Static Code Analysis

Lecture 8
Sept 28-Oct 5, 2018

Source:
"Secure Programming with Static Analysis"

Static Analysis

- Analyzing code before executing it
  - Analogy: Spell checker
- Suited to problem identification because
  - Checks thoroughly and consistently
  - Can point to the root cause of the problem
    - E.g., presence of buffer overflow; helps to focus on what to fix
  - Help find errors/bugs early in the development
    - Helps reduce cost
  - New information can be easily incorporated to recheck a given program

Usefulness

- Better than manual code review
- Faster and more concrete than testing
- Consistency in coverage
- Embody the existing security knowledge and gets extended
- Great for use by non-experts

Key Issues

- Can give a lot of noise!
- False Positives & False Negative
  - Which is worse? Need to balance the FP and FN
- Defects must be visible to the tool
- Different types of Static analysis:
  - Type checking; Style checking
  - Program understanding ; Program verification
  - Property checking; Bug finding
  - Security Review

It is Computationally undecidable problem

Type Checking

Example 2.1 A type-checking false positive: These Java statements do not meet type safety rules even though they are logically correct.

```
10  short s = 0;
11  int i = s;   /* the type checker allows this */
12  short r = i; /* false positive: this will cause a
13                  type checking error at compile time */
```

Example 2.2 Output from the Java compiler demonstrating the type-checking false positive.

```
$ javac bar.java
bar.java:12: possible loss of precision
found    : int
required: short
  short r = i; /* false positive: this will cause a
             ^
1 error
```

Example 2.3 These Java statements meet type-checking rules but will fail at runtime.

```
Object[] objs = new String[1];
objs[0] = new Object();
```

Style Checking

- Superficial set of rules
- Focused on rules related to
  - Whitespace, naming, deprecated functions, commenting, program structure
  - Affect: readability and maintainability rather than coding error
  - -Wall in gcc
    - Detect when a switch statement does not account for all possible values
  - For a large project many people with their own style may be involved
  - Examples: lint, PMD

Program Understanding

- Helps make sense of a large Codebase
  - Examples
    - Tool example: Fujaba
      - UML and Java Code – can help back and forth
    - “Finding all uses of a method”
    - “Finding declaration of a global variable”
  - Helpful to work on code one has not written
    - some reverse engineer the design – “big picture”
  - IDEs typically include some PU functionality

Program verification and Property checking

- Accepts a specification and associated Code
    - Aims to prove that the code is faithful implementation
    - “*equivalence checking*” to check the two match
- Complete specific
  consuming !
    - So “Partial” verifi
      verification”
        - Try to find a “cc
    - Sound wrt the spec
        - It will always return a problem if one exists !
            - (false negative? False positive?)
            - Soundness may be very difficult to establish

Memory leak

```
1  inBuf = (char*) malloc(bufSz);
2  if (inBuf == NULL)
3    return -1;
4  outBuf = (char*) malloc(bufSz);
5  if (outBuf == NULL)
6    return -1;
```

```
Violation of property "allocated memory should always be freed":
  line 2: inBuf != NULL
  line 5: outBuf == NULL
  line 6: function returns (-1) without freeing inBuf
```

Counter example for: Allocated memory should always be freed

Bug Finding

- Points out places where the program will behave in a way that the coder did not intend
  - Use patterns that indicate bugs
  - Example: FindBug (Java), Coverity (C, C++)
- Early tools: ITS4, RATS, Flawfinder
  - Little more than glorified "grep"
  - Closer to style checkers
- Modern tools
  - Typically hybrid of property checkers and bug finders

Factors for utility of SA

- Ability of the tool to make sense of the program
- Trade-offs it makes between precision and scalability
- Errors that it can check/detect
- How easily usable by programmers/users

Some examples

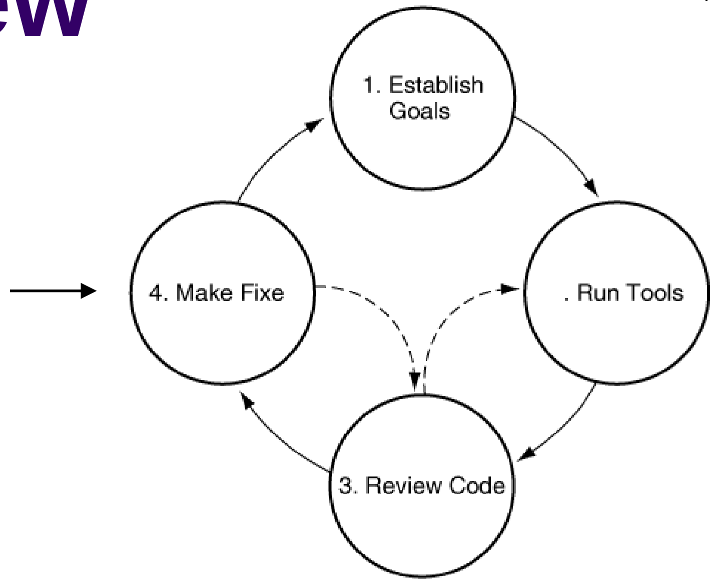
Type of Tool/Vendors	Web Site
Style Checking	
PMD	http://pmd.sourceforge.net
Parasoft	http://www.parasoft.com
Program Understanding	
Fujaba	http://wwwcs.uni-paderborn.de/cs/fujaba/
CAST	http://www.castsoftware.com
Program Verification	
Praxis High Integrity Systems	http://www.praxis-his.com
Escher Technologies	http://www.eschertech.com
Property Checking	
Polyspace	http://www.polyspace.com
Grammatech	http://www.gramatech.com
Bug Finding	
FindBugs	http://www.findbugs.org
Coverity	http://www.coverity.com
Visual Studio 2005 \analyze	http://msdn.microsoft.com/vstudio/
Klocwork	http://www.klocwork.com
Security Review	
Fortify Software	http://www.fortify.com
Ounce Labs	http://www.ouncelabs.com

