Secure Programming Lecture 14: Static Analysis II

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17th March 2017

Recap

We're looking at

- **principles and tools**

for ensuring software security.

This lecture looks at:

- further **example uses** of static analysis
- some details of **how static analysis works**

Advanced static analysis jobs

Static analysis is used for a range of tasks that are useful for ensuring secure code.

Basic tasks include **type checking** and **style checking**, described last lecture.

More advanced tasks are:

- **Program understanding**: inferring meaning
- **Property checking**: ensuring no bad behaviour
- **Program verification**: ensuring correct behaviour
- **Bug finding**: detecting likely errors

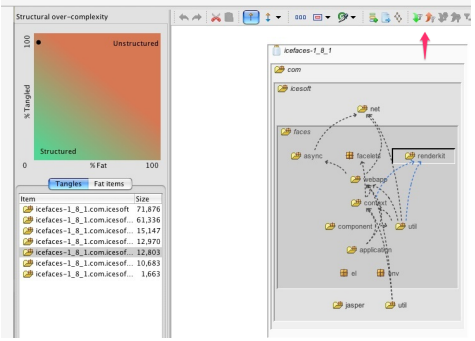
Program understanding tools

Help developers understand and manipulate large codebases.

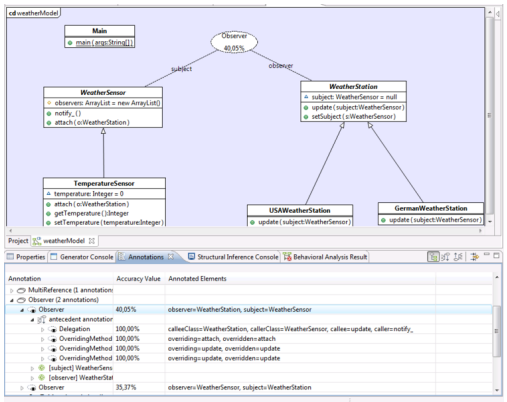
- Navigation swiftly inside the code
  - finding definition of a constant
  - finding call graph for a method
- Support *refactoring* operations
  - re-naming functions or constants
  - move functions from one module to another
  - needs internal model of whole code base
- Inferring *design* from *code*
  - Reverse engineer or check informal design

Outlook: may become increasingly used for security review, with dedicated tools. Close relation to tools used for malware analysis (reverse engineering).

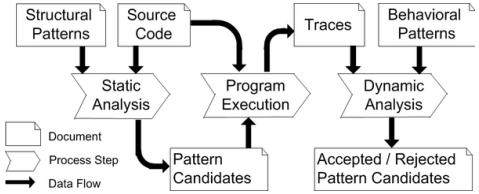
Commercial example: Structure101



Research example: Fujaba and Reclipse



How Reclipse works



We'll explain some of these processes later.

See Fujaba project at University of Paderborn

Program verification

- The gold standard, ultimate guarantee
- Uses **formal methods** techniques, e.g.,
  - theorem proving
  - model checking
- Drawback: needs precise **formal specification** to verify against
- Very expensive to industry
  - time consuming
  - needs experts (logic/maths)
- Currently only used in safety critical domains
  - e.g., railway, nuclear, aeronautics
  - emerging: automobile, *security*

Examples: SPARK, Event-B. Also general purpose **interactive theorem provers** (HOL, ACL2, Isabelle, Coq). Many research-quality or legacy tools.

Property checking

***Lightweight* formal methods**

- Make specifications be *standard* and *generic*
- this program cannot raise NullPointerException
- all database connections are closed after use

Static *checking* (not verification)

- Prevent many violations of specification, not all
- May produce *counterexamples* to explain violations
- Chain pre-conditions (`requires`) and post-conditions (`ensures`)
  - allows *inter-procedural* analysis

Examples: Code Contracts, Splint, JML, Grammatech CodeSonar, PolySpace, ThreadSafe, PRQA, Facebook Infer.

Assertion checking

Many languages have support for *assertions*.

