Secure Programming Lecture 13: Code Review and Static Analysis

David Aspinall

Informatics @ Edinburgh

Outline

Recap

We have looked at:

- examples of vulnerabilities and exploits
- particular programming failure patterns
- secure development processes

Now it’s time to look at some:

- **principles and tools**

for ensuring software security.

Outline

Code review and architectural analysis

Remember the secure software development process “touchpoints”, in priority order:

1. **Code review and repair**
2. **Architectural risk analysis**
3. Penetration testing
4. Risk-based security testing
5. Abuse cases
6. Security requirements
7. Security operations

This lecture examines **static analysis** as a set of techniques to help with code review and repair.

Some advanced static analysis techniques may help with architectural (design) understanding too.

Vulnerabilities in design

Design flaws are best found through *architectural analysis*. They may be generic or context-specific.

Generic flaws

- Bad behaviour that *any* system may have
- e.g., revealing sensitive information

Context-specific flaws

- Particular to security requirements of system
- e.g., key length too short for long term usage

Vulnerabilities in code

Security programming bugs (sometimes more serious flaws) are best found through *static code analysis*.

Generic defects

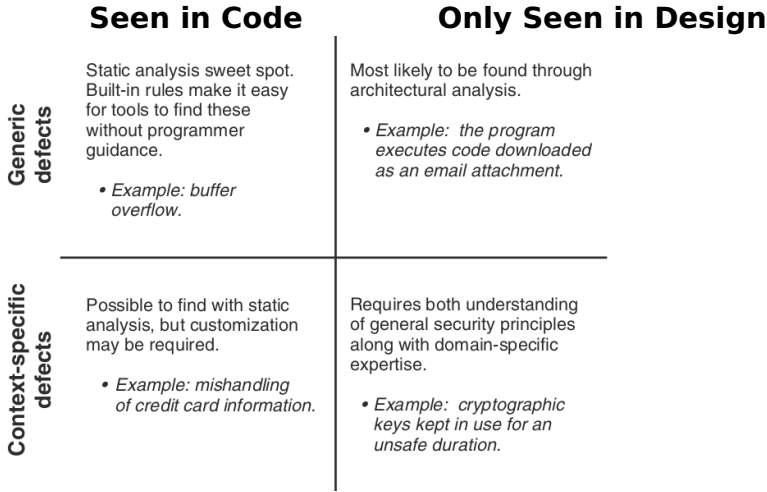
- Independent of what the code does
- May occur in any program
- May be language specific
- e.g., buffer overflow in C or C++

Context-specific defects

- Depend on particular meaning of the code
- Even when *requirements* may be general
- Language agnostic. AKA *logic errors*.
- e.g., PCI DSS rules for CC number display violated

Testing is also vital, of course, but has failed spectacularly in some cases.

Vulnerabilities matrix



Matrix from *Secure Programming with Static Analysis*, Chess and West, 2007.

Common Weakness Enumeration

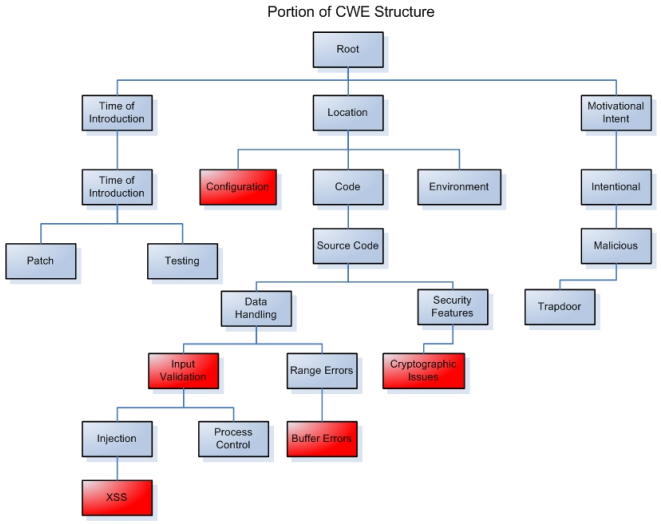
Recall (from Lecture 7):

- **Weaknesses** classify **Vulnerabilities**
- A **CWE** is an identifier such as `CWE-287`
- CWEs are organised into a hierarchy
- The hierarchy (perhaps confusingly) allows:
  - multiple appearances of same CWE
  - different types of links
  - different ways of grouping CWEs
- This allows multiple *views*
  - different ways to structure the same things
  - also given CWE numbers

E.g., the **Top 2022 CWE Top 25** is CWE-1387.

