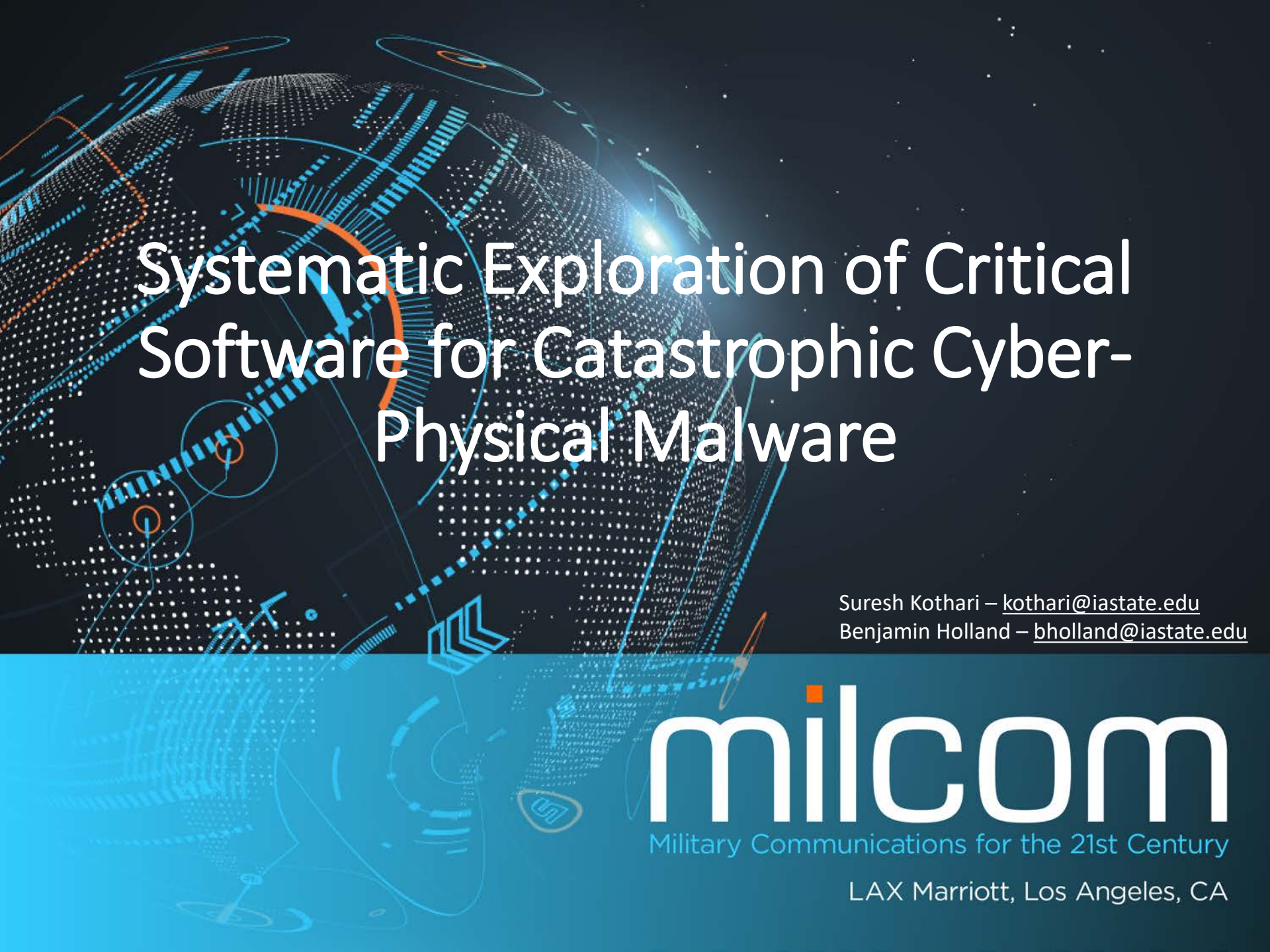


Systematic Exploration of Critical Software for Catastrophic Cyber-Physical Malware

Suresh Kothari – kothari@iastate.edu
Benjamin Holland – bholland@iastate.edu

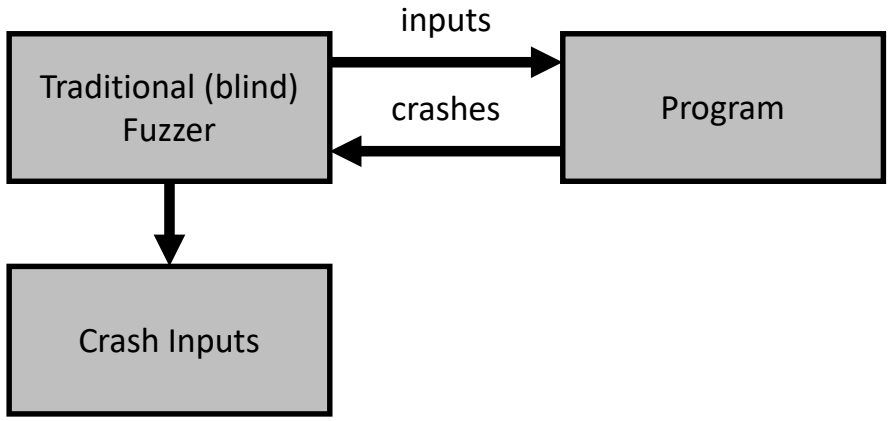
milcom
Military Communications for the 21st Century
LAX Marriott, Los Angeles, CA

How do we analyze a program?

- Two main camps
  - Dynamic analysis
    - Run the program with some inputs and see what it does
    - Advantage: Everything we observe is feasible (we just saw it happen)
    - Concern: Input space is HUGE
    - Concern: Did we test the *interesting* inputs?
  - Static analysis
    - Don't run the program, dissect the logic and examine program artifacts
    - Advantage: Bird's eye view of everything that could possibly happen during execution
    - Concern: Number of program behaviors is HUGE
    - Concern: Is it feasible to reach/trigger an artifact of concern?
- What are we looking for?
  - Bugs: Memory corruption, rounding errors, null pointers, infinite loops, stack overflows, race conditions, memory leaks, business logic flaws, …
  - Not every issue translates to a crash!

Traditional/Dumb (Blind) Fuzzing

- Start with a test corpus of well formed program inputs
- Apply random or systematic mutations to program inputs
- Run program with mutated inputs and observe whether or not the program crashes
- Repeat until the program crashes
- Input space
  - Reading data in a loops could make the input space infinite
  - There are 2^n possible inputs for a binary input of length *n*



This is about all we can do without examining program artifacts…

Building a Static Analysis Tool

- Compiler: Lexer → Parser → AST → Semant → Code Generation
- Static Analysis: Lexer → Parser → AST → Semant → Graph of Program Artifacts → Graph Queries of Concerning Program Relationships

- Demo Eclipse Plugin: http://ben-holland.com/AtlasBrainfuck/updates

Brainf*ck Language

- Designed by Urban Müller in 1992 with the goal of implementing the smallest possible compiler.
- Compiler can be implemented in less than 100 bytes
- Implements a Turing machine

Reference:
https://en.wikipedia.org/wiki/Brainfuck

Character	Meaning
>	increment the data pointer (to point to the next cell to the right).
<	decrement the data pointer (to point to the next cell to the left).
+	increment (increase by one) the byte at the data pointer.
-	decrement (decrease by one) the byte at the data pointer.
.	output the byte at the data pointer.
,	accept one byte of input, storing its value in the byte at the data pointer.
[	if the byte at the data pointer is zero, then instead of moving the instruction pointer forward to the next command, jump it *forward* to the command after the *matching*] command.
]	if the byte at the data pointer is nonzero, then instead of moving the instruction pointer forward to the next command, jump it *back* to the command after the *matching* [command.

Brainf*ck (Hello World)

++++++++[>++++[>++>+++>+++>+<<<<-]>+>+>->>+[<]<-]>>.>---.+++++++..+++.>>.<-.<.+++.------.--------.>>+.>++.

Brainf*ck Lexical Analysis

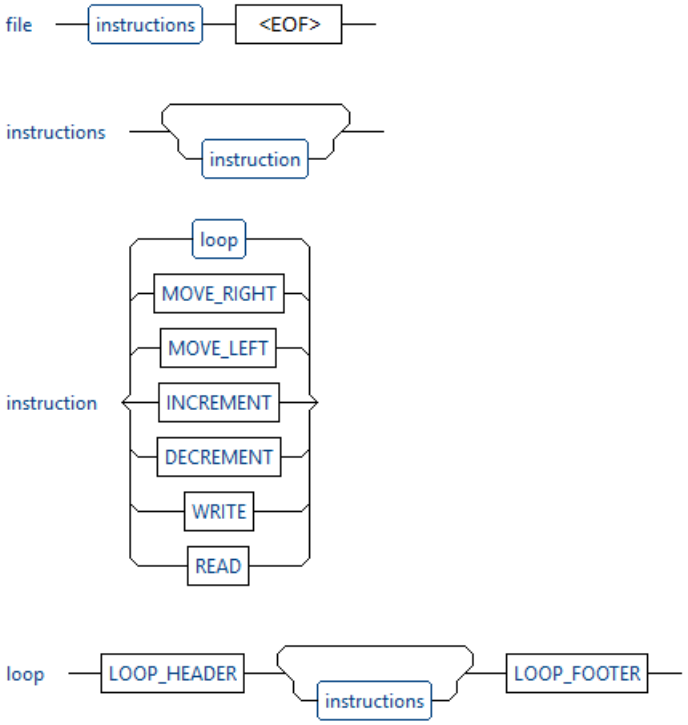
```
MOVE_RIGHT: '>';
MOVE_LEFT: '<';
INCREMENT: '+';
DECREMENT: '-';
WRITE: '.';
READ: ',';
LOOP_HEADER: '[';
LOOP_FOOTER: ']';
```

Program: ***++[>+[+]].***

Program Tokens: **INCREMENT INCREMENT LOOP_HEADER MOVE_RIGHT INCREMENT LOOP_HEADER INCREMENT LOOP_FOOTER LOOP_FOOTER WRITE <EOF>**

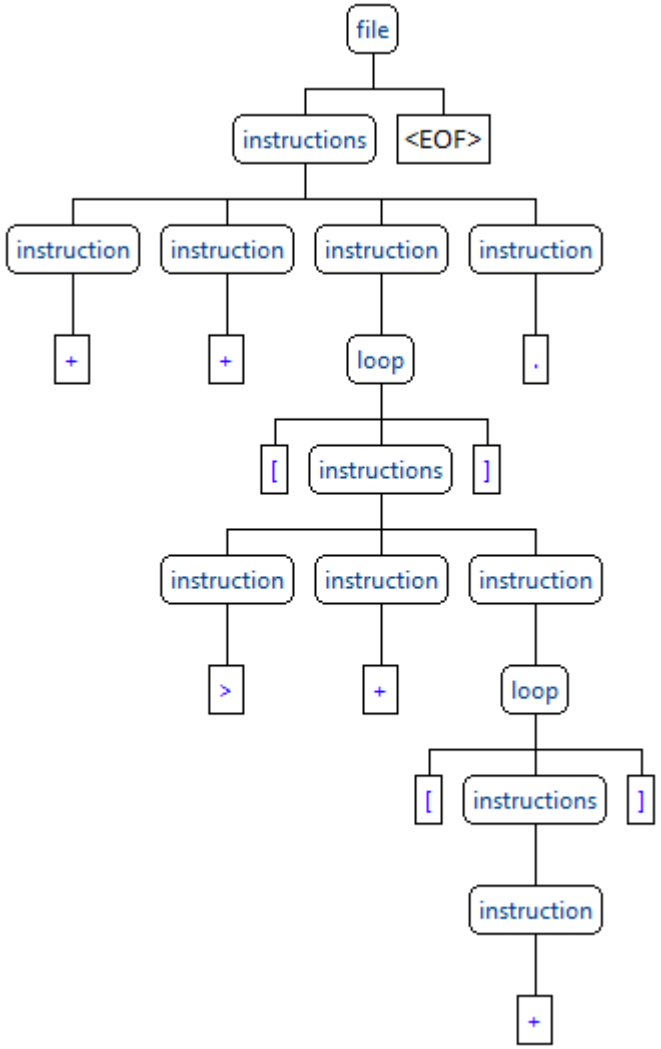
Brainf*ck Parsing Rules

```
file: instructions EOF;

instructions: instruction+;

instruction: loop
           | MOVE_RIGHT
           | MOVE_LEFT
           | INCREMENT
           | DECREMENT
           | WRITE
           | READ
           ;

loop: LOOP_HEADER instructions+ LOOP_FOOTER;
```

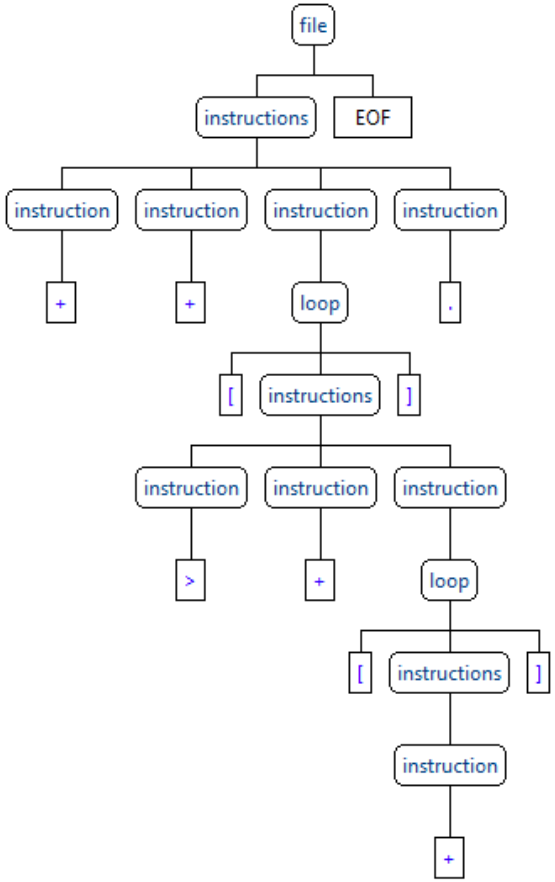


Brainf*ck Parse Tree

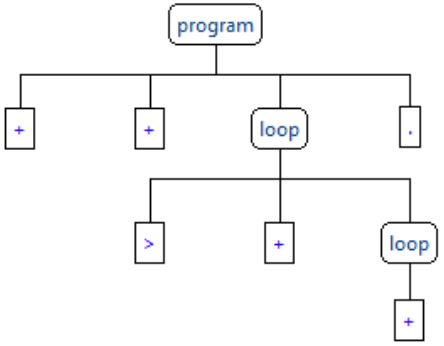
Program: ***++[>+[+]].***



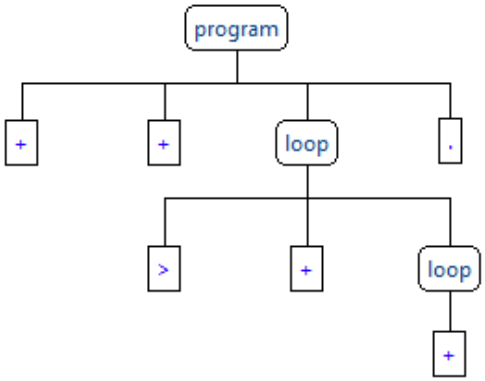
Brainf*ck Abstract Syntax Tree (AST)



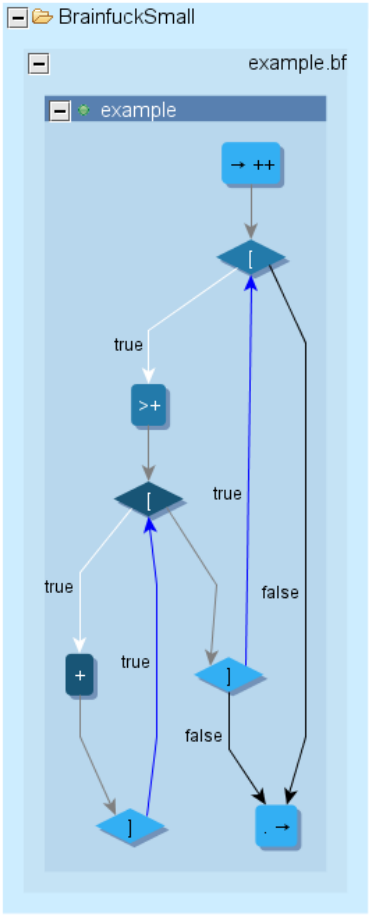
Parse Tree(s) to AST



Brainf*ck AST to Program Graph



Parse Tree(s) to AST

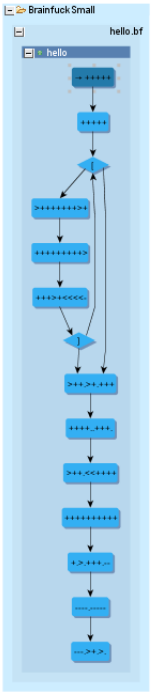


hello.bf

```
1 +++++
2 +++++
3 [>++++++++>++++++++++>+++>+<<<<-]
4 >++.>+.+++++++..+++.>++.<<+++++++++++++++.>.+++.------.--------.>+.>.
```

- Brainf*ck Hello World Program
- Graph contains information necessary to execute program
- This language should be simple to analyze right???
  - No variables, just tape cells
  - How many behaviors could there be?