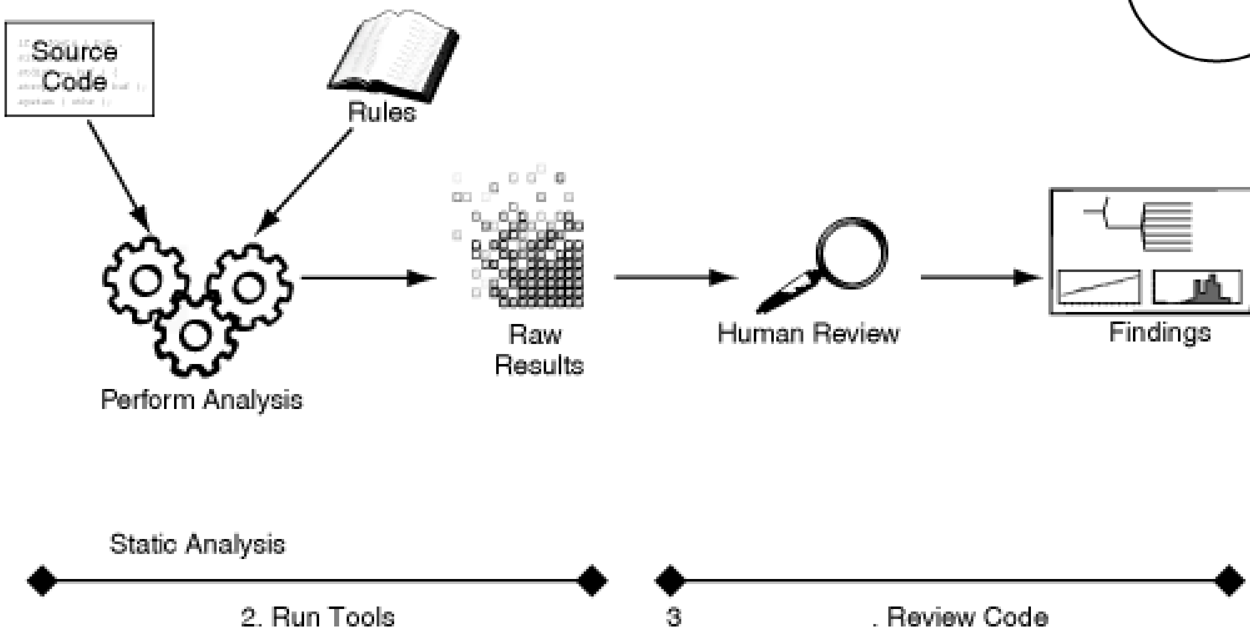
Analyzing Source vs Compiled

- Static analysis can examine a program
  - As a compiler sees it (Source code) OR
  - As a run-time env sees it (in some cases – bytecode or executable)
- Advantages of compiled code analysis
  - No need to guess how compiler will interpret
  - Source code may be not available
- Disadvantages
  - Making sense is more difficult (e.g., may lack type info)