These are dynamic (runtime) checks that can be used to test properties the programmer expects to be true.

assert(exp)

- fails if exp evaluates to false
- assertion tests **usually disabled** in deployment
  - treated as comments
  - may be enabled for testing during development
  - or when running unit tests

Question. What is the risk with running tests only with assertions enabled?

Assertions in Java APIs

```
private static int addHeights(int ah, int bh) {
    assert ah > 0 && bh > 0 : "parameters should be positive";
    return ah+bh;
}
```

Notice above method is private.

- API (public) functions should *always* test constraints
  - throw exceptions if not met
  - eliminate clients (or attackers) who break API contract
- Internal functions may rely on local properties
  - if maintained in same class, easier to check/ensure

Assertions for security

We might could use assertions as safety checks for functions that are at risk of being used in a buggy way.

```
assert(alloc_size(dest) > strlen(src));
strcpy(dest, src);
```

Question. Do you think this is a good use of assertions?

Note `alloc_size()` is not a standard C function, but GCC, for example, has support for trying to track the size of allocated functions with function attributes]

From dynamic to static

With static analysis, we *may* be able to automatically determine whether assertions (if enabled) will:

1. always succeed
2. may sometimes fail (unknown)
3. will always fail

Easy cases:

1. `assert(true);`
2. `x=readint(); assert(x>0);`
3. `assert(false);`

The perfect case would be showing that assertions in a program can only succeed: thus they do not need to be checked dynamically.

Question. what troubles can you see with case 2?

Reasoning with assertions

How does a static analyser reason?

Computations about assertions can be chained through the program, using a *program logic* inside the tool.

E.g., build up a set of facts known before each statement:

```
                        //  { }   (nothing known)
x = 1;                  //  { x = 1 }
y = 1;                  //  { x = 1, y = 1 }
assert (x < y);         //  FAIL
```

Symbolic evaluation

This can work also with variables, whose value is not known statically:

```
                        //  { }   (nothing known)
x = z;                  //  { x = z }
y = z+1;                //  { x = z, y = z+1 }
assert (x < y);         //  SUCCEED  (provided z<MAXINT)
```

Conditionals and loops

These make static analysis *much* harder, of course.

```
                        // {}    (nothing known)
x = v;                  // {x=v}
if (x < y)              //
   y = v;               // {x=v, x<y}
assert (x < y)          // Either: {x=v,y=v}: FAIL
                        // Or: {x=v,¬(x<y)}: FAIL
```

For conditionals, we need to either

- explore every path
- merge information at *join-points*

For loops, we need to either

- unroll for a finite number of iterations
- capture variation using logical *invariants*

Security assertions

Using logical (or other) reasoning techniques, there are various different types of assertions that are useful for security checking, for example:

- **Bounds and range analysis**
- **Tainted data analysis**
- **Type state** and **Resource** tracking

Exercise. What kinds of security issues can these assertions help with? What kinds of security issues would need other assertions?

Bound/range Analysis

Check integers are in required ranges:

alloc_size(dest)>strlen(src)

array_size(a)>n before a[n] access

Taintedness

tainted(mypageinput)

untainted(newkey)

- Tracks whether data can be affected by adversary.
- Tainted input shouldn't be used for security sensitive choices
- and should be sanitized before being output
- Taint analysis approximates information flow
  - information may be leaked *indirectly* as well as directly

Type State (Resource) Tracking

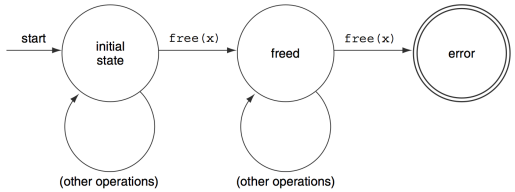
isnull(ptr), **nonull**(ptr)

isopen_for_read(handle), **isclosed**(handle)

uninitialized(buffer), **terminatedstring**(buffer)

- Tracks status of data value held by a variable
- Helps enforce API usage contracts to avoid errors
  - e.g., DoS
- Usage/lifecycle may be expressed with automaton

Example: avoiding double-free errors



Null Pointers in CodeSonar

Not all null pointer analyses are equal! Some compilers spot only "obvious" null pointer risks, others perform deeper analysis like CodeSonar. IDE analysis may be in between.