Graph 2



atlas

Error Log | Search | Problems | Atlas Shell | Console | Progress | Analysis Keys | Git Staging

```
Operation completed successfully...

show(cfg(universe.nodes(XCSG.Function)))

com.benjholla.atlas.brainfuck.interpreter.BrainfuckGraphInterpreter.execute(selected)
res1: String =
"Hello World!
"
```

Evaluate:

atlas

Elemental: A Brainf*ck Derivative

- github.com/benjholla/Elemental
  - Goal is to be basic, not to be tiny
  - Separates looping and branching
  - New features to explore impacts of modern language features

Instruction	Description
+	Increment the byte at the current tape cell by 1
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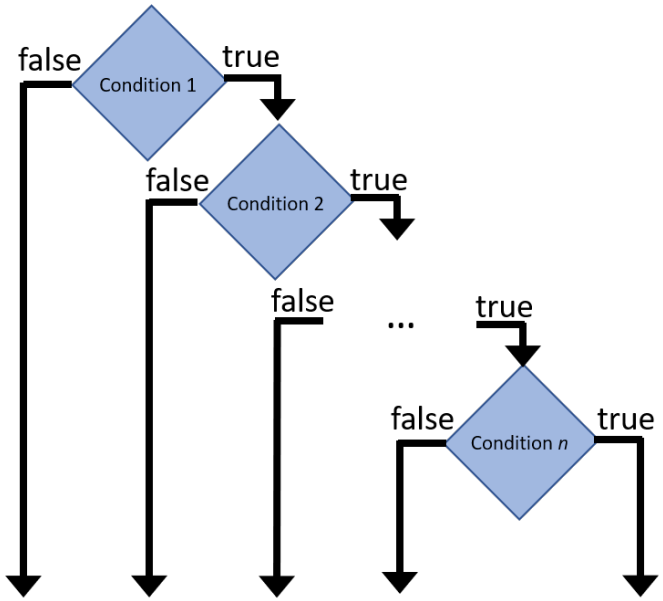
#	A one line comment

Counting Program Paths: Branching

How many paths are there for *n* nested branches?

```
if(condition_1){
   if(condition_2){
      if(condition_3){
         …
         if(condition_n){
            // conditions 1 through n
            // must all be true to reach here
         }
      }
   }
}
```

n+1 paths!

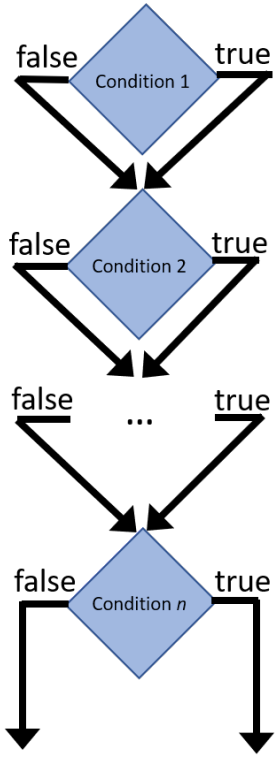


Counting Program Paths: Branching

How many paths are there for *n* non-nested branches?

```
if(condition_1){
   // code block 1
}
if(condition_2){
   // code block 2
}
if(condition_3){
   // code block 3
}
...
if(condition_n){
   // code block n
}
```

2^n paths!



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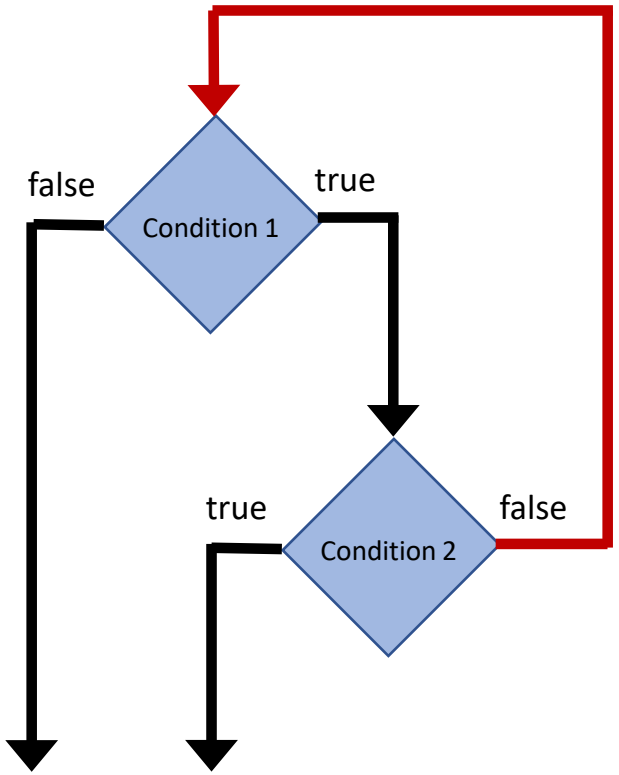
#	A one line comment

Considering Loops

- Programs may have loops
  - How many paths does this program have?
  - Can we say if this program halts?

```
while(condition_1){
    if(condition_2){
        break;
    }
}
```



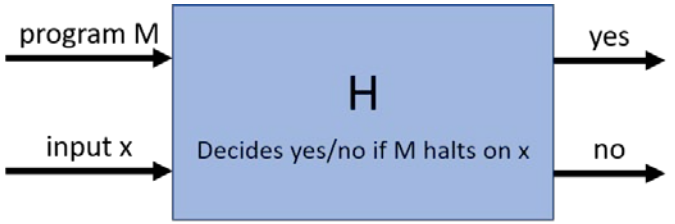
The Halting Problem

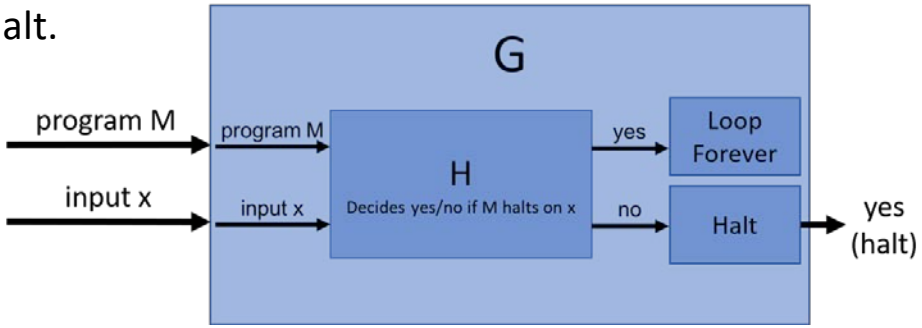
Suppose, we could construct:
H(M, x) := if *M* halts on *x* then return true else return false

Then we could construct:
G(M, x) := if G(M, *x)* is false then return true else loop forever

But if we then pass *G* to itself, that is G(G,G), we get a contradiction between what *G* does and what *H* says that *G* does. If *H* says that *G* halts, then *G* does not halt. If *H* says that *G* does not halt, then it does halt.

H cannot exist.





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  - Goal is to be basic, not to be tiny
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  - New features to explore impacts of modern language features

- '?' could pass control to any function!
- '&' could jump to any line!
- Goto labels with '?' or '&' could be simulated with branching or loops
- These blur control flow with data

Instruction	Description
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Positive Trend – Address the Languages

- Data drives execution
  - Data is half of the program!
  - “The illusion that your program is manipulating its data is powerful. But it is an illusion: The data is controlling your program.”

- Crema: A LangSec-Inspired Programming Language
  - Giving a developer a Turning complete language for every task is like *giving a 16 year old a formula one car* (something bad is bound to happen soon)

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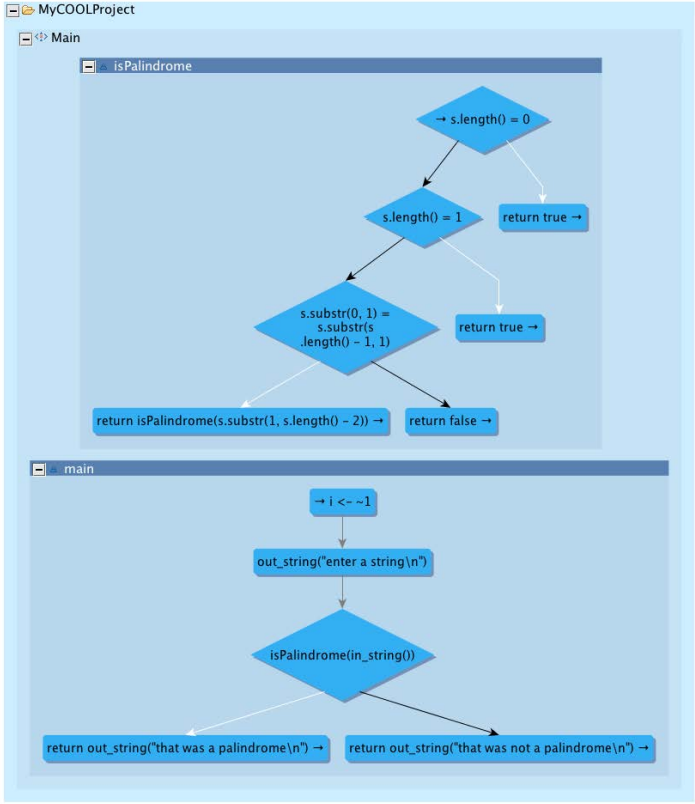
- Crema: A LangSec-Inspired Programming Language
  - Giving a developer a Turning complete language for every task is like *giving a 16 year old a formula one car* (something bad is bound to happen soon)
  - Apply principle of least privilege to computation (least computation principle)
    - Computational power exposed to attacker ***is*** privilege. Minimize it.
    - Try copy-pasting the XML billion-laughs attack from Notepad into MS Word if you want to see why…

Scaling Up: Program Analysis for COOL

- Classroom Object Oriented Language (COOL)
  - https://en.wikipedia.org/wiki/Cool_(programming_language)
  - http://openclassroom.stanford.edu/MainFolder/CoursePage.php?course=Compilers

- COOL Program Graph Indexer
  - Type hierarchy
  - Containment relationships
  - Function / Global variable signatures
  - Function Control Flow Graph
  - Data Flow Graph (in progress)
  - Inter-procedural relationships:
    - Call Graph (implemented via compliance to XCSG!)
  - https://github.com/benjholla/AtlasCOOL (currently private)



Program Analysis for Contemporary Languages

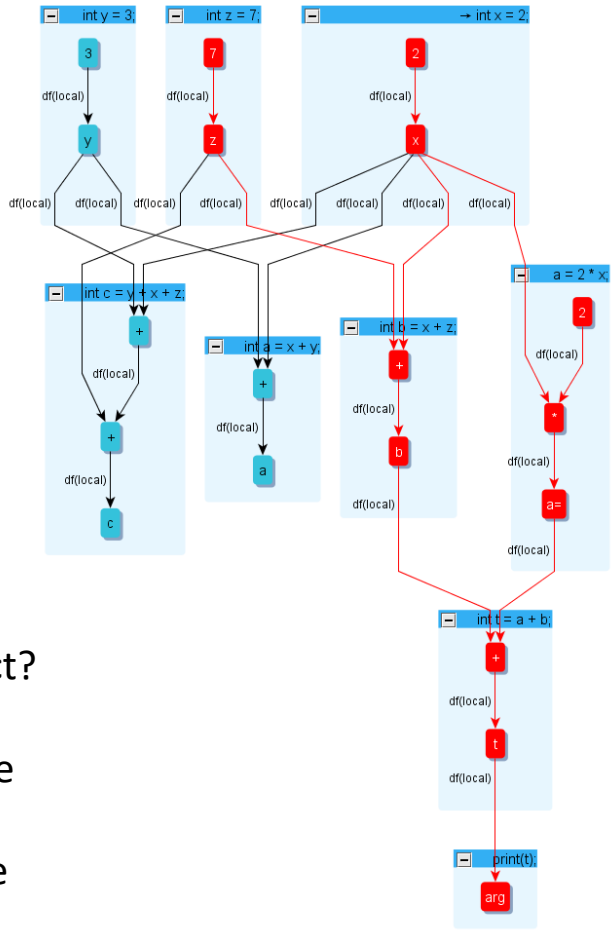
- http://www.ensoftcorp.com/atlas (Atlas)
  - C, C++, Java Source, Java Bytecode, *and now Brainfuck/COOL!*
- https://scitools.com (Understand)
  - C, C++ Source
- http://mlsec.org/joern (Joern)
  - C, C++, PHP Source
- https://www.hex-rays.com/products/ida (IDA)
- https://binary.ninja (Binary Ninja)
- https://www.radare.org (Radare)

Data Flow Graph (DFG)

Example:

1. x = 2;
2. y = 3;
3. z = 7;
4. a = x + y;
5. b = x + z;
6. a = 2 * x;
7. c = y + x + z;
8. t = a + b;
9. print(t); ← detected failure

Relevant lines:
1,3,5,6,8



- What lines must we consider if the value of *t* printed is incorrect?
- A *Data Flow Graph* creates a graph of primitives and variables where each assignment represents an edge from the RHS to the LHS of the assignment
- The *Data Flow Graph* represents global data dependence at the operator level (the atomic level) [FOW87]

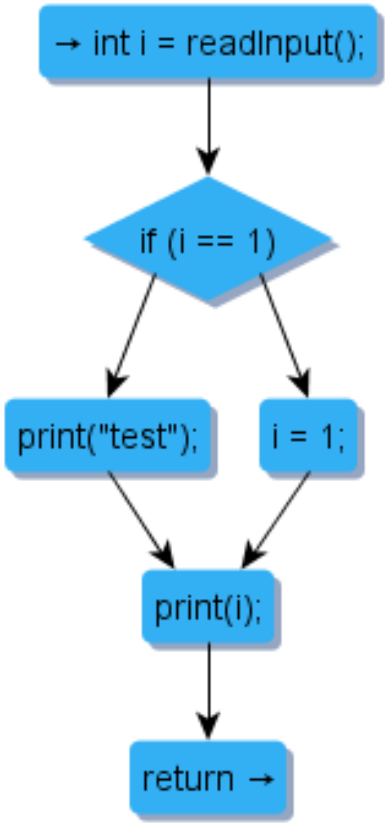
Control Flow Graph (CFG)

Example:

```
1. i = readInput();
2. if(i == 1)
3.       print("test");
   else
4.       i = 1;
5. print(i);
6. return; // terminate
```

Relevant lines:
1,2,4

detected failure

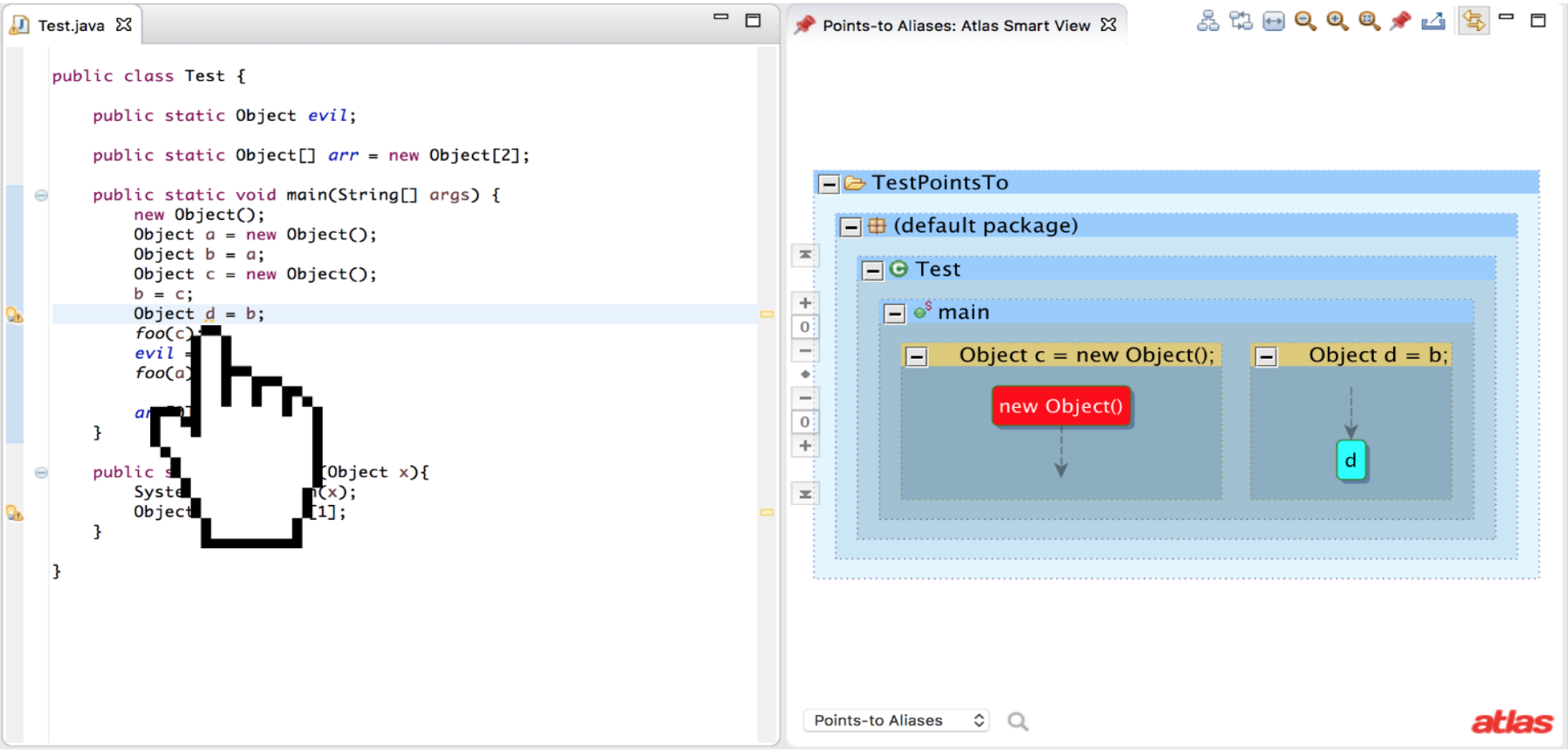


What lines must we consider if the value of *i* printed is incorrect?