SA in Code Review

Code review cycle



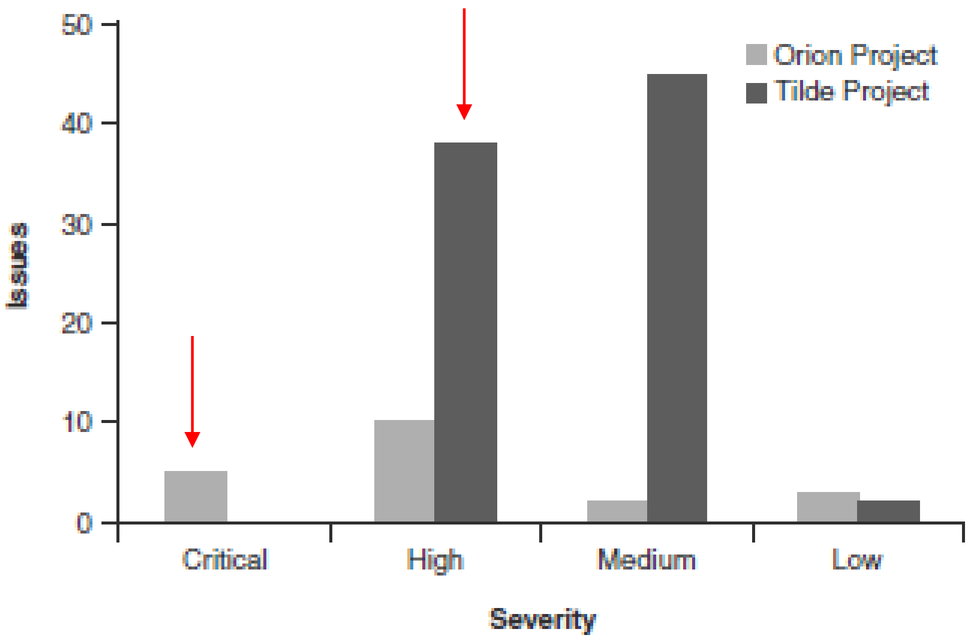


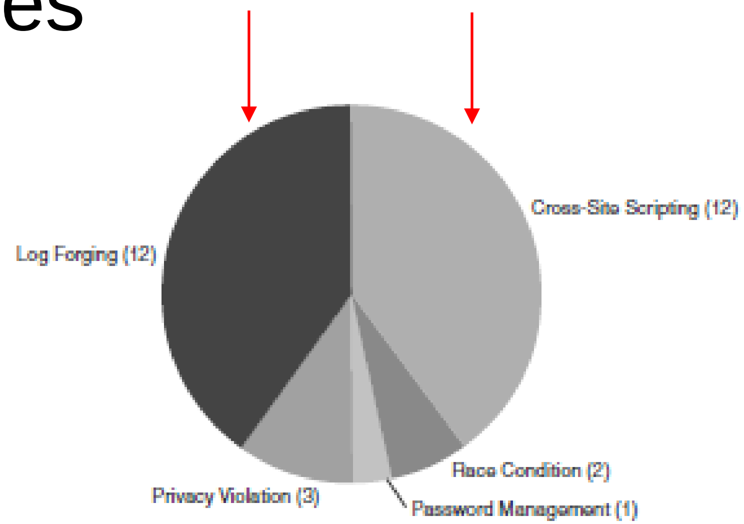
Establish Goals: SA Metrics

- Prioritize code to review + criteria … based on risks
- Metrics helps
  - Prioritizing remedial efforts
  - Estimating risk associated with code (tricky!)
    - False positive/negative – manual inspection needed
    - No way to sum/aggregate risks from flaws
- Some metrics for tactical focus
    - Measuring vulnerability density
      - #results/LOC – maybe deceptive
    - Comparing projects by severity
    - Breaking down results by category
    - Monitoring trends – from one group (dev) to another (security)

SA Metrics

- Comparing modules based on severity
- Breaking down by categories

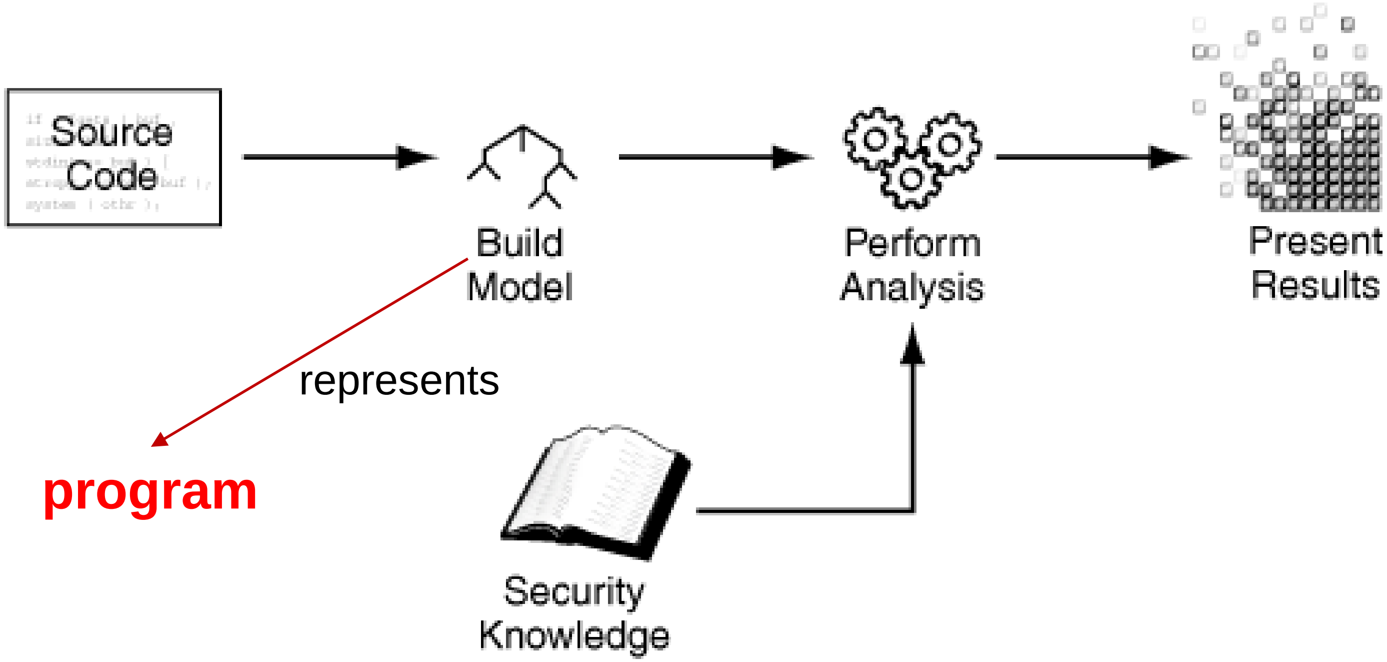




Prioritizing remedial efforts

SA Internals

- A Generic SA Tool



Building a model

- Creates a program model from code
  - A set of data structures representing the code
  - Depends on the type of analysis that a tool performs
- SA - Closer to compiler
  - Lexical analysis – e.g., regular expression for tokens
  - Parsing – uses a context free grammar
    - Set of production rules
    - Parse tree: Lex and Yacc