Code Contracts in .NET

```
public string ReturnFirstThreeCharacters(string s) {
  return s.Substring(0, 3);
}
```

```
string string.Substring(int startIndex, int length)  (+ 1 overload(s))
Retrieves a substring from this instance. The substring starts at a specified character position and has a specified length.

Exceptions:
  System.ArgumentOutOfRangeException
Contracts:
  [Pure]
  requires 0 <= startIndex
  requires 0 <= length
  requires startIndex + length <= this.Length
  ensures result != null
  ensures result.Length == length
```

For Java, there is a language called JML which adds similar pre- and post-conditions (requires/ensures). Open source JML toolsets have been through several versions but have had trouble keeping up with Java, Eclipse changes.

Bug finding

Bug finding tools look for suspicious patterns in code.

FindBugs is an example:

- Finds possible Java bugs according to *rules*
  - rules are suspicious patterns in code
  - designed by experience of buggy programs
  - . . . collected from real world and student(!) code
- Warnings are categorized by
  - **severity**: how serious in general the problem is
  - **confidence**: tool's belief of true problem

Example bugs

Common accidents

An error found in Sun's JDK 1.6:

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

Misunderstood APIs

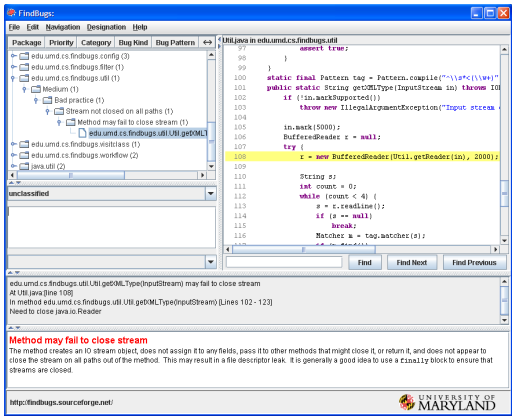
```
public String makeUserid(String s) {
   s.toLowerCase();
   return s;
}
```

Anti-idiom: double-checked locking in Java

```
if (this.fitz == null) {
    synchronized (mylock) {
        if (this.fitz == null) {
            this.fitz = new Fitzer();
        }
    }
}
```

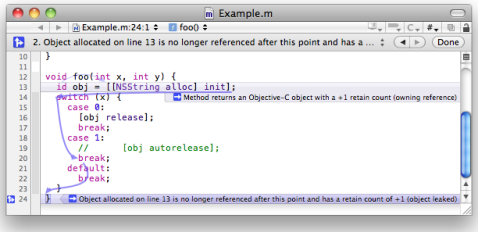
```
[dice]da: findbugs Fitz.class
M M DC: Possible doublecheck on Fizz.fitz in Fitz.getFitz()
        At Fitz.java:[lines 1-3]
```

Findbugs GUI



Clang Static Analyser

An open source tool for C, C++, Objective-C included in XCode.



Clang Static Analyser HTML reports

openssl-1.0.0 - scan-build results

User:	user@localhost
Working Directory:	/home/user/Exercise-4/openssl-1.0.0
Command Line:	make
Clang Version:	clang version 3.4 (tags/RELEASE_34/final)
Date:	Fri Jan 17 12:03:31 2014

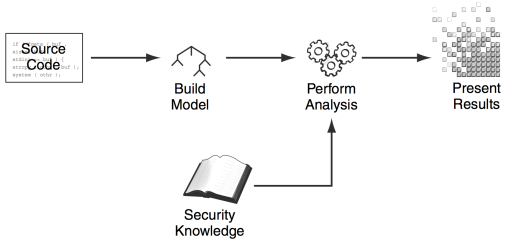
Bug Summary

Bug Type	Quantity	Display?
All Bugs	**269**	✓
API		
Argument with 'nonnull' attribute passed null	7	✓
Dead store		
Dead assignment	203	✓
Dead increment	11	✓
Dead initialization	2	✓
Logic error		
Assigned value is garbage or undefined	3	✓
Branch condition evaluates to a garbage value	1	✓
Dereference of null pointer	30	✓
Division by zero	1	✓
Result of operation is garbage or undefined	7	✓
Uninitialized argument value	4	✓