- A *Control Flow Graph* (CFG) represents the possible sequential execution orderings of each statement in a program
- Data flow influences control flow, so this graph is not enough

Analysis Woes: Going Inter-procedural

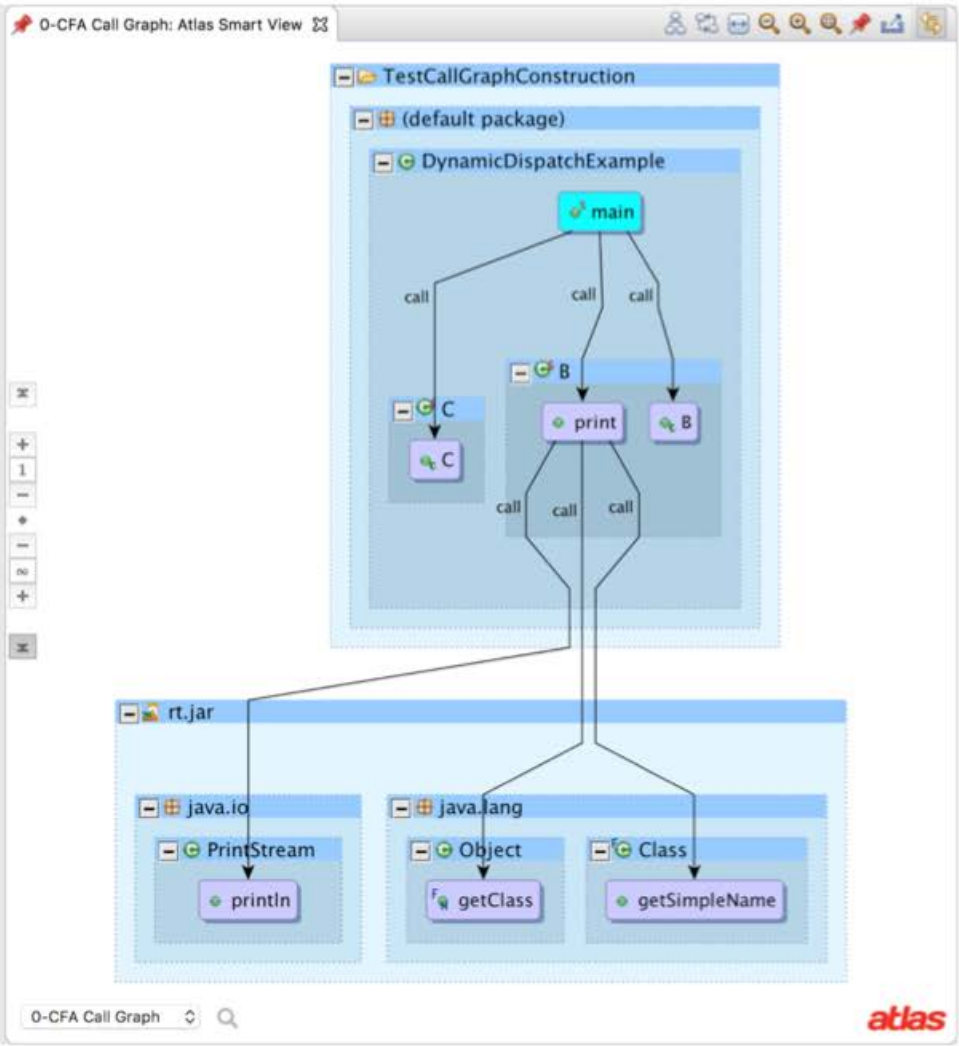
- Function pointers and dynamic dispatches force us to solve data flow problems to precisely identify inter-procedural control flows
- Class Hierarchy Analysis / Rapid Type Analysis
  - Cheap but *very* conservative results
- Points-to Analysis
  - A variable *v* points-to what data in memory? Knowing this we can more precisely resolve
  - Obtaining a perfect solution has been proven to reduce to solving the halting problem…
  - Expensive even for conservative results!!!
    - Each level of precision adds an exponent
    - Not really a lot to be gained (in our opinion)



https://github.com/EnSoftCorp/points-to-toolbox

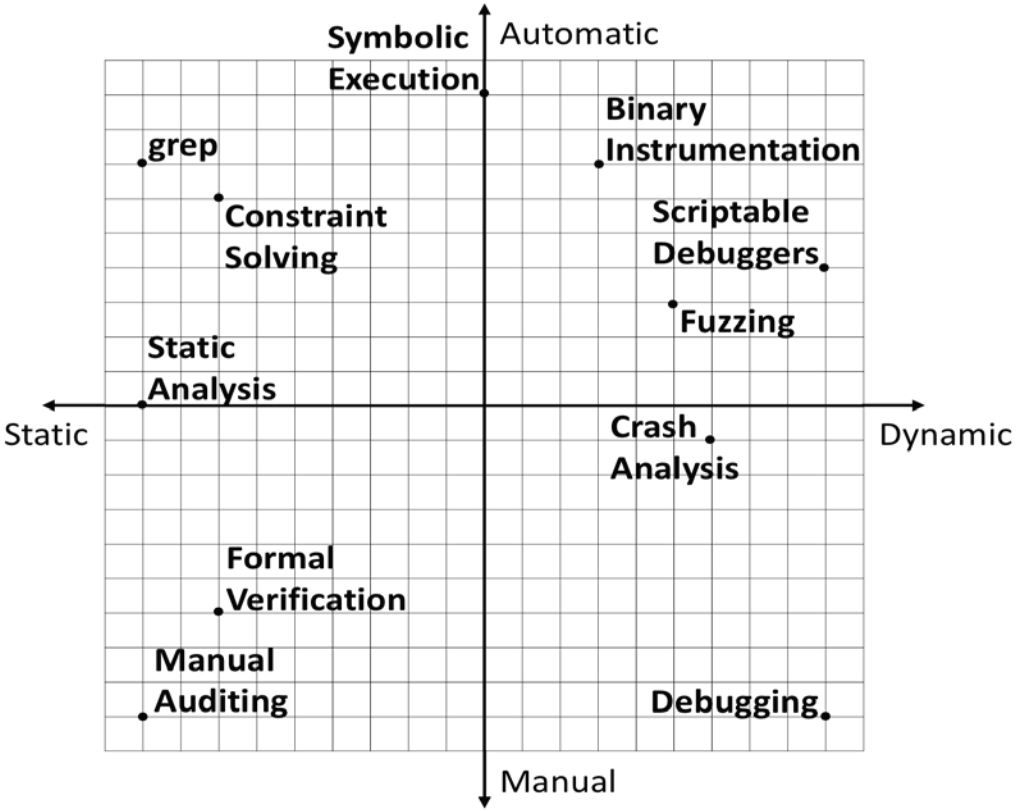
DynamicDispatchExample.java

```
public class DynamicDispatchExample {

    public static void main(String[] args){
        A b1 = new B();
        A c1 = new C();

        A b2 = b1;
        A c2 = c1;

        // what will get
        b2.print(c2);
    }

    public static class A extends Object {
        public void print(A object) {
            System.out.println("An instance of " + object.getClass().getSimpleN
                    + " was passed to A's print(A object)");
        }
    }

    public static class B extends A {
        public void print(A object) {
            System.out.println("An instance of " + object.getClass().getSimpleN
                    + " was passed to B's print(A object)");
        }
    }

    public static class C extends B {
        public void print(A object) {
            System.out.println("An instance of " + object.getClass().getSimpleN
                    + " was passed to C's print(A object)");
        }
    }

    public static class D extends A {
        public void print(A object) {
            System.out.println("An instance of " + object.getClass().getSimpleN
                    + " was passed to D's print(A object)");
        }
    }
```



https://ensoftcorp.github.io/call-graph-toolbox

A Spectrum of Program Analysis Techniques



Source: Contemporary Automatic Program Analysis,
Julian Cohen, Blackhat 2014

Symbolic Execution

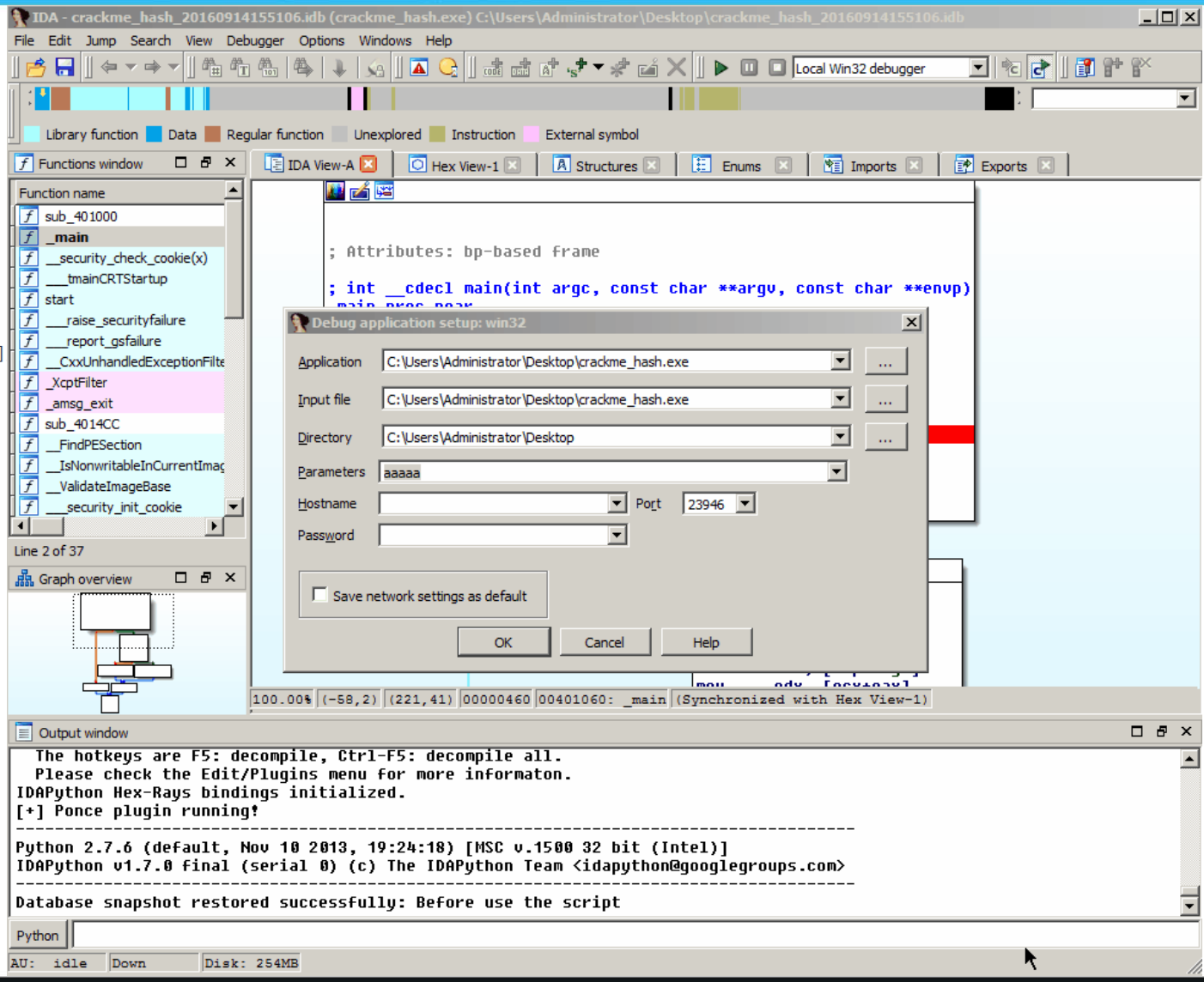
- Replace concrete assignment values with symbolic values
- Perform operations on symbolic values abstractly
- At each branch fork the abstracted logic
  - Dealing with path explosion problem is a challenge
- Utilize SAT/SMT solvers to determine if the constraints are satisfiable for a path of interest
  - Example: fail occurs if y * 2 = z = 12 is satisfiable
    - Solve(y * 2 = 12, y), y = 6 satisfies the constraint
    - Program crash occurs when read() returns 6

```
int f() {
  ...
  y = read();
  z = y * 2;
  if (z == 12) {
    crash();
  } else {
    printf("OK");
  }
}
```

On what inputs does the code crash?

```c
#include <stdio.h>
#include <stdlib.h>

char *serial = "\x31\x3e\x3d\x26\x31";

int check(char *ptr)
{
	int i;
	int hash = 0xABCD;

	for (i = 0; ptr[i]; i++)
		hash += ptr[i] ^ serial[i % 5];

	return hash;
}

int main(int ac, char **av)
{
	int ret;

	if (ac != 2)
		return -1;

	ret = check(av[1]);
	if (ret == 0xad6d)
		printf("Win\n");
	else
		printf("fail\n");

	return 0;
}
```

https://github.com/illera88/Ponce

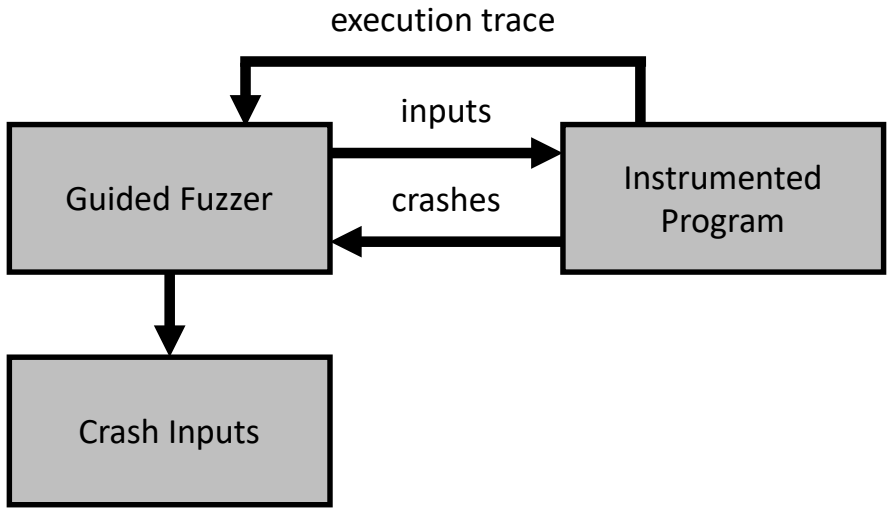


Concolic Execution

- A hybrid of dynamic analysis and symbolic execution
  - Perform symbolic execution on some variables and concrete execution on other variables
  - Symbolic variables could be made concrete in order to:
    - Move past symbolic limitations such as challenges in modeling the program environment (example network interaction)
    - Deal with path explosion problem and satisfiability problem by replacing difficult symbolic values with concrete values to simplify analysis
  - Pays cost in time for symbolic computations and execution time of program
- Several well known tools:
  - Angr - http://angr.io
  - KLEE - https://klee.github.io
  - DART - https://dl.acm.org/citation.cfm?id=1065036
  - CREST (formerly CUTE) - https://code.google.com/archive/p/crest
  - Microsoft SAGE - https://patricegodefroid.github.io/public_psfiles/ndss2008.pdf

Smart (Guided) Fuzzing

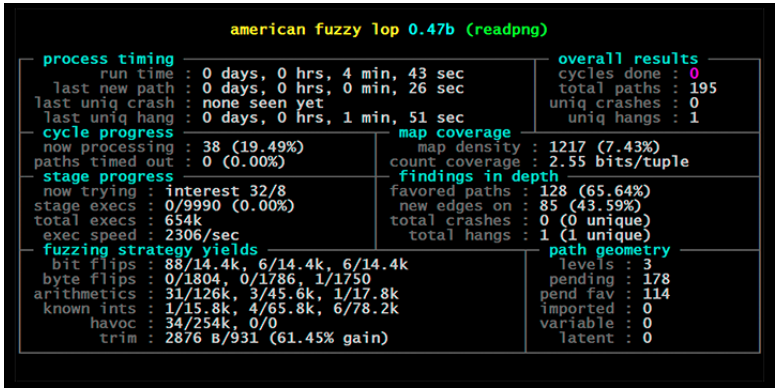
- Start with a test corpus of well formed program inputs
- Apply random or systematic mutations to program inputs
- Instrument the program branch points
- Run the instrumented program with mutated inputs and 1) observe whether or not the program crashes and 2) record the program execution path coverage
- If the input results in new program paths being explored then prioritize mutations of the tested input
- Repeat until the program crashes



Heuristics guide genetic algorithm to generate program inputs that push the fuzzer deeper into the program control flow, avoiding the common pitfalls of fuzzers to only test “shallow” code regions.