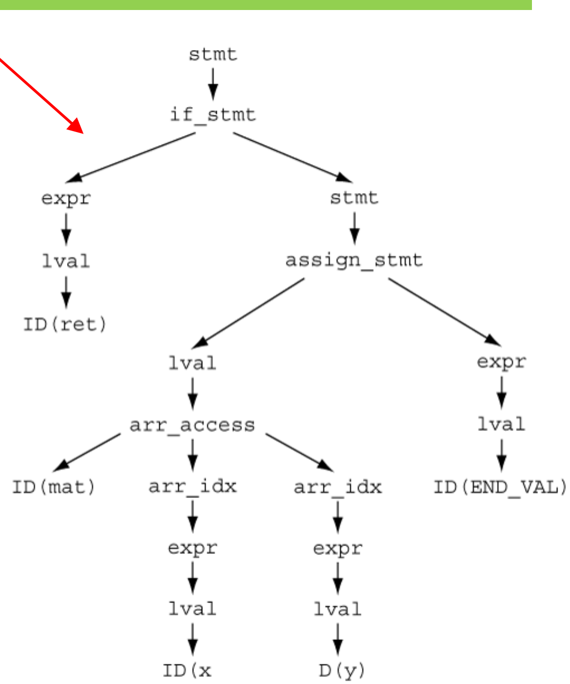
```
Lexical Rules:

if                        { return IF; }
(                         { return LPAREN; }
)                         { return RPAREN; }
[                         { return LBRACKET; }
]                         { return LBRACKET; }
=                         { return EQUAL; }
;                         { return SEMI; }
/[ \t\n]+/                { /* ignore whitespace */ }
/\/\/.*/                  { /* ignore comments */ }
/[a-zA-Z][a-zA-Z0-9]*/    { return ID; }
```

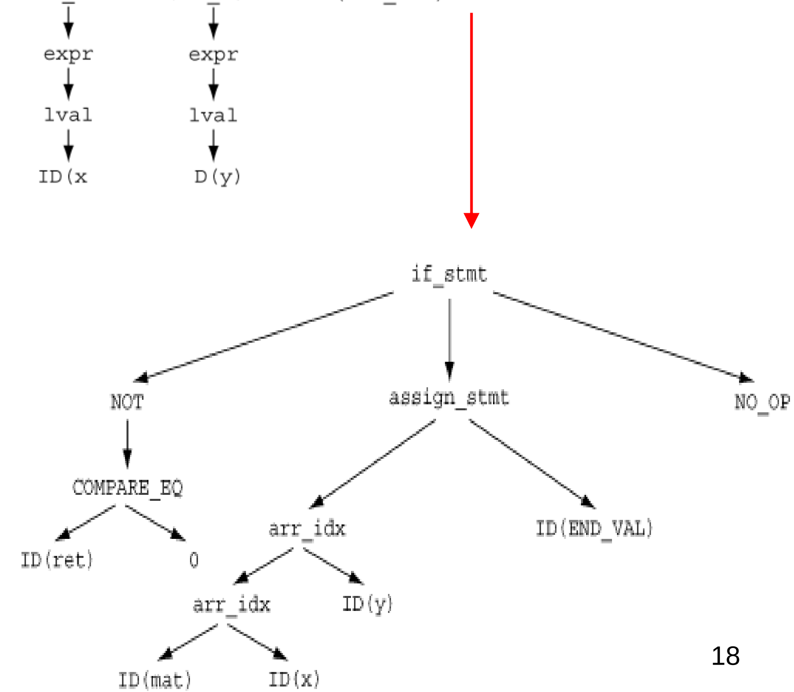
Parsing

```
if (ret) // probably true
  mat[x][y] = END_VAL;
```

- Can have nonterminal symbols
  - Syntactic sugar!
- Can perform analysis on Parse Tree – can be inconvenient
  - Directly from grammar

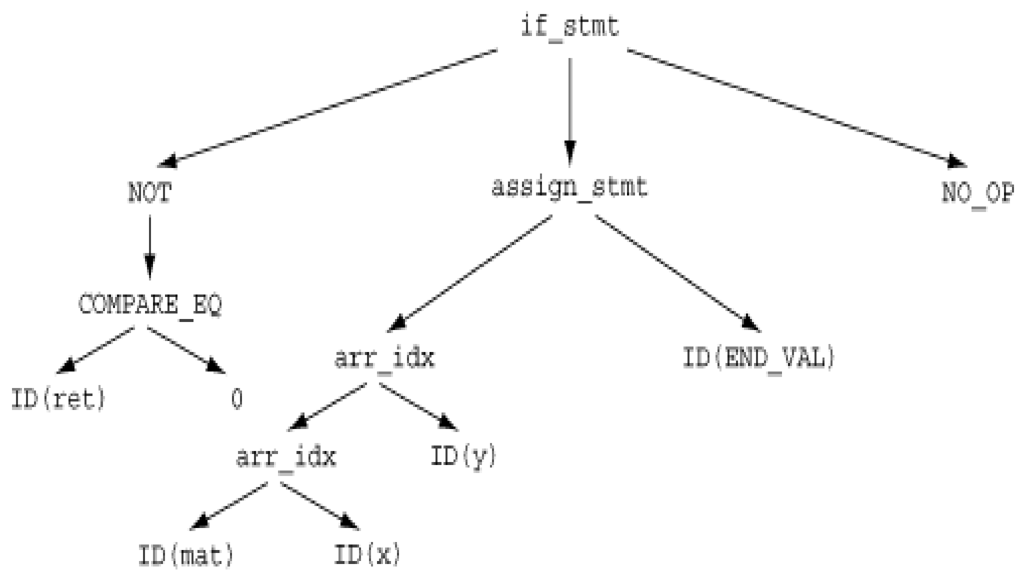



```
stmt := if_stmt | assign_stmt
if_stmt := IF LPAREN expr RPAREN stmt
expr := lval
assign_stmt := lval EQUAL expr SEMI
lval = ID | arr_access
arr_access := ID arr_index+
arr_idx := LBRACKET expr RBRACKET
```



