Program analysis for security

Two main classes

- Static:
  - Operates on source or binary at rest
- Dynamic:
  - Operates at runtime
- Also hybrids of the two

Static: Examples

- Code review
- Grep
- Taint analysis
- Symbolic execution
- Templates/specifications (metacompilation)

Dynamic: Examples

- Testing
- Debugging
- Log-tracing
- Fuzzing

Static: Pros and Cons

- Analyze everything in the program
    - Not just what runs during this execution
- Don't need running environment (e.g. comms)
    - Can analyze incomplete programs (libraries)
        - If you have the source code
- Everything could be a lot of stuff!
    - Scalability
    - Code that never runs in practice (or dead)
- No side effects
- Only find what you are looking for

Dynamic: Pros and Cons

- Concrete failure proves an issue
  - May aid fix
- Computationally scalable
- Coverage?
- Resources/environment?

Static Analysis

Some material from Dave Levin, Mike Hicks, Dawson Engler, Lujo Bauer

http://philosophyofscienceportal.blogspot.com/2013/04/van-de-graaff-generator-redux.html

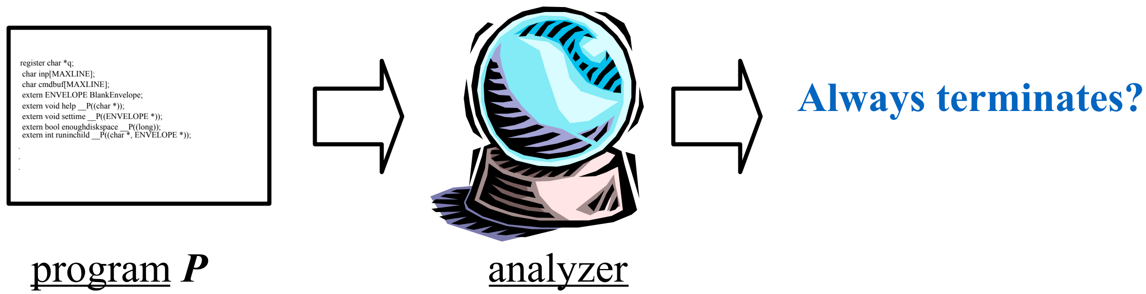
From here we mostly mean automated: in a sense, ask a computer to do your code review

High-level idea

- Model program properties abstractly
- Set some rules/constraints and then check them
- Tools from program analysis:
    - Type inference
    - Theorem proving
    - etc.

- What kinds of properties are checkable this way?
- What guarantees can we have? (FP/FN)
- Resources/scalability?

The Halting Problem



- Can we write an analyzer that can prove, for any program *P* and inputs to it, *P* will terminate?
  - Doing so is called the **halting problem**
  - Unfortunately, this is **undecidable:** any analyzer will fail to produce an answer for at least some programs and/or inputs

Some material inspired by work of Matt Might: http://matt.might.net/articles/intro-static-analysis/

Check other properties instead?

- Perhaps security-related properties are feasible
  - E.g., that all accesses `a[i]` are in bounds
- *But* these **properties can be converted into the halting problem** by transforming the program
  - A perfect array bounds checker could solve the halting problem, which is impossible!
- Other undecidable properties (Rice's theorem)
  - Does this **string** come from a **tainted source**?
  - Is this **pointer used after** its memory is **freed**?
  - Do any variables experience **data races**?

So is static analysis impossible?