AFL (American Fuzzy Lop) Fuzzer

- Recognized as the current state of art implementation of guided fuzzing
  - Effective mutation strategy to generate new inputs from initial test corpus
  - Lightweight instrumentation at branch points
  - Genetic algorithm promotes mutations of inputs that discover new branch edges
    - Aims to explore all code paths
  - Huge trophy case of bugs found in wild
    - 371+ reported bugs in 161 different programs as of March 2018
    - http://lcamtuf.coredump.cx/afl/
- A game of economics. AFL tends to “guess” the correct input faster than a smart tool “computes” the correct input.



DARPA's Cyber Grand Challenge (CGC)

"Cyber Grand Challenge (CGC) is a contest to build high-performance computers capable of playing in a Capture-the-Flag style cyber-security competition."

https://www.darpa.mil/program/cyber-grand-challenge

DARPA's Cyber Grand Challenge (CGC)

- Fully automatic reasoning to:
  - Detect program vulnerabilities
  - Patch programs to prevent exploitation
  - Develop and execute vulnerability exploits against competitors
- No human players!

CGC Results (Reading Between the Lines)

- All teams published the same essential combination of strategies
  - Guided fuzzing (nearly every team modified AFL)
  - Symbolic execution to assist fuzzer sometimes aided by classical program analyses (points-to, reachability, slicing, etc.)
  - Some state space pruning and prioritization scheme catered to expected vulnerability types
- Effective patches were more often generic patches which addressed the class of vulnerabilities not the one-off vulnerability that was given
  - Example: Adding stack guards for memory protection
- Competitor scores were close!
  - The difference between 1st and 7th place was not substantial
- Classes of vulnerabilities were known *a priori*

Context Matters!

- Head problems vs. hand problems
  - Design vs. implementation errors
- Implementation errors may be eventually largely eliminated with advances in programming languages, compilers, theorem provers, etc.
- Security design problems tend to be closely tied to failures in threat modeling, which is largely a human task
  - Many security problems arise due to reuse of software in changing contexts
    - Example: SCADA devices designed for isolated networks being placed on the internet

DARPA's High-Assurance Cyber Military Systems (HACMS) Program

- "formal methods-based approach to enable semi-automated code synthesis from executable, formal specifications"
- Creation of an "unhackable" drone!

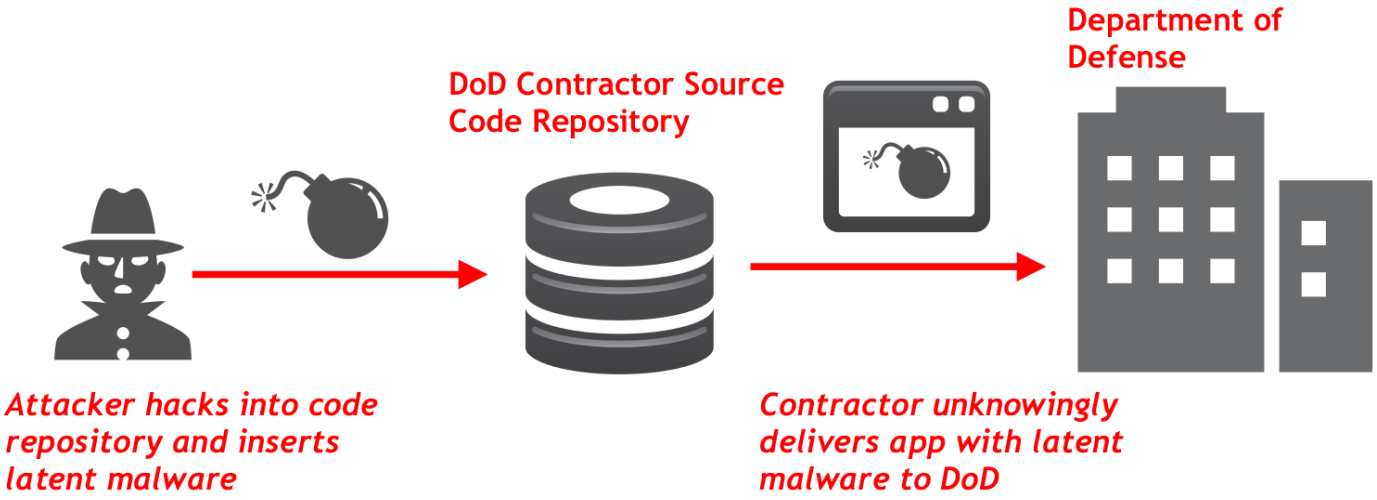
https://www.darpa.mil/program/high-assurance-cyber-military-systems

HACMS Results (Reading Between the Lines)

- Failures tended to stem back to human failures to fully account for the attack model
  - Example: Red Team debrief noted that Red team sent a radio reboot command that dropped that shut off drone engines for 3 seconds (enough to crash the drone). Blue's response was "Oh! We didn't think of that!"
- The "unhackable" drone produced by the program was not protected from the later discovered Meltdown and Spectre exploits

DARPA's APAC Program

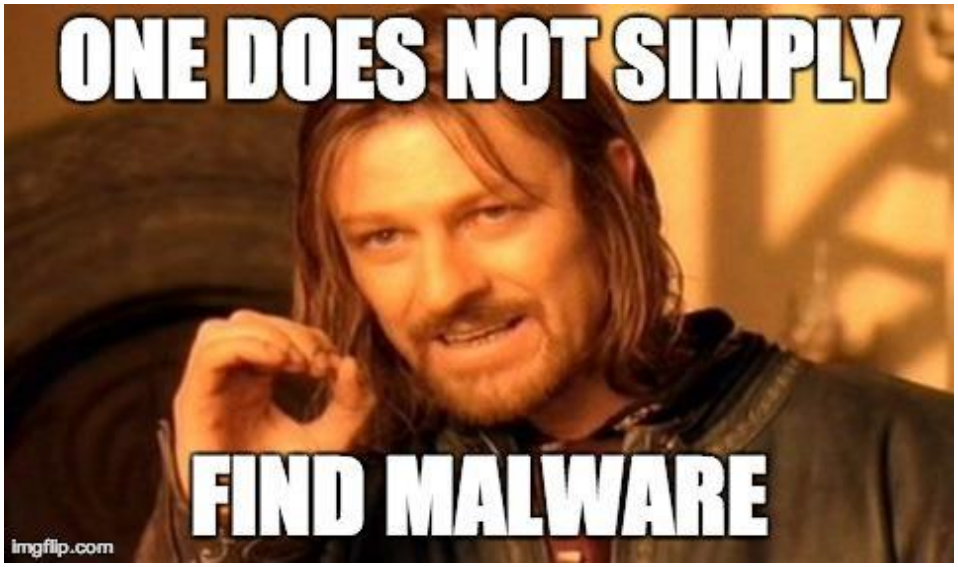
- Automated Program Analysis For Cybersecurity (APAC)
- Scenario: Hardened devices, internal app store, untrusted contractors, expert adversaries
- Focused on Android



https://www.darpa.mil/program/automated-program-analysis-for-cybersecurity

APAC Results (Reading Between the Lines)

- Is a bug malware? What if its planted intentionally? We know bug finding is hard…
- Bugs have plausible deniability and malicious intent cannot be determined from code.
- Novel attacks have escaped previous threat models.
- Need precision tools to detected **novel** and **sophisticated** malware in advance!



APAC Example: DARPA's Transformative Apps

- 55K lines of code

- Data gathering and relaying tool for military
  - Strategic mission planning/review
  - Audio and video recording
  - Geo-tagged camera snapshots
  - Real-time map updates based on GPS

APAC Example: DARPA's Transformative Apps

```
@Override
public void onLocationChanged(Location tmpLoc) {
     location = tmpLoc;
   double latitude = location.getLatitude();
   double longitude = location.getLongitude();
   if((longitude >= 62.45 && longitude <= 73.10) &&
         (latitude >= 25.14 && latitude <= 37.88)) {
        location.setLongitude(location.getLongitude() + 9.252);
        location.setLatitude(location.getLatitude() + 5.173);
   }
          …
 }
```

One of several locations were GPS coordinates were modified.
This corrupts GPS coordinates if user is in Afghanistan/Pakistan!

milcom

Military Communications for the 21st Century

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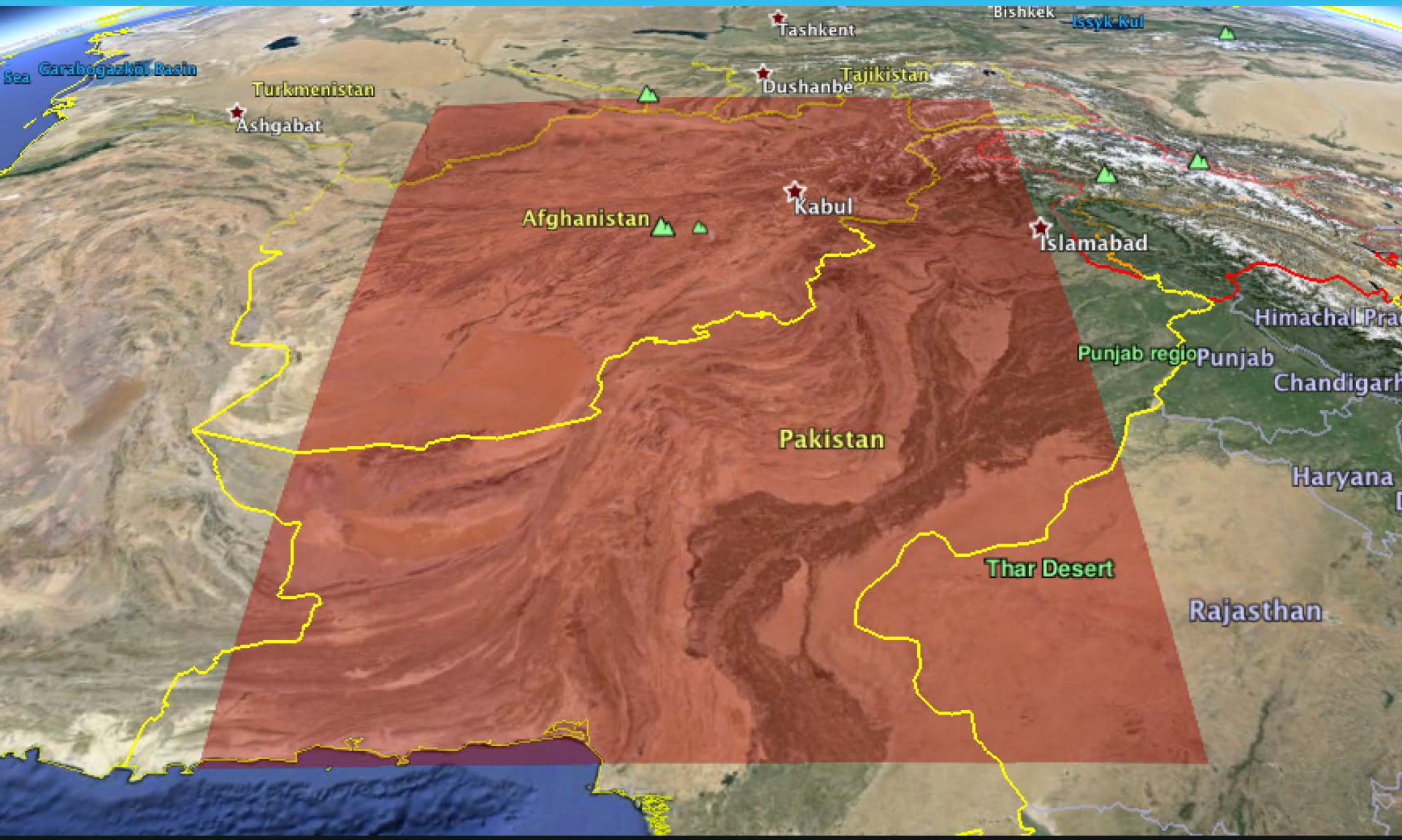
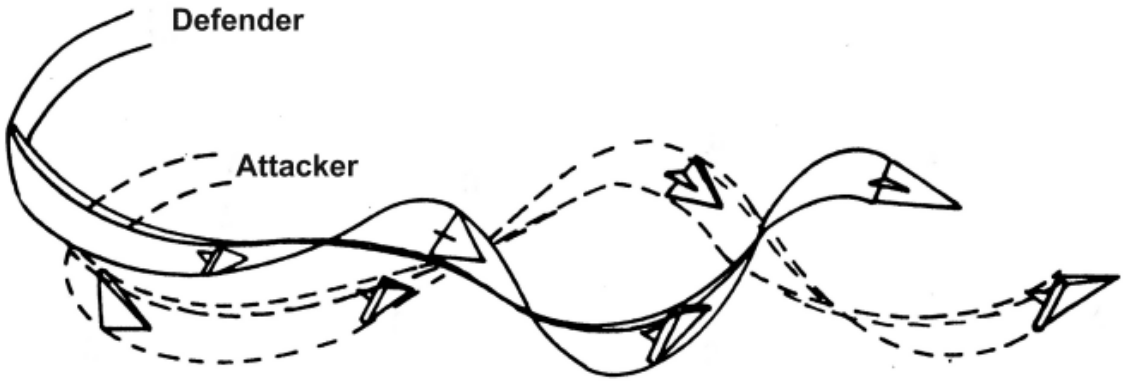
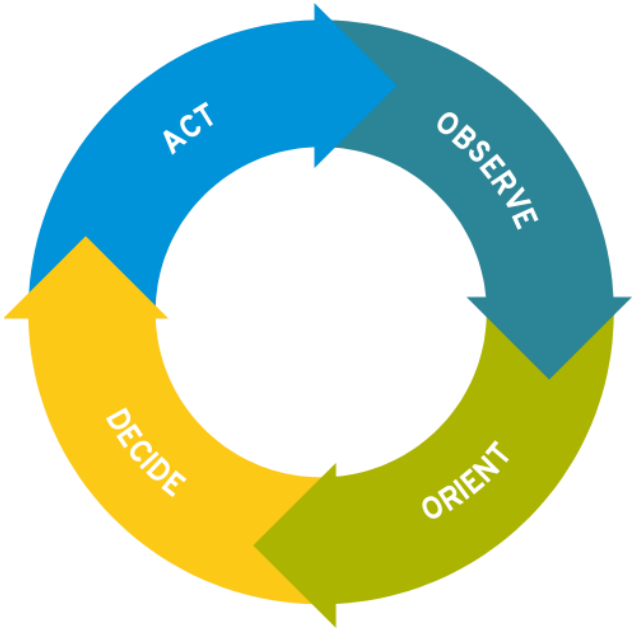


Program Analysis, OODA, and YOU

"Security is a process, not a product" – Bruce Schneier





Program Analysis, OODA, and YOU

Our opponent

- Time
- Evolution of malware

"...IA > AI, that is, that intelligence amplifying systems can, at any given level of available systems technology, beat AI systems. That is, a machine and a mind can beat a mind-imitating machine working by itself."
– Fred Brooks

Positive Trend – Employ Human Reasoning

- DARPA Programs on the verge
  - Computers and Humans Exploring Software Security (CHESS)
  - Explainable Artificial Intelligence (XAI)

- Let human's do what humans are good at
- Let machines do what machines are good at
- Enable collaboration between the two

Your job in security is not going away soon…

Your job in security is not going away soon…
…probably.