Abstract Syntax Tree

- Does away with the details of grammar and *syntactic sugar*
  - Create a standard version of program
  - *Lowering* (e.g., loops may be converted to while loop)



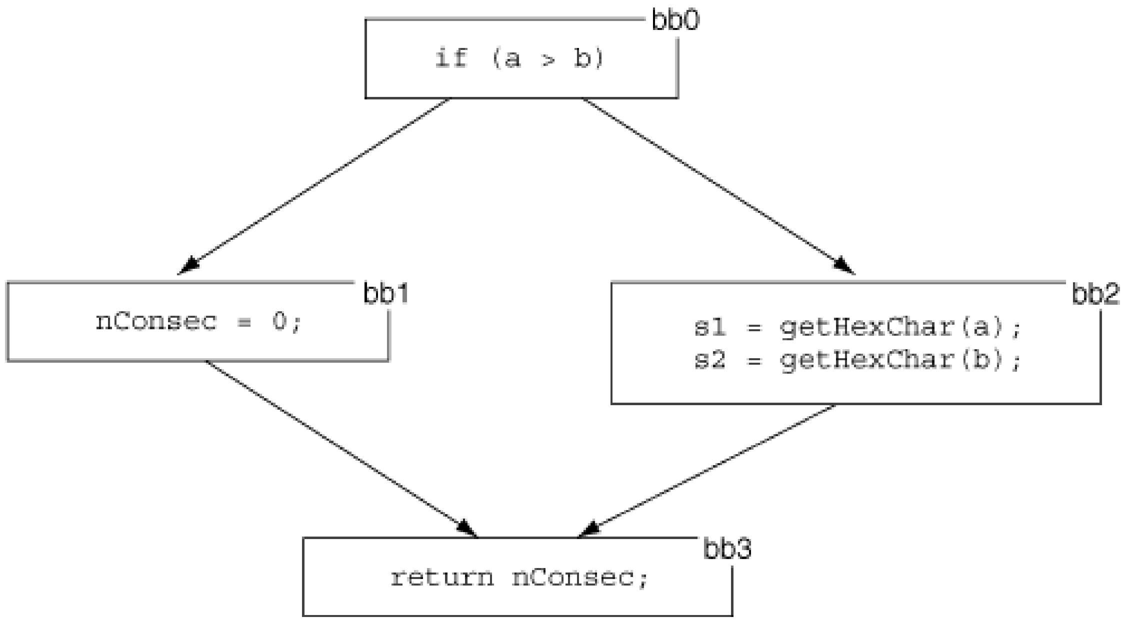
Semantic Analysis & Control Flow

- Semantic analysis based on: AST + Symbol table
  - Type checking can be done
  - Semantic analysis – symbol resolution and type checking
  - Optimization or *intermediate* forms may be created
- Tracking Control Flow
  - Different execution paths need to be explored
  - Build a control flow graph on top of AST

Control Flow Graph

- ***Trace***: sequence of blocks that define a path
  - E.g., bb0, bb1, bb3

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



Call graph

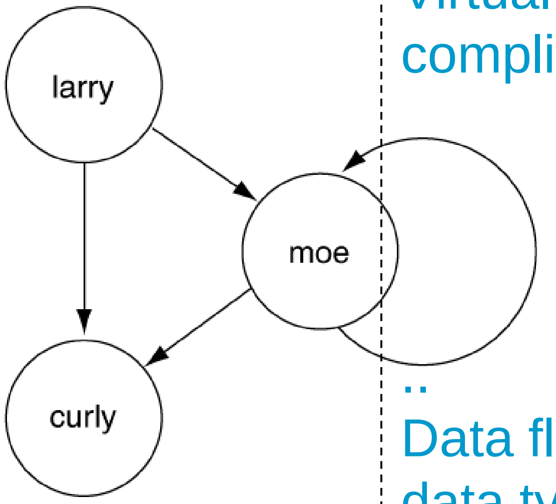
- Call graph – control flow between functions

```
int larry(int fish) {
  if (fish) {
    moe(1);
  } else  {
    curly();
  }

}

int moe(int scissors) {
  if (scissors) {
    curly();
    moe(0);
  } else {
    curly();
  }
}

int curly() {
  /* empty */
}
```



Function pointers & Virtual functions complicate things

..