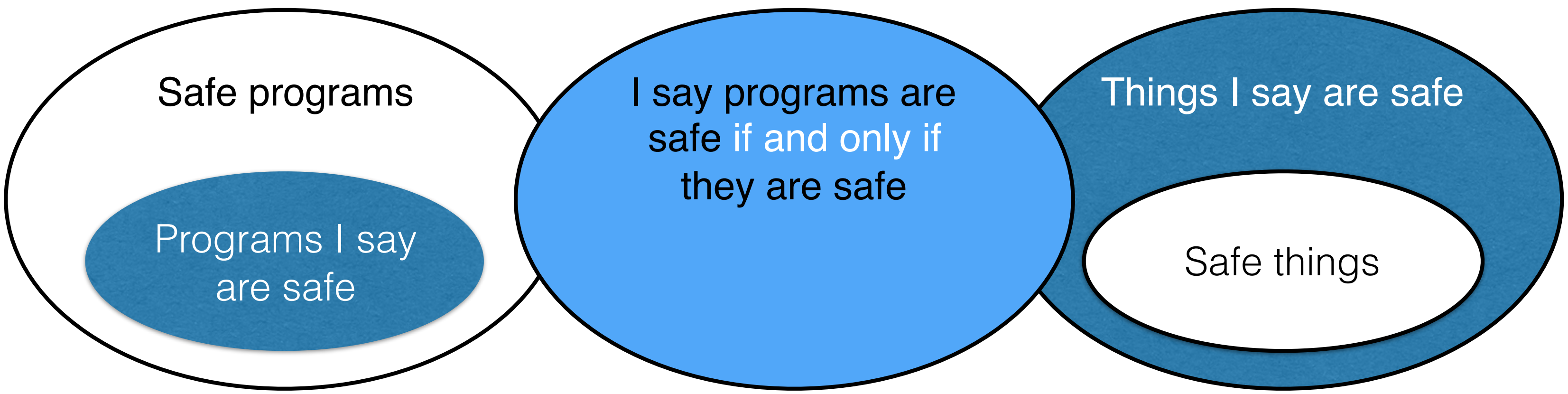
- **Perfect** static analysis is **not possible**
- **Useful** static analysis is **perfectly possible**, despite
  1. **Nontermination** - analyzer never terminates, or
  2. **False alarms** - claimed errors are not really errors, or
  3. **Missed errors** - no error reports ≠ error free
- Nonterminating analyses are confusing, so tools tend to exhibit only false alarms and/or missed errors

Soundness

If analysis says that X is safe, then X is safe.

Completeness

If X is safe, then analysis says X is safe.



Trivially Sound: Say nothing is safe

Trivially Complete: Say everything is safe

Sound and **Complete**:

Say exactly the set of true things

- **Soundness**: No error found = no error exists
  - Alarms may be false errors
- **Completeness**: Any error found = real error
  - Silence does not guarantee no errors
- Basically any useful analysis
  - is neither **sound** nor **complete** (def. not **both**)
  - … usually *leans* one way or the other

The Art of Static Analysis

- **Precision**: Carefully model program, minimize false positives/negatives
- **Scalability**: Successfully analyze large programs
- **Understandability**: Actionable reports

- Observation: **Code style is important**
  - Aim to be precise for “good” programs
    - OK to forbid yucky code in the name of safety
    - Code that is more understandable to the analysis is more understandable to humans

Adding some depth:
Dataflow (taint) analysis

Tainted Flow Analysis

- Cause of many attacks is **trusting unvalidated input**
  - Input from the user (network, file) is **tainted**
  - Various data is used, assuming it is **untainted**
- Examples expecting untainted data
  - source string of **`strcpy`** (≤ target buffer size)
  - format string of **`printf`** (contains no format specifiers)
  - form field used in constructed SQL query (contains no SQL commands)

Recall: Format String Attack

- Adversary-controlled format string

```
char *name = fgets(…, network_fd);
printf(name);      // Oops
```

The problem, in types

- Specify our requirement as a *type qualifier*

```
int printf(untainted char *fmt, …);
tainted char *fgets(…);
```

- **tainted** = possibly controlled by attacker
- **untainted** = **must not be** controlled by attacker

```
tainted char *name = fgets(…,network_fd);
printf(name);    // FAIL: untainted <- tainted
```

Analyzing taint flows

- **Goal**: For all possible inputs, prove tainted data will never be used where untainted data is expected
  - **untainted** annotation: indicates a **trusted** **sink**
  - **tainted** annotation: an **untrusted** **source**
  - *no annotation* means: not specified (analysis must figure it out)
- Solution requires inferring **flows** in the program
  - What **sources can reach what sinks**
  - If any flows are *illegal*, i.e., whether a **tainted** source may flow to an **untainted** sink
- We will aim to develop a (mostly) *sound* analysis

Legal Flow

```
void f(tainted int);
untainted int a = …;
f(a);
```

`f` accepts **tainted** *or* **untainted** data

Illegal Flow

```
void g(untainted int);
tainted int b = …;
g(b);
```

`g` accepts *only* **untainted** data

Define allowed flow as a **constraint:**

untainted < **tainted**

At each program step, **test** whether inputs ≤ policy

(Read as: input less tainted (or equal) than policy

Analysis Approach

- If no qualifier is present, we must **infer** it
- Steps:
  - **Create** a **name** for each missing qualifier (e.g., **α, β**)
  - For each program statement, **generate constraints**
    - Statement `x = y` generates constraint $q_y \leq q_x$
  - **Solve the constraints** to produce solutions for **α, β,** etc.
    - A solution is a *substitution* of qualifiers (like **tainted** or **untainted**) for names (like **α** and **β**) such that all of the constraints are legal flows
- If there is **no solution**, we (may) have an **illegal flow**