See https://cwe.mitre.org

CWE cross section



Seven Pernicious Kingdoms

This developer-oriented classification was introduced by Tsipenyuk, Chess, and McGraw in 2005.

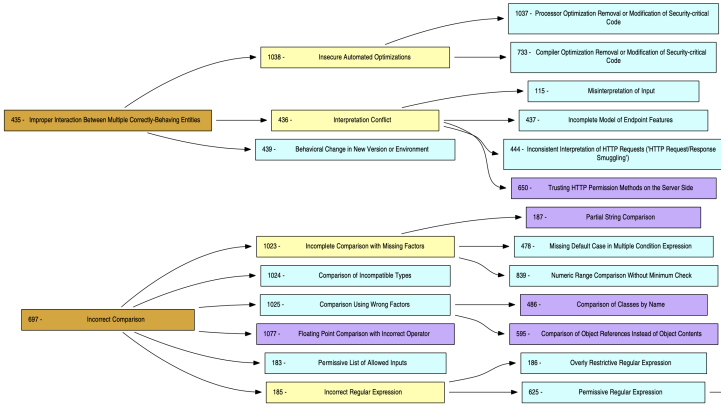
1. Input validation and representation
2. API abuse
3. Security features
4. Time and state
5. Error handling
6. Code quality
7. Encapsulation
8. Environment (“a separate realm”)

This appears as the view CWE 700.

Exercise. Browse the CWE hierarchy to understand representative weaknesses in each category.

CWE 700 at Mitre

An abstract view



Pillars categorise *Classes* which collect *Base* items and *Variants*. Other high-level views use *Categories* and *Compounds*.

See https://cwe.mitre.org/data/pdfs.html

Outline

Static analysis

A **white box** technique. Takes as input

- source code, usually
- binary code, sometimes (**Q.** Why?)

As output, provides a report listing either

- assurance of **good behaviour** (“no bugs!”) or
- evidence of **bad behaviour**; ideally proposed fixes

40 years of research, now a range of practical tools. Standalone, inside compilers, IDEs and CI/CD toolchains, code repository platforms like Github, etc. Complexity range from simple scanners (linear in code size) to expensive, deep code analysis, exploring possible states in program execution.

CI/CD=Continuous Integration, Continuous Delivery: part of modern DevOps, promoting repeatable short-cycle releases and deployment.

Static analysis for security

A perfect fit for security because in principle:

- it examines every code path, and
- it considers every possible input

Only a single path/input is needed for a security breach.

Dynamic testing only reaches paths determined by test cases and only uses input data given in test suites.

Other advantages:

- often finds root cause of a problem
- can run before code complete, even as-you-type

But also some disadvantages/challenges. . .

Solving an impossible task

Perfect static security analysis is impossible.

```
if halts(f) then
    call expose_all_my_secrets
```

Rice's Theorem (informal)

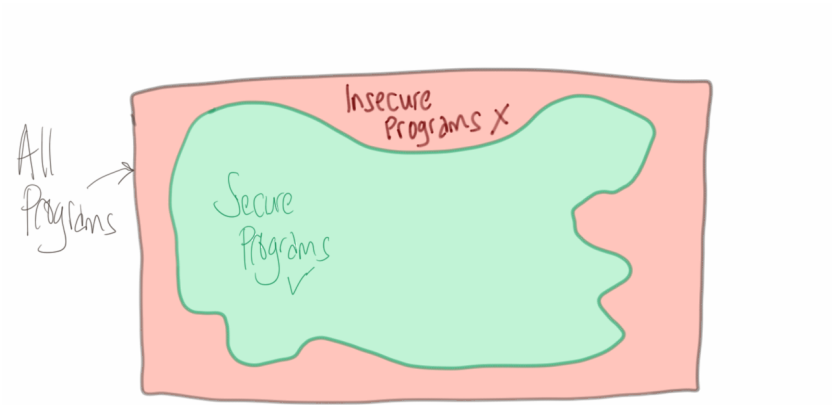
For any non-trivial property of partial functions, there is no general and effective method to decide whether an algorithm computes a partial function with that property.