Data flow & data type analysis may be needed

Dynamically loaded modules make it further challenging

Call graph may be incomplete

Dataflow

- Analyzes how data move through the program ..
  - Helps compilers optimize!
- Traverse function's control flow graph
  - Where data values are generated & where used
  - Convert a function to *static single assignment* form (SSA)
    - SSA: allows assigning a value to a variable only once
      - New variables may need to be added
    - SSA variable can have a constant (use that to replace future variable places) – constant propagation (pwds?, keys)
    - SSA variable may have different values along different control paths – need to be reconciled
      - Merge point: φ-*function*

SSA Examples

Regular source code form:

```
sum = sum + delta ;
sum = sum & top;
y = y + (z<<4)+k[0] ^ z+sum ^ (z>>5)+k[1];
y = y & top;
z = z + (y<<4)+k[2] ^ y+sum ^ (y>>5)+k[3];
z = z & top;
```

SSA form:

$sum_2 = sum_1 + delta_1$;

$sum_3 = sum_2$ & top_1;

$y_2 = y_1 + (z_1 \ll 4) + k[0]_1 \wedge z_1 + sum_3 \wedge (z_1 \gg 5) + k[$

$y_3 = y_2$ & top_1;

$z_2 = z_1 + (y_3 \ll 4) + k[2]_1 \wedge y_3 + sum_3 \wedge (y_3 \gg 5) + k[3]_1$;

$z_3 = z_2$ & top_1;

Regular source form:

```
if (bytesRead < 8) {
  tail = (byte) bytesRead;
}
```

SSA form:

if ($bytesRead_1 < 8$) {

  $tail_2$ = (byte) $bytesRead_1$;

}

$tail_3 = \phi(tail_1, tail_2)$;

Taint Propagation

- It is important
  - to identify which values in a program an attacker could potentially control/target
    - Need to know where values enter and how they move
      - E.g., Buffer overflow vulnerability
  - *Taint propagation* algorithm
    - Key to identifying many input validation and representation defects
    - Static as well as dynamic taint propagation analysis

Pointer Aliasing

- Several pointers may refer to the same memory

```
*p1 = 1
*p2 = 2
```

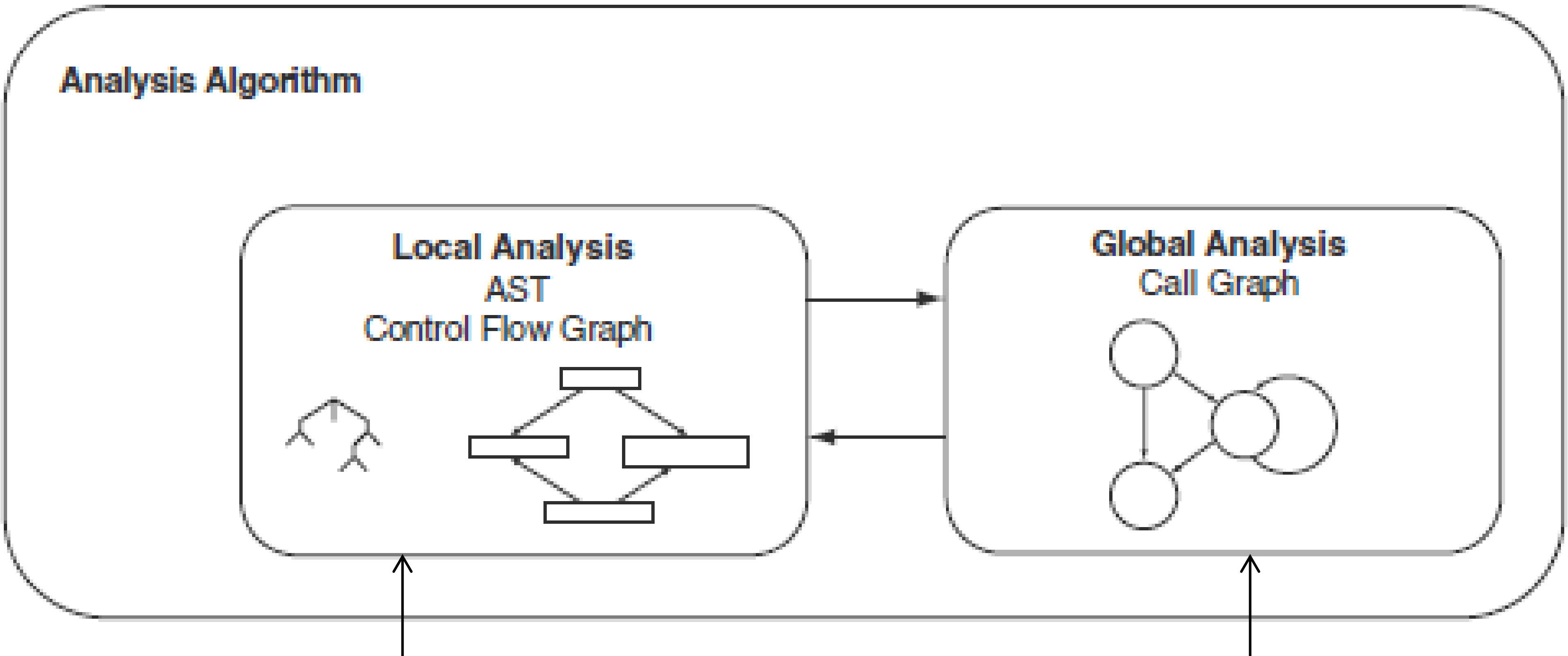
Can p1 and p2 refer to the same location?
Can these be reordered?

