compatible with JSE 5.0+ Java
- Hope to have usable drafts and preliminary tool support out by the end of the summer

JSR-308

- Annotations on Java Types
- Designed to allow annotations to occur in many more places than they can occur now
  - ArrayList<@Nonnull String> a = ...
- Targets JSE 7.0
- Will add value to JSR-305, but JSR-305 cannot depend upon JSR-308

Nullness

- Nullness is a great motivating example
- Most method parameters are expected to always be nonnull
  - some research papers support this
- Not always documented in JavaDoc

Documenting nullness

- Want to document parameters, return values, fields that should always be nonnull
  - Should warn if null passed where nonnull value required
- And which should not be presumed nonnull
  - argument to equals(Object)
  - Should warn if argument to equals is immediately dereferenced

Only two cases?

- What about Map.get(...)?
- Return nulls if key not found
  - even if all values in Map are nonnull
- So the return value can't be @Nonnull
- But lots of places where you "know" that the value will be nonnull
  - you know key is in table
  - you know value is nonnull

3 cases?

- May need to have 3 cases for nullness
  - @Nonnull
  - @NullFeasible
  - @UnknownNullness
    - same as no annotation
- Names in flux, might use Nullable for one of these (but which one?)

@Nonnull

- Should not be null
  - For fields, should be interpreted as should be nonnull after object is initialized
- Tools will try to generate a warning if they see a possibly null value being used where a nonnull value is required
  - same as if they see a dereference of a possibly null value

@NullFeasible

- Code should always worry that this value might be null
  - e.g., argument to equals

@UnknownNullness

- Same as no annotation
  - Needed because we are going to introduce default and inherited annotations
  - Need to be able to get back to unannotated state
- Null under some circumstances
  - might vary in subtypes

@NullFeasible requires work

- If you mark a return value as @NullFeasible, you will likely have to go make a bunch of changes
  - kind of like const in C++
- My experience has been that there are lots of methods that could return null
  - but that in a particular calling context, you might know that it can't

Type Qualifiers

- Many of the JSR-305 annotations will be type qualifiers: additional type constraints on top of the existing Java type system

@Untainted / @Tainted

- Needed for security analysis
- Information derived directly from web form parameters is tainted
  - can be arbitrary content
- Strings used to form SQL queries or HTML responses must be untainted
  - otherwise get SQL Injection or XSS

@Syntax

- Used to indicate String values with particular syntaxes
  - @Syntax(“RegEx”)
  - @Syntax(“Java”)
  - @Syntax(“SQL”)
- Allows for error checking and used by IDE’s in refactoring

@Pattern

- Provides a regular expression that describes the legal String values
  - @Pattern(“\\d+”)
    - Indicates that the allowed values are non-empty strings of digits

@Nonnegative and friends

- Fairly clear motivation for @Nonnegative
- More?
  - @Positive
- Where do we stop?
  - @NonZero
  - @PowerOfTwo
  - @Prime

Three-way logic again

- If we have @Nonnegative, do we also need:
  - @Signed
    - similar to @NullFeasible
    - returned by hashCode(), Random.nextInt()
  - @UnknownSign
    - similar to unknown nullness

User defined type qualifiers

- In (too many) places, Java APIs use integer values or Strings where enumerations would have been better
  - except that they weren't around at the time
- Lots of potential errors, uncaught by compiler

Example in java.sql.Connection

createStatement(int resultSetType, int resultSetConcurrency, int resultSetHoldability)

Creates a Statement object that will generate ResultSet objects with the given type, concurrency, and holdability.

resultSetType: one of the following ResultSet constants: ResultSet.TYPE_FORWARD_ONLY, ResultSet.TYPE_SCROLL_INSENSITIVE, or ResultSet.TYPE_SCROLL_SENSITIVE

resultSetConcurrency: one of the following ResultSet constants: ResultSet.CONCUR_READ_ONLY or ResultSet.CONCUR_UPDATABLE

resultSetHoldability: one of the following ResultSet constants: ResultSet.HOLD_CURSORS_OVER_COMMIT or ResultSet.CLOSE_CURSORS_AT_COMMIT

