Advanced Systems Security
Fuzz Testing

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Detect Vulnerabilities

- We want to develop techniques to detect vulnerabilities automatically before they are exploited
  - What's a vulnerability?
  - How to find them?

Vulnerability

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- How do you define computer ‘vulnerability’?

Vulnerability

- How do you define computer ‘vulnerability’?
  - *Flaw*
  - *Accessible to adversary*
  - *Adversary has ability to exploit*

One Approach

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- Run the program on various inputs
  - See what happens
  - Maybe you will find a flaw
- How should you choose inputs?

Dynamic Analysis Options

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- Regression Testing
  - Run program on many normal inputs and look for bad behavior in the responses
    - Typically looking for behavior that differs from expected – e.g., a previous version of the program
- Fuzz Testing
  - Run program on many abnormal inputs and look for bad behavior in the responses
    - Looking for behaviors that may be triggered by adversaries
      - Bad behaviors are typically crashes caused by memory errors

Dynamic Analysis Options

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- Why do you think fuzz testing is more appropriate for finding vulnerabilities than regression testing?

Fuzz Testing

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- Fuzz Testing
  - Idea proposed by Bart Miller at Wisconsin in 1988
- Problem: People assumed that utility programs could correctly process any input values
  - Available to all
- Result: Found that they could crash 25-33% of UNIX utility programs

Fuzz Testing

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- Fuzz Testing
  - Idea proposed by Bart Miller at Wisconsin in 1988
- Approach
  - Generate random inputs
  - Run lots of programs using random inputs
  - Identify crashes of these programs
  - Correlate with the random inputs that caused the crashes
- Problems: Not checking returns, Array indices…

Fuzzing Example

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- Fuzz Testing
  - Example

```
format.c (line 276):
...
while (lastc != '\n') {
    rdc();
}
...

input.c (line 27):
rdc()
{ do { readchar(); }
    while (lastc == ' ' || lastc == '\t'); return (lastc);
}
```

Challenges

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- Idea: Search for possibly accessible and exploitable flaws in a program by running the program under a variety of inputs
- Challenge: Selecting input values for the program
  - What should be the goals in choosing input values for dynamic analysis?

Challenges

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- Idea: Search for possibility exploitable flaws in a program by running the program under a variety of inputs
- Challenge: Selecting input values for the program
  - What should be the goals in choosing input values for dynamic analysis?
  - *Find all exploitable flaws*
  - *With the fewest possible input values*
- How should these goals impact input choices?

Black Box Fuzzing

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- Like Miller – Feed the program random inputs and see if it crashes
- Pros: Easy to configure
- Cons: May not search efficiently
  - May re-run the same path over again (low coverage)
  - May be very hard to generate inputs for certain paths (checksums, hashes, restrictive conditions)
  - May cause the program to terminate for logical reasons – fail format checks and stop

Black Box Fuzzing

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- Example

```
function( char *name, char *passwd, char *buf )
{
     if ( authenticate_user( name, passwd )) {
          if ( check_format( buf )) {
               update( buf );
          }
     }
}
```

Mutation-Based Fuzzing

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- Supply a well-formed input
  - Generate random changes to that input
- No assumptions about input
  - Only assumes that variants of well-formed input may problematic
- Example: zzuf
  - http://sam.zoy.org/zzuf/
  - Reading: The Fuzzing Project Tutorial

Mutation-Based Fuzzing

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- Example: zzuf
  - http://sam.zoy.org/zzuf/
- The Fuzzing Project Tutorial
  - zzuf -s 0:1000000 -c -C 0 -q -T 3 objdump -x win9x.exe
  - Fuzzes the program `objdump` using the sample input `win9x.exe`
  - Try 1M seed values (-s) from command line (-c) and keep running if crashed (-C 0) with timeout (-T 3)

Mutation-Based Fuzzing

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- Easy to setup, and not dependent on program details
- But may be strongly biased by the initial input
- Still prone to some problems
  - May re-run the same path over again (same test)
  - May be very hard to generate inputs for certain paths (checksums, hashes, restrictive conditions)