(but it is an exciting field)

Activity: Does this program contain a vulnerability?

```
#include <stdio.h>
int main(int argc, char *argv) {
    char buf[64];
    strcpy(buf, argv[1]);
    return 0;
}
```

Activity: Does this program contain a vulnerability?

```
#include <stdio.h>
int main(int argc, char *argv) {
    char buf[64];
    a = read_user_input();
    b = read_user_input();
    …
    if(a * b == c){
      strcpy(buf, argv[1]);
    }
    return 0;
}
```

What if *c* is the product of two large primes?

Then yes, but only if you know the prime factorization…

Activity: Does this program contain a vulnerability?

```
#define BUFFERSIZE 200
int copy_it (char* input , unsigned int length){
   char c, localbuf[BUFFERSIZE];
   unsigned int upperlimit = BUFFERSIZE - 10;
   unsigned int quotation = roundquote = FALSE;
   unsigned int input_index = output_index = 0;
   while (input_index < length){ c = input[input_index++];
      if((c == '<') && (!quotation)){ quotation = true; upperlimit--; }
      if((c == '>') && (quotation)){ quotation = false; upperlimit++; }
      if((c == '(') && (!quotation) && (!roundquote)){ roundquote = true; }
      if((c == ')') && (!quotation) && (roundquote)){ roundquote = false; upperlimit++; }
      // if there is sufficient space in the buffer, write the character
      if(output_index < upperlimit){ localbuf[output_index] = c; output_index++; }
   }
   if(roundquote){ localbuf[output_index] = ')'; output_index++; }
   if(quotation){ localbuf[output_index] = '>'; output_index++; }
   return output_index;
}
```

Activity: Does this program contain a vulnerability?

```
#define BUFFERSIZE 200
int copy_it (char* input , unsigned int length){
   char c, localbuf[BUFFERSIZE];
   unsigned int upperlimit = BUFFERSIZE - 10;
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   while (input_index < length){ c = input[input_index++];
      if((c == '<') && (!quotation)){ quotation = true; upperlimit--; }
      if((c == '>') && (quotation)){ quotation = false; upperlimit++; }
      if((c == '(') && (!quotation) && (!roundquote)){ roundquote = true; ; /* (missing) upperlimit--; */ }
      if((c == ')') && (!quotation) && (roundquote)){ roundquote = false; upperlimit++; }
      // if there is sufficient space in the buffer, write the character
      if(output_index < upperlimit){ localbuf[output_index] = c; output_index++; }
   }
   if(roundquote){ localbuf[output_index] = ')'; output_index++; }
   if(quotation){ localbuf[output_index] = '>'; output_index++; }
   return output_index;
}
```
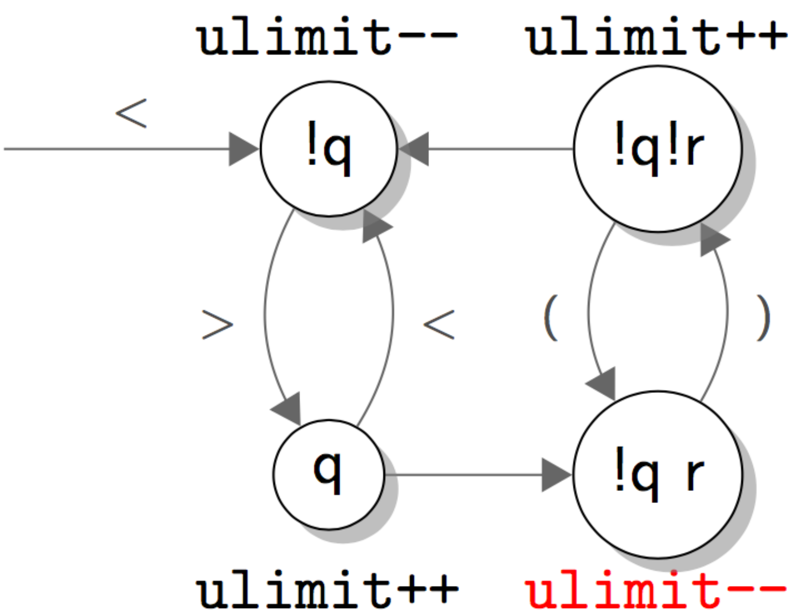
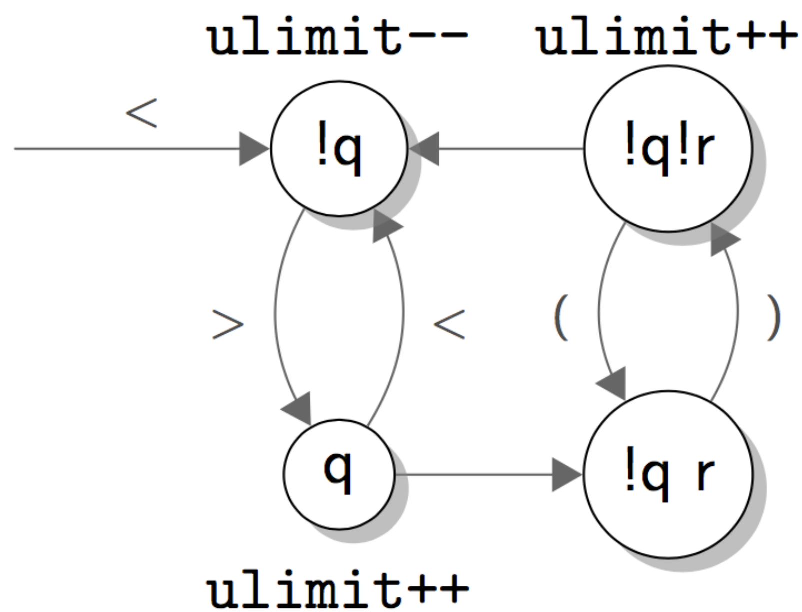

Good:



Bad:



input = "Name Lastname < name@mail.org >
()
()
()()()"

Source: Cracking Sendmail crackaddr Still a challenge for automated program analysis?

Activity: Does this program contain a vulnerability?

```
int main(int argc, char *argv[]) {
  int64_t x = strtoll(argv[1], NULL, 10);
  char buf[64];
  if (x <= 2 || (x & 1) != 0)
    return 1;
  int64_t i;
  for (i = x; i > 0; i--)
    if (foo(i) && foo(x - i))
      return 1;
  strcpy(buf, argv[2]); // reachable?
}
```

```
int foo(int64_t x) {
  int64_t i, s;
  for (i = x – 1; i >= 2; i--)
    for (s = x; s >= 0; s -= i)
      if (s == 0)
        return FALSE;
  return TRUE;
}
```

Activity: Does this program contain a vulnerability?

```
int main(int argc, char *argv[]) {
  int64_t x = strtoll(argv[1], NULL, 10);
  char buf[64];
  // x is an even number that is greater than 2
  if (x <= 2 || (x & 1) != 0)
    return 1;
  // x can be expressed as the sum of 2 primes
  int64_t i;
  for (i = x; i > 0; i--)
    if (is_prime(i) && is_prime(x - i))
      return 1;
  strcpy(buf, argv[2]); // reachable?
}
```

```
int is_prime(int64_t x) {
  int64_t i, s;
  for (i = x - 1; i >= 2; i--)
    for (s = x; s >= 0; s -= i)
      if (s == 0)
        return FALSE;
  return TRUE;
}
```

Answer: No for all 32 bit integers, but unknown for all 64bit integers…

Goldbach's conjecture:
275+ year old unsolved math problem

Decompositional Approach: Program Slicing

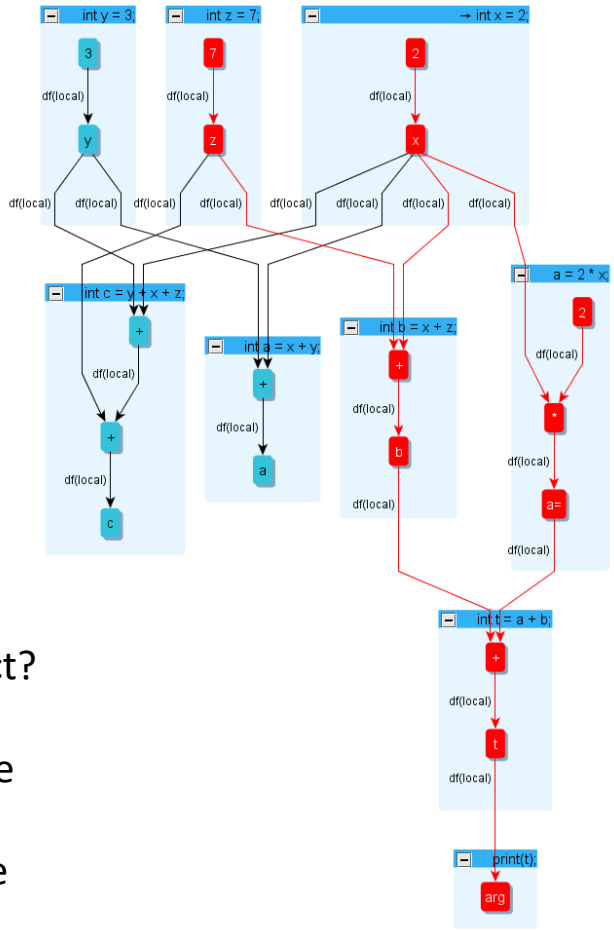
- Mark Weiser. 1981. Program slicing. In Proceedings of the 5th international conference on Software engineering (ICSE '81). IEEE Press, Piscataway, NJ, USA, 439-449.
- Ferrante, Jeanne, Karl J. Ottenstein, and Joe D. Warren. "The program dependence graph and its use in optimization." *ACM Transactions on Programming Languages and Systems (TOPLAS)* 9.3 (1987): 319-349.

Data Flow Graph (DFG)

Example:

1. x = 2;
2. y = 3;
3. z = 7;
4. a = x + y;
5. b = x + z;
6. a = 2 * x;
7. c = y + x + z;
8. t = a + b;
9. print(t); ← detected failure

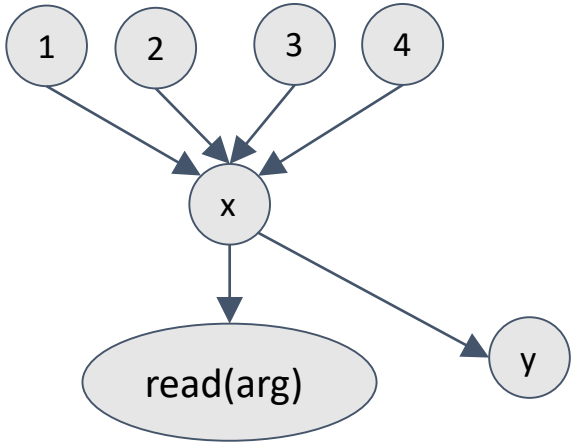
Relevant lines:
1,3,5,6,8



- What lines must we consider if the value of *t* printed is incorrect?
- A *Data Flow Graph* creates a graph of primitives and variables where each assignment represents an edge from the RHS to the LHS of the assignment
- The *Data Flow Graph* represents global data dependence at the operator level (the atomic level) [FOW87]

Code Transformation (before – flow insensitive): Static Single Assignment Form

1. x = 1;
2. x = 2;
3. if(condition)
4. x = 3;
5. read(x);
6. x = 4;
7. y = x;

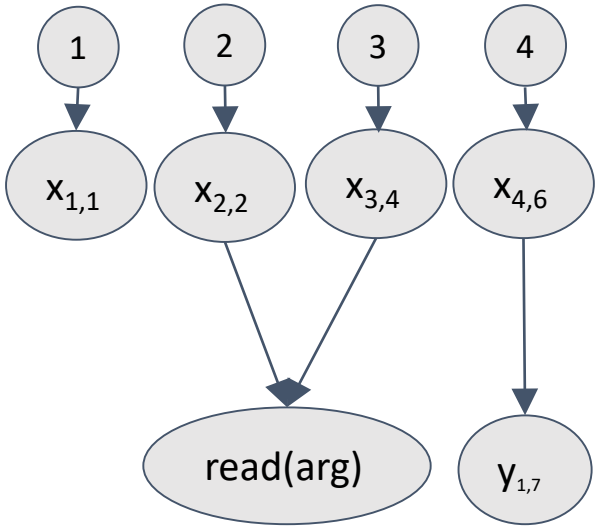


Resulting graph when statement ordering is not considered.

Code Transformation (after – flow sensitive): Static Single Assignment Form

1. x = 1;
2. x = 2;
3. if(condition)
4. x = 3;
5. read(x);
6. x = 4;
7. y = x;

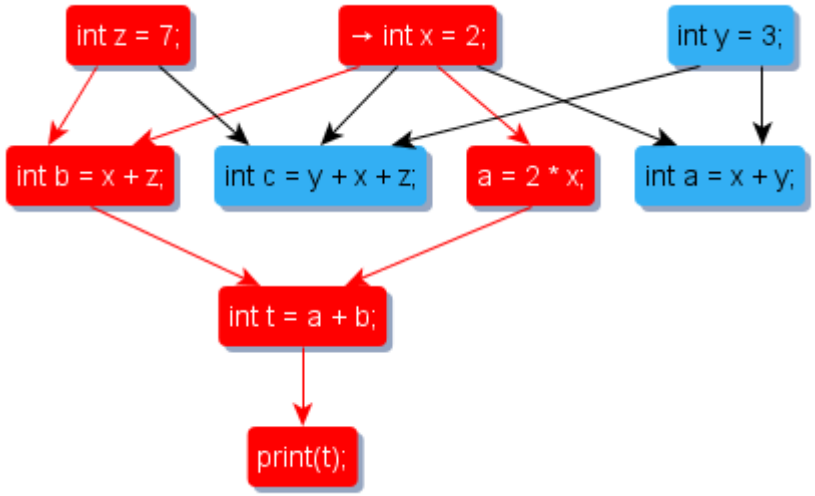
1. $x_{1,1}$ = 1;
2. $x_{2,2}$ = 2;
3. if(condition)
4. $x_{3,4}$ = 3;
5. read($x_{2,2}$,$_{3,4}$);
6. $x_{4,6}$ = 4;
7. $y_{1,7}$ = $x_{4,6}$;



Note: <Def#,Line#>

Data Dependence Graph (DDG)

- Note that we could summarize data flow on a per statement level
- This graph is called a *Data Dependence Graph* (DDG)
- DDG dependences represent only the *relevant* data flow relationships of a program [FOW87]



Data Dependence Slicing

- Reverse Data Dependence Slice
  - What statements influence the assigned value in this statement?
- Forward Data Dependence Slice
  - What statements could the assigned value in this statement influence?