Example Analysis

```
int printf(untainted char *fmt, …);
tainted char *fgets(…);
```

```
α char *name = fgets(…, network_fd);
β char *x = name;
printf(x);
```

(1) tainted ≤ α

(2) α ≤ β

(3) β ≤ untainted

Illegal flow!

No possible solution for **α** and **β**

First constraint requires **α = tainted**
To satisfy the second constraint implies **β = tainted**
But then the third constraint is illegal: **tainted ≤ untainted**

Taint Analysis: Adding ***Sensitivity***

But what about?

```
int printf(untainted char *fmt, …);
tainted char *fgets(…);
```

```
→ α char *name = fgets(…, network_fd);
  β char *x;
x = name;
x = “hello!”;
printf(x);
```

tainted $\leq$ α

α $\leq$ β

untainted $\leq$ β

β $\leq$ untainted

No constraint solution. Bug?

False Alarm!

Flow Sensitivity

- Our analysis is **flow *in*sensitive**
  - Each variable has **one qualifier**
  - Conflates the taintedness of all values it ever contains
- **Flow-sensitive analysis** accounts for variables whose contents change
  - Allow each assigned use of a variable to have a different qualifier
    - E.g., α_1 is x's qualifier at line 1, but α_2 is the qualifier at line 2, where α_1 and α_2 can differ
  - Could implement this by transforming the program to assign to a variable at most once

Reworked Example

```
int printf(untainted char *fmt, …);
tainted char *fgets(…);
```

```
→ α char *name = fgets(…, network_fd);
char β *x1, γ *x2;
x1 = name;
x2 = “%s”;
printf(x2);
```

tainted ≤ α

α ≤ β

untainted ≤ γ

γ ≤ untainted

No Alarm

Good solution exists:

γ = untainted

α = β = tainted

Handling conditionals

```
int printf(untainted char *fmt, …);
tainted char *fgets(…);
```

```
→ α char *name = fgets(…, network_fd);
  β char *x;
  if (…)   x = name;
  else     x = “hello!”;
  printf(x);
```

tainted $\leq$ **α**

α $\leq$ **β**

~~**untainted** $\leq$ **β**~~

β $\leq$ **untainted**

Constraints still unsolvable

Illegal flow

Multiple Conditionals

```
int printf(untainted char *fmt, …);
tainted char *fgets(…);
```

```
void f(int x) {
   α char *y;
→  if (x) y = "hello!";
   else   y = fgets(…, network_fd);
   if (x) printf(y);
}
```

~~untainted ≤ α~~

tainted ≤ α

α ≤ untainted

No solution for **α**. Bug?

False Alarm!

(and flow sensitivity won't help)

Path Sensitivity

- Consider *path feasibility*. E.g., `f(x)` can execute path
  - **1-2-4-5-6** when `x ≠ 0`, or
  - **1-3-4-6** when `x == 0`. But,
  - path **1-3-4-5-6** *infeasible*

```
void f(int x) {
  char *y;
  1if (x) 2y = "hello!";
   else   3y = fgets(…);
  4if (x) 5printf(y);
6}
```

- A **path sensitive analysis** checks feasibility, e.g., by qualifying each constraint with a **path condition**
  - $x \neq 0 \Longrightarrow$ **untainted** $\leq \alpha$ (segment 1-2)
  - $x = 0 \Longrightarrow$ **tainted** $\leq \alpha$ (segment 1-3)
  - $x \neq 0 \Longrightarrow \alpha \leq$ **untainted** (segment 4-5)

Why *not* use flow/path sensitivity?