For the following, compiler should understand that input data flows to process Input

```
p1 = p2;
*p1 = getUserInput();
processInput(*p2);
```

SA Algorithms

- Local component and global component
  - Improve context sensitivity



intraprocedural *analysis component for analyzing an individual function*

interprocedural *analysis component for analyzing interactions*

Assertions

- Many properties can be specified as assertions – which need to be true

  Example: Buffer Overflow prevention check

  ```
  strcpy(dest, src);
  ```

  Add assertion before the call

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

- If there are conditions under which an assertion can fail – report potential overflow

Assertions

- Typically three varieties of assertions
  - Taint propagation problems
    - When programmers trust input when they should not – so SA should check data values moving
    - data is either tainted (controlled by an attacker) or not
  - Range Analysis
    - To Identify buffer overflow – need to know the size of the buffer and the data value
      - Understand the range of values data or size may have
  - Type state: concern about the state of an object as execution proceeds
    - In freed state (can lead to double free vulnerability?)

Naïve Local Analysis (informal)

No concrete values needed

Consider

```
x = 1;
y = 1;
assert(x < y);
```

x = v;
y = v;
assert(x < y);
Same Result

Symbolic Simulation

- Maintain facts before each statement is executed

x = 1;	{} (no facts)
y = 1;	{ x = 1 }
assert(x < y);	{ x = 1, y = 1 }

  - Always false!! SA should report a problem

Conditionals make it complex!

```
x = v;
if (x < y) {
    y = v;
}
assert (x < y);
```

this condition may or may not be TRUE

x = v;	{} (no facts)
if (x < y)	{ x = v }
assert (x < y)	{ x = v, ¬(x < y) }

When BRANCH is not taken x < y is FALSE

x = v;	{}(no facts)
if (x < y)	{ x = v }
y = v;	{ x = v, x < y }
assert (x < y)	{ x = v, x < y, y = v }

When BRANCH is taken x < y is TRUE

v < v means assertion is violated

Need to check the conjunction of assertion predicate and all the facts:

$$(x < y) \wedge (x = v) \wedge \neg(x < y)$$

Again fails!

Conditionals make it complex! Loops add further ..

- The previous approach is problematic
- #paths grows with the number of conditionals
  - Share info among common subpaths
  - *Program slicing* – to remove code that cannot affect the outcome of the assert predicate
  - Also eliminate *false paths* – logically inconsistent paths that will never be executed
- Adding loops makes it even more complex!

Approaches to Local Analysis

- Abstract interpretation
  - Abstract away aspects of the program that are not relevant to properties of interest and then perform an interpretation
  - Loop problems – do flow-insensitive analysis
    - Tries to guarantee that all statement orderings are considered (not follow the program statement order)
      - No need for control flow analysis
      - But some useless execution order may be performed as well
    - More practical tools – partially flow sensitive!

Predicate Transformers

- Use the weakest precondition
  - Fewest set of requirements on the callers of a program that are necessary to arrive at a desired final state or post condition

    E.g., consider assert(x < y)

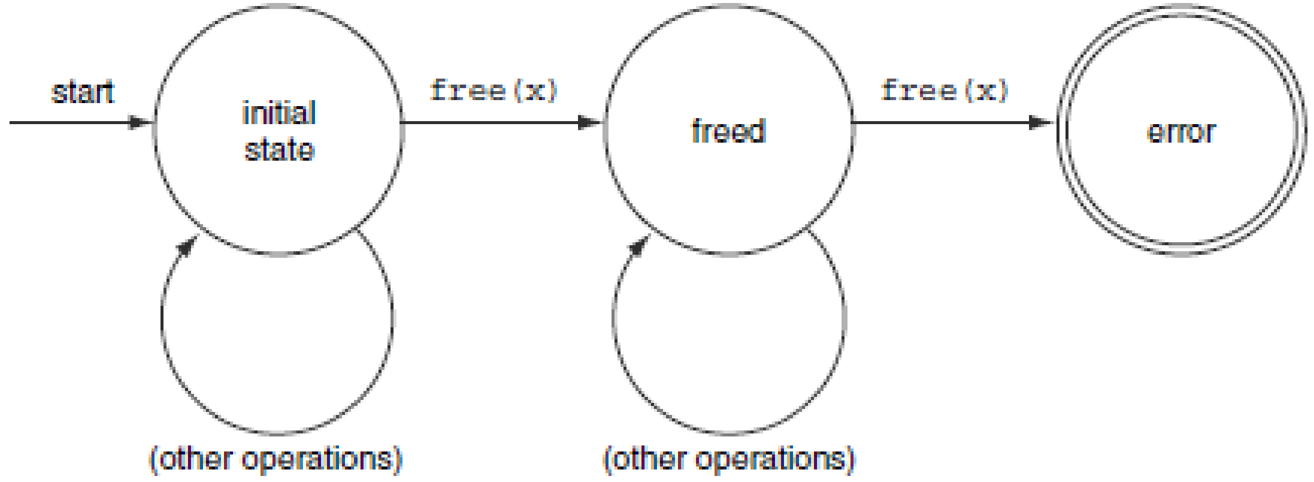
$(x < 0 \wedge y > 0)$ // always satisfied

is a strong requirement than

$(x < y)$;

Model Checking Approach

- Accepts properties as specifications, transforms the program to be check into an automaton (called the model)
  - Now compare the specification to the model
  - Example: “memory should be freed only once”