For a more formal treatment, see a book on computability or Wikipedia page on Rice's Theorem

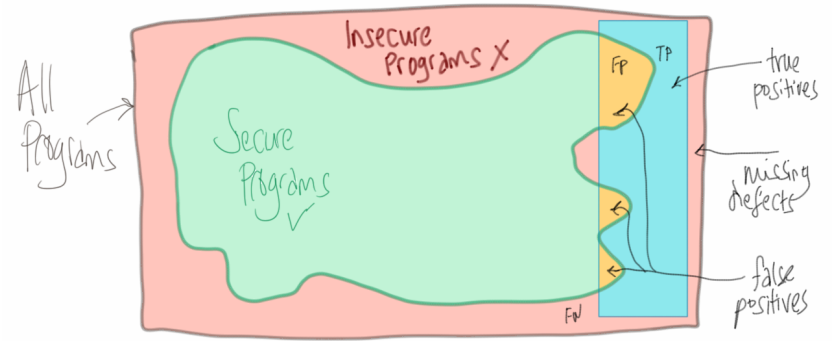
Static analysis in practice

- Correctness is undecidable in general
  - focus on decidable (approximate) solution
  - or *semi-decidable* + manual assistance/timeouts
- Avoiding state-space explosion exploring all paths
  - must design/derive *abstractions*
  - data: restricted domains (*abstract interpretation*)
  - code: approximate *calling contexts*
- Environment is unknown
  - program takes input (maybe even code) from outside
  - other factors, e.g., scheduling of multiple threads
  - again, use *abstractions* and *simplified assumptions*
- Complex behaviours difficult to specify
  - use *generic specifications* (overflow, NPE)
  - so-called lightweight methods

Space of programs



Results of a static analysis tool



Tool’s job is to identify insecure programs. "Missing defects" are insecure programs that the tool failed to warn about, i.e., false negatives.

False positive: false alarms on secure programs

Because the security or correctness question must be approximated, tools cannot be perfectly precise. They may raise false alarms, or may miss genuine vulnerabilities.

The **false positive** problem is hated by users:

- too many potential problems raised by tool
- programmers have to wade through long lists
- true defects may be lost, buried in details

Modern tools *minimise false positive rates* for usability.

False negatives: defective programs not caught

In practice, tools trade-off false positives with false negatives, missing defects.

Risky for security:

- one missed bug enough for an attacker to get in!

Academic research usually concentrates on *sound* techniques (an algorithm guarantees some security property), with no false negatives.

But strong assumptions are needed for soundness. In practice, tools must accept missing defects.

How are imprecise tools measured and compared? It is difficult. The US NIST SAMATE project has worked on **static analysis benchmarks**.

Soundiness: in defence of unsoundness

In 2015, a group of researchers wrote a “manifesto” to encourage the academic community to accept unsound analyses as being necessary in practice:

- a **soundy** analysis, aims to capture all possible behaviours within reason, *over-approximating* actual behaviour and maintaining a sound core (but omitting difficult language features like, e.g., `eval` in JavaScript). Most published academic algorithms and tools are like this.
- an **unsound** analysis deliberately ignores (under-approximates) program behaviours and may not have a proven-sound sub-part; many practical tools are like this.

See http://soundiness.org/

Incorrectness Logic

A different approach is to focus on precise (sound) but incomplete *bug finding*. Facebook's **Infer** tool had most success used this way.

This observation was turned into a logic for *incorrectness* designed by Peter O'Hearn in 2019 and built into a tool **Pulse-X** reported on in 2022.

- Traditional correctness logics such as Separation Logic (Infer): prove the absence of bugs
  - heuristics reduce false positives when correctness can't be proved
- Incorrectness Logic proves the presence of bugs instead
  - all reported bugs are actual bugs
  - still no completeness; some bugs may be missed

See *Finding Real Bugs in Big Programs with Incorrectness Logic*, Quang Loc Le et al, Proc. ACM Programming Languages, 2022. Available at https://doi.org/10.1145/3527325.