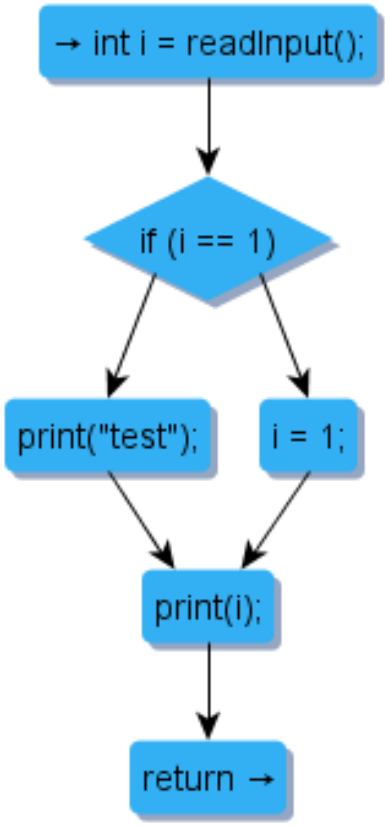
Control Flow Graph (CFG)

Example:

```
1. i = readInput();
2. if(i == 1)
3.       print("test");
   else
4.       i = 1;
5. print(i);
6. return; // terminate
```

Relevant lines:
1,2,4

detected failure

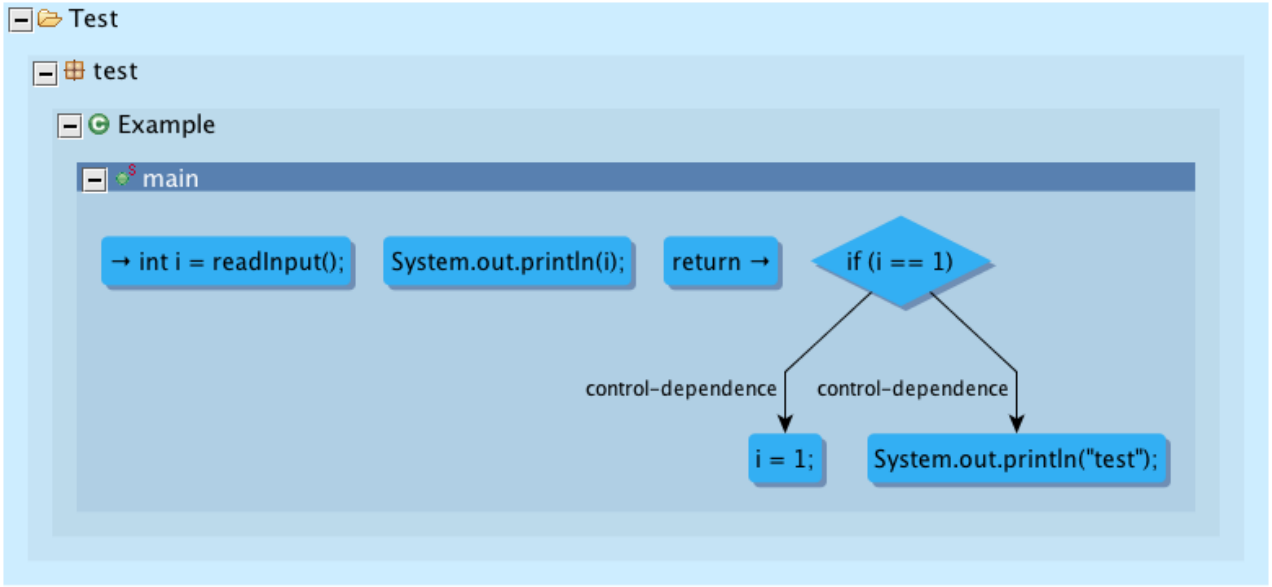


What lines must we consider if the value of *i* printed is incorrect?

- A *Control Flow Graph* (CFG) represents the possible sequential execution orderings of each statement in a program
- Data flow influences control flow, so this graph is not enough

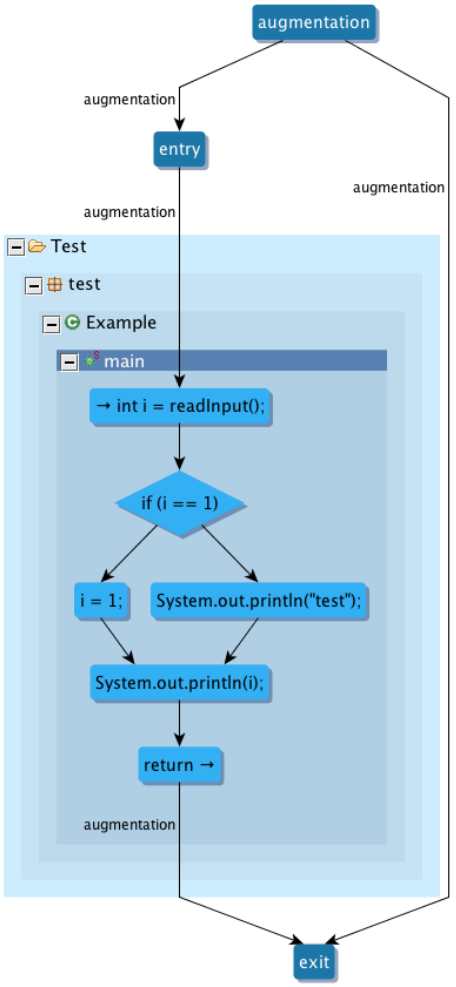
Control Dependence Graph (CDG)

- If a statement X determines whether a statement Y can be executed then statement Y is *control dependent* on X
- Control dependence exists between two statements, if a statement directly controls the execution of the other statement [FOW87]



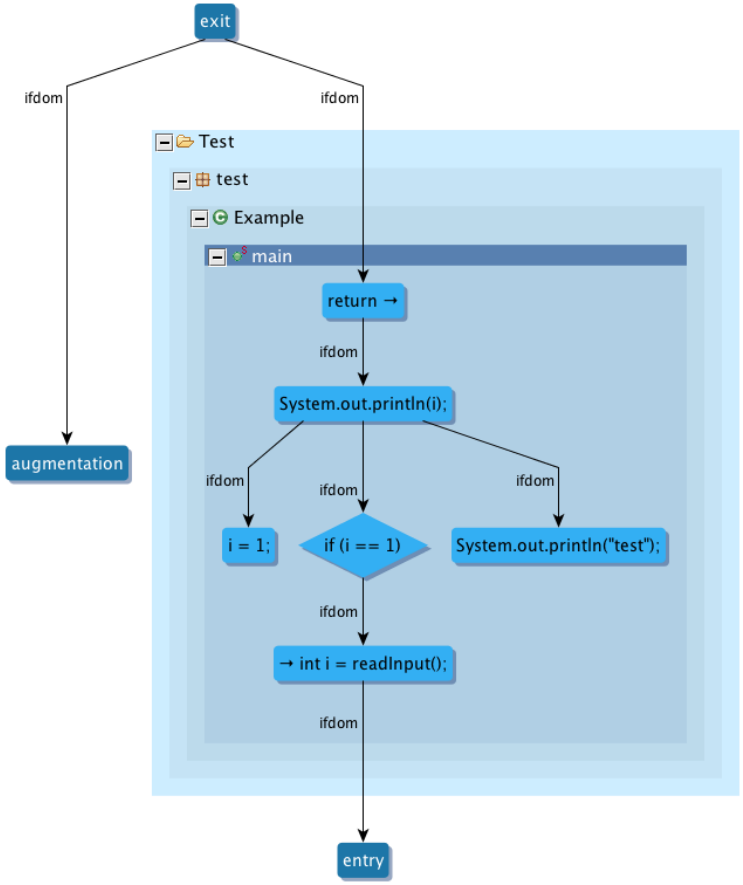
Building a CDG (1)

- First augment the CFG with a single “entry” node and single “exit” node.
- Create an “augmentation” node which has the “entry” and “exit” nodes as children.



Building a CDG (2)

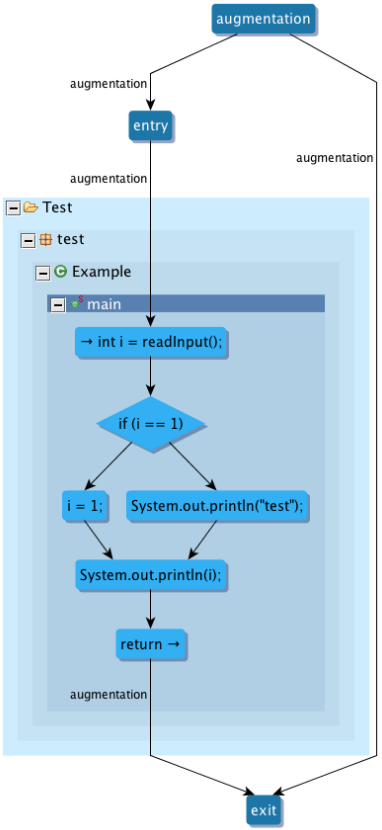
- X *dominates* Y if every path from the entry node to Y must go through X
- A *dominator tree* is a tree where each node's children are those nodes it immediately dominates
- Compute a forward dominance tree (i.e. post-dominance analysis) of the augmented CFG



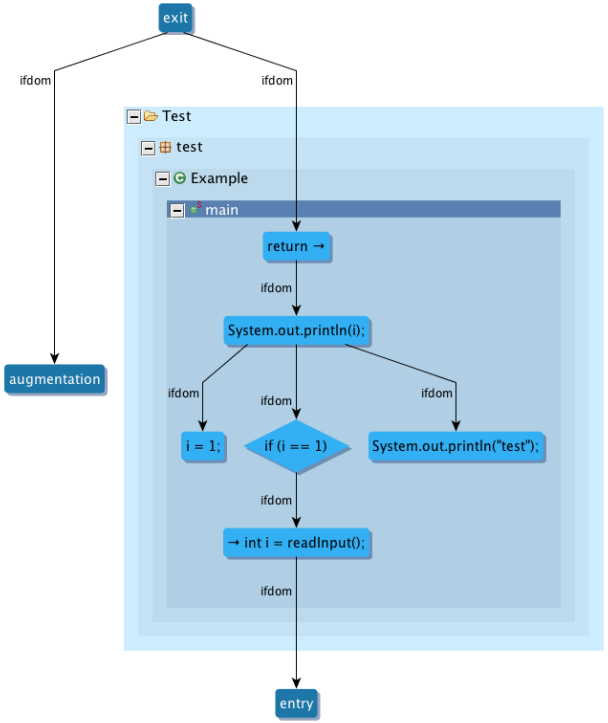
Building a CDG (3)

- The *least common ancestor* (LCA) of two nodes X and Y is the deepest tree node that has both X and Y as descendants
- For each edge (X → Y) in CFG, find nodes in FDT from LCA(X,Y) to Y, which are *control dependent* on X.
  - Exclude LCA(X,Y) if LCA(X,Y) is not X

Augmented CFG (ACFG)



Forward Dominance Tree (FDT)



Building a CDG (4)

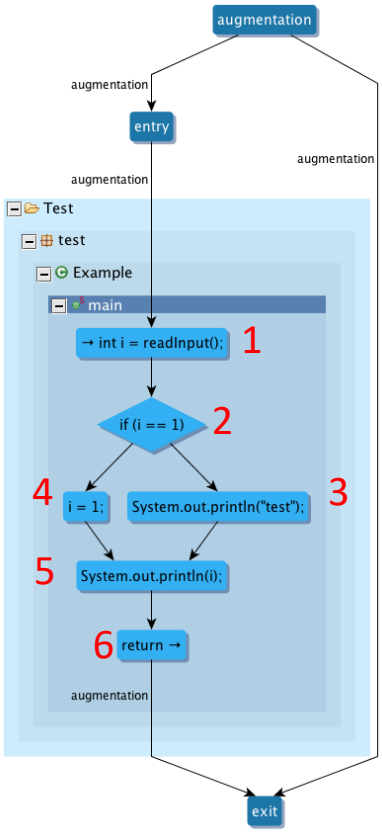
Edge X→Y in ACFG	LCA(X,Y) in FDT	FDT Nodes Between(LCA, Y)
1 → 2	2	~~2~~
2 → 3	5	~~5~~, 3
2 → 4	5	~~5~~, 4
4 → 5	5	~~5~~
3 → 5	5	~~5~~
5 → 6	6	~~6~~

Note: Remove LCA(X,Y) if LCA(X,Y) != X

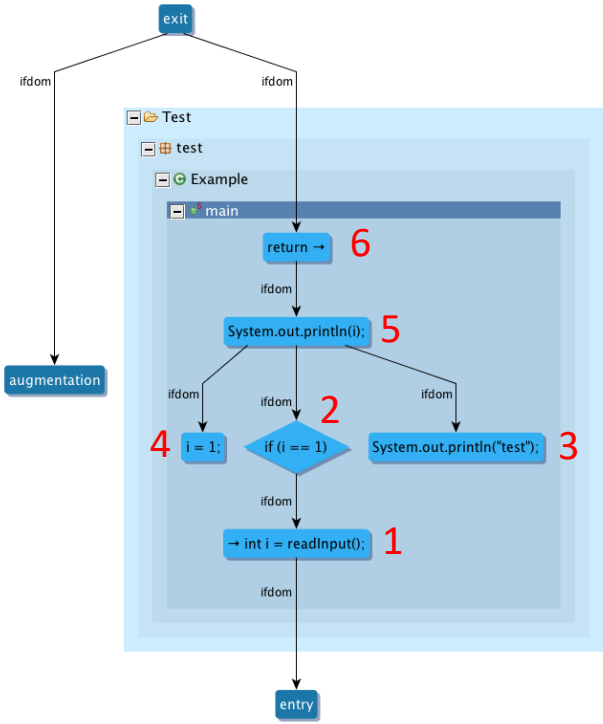
Example:

```
1. i = readInput();
2. if(i == 1)
3.     print("test");
   else
4.     i = 1;
5. print(i);
6. return; // terminate program
```

Augmented CFG (ACFG)



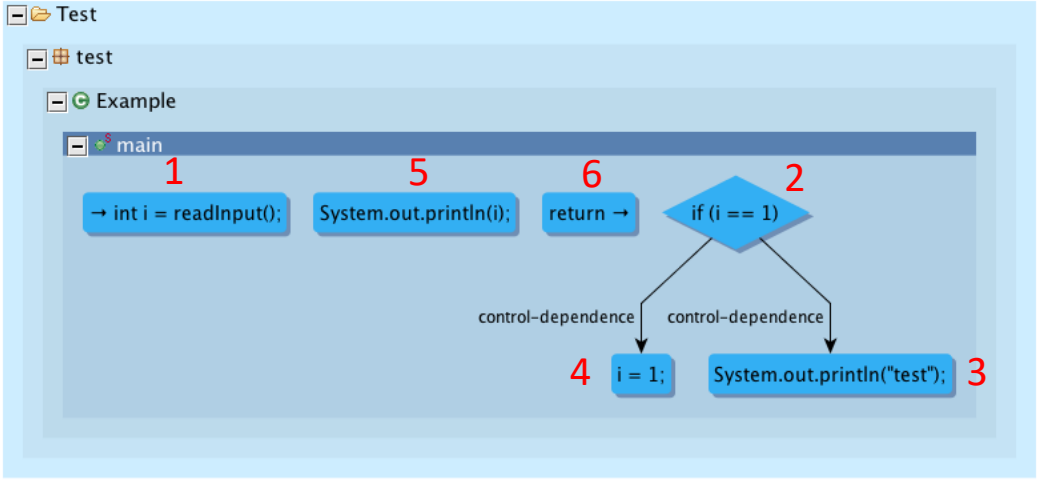
Forward Dominance Tree (FDT)



Control Dependence Graph

Edge X→Y in ACFG	LCA(X,Y) in FDT	FDT Nodes Between(LCA, Y)
1 → 2	2	~~2~~
2 → 3	5	~~5~~, 3
2 → 4	5	~~5~~, 4
4 → 5	5	~~5~~
3 → 5	5	~~5~~
5 → 6	6	~~6~~

FDT Nodes Between(LCA, Y) are *Control Dependent* on X.



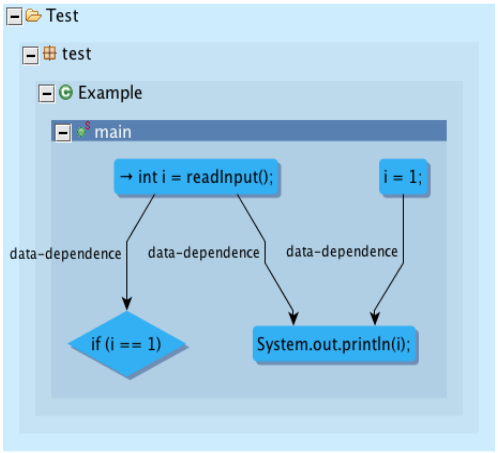
Control Dependence Slicing

- Reverse Control Dependence Slice
  - What statements does this statement's execution depend on?
- Forward Control Dependence Slice
  - What statements could execute as a result of this statement?