Model checking will look for a variable wrt which system will reach state error

Global Analysis

- Context-sensitive analysis
  - Takes into account the context of the calling function
- Whole-program analysis
  - Tries to analyze every function with a complete understanding of the context of its calling functions
  - One way is "*inlining*" (Recursion will be problem)
  - Time consuming and very ambitious
- More flexible approach
  - Local analysis generates the *function summaries*
  - Example →

```
memcpy(dest, src, len) [
  requires:
    ( alloc_size(dest) >= len ) ∧ ( alloc_size(src) >= len )
  ensures:
    ∀ i ∈ 0 .. len-1: dest[i]' == src[i]
]
```

Rules

- Good SA tools externalize the rules they check
  - Added, removed, altered easily

RATS will report a violation of the rule whenever it sees a call to system() where the first argument is not constant.

```
<Vulnerability>
  <Name>system</Name>
  <InputProblem>
    <Arg>1</Arg>
    <Severity>High</Severity>
  </InputProblem>
</Vulnerability>
```

The argument number

In some cases rules are *annotated* within the program (in JML)

```
/*@ public normal_behavior
  @   requires    valid;
  @   assignable  state;
  @   ensures     -1 <= \result && \result <= 65535;
  @*/
public int read();
```

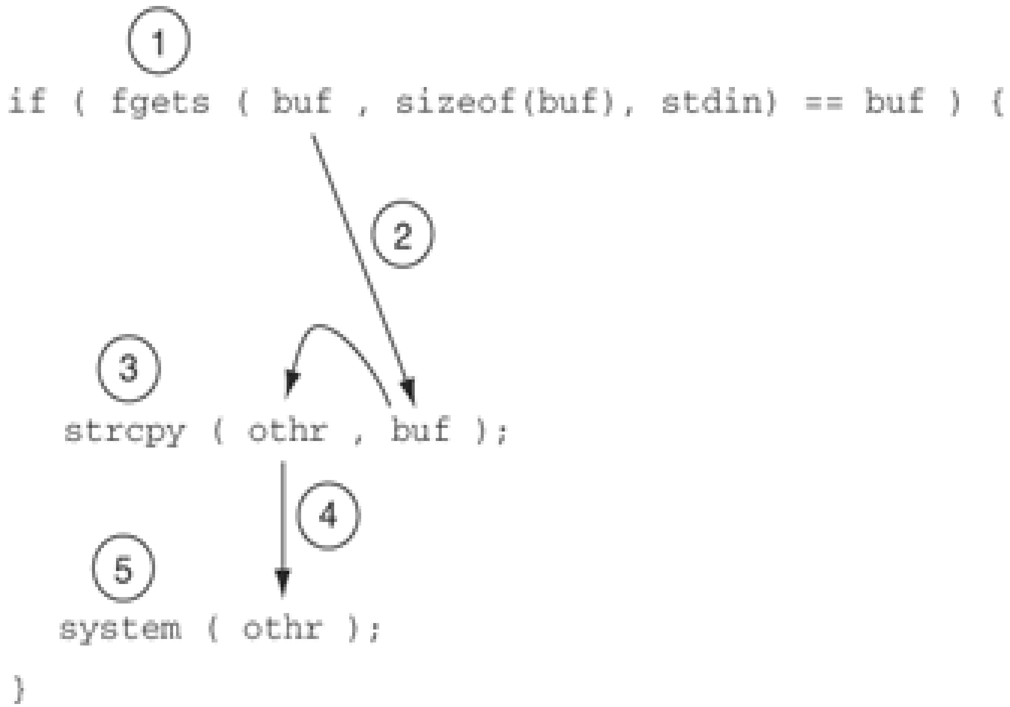
Rules for Taint Propagation

- Variety of rule types to accommodate different *taint propagation* problems
  - **Source rules** define program locations where tainted data enter the system.
    - Functions named read() often introduce taint in an obvious manner; others: getenv(), getpass(), gets().
  - **Sink rules** define program locations that should not receive tainted data.
    - For SQL injection in Java, Statement.executeQuery() is a sink.
    - For buffer overflow in C, assigning to an array is a sink, as is the function strcpy()

Rules for Taint Propagation

- Pass-through rules define the way a function manipulates tainted data.
  - E.g.,, a pass-through rule for the java.lang.String method trim() might explain “if a String s is tainted, the return value from calling s.trim() is similarly tainted.”
- Cleanse rule is a form of pass-through rule that removes taint from a variable.
  - represents input validation functions.
- Entry-point rules (similar to source)-
  - they introduce taint into the program, entry-point functions are invoked by an attacker.
    - E.g., main() is an entry point (java, C)

Example: Command injection vulnerability



1. A source rule for `fgets()` taints `buf othr`
2. Dataflow analysis connects uses of `buf`
3. A pass-through rule for `strcpy` taints
4. Dataflow analysis connects uses of `othr`
5. Because `othr` is tainted, a sink rule for `system()` reports a command injection vulnerability

Taints

- Essentially BINARY attribute
  - But can have taint flags to indicate variety of tainted data – can help prioritize!
    - FROM_NETWORK data from network
    - FROM_CONFIGURATION data from config file
  - Sink functions may be dangerous for a specific taint type
    - E.g., arbitrary user-controlled data vs. numeric data
- Taint propagation rules include various elements
  - Method or function – to apply to
  - Precondition – on taint propagation
  - Postcondition – changes to taint propagation (taint or cleanse)
  - Severity – when the sink rule is triggered

Summary

- Overview of Static Analysis