Outline

Static analysis jobs

A range of jobs can be undertaken by static analysis:

- **Style checking**: ensuring good practice
- **Type checking**: maybe as part of language
- **Program understanding**: inferring meaning
- **Property checking**: ensuring no bad behaviour
- **Program verification**: ensuring correct behaviour
- **Bug finding**: detecting likely errors

General tools in each category may be useful for security. Dedicated **static security analysis tools** also exist. Examples are Fortify and Coverity, both now integrated into larger secure development products.

Other popular tools include Snyk and CodeQL (available standalone or integrated into GitHub CI).

Outline

Style checking for good practice

Informally, comparing with natural language (intuition)

- type system: becomes part of *syntax* of language
- style checking: a bit like grammar checking in NL

Style checking traditionally covers *good practice*

- syntactic coding standards (layout, bracketing etc)
- naming conventions (e.g., UPPERCASE constants)
- **lint**-like checking for dubious/non-portable code
  - modern languages are stricter than old C
  - (or have fewer implementations)
  - style checking becoming part of compiler/IDE
  - but also dedicated tools with 1,000s rules

Example tools: PMD, Parasoft.

Style checking for good practice

```
typedef enum { RED, AMBER, GREEN } TrafficLight;

void showWarning(TrafficLight c)
{
  switch (c) {
  case RED:
    printf("Stop!");
  case AMBER:
    printf("Stop soon!");
  }
}
```

Style as safe practice

Legal in C language, type checks and compiles fine:

```
[dice] da: gcc enum.c
```

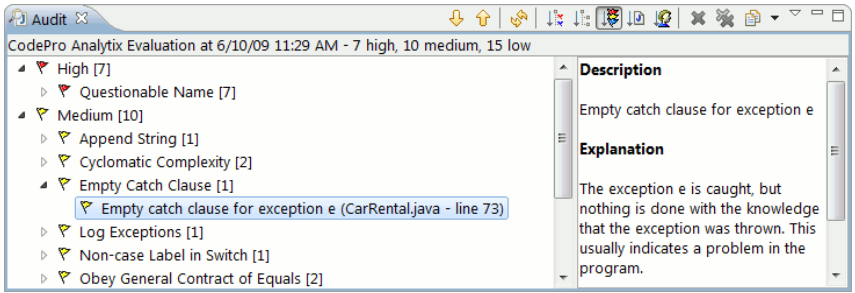
But with warnings:

```
[dice] da: gcc -Wall enum.c
enum.c: In function ‘showWarning’:
enum.c:7:3: warning: enumeration value ‘GREEN’ not handled in switch [-Wswitch]
   switch (c) {
   ^
```

Question. Why have some languages decided that omitted cases should *not* be allowed?

View in IDE (CodePro Analytix)

A nice Java program analysis tool acquired by Google and made freely available for a while:



Unfortunately it is no longer available: Google hoped but “had no time” to make it open-source. Their current developer tools include a range of app testing mechanisms.

Outline

Type systems: a discipline for programming

Proper type systems provide **strong guarantees**

- Java, ML, Haskell: no type/memory corruption
- These are *strongly typed* languages

Sometimes frustrating: seen as a hurdle. Old joke:

- *When your Haskell program finally type-checks, it must be right!*

Do programmers accept type systems?

- yes: type errors are necessary, not “false”
- no: they’re overly restrictive, complicated
  - . . . likely influence on rise of scripting languages

Nowadays: types are important for reliability, security

- idea of *gradual typing*
- “subset” languages Hack (from PHP) and TypeScript (from JavaScript)

False positives in type checking

```
short s = 0;
int i = s;
short r = i;
```

False positives in type checking

```
[dice]da: javac ShortLong.java
ShortLong.java:5: error: possible loss of precision
    short r = i;
              ^
  required: short
  found:    int
1 error
```

False positives in type checking

```
int i;
if (3 > 4) {
     i = i + "hello";
}
```

False positives in type checking

```
[dice]da: javac StringInt.java
StringInt.java:5: error: incompatible types
        i = i + "hello";
                ^
  required: int
  found:    String
```

No false positives in Python

```
i = 0;
if (4 < 3):
    i = i + "hello";
```

The other way around gives an error in execution:

```
Traceback (most recent call last):
  File "src/stringint.py", line 3, in <module>
    i = i + "hello";
TypeError: unsupported operand type(s) for +: 'int' and 'str'
```

Question. Is this an advantage?