Program Dependence Graph (PDG)

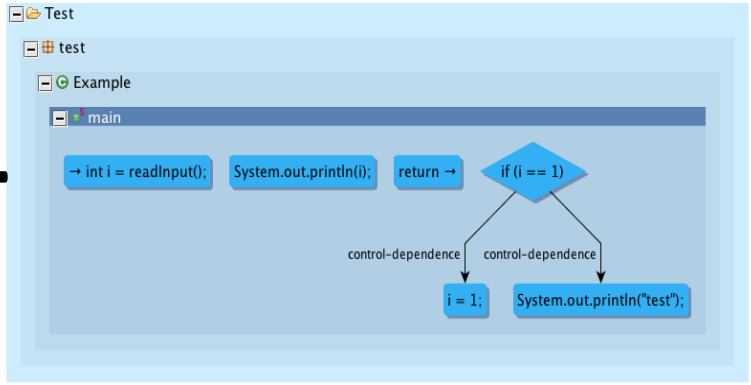
- Both DDG and CDG nodes are statements
- The union of a DDG and the CDG is a PDG

DDG



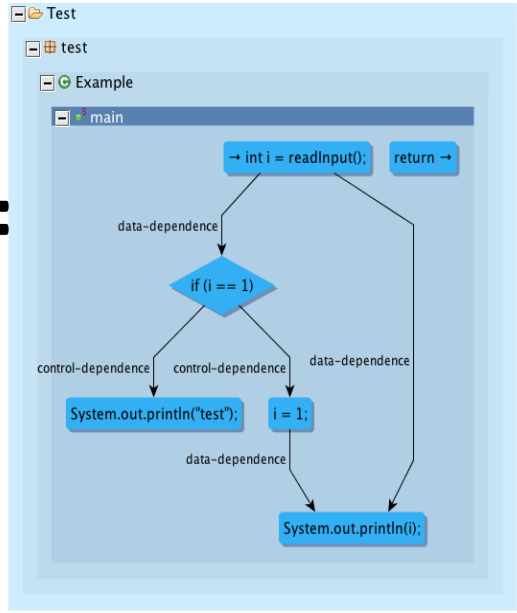
+

CDG



=

PDG



Program Slicing (Impact Analysis)

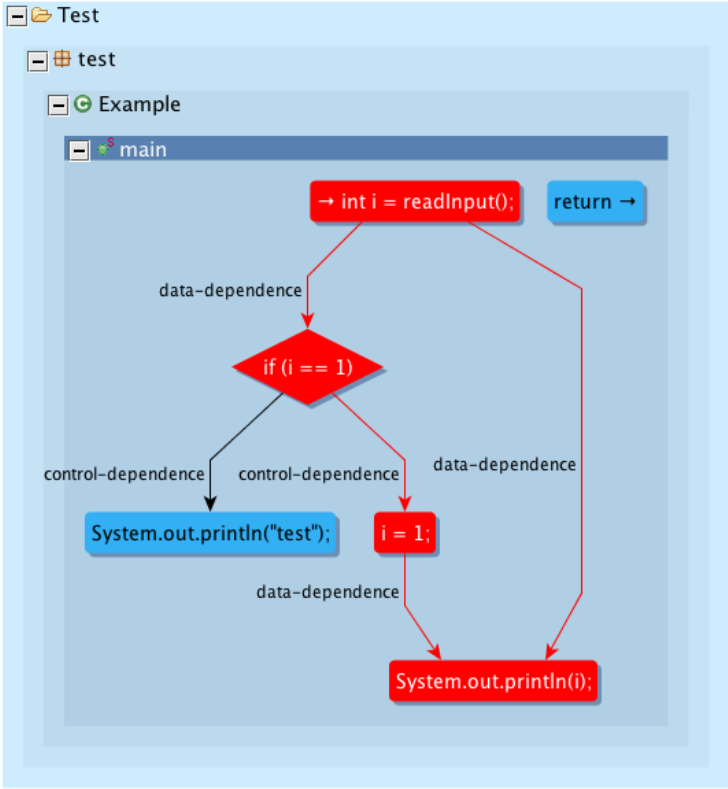
- Reverse Program Slice
  - Answers: What statements does this statement's execution depend on?
- Forward Program Slice
  - Answers: What statements could execute as a result of this statement?

Example:

```
1. i = readInput();
2. if(i == 1)
3.       print("test");
   else
4.       i = 1;
5. print(i);
6. return; // terminate
```

Relevant lines:
1,2,4

detected failure



Taint Analysis

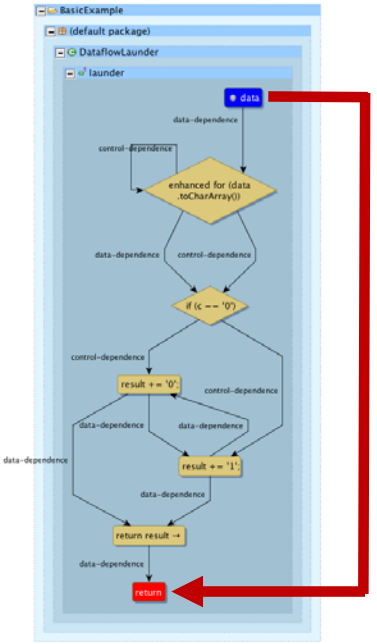
- How can we track the flow of data from the source (*x*) to the sink (*y*)?
- Neither DFG/DDG nor CFG/CDG alone are enough to answer whether *x* flows to *y*
- Taint = (forward slice of *source)* intersection (reverse slice of *sink)*

```
public class DataflowLaunder {

        public static void main(String[] args) {
                String x = "1010";
                String y = launder(x);
                System.out.println(y + " is a laundered version of " + x);
        }

        public static String launder(String data){
           String result = "";
           for(char c : data.toCharArray()){
             if(c == '0')
                result += '0';
             else
                result += '1';
           }
           return result;
        }

}
```

DataflowLaunder.java

```
1
2  /**
3   * A toy example of laundering data through "implicit dataflow paths"
4   * The launder method uses the input data to reconstruct a new result
5   * with the same value as the original input.
6   *
7   * @author Ben Holland
8   */
9  public class DataflowLaunder {
10
11     public static void main(String[] args) {
12         String x = "1010";
13         String y = launder(x);
14         System.out.println(y + " is a laundered version of " + x);
15     }
16
17     public static String launder(String data){
18        String result = "";
19        for(char c : data.toCharArray()){
20          if(c == '0')
21             result += '0';
22          else
23             result += '1';
24        }
25        return result;
26     }
27
28 }
```

Taint Graph



atlas

Problems | Javadoc | Declaration | Console | Progress | Atlas Shell (shell) | Error Log | Analysis Keys | Element Detail View | Call Hierarchy

Atlas Shell (Project: shell)

```
var taint = new com.ensoftcorp.open.slice.analysis.TaintGraph(source, sink)

taint: com.ensoftcorp.open.slice.analysis.TaintGraph = com.ensoftcorp.open.slice.analysis.TaintGraph@13df7ce4

show(taint.getGraph(), taint.getHighlighter(), title="Taint Graph")
```

Evaluate: <type an expression or enter ":help" for more information>

https://github.com/EnSoftCorp/slicing-toolbox

atlas

Atlas Extensible Common Software Graph (XCSG) Schema

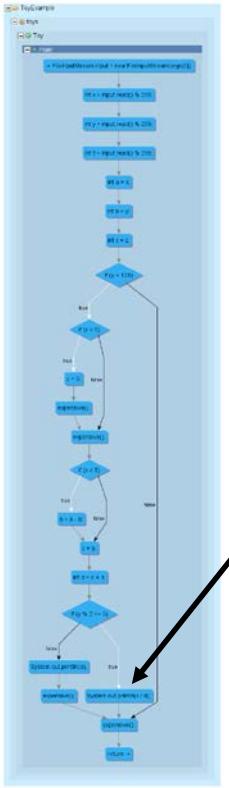
- XCSG's use of XCSG.DataFlow_Edge and XCSG.ControlFlow_Edge are compatible with the definitions of control and data flow as put forward by FOW87 paper
- https://ensoftatlas.com/wiki/Extensible_Common_Software_Graph

Slicing Continuations

- System Dependence Graphs
  - Reps, Thomas, Susan Horwitz, and Mooly Sagiv. "Precise interprocedural dataflow analysis via graph reachability." *Proceedings of the 22nd ACM SIGPLAN-SIGACT symposium on Principles of programming languages*. ACM, 1995.
- Survey of Slicing Techniques
  - Tip, Frank. *A survey of program slicing techniques*. Centrum voor Wiskunde en Informatica, 1994.

Projected Control Graphs

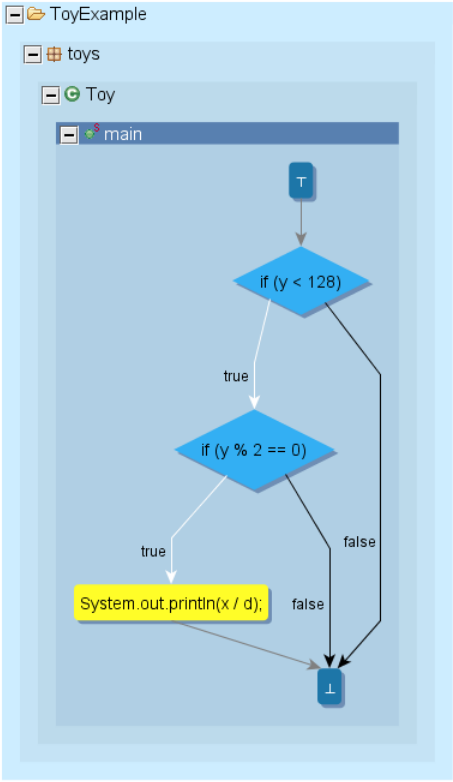
- Projected Control Graph (PCG)
  - Proposed by Ahmed Tamrawi in 2016
  - Efficiently groups program behaviors into equivalence classes of homomorphic behaviors
    - Parameterized by events of interest
    - Only event statements and necessary conditions are retained
  - Result is a compact structure-preserving model of a CFG w.r.t. events of interest



CFG

Compaction

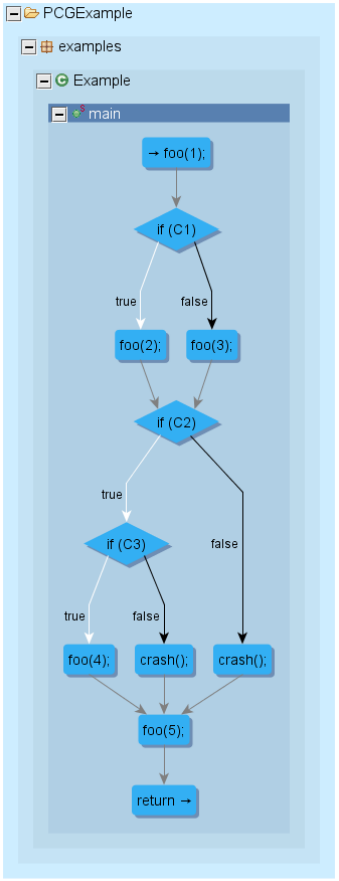
print(x / d)



PCG(E), E=Division Statement

Concept: Projected Control Graph

```
1  public void main() {
2      foo(1);
3      if (C1) {
4          foo(2);
5      } else {
6          foo(3);
7      }
8      if (C2) {
9          if (C3) {
10             foo(4);
11         } else {
12             crash();
13         }
14     } else {
15         crash();
16     }
17     foo(5);
18     return;
19 }
```

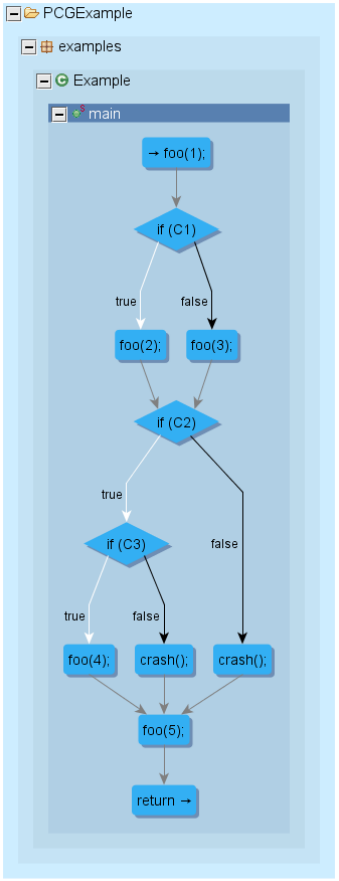


2^3=8 possible values for the tuple (C1, C2, C3)

C1	C2	C3	Behavior
False	False	False	
False	False	True	
False	True	False	
False	True	True	
True	False	False	
True	False	True	
True	True	False	
True	True	True	

Concept: Projected Control Graph

```
1  public void main() {
2      foo(1);
3      if (C1) {
4          foo(2);
5      } else {
6          foo(3);
7      }
8      if (C2) {
9          if (C3) {
10             foo(4);
11         } else {
12             crash();
13         }
14     } else {
15         crash();
16     }
17     foo(5);
18     return;
19 }
```

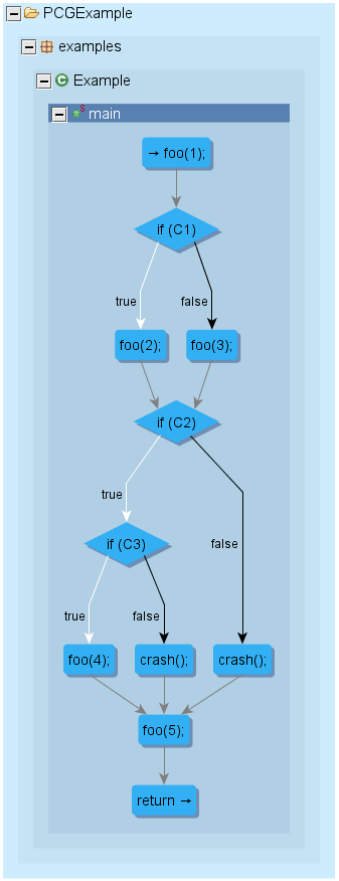


If C2 is false then C3 is not evaluated.

C1	C2	C3	Behavior
False	False	N/A	
False	False	N/A	
False	True	False	
False	True	True	
True	False	N/A	
True	False	N/A	
True	True	False	
True	True	True	

Concept: Projected Control Graph

```
1  public void main() {
2      foo(1);
3      if (C1) {
4          foo(2);
5      } else {
6          foo(3);
7      }
8      if (C2) {
9          if (C3) {
10             foo(4);
11         } else {
12             crash();
13         }
14     } else {
15         crash();
16     }
17     foo(5);
18     return;
19 }
```

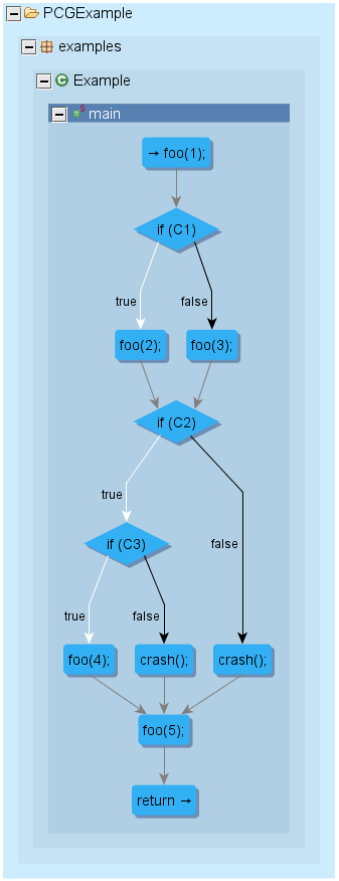


CFG has 6 paths.

C1	C2	C3	Behavior
False	False	N/A	
False	True	False	
False	True	True	
True	False	N/A	
True	True	False	
True	True	True	

Concept: Projected Control Graph

```
1  public void main() {
2      foo(1);
3      if (C1) {
4          foo(2);
5      } else {
6          foo(3);
7      }
8      if (C2) {
9          if (C3) {
10             foo(4);
11         } else {
12             crash();
13         }
14     } else {
15         crash();
16     }
17     foo(5);
18     return;
19 }
```



What paths include a “crash” event?

C1	C2	C3	Behavior
False	False	N/A	2,3,6,8,15,17,18
False	True	False	2,3,6,8,9,12,17,18
False	True	True	2,3,6,8,9,10,17,18
True	False	N/A	2,3,4,8,15,17,18
True	True	False	2,3,4,8,9,12,17,18
True	True	True	2,3,4,8,9,10,17,18

Concept: Projected Control Graph

```
1  public void main() {
2      foo(1);
3      if (C1) {
4          foo(2);
5      } else {
6          foo(3);
7      }
8      if (C2) {
9          if (C3) {
10             foo(4);
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12             crash();
13         }
14     } else {
15         crash();
16     }
17     foo(5);
18     return;
19 }
```

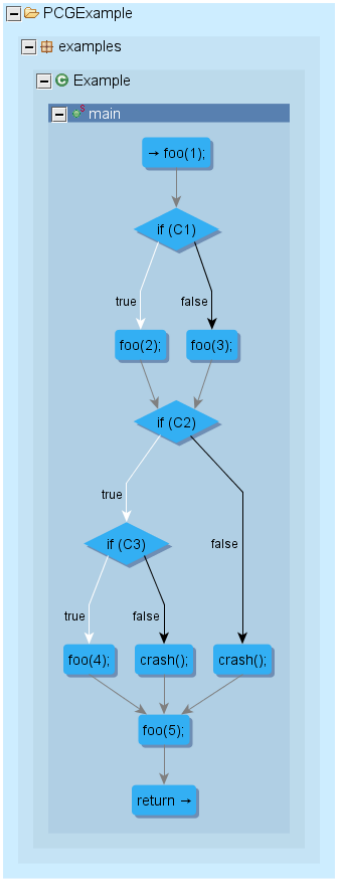

4 of 6 behaviors have “crash” events.
2 of 6 behaviors do not have “crash” events.