- Flow sensitivity **adds precision**, path sensitivity adds more
  - Reduce false positives: less developer effort!
- But both of these **make solving more difficult**
  - Flow sensitivity *increases the number of nodes* in the constraint graph
  - Path sensitivity *requires more general solving procedures* to handle path conditions
- In short: **precision** (often) **trades off scalability**
  - Ultimately, limits the size of programs we can analyze

Implicit flows

```
void copy(tainted char *src,
          untainted char *dst,
          int len) {
  untainted int i;
  for (i = 0; i<len; i++) {
    dst[i] = src[i]; //illegal
  }
}
```

Illegal flow :

tainted $\not\leq$ untainted

Implicit flows

```
void copy(tainted char *src,
          untainted char *dst,
          int len) {
  untainted int i, j;
  for (i = 0; i<len; i++) {
    for (j = 0; j<sizeof(char)*256; j++) {
      if (src[i] == (char)j)
        dst[i] = (char)j;     //legal?
    }
  }    untainted char     untainted char
}
```

Missed flow !

Implicit flow analysis

- **Implicit flow:** one value *implicitly* influences another
- One way to find these: maintain a scoped **program counter (*pc*) label**
  - Represents the maximum taint affecting the current pc
- Assignments generate constraints involving the *pc*
  - `x = y` produces two constraints:

    $label(\mathtt{y}) \leq label(\mathtt{x})$ (as usual)

    $pc \leq label(\mathtt{x})$

Implicit flow example

```
tainted int src;
α int dst;
if (src == 0)
 dst = 0;
else
 dst = 1;

dst += 0;
```

pc_1 = **untainted**

pc_2 = **tainted**

pc_3 = **tainted**

pc_4 = **untainted**

untainted $\leq$ **α**
$pc_2 \leq$ **α**

untainted $\leq$ **α**
$pc_3 \leq$ **α**

untainted $\leq$ **α**
$pc_4 \leq$ **α**

: **tainted** $\leq$ **α**

Taint on α is identified.
Discovers implicit flow!

Why not implicit flow?

- Tracking implicit flows can lead to **false alarms**
  - E.g., ignores values

```
tainted int src;
α int dst;
if (src > 0) dst = 0;
else         dst = 0;
```

- Extra constraints **hurt performance**
- The evil copying example is *pathological*
  - We typically don't write programs like this*
  - Implicit flows will have little overall influence
- *So*: **taint analyses tend to ignore implicit flows**

* Exception coming in two slides

Other challenges

- Taint through operations
  - `tainted a; untainted b; c=a+b` — is `c` tainted? (yes, probably)
- Function calls and context sensitivity
  - Function pointers: Flow analysis to compute possible targets
- Struct fields
  - Track taint for the whole struct, or each field?
  - Taint per instance, or shared among all of them (or something in between)?
    - Note: objects ≈ structs + function pointers
- Arrays: Track taint per element or across whole array?