Type systems: intrinsic part of the language

In a statically type language, programs that can't be type-checked don't even have a meaning.

- Compiler will not produce code
- So code for ill-typed programs cannot be executed
- Programming language specifications (formal semantics or plain English): may give no meaning, or a special meaning.

Well-typed Programs Can't Go Wrong

Robin Milner (1934-2010) working at Edinburgh, captured this intuition precisely as a theorem about *denotational semantics*. Adding a number to a string gives a special denotational value "`wrong`". Any calculation with `wrong` gives `wrong` again.

Type systems: flexible part of the language

In practice, programmers and IDEs do give meaning (sometimes even execute) partially typed programs.

Recent research: *gradual* typing (and related work) to make this more precise:

- start with untyped scripting language
- infer types in parts of code where possible
- manually add type annotations elsewhere
- . . . so compiler recovers **safety** in some form
- A good example is TypeScript

Sometimes even strongly-typed languages have escape routes, e.g., via C-library calls or abominations like unsafePerformIO

Type systems: motivating new languages

High-level languages arrived with strong type systems early on (inspired from mathematical ideas in **functional languages**, e.g., Standard ML, Haskell).

Language designers asked if static typing can be provided for systems programming languages, without impacting performance *too much*. Two prominent young examples:

- **Go** (2007-)
- **Rust** (2009-)

both are conceived as **type safe** low-level languages with built-in **concurrency support**.

Question. Why add concurrency support? Are there benefits for secure programming?

Type systems: modularity advantage

By design, types provide *modularity*.

- write programs in separate pieces
- type check the pieces
- put the types together: the whole is type-checked

This property extends to the basic parts of the language: we find the type of an expression from the type of its parts. Programming language researchers call this **compositionality**.

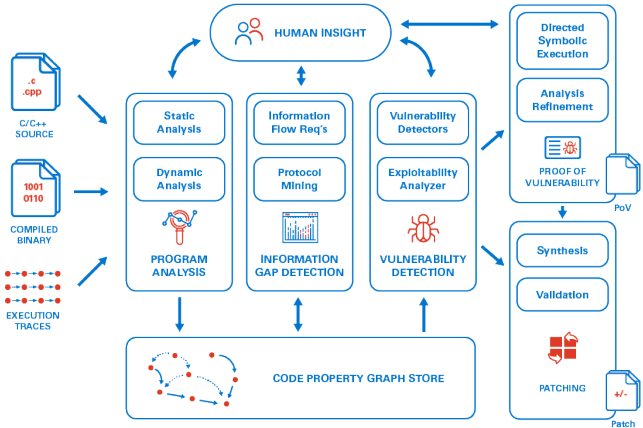
Because of this type systems are a good way to define new static analyses for particular purposes.

Unfortunately security is often a **non-compositional** property.

Research question: can we find type systems that provide compositional guarantees for security?

Galois MATE

A tool made available as open source in 2022 is Galois Inc's MATE, "Merged Analysis To prevent Exploits".



Outline

Review Questions

Static versus dynamic analysis

- Static analysis requires access to source (sometimes binary) code. What advantages does that enable?
- Why do practical static analysis tools both miss problems and report false problems?

Types of static analysis tool

- Apart from type and style checking, describe three other jobs a static analysis tool may perform.

References and credits

Some of this lecture (and the next) is based Chapters 1-4 of

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

Recommended reading:

- Ayewah et al. *Using static analysis to find bugs*, IEEE Software, 2008.

Recommended and further reading

Weakness classification in CWE

- See *Seven pernicious kingdoms: a taxonomy of software security errors*, IEEE Security & Privacy, 3(6), 2005. Browse the CWE View: Seven Pernicious Kingdoms.

Static analysis introduction

- Ayewah et al. *Using static analysis to find bugs*, IEEE Software, 2008.
- Distefano et al. *Scaling Static Analyses at Facebook*, CACM 62/8, 2019.

For **type systems** you may know the typing system of Java already, including features like **exceptions** and **generics**. To extend the robustness of static typing to low-level languages, new languages are emerging such as

- **Go**, supported by Google
- **Rust**, supported by Mozilla.