C1	C2	C3	Behavior
False	False	N/A	2,3,6,8,15,17,18
False	True	False	2,3,6,8,9,12,17,18
~~False~~	~~True~~	~~True~~	~~2,3,6,8,9,10,17,18~~
True	False	N/A	2,3,4,8,15,17,18
True	True	False	2,3,4,8,9,12,17,18
~~True~~	~~True~~	~~True~~	~~2,3,4,8,9,10,17,18~~

Concept: Projected Control Graph

```
1  public void main() {
2      foo(1);
3      if (C1) {
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5      } else {
6          foo(3);
7      }
8      if (C2) {
9          if (C3) {
10             foo(4);
11         } else {
12             crash();
13         }
14     } else {
15         crash();
16     }
17     foo(5);
18     return;
19 }
```
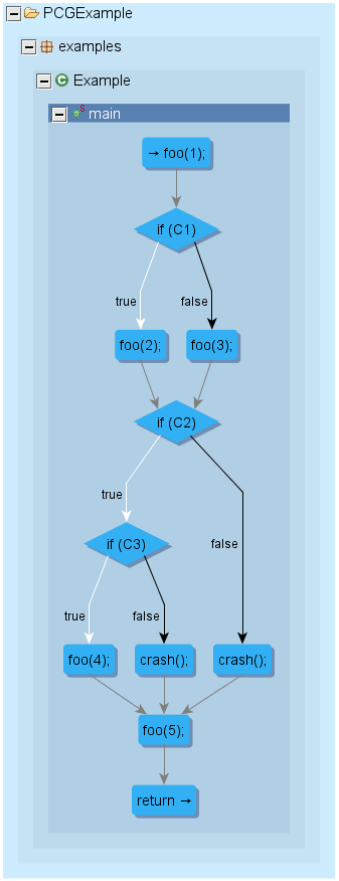
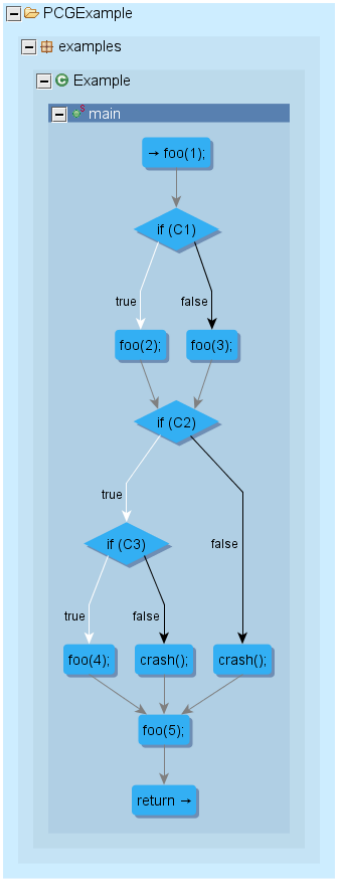



There are 3 unique behaviors w.r.t. “crash” events.

C1	C2	C3	Homomorphic Behavior
False	False	N/A	8,15
False	True	False	8,9,12
~~False~~	~~True~~	~~True~~	~~8,9~~
True	False	N/A	8,15
True	True	False	8,9,12
~~True~~	~~True~~	~~True~~	~~8,9~~

Concept: Projected Control Graph

```
1  public void main() {
2      foo(1);
3      if (C1) {
4          foo(2);
5      } else {
6          foo(3);
7      }
8      if (C2) {
9          if (C3) {
10             foo(4);
11         } else {
12             crash();
13         }
14     } else {
15         crash();
16     }
17     foo(5);
18     return;
19 }
```



2 of 3 homomorphic behaviors (B1, B2) have "crash" events.
1 of 3 homomorphic behaviors (B3) are void w.r.t. "crash" events.

C1	C2	C3	Homomorphic Behavior
False	False	N/A	8,15
False	True	False	8,9,12
~~False~~	~~True~~	~~True~~	~~8,9~~
True	False	N/A	8,15
True	True	False	8,9,12
~~True~~	~~True~~	~~True~~	~~8,9~~

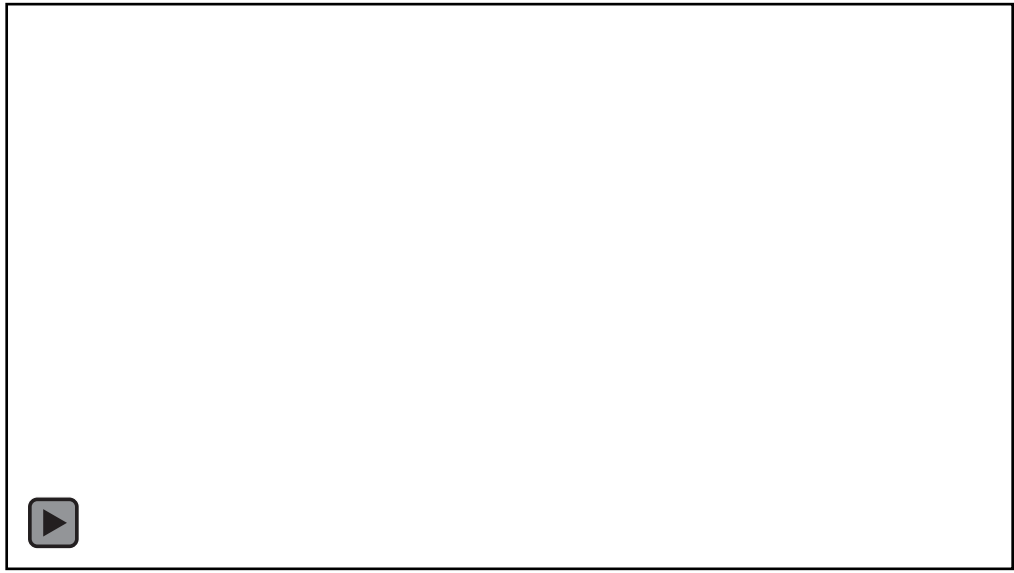
B1
B2
B3

PCGs in Practice

- We research tools and techniques that:
  - Produce human-verifiable and comprehensible evidence
  - Are scalable
- Verification of lock/unlock pairs in Linux
  - Over 66,000 instances (3 versions of Linux)
  - L-SAP tool has resulted in 8 bug reports which have been fixed
- Resulted in key concept: Projected Control Graph (PCG)
  - Retains minimal necessary program behaviors

Motivation Behind PCGs

- Control Flow Graphs can be HUGE
  - CFG of a single function in Linux
    - lustre_assert_wire_constants function has 2^656 paths!
  - Programmers don’t play dice…
  - Is all of this complexity necessary to solve a given analysis problem?
  - Is there an underlying design pattern that can be leveraged to complete the analysis?

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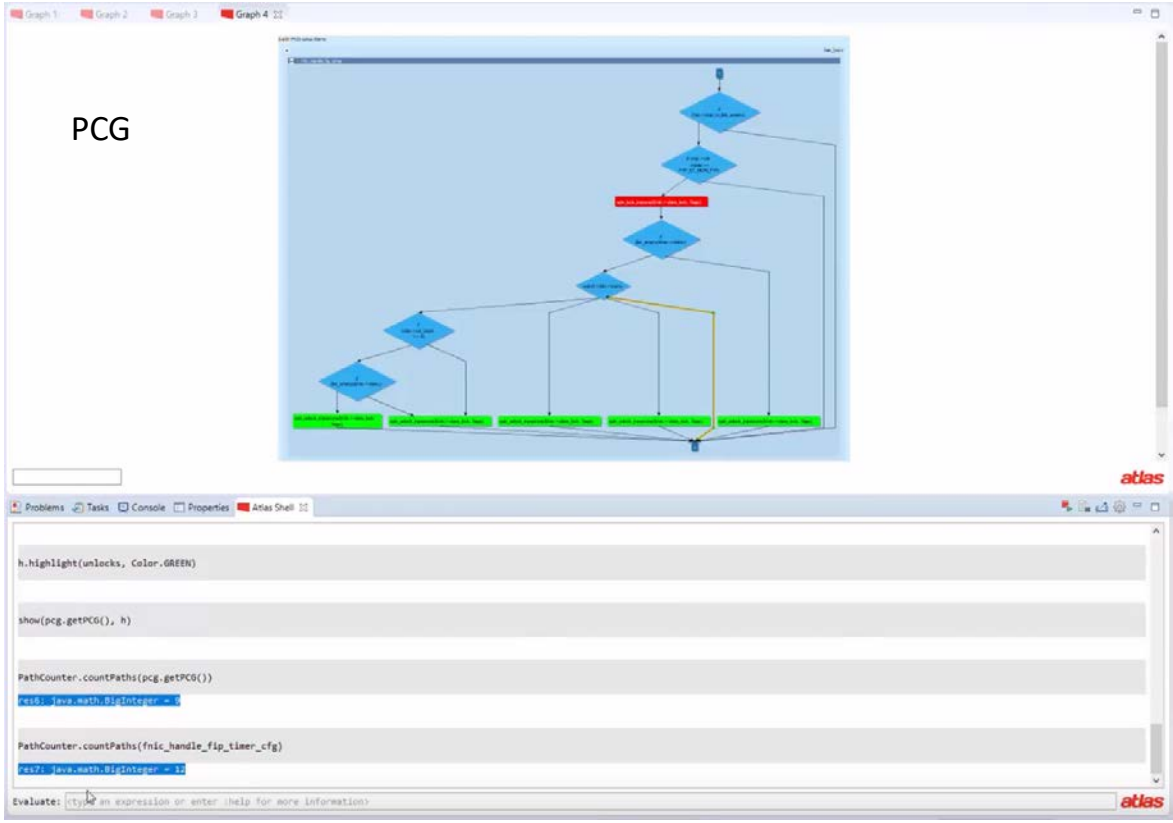
Military Communications for the 21st Century
October 29-31, 2018 • LAX Marriott, Los Angeles, CA

PCG Example from Linux Kernel

- Example usage: verifying Linux lock/unlock pairs. Lock must be followed by unlock on all paths.
  - Research group found 8 unknown and now accepted bugs in Linux 3.13 to 4.3, 13 reported
  - Real Example from Linux 3.13: Red=LOCK, Green=UNLOCK; this PCG reveals the CFG has a path (via a missing switch default statement) where a LOCK can occur without a corresponding UNLOCK.

PCG



https://github.com/EnSoftCorp/pcg-toolbox
https://kcsl.github.io/L-SAP/bugs (Linux study results)

L-SAP

Secure | https://lsap.knowledgecentricsoftwarelab.com/v/413

L-SAP 4.13

Search

Type
Filter by Type

Status
Filter by Status

Driver
Filter by Driver

serial8250_interrupt → __raw_spin_lock, __raw_spin_unlock	serial_do_unlink → __raw_spin_unlock, __raw_spin_lock	serial_link_irq_chain → __raw_spin_lock, __raw_spin_unlock
LOCK	LOCK	LOCK
spin 41016	spin 41086	spin 41178
serial8250_unregister_port → __raw_spin_lock, __raw_spin_unlock	rtc_handle_legacy_irq → __raw_spin_lock, __raw_spin_unlock	rtc_irq_register → __raw_spin_lock, __raw_spin_unlock
LOCK	IRQ_TASK_LOCK	IRQ_TASK_LOCK
spin 118673	spin 155353	spin 155443
rtc_irq_set_state → __raw_spin_lock, __raw_spin_unlock	i915_gem_pageflip_info → __raw_spin_unlock, __raw_spin_lock	i915_gen6_forcewake_count_info → __raw_spin_lock, __raw_spin_unlock
IRQ_TASK_LOCK	EVENT_LOCK	LOCK
spin 155475	spin 168559	spin 169939
i915_pipe_crc_open → __raw_spin_unlock, __raw_spin_lock	i915_pipe_crc_release → __raw_spin_lock, __raw_spin_unlock	i915_pipe_crc_read → __raw_spin_lock, __raw_spin_unlock
LOCK	LOCK	LOCK
spin 171175	spin 171193	spin 171238
i915_pipe_crc_read	wakeup_source_add	wakeup_source_remove

L-SAP

Secure | https://lsap.knowledgecentricsoftwarelab.com/v/413/i/246193

L-SAP 4.13

Search

Type

Filter by Type

Status

Filter by Status

Driver

Filter by Driver

drivers/tty/serial/8250/8250_port.c

Locking type: spin

Instance ID: 246193

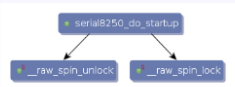
Length: 38

Title: lock

Offset: 58110

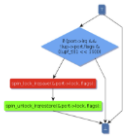
Status: PAIRED

Old Version	New Version



Control Flow Graphs

Projected Control Graphs



CFG to PCG Reduction Statistics

- For Linux 3.19-rc1, the average CFG to PCG reduction is 73.4% for the number of nodes and 75.5% for the number of edges

- Extreme example from Linux study: client_common_fill_super
  - CFG: 1, 101 nodes, 1, 179 edges, and 249 branch nodes
  - PCG: 15 nodes, 28 edges, and 13 branch nodes

Comparison to BLAST

- Berkeley Lazy Abstraction Software Verification Tool (BLAST) is a top-rated tool in the software verification competition (SV-COMP).
- BLAST verifies 43,766 (65.7)% of Lock instances as safe, and it is inconclusive (crashes or times out) on 22,843 instances. BLAST does not find any unsafe instances.
- The PCG-based automated verification tool verifies 66,151 (99.3)% of Lock instances as safe, and it is inconclusive on 451 instances. One of the bugs we found is an instance that BLAST reported as a safe instance.

Discovered Bugs – L-SAP

Secure | https://knowledgecentricsoftwarelab.com/L-SAP/bugs/

L-SAP
Scalable and Accurate Linux Lock/Unlock Pairing

Home Install Tutorials Bugs

Discovered Bugs

Below is a list of all bug cases that have been discovered with L-SAP.

Bug - 10/18/2015

Version: `4.3-rc6`

Source File: `/v4.3-rc6/drivers/media/pci/ddbridge/ddbridge-core.c`

Function `tuner_attach_tda18271` (line 595) acquires a lock on `port->i2c_gate_lock` via the call to the function pointer (`input->fe->ops.i2c_gate_ctrl(input->fe, 1)`) (line 601) which calls function `drxk_gate_ctrl`. However, when the call to function `dvb_attach` on line 602 fails (returns `NULL`), the lock on `port->i2c_gate_lock` is never released.

The bug was currently on the master branch of `v4.3-rc6` as of writing the paper.

Bug - Paper Case Study I

Version: `3.19-rc1`

Source File: `/v3.19-rc1/drivers/mmc/host/toshsd.c`

Function `toshsd_thread_irq` has an unpaired lock `spin_lock_irqsave(&host->lock, flags)` at line 176. The bug occurs when the function returns at line 179 without unlocking the spin object host->lock.

The bug was spread across all the release candiates of `3.19-rc1` through `3.19-rc7` and got fixed in `4.0`. The fixing commit ID is: `8a66fdae771487762519db0546e9ccb648a2f911`.

Bug - Paper Case Study II

Version: `3.19-rc1`

Source File: `/v3.19-rc1/drivers/scsi/fnic/fnic_fcs.c`

Function `fnic_handle_fip_timer` has an unpaired lock

Interactive Audit of Android Application

- ConnectBotBad
  - Several thousand lines of source code
  - Has multiple malwares
  - Work smarter not harder
  - Use control flow, data flow, program slices to test hypotheses
  - Leverage some knowledge of Android APIs to search sensitive interactions
- FlashBang
  - Example from the wild (but decompiled and refactored for this lab)
  - Try auditng the source code version
  - Try auditing the binary version
- Timelapse Audit of DARPA APAC Challenge Application
  - https://www.youtube.com/watch?v=p2mhfOMmgKI

Additional Resources

- https://www.ece.iastate.edu/kcsl
- Reach out to us and start a discussion!
  - Suresh Kothari – kothari@iastate.edu
  - Benjamin Holland – bholland@iastate.edu