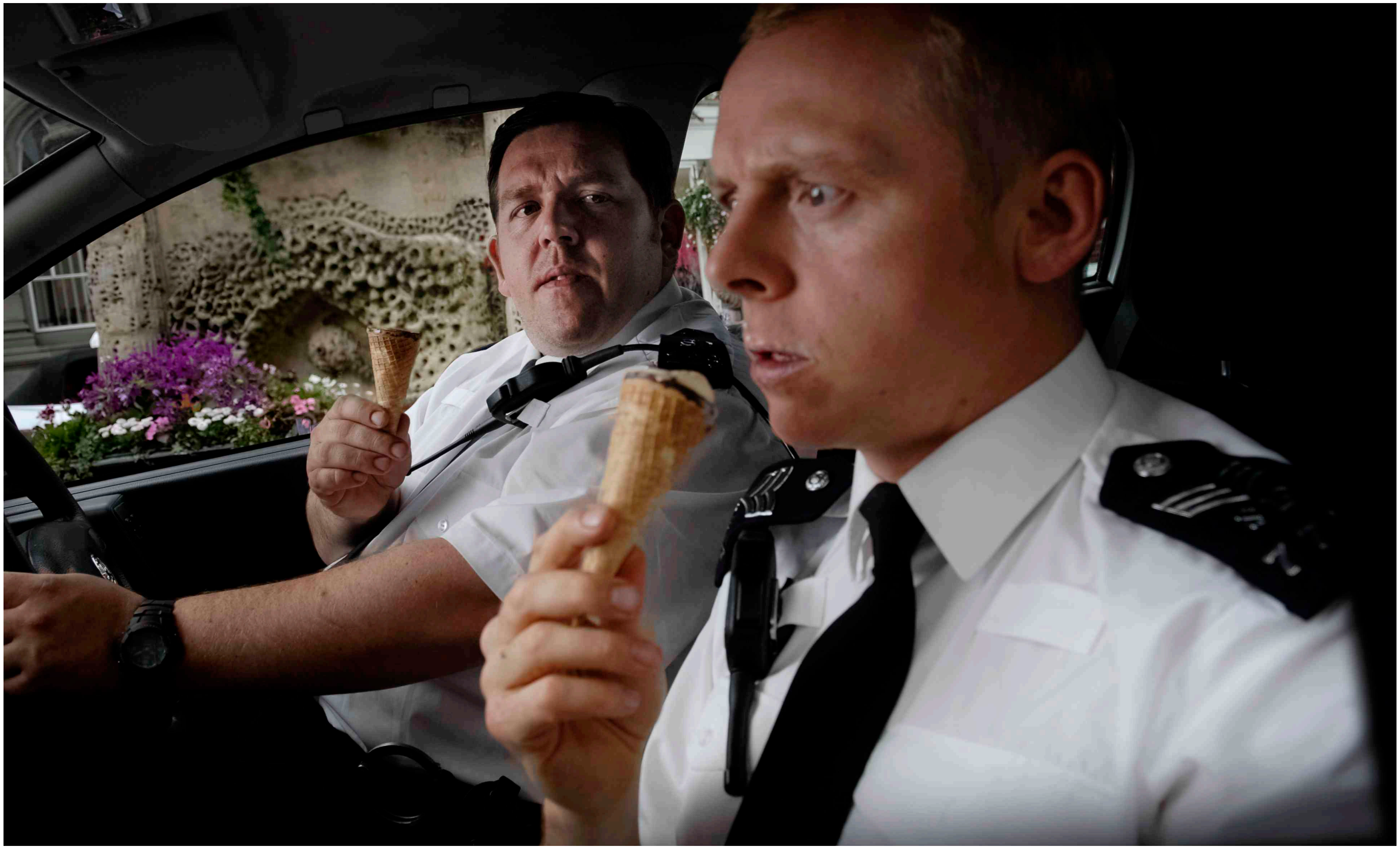
No single correct answer!
(Tradeoffs: Soundness, completeness, performance)

Other refinements

- Label *additional* sources and sinks
  - e.g., Array accesses must have untainted index
- Handle ***sanitizer functions***
  - Convert tainted data to untainted
- Complementary goal: Leaking confidential data
  - Don't want **secret sources** to go to **public sinks**
    - Implicit flows more relevant (malicious code)
  - *Dual* of tainting

Static analysis in practice

- Thoroughly check limited but useful properties
  - **Eliminate** some categories of errors
  - Developers can concentrate on **deeper reasoning**
- Encourage **better development practices**
  - Programming models that avoid mistakes
  - Teach programmers to manifest their assumptions
    - Using **annotations** that improve tool precision
- Seeing **increased commercial adoption**



Fuzzing

Some material from Tal Garfinkel, Dmitry Vyukov

https://reviewsfromtheabyss.files.wordpress.com/2012/07/2007_hot_fuzz_002.jpg

Testing vs. Fuzzing

- Testing: Test many (mostly) normal inputs
  - Goal: Keep user from encountering bugs
- Fuzzing: Test abnormal inputs
  - Goal: Look for exploitable weakness

High-level idea

- Generate many weird inputs
  - Files (.pdf, .wav, .html, etc)
  - Network packets
  - Other?
- Monitor application for errors
  - Crashes $\stackrel{?}{=}$ vulnerabilities?

How to generate inputs?

- Random/brute force (hmm….)
- Mutation: Tweak valid inputs
- Grammar-based
- Using symbolic execution / static analysis (whitebox)
- **Coverage-guided** (greybox)

Coverage-guided fuzzing

- While (true):
  - Select input from corpus
  - Mutate input
  - Run target program, collect code coverage
  - If got new coverage, add input back to corpus

Types of mutations

- Add/remove/swap bytes from one input
- Splice two inputs
- Insert token from dictionary or magic number
- Change semantic token (“123”-> “456”, “cat”-> “dog”)
- etc.

Detecting a “problem”

- Did it crash?
- Did it freeze?
- Did it give the correct output?
  - Round trip: encode/decode, etc.
  - Compare to reference implementation

How much fuzz is enough?

- Random mutations can take a while to hit
- Even w/ coverage metrics!
  - Can cover it without hitting the bug
  - Lots of code you never reach