The fix

- Declare
  - public @TypeQualifier @interface ResultSetType {}
  - public @TypeQualifier @interface ResultSetConcurrency {}
  - public @TypeQualifier @interface ResultSetHoldability {}
- Annotate static constants and method parameters

User defined Type Qualifiers

- JSR-305 won’t define @ResultSetType
- Rather JSR-305 will define the meta-annotations
  - that allow any developer to define their own type qualifier annotations
  - which they can apply and will be interpreted by defect detection tools

TypeQualifier families

```
public @interface ClassName {
   @Exclusive Kind value();
   enum Kind { SLASHED, DOTTED };
}

Defines two type exclusive type qualifiers:
  @ClassName(ClassName.Kind.SLASHED)
  @ClassName(ClassName.Kind.DOTTED)
```

Type qualifier validators

- A type qualifier can define a validator
  - typically, a static inner class to the annotation
- Checks to see if a particular value is an instance of the type qualifier
  - Static analysis tools can execute the validator at analysis time to check constant values
  - Dynamic instrumentation could check validator at runtime

CreditCard example

```
@Documented @TypeQualifier @Retention(RetentionPolicy.RUNTIME)
    @Pattern("[0-9]{16}")
public @interface CreditCardNumber {
 class Validator implements TypeQualifierValidator<CreditCardNumber> {
  public boolean forConstantValue(CreditCardNumber annotation, Object v) {
    if (v instanceof String) {
     String s = (String) v;
      if (java.util.regex.Pattern.matches("[0-9]{16}", s)
          && LuhnVerification.checkNumber(s))
        return true;
      }
   return false;
  }}}
```

Default and Inherited Type Qualifiers

Most parameters are nonnull

- Most references parameters are intended to be non-null
  - many return values and fields as well
- Adding a @Nonnull annotation to a majority of parameters won’t sell
- Treating all non-annotated parameters as nonnull also won’t sell

Default type qualifiers

- Can mark a method, class or package as having nonnull parameters by default
  - If a parameter doesn’t have a nullness annotation
    - climb outwards, looking at method, class, outer class, and then package, to find a default annotation
- Can mark a package as nonnull parameters by default, and change that on a class or parameter basis as needed

Inherited Annotations

- We want to inherit annotations
  - Object.equals(@CheckForNull Object obj)
  - int compareTo(@Nonnull E e)
  - @Nonnull Object clone()

Inherited qualifiers take precedence over default

- Default qualifiers shouldn't interfere with or override inherited type qualifiers

Do defaults apply to most JSR-305 type qualifiers?

- Case for default and inherited nullness annotations is very compelling
- Should it be general mechanism?

Thread/Concurrency Annotations

- Annotations to denote how locks are used to guard against data races
- Annotations about which threads should invoke which methods
- See annotations from *Java Concurrency In Practice* as a starting point

What is wrong with this code?

```
Properties getProps(File file)
throws ... {
  Properties props = new Properties();
  props.load(new FileInputStream(file));
  return props;
  }
```

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throws ... {
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   return props;
   }
```

Doesn't close file

Resource Closure

- @WillNotClose
  - this method will not close the resource
- @WillClose
  - this method will close the resource
- @WillCloseWhenClosed
  - Usable only in constructors: constructed object decorates the parameter, and will close it when the constructed object is closed

Miscellaneous

- @CheckReturnValue
- @InjectionAnnotation

@CheckReturnValue

- Indicates a method that should always be invoked as a function, not a procedure.
- Example:
  - String.toLowerCase()
  - BigInteger.add(BigInteger val)
- Anywhere you have an immutable object and methods that might be thought of a a mutating method return the new value

@InjectionAnnotation

- Static analyzers get confused if there is a field or method that is accessed via reflection/injection, and they don't understand it
- Many frameworks have their own annotations for injection
- Using @InjectionAnnotation on an annotation @X tells static analysis tools that @X denotes an injection annotation

Wrap up

- Static analysis is effective at finding bad code
  - Is bad code found by static analysis an important problem?
- Getting static analysis into the software development process can't be taken for granted
- Annotations will be helpful
  - If we can get developers to use them