Reports

Bug Group	Bug Type	File	Line	Path Length	
API	Argument with 'nonnull' attribute passed null	ssl/d1_both.c	1015	9	View Report
API	Argument with 'nonnull' attribute passed null	ssl/d1_srvr.c	1184	10	View Report
API	Argument with 'nonnull' attribute passed null	ssl/s3_srvr.c	1725	10	View Report
API	Argument with 'nonnull' attribute passed null	crypto/asn1/a_bytes.c	295	21	View Report

Basic architecture of a static analysis tool



Building a program model

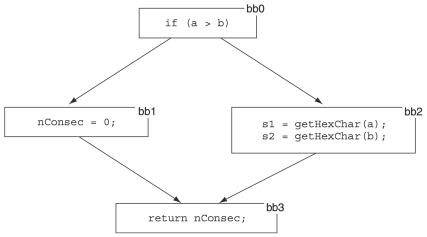
Starts off like a compiler, in stages. Simpler/older static analysis tools only use first stages.

1. **Lexical analysis**: tokenise input
2. **Parsing**: builds a *parse tree* from grammar
3. **Abstract Syntax Tree**: simplify parse tree
4. **Semantic analysis**
   - check program well-formedness
   - including **type-checking**
5. Produce an **Intermediate Representation** (IR)
   - higher level than for compiler
6. Produce **model** to capture control/data flows
   - *control-flow* and *call graphs*
   - variable-contains-data relationships
   - pointer analysis: aliasing, points-to

Control flow graphs

```
if (a > b) {
  nConsec = 0;
} else {
  s1 = getHexChar(1);
  s2 = getHexChar(2);
}
return nConsec;
```

The CFG consists of *basic blocks* and the paths between them.

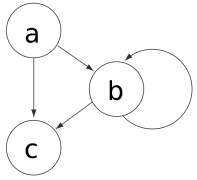


- A *trace* is a possible sequence of basic blocks.
- Above: [bb0,bb1,bb3] and [bb0,bb2,bb3].

Traces can be used to check against security constraints (e.g., as automata), to construct counterexamples. The CFG is also used to combine/chain assertions.

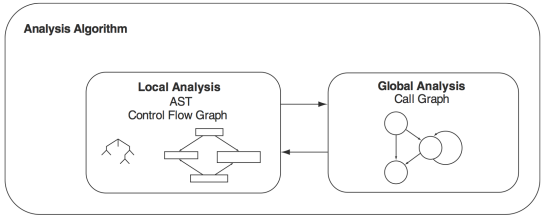
Call graphs

```
int a(int x) {
  if (x) {  b(1);  } else  { c(); }
}
int b(int y) {
  if (y) { c(); b(0); } else { c(); }
}
int c() { /* empty */ }
```



- Call graphs are used for *inter-procedural* analysis
- Check requires-ensures contracts connect together

Putting them together: local and global



Take away points

Static analysis tools can help find security flaws.

Massive benefits:

- examine millions of lines of code, repeatedly

Some tools are generic bug finding, built into IDE.

Others are specific to security, may include.

- risk analysis, including impact/likelihood
- issue/requirements tracking
- metrics

Expect these (gradually?) to become mainstream

- current frequency of security errors unacceptable
- incentives will eventually affect priorities

References and credits

Some of this lecture is based Chapters 2-4 of

- *Secure Programming With Static Analysis* by Brian Chess and Jacob West, Addison-Wesley 2007.

Recommended reading:

- Al Bessey et al. *A few billion lines of code later: using static analysis to find bugs in the real world*, CACM 53(2), 20101.