Generation-Based Fuzzing

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- Generational fuzzer generate inputs “from scratch” rather than using an initial input and mutating
- However, to overcome problems of naïve fuzzers they often need a format or protocol spec to start
- Examples include
  - SPIKE, Peach Fuzz
- However format-aware fuzzing is cumbersome, because you'll need a fuzzer specification for every input format you are fuzzing

Generation-Based Fuzzing

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- Can be more accurate, but at a cost
- Pros: More complete search
  - Values more specific to the program operation
  - Can account for dependencies between inputs
- Cons: More work
  - Get the specification
  - Write the generator – ad hoc
- Need to do for each program

Grey Box Fuzzing

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- Rather than treating the program as a black box, instrument the program to track the paths run
- Save inputs that lead to new paths
  - Associated with the paths they exercise
- Example
  - American Fuzzy Lop (AFL)
- "State of the practice" at this time

AFL

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- Provides compiler wrappers for gcc to instrument target program to collect fuzzing stats

- http://lcamtuf.coredump.cx/afl/

AFL Display

- Tracks the execution of the fuzzer

- Key information are
  - "total paths" – number of different execution paths tried
  - "unique crashes" – number of unique crash locations

AFL Output

- Shows the results of the fuzzer
  - E.g., provides inputs that will cause the crash
- File "fuzzer_stats" provides summary of stats – UI
- File "plot_data" shows the progress of fuzzer
- Directory "queue" shows inputs that led to paths
- Directory "crashes" contains input that caused crash
- Directory "hangs" contains input that caused hang

AFL Operation

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- How does AFL work?
  - http://lcamtuf.coredump.cx/afl/technical_details.txt
- The instrumentation captures branch (edge) coverage, along with coarse branch-taken hit counts.
  - `cur_location = <COMPILE_TIME_RANDOM>;`
  - `shared_mem[cur_location ^ prev_location]++;`
  - `prev_location = cur_location >> 1;`
- Record branches taken with low collision rate
- Enables distinguishing unique paths

AFL Operation

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- How does AFL work?
  - http://lcamtuf.coredump.cx/afl/technical_details.txt
- When a mutated input produces an execution trace containing new tuples, the corresponding input file is preserved and routed for additional processing
  - Otherwise, input is discarded
- Mutated test cases that produced new state transitions are added to the input queue and used as a starting point for future rounds of fuzzing

AFL Operation

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- How does AFL work?
  - http://lcamtuf.coredump.cx/afl/technical_details.txt
- Fuzzing strategies
  - Highly deterministic at first – bit flips, add/sub integer values, and choose interesting integer values
  - Then, non-deterministic choices – insertions, deletions, and combinations of test cases

Grey Box Fuzzing

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- Finds flaws, but still does not understand the program
- Pros: Much better than black box testing
  - Essentially no configuration
  - Lots of crashes have been identified
- Cons: Still a bit of a stab in the dark
  - May not be able to execute some paths
  - Searches for inputs independently from the program
- Need to improve the effectiveness further

White Box Fuzzing

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- Combines test generation with fuzzing
  - Test generation based on static analysis and/or symbolic execution
  - Rather than generating new inputs and hoping that they enable a new path to be executed, compute inputs that will execute a desired path
    - And use them as fuzzing inputs
- Goal: Given a sequential program with a set of input parameters, generate a set of inputs that maximizes code coverage

Helping Fuzzing

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- One problem in fuzzing is to generate inputs to cover all paths
  - Can symbolic execution help with this?
  - Driller: Augmenting Fuzzing through Symbolic Execution
    - Slides from Nick Stephens at NDSS 2016

Helping Fuzzing

```
x = int(input())
if x > 10:
    if x < 100:
        print "You win!"
    else:
        print "You lose!"
else:
    print "You lose!"
```

Let's fuzz it!

1 ⇒ "You lose!"

593 ⇒ "You lose!"

183 ⇒ "You lose!"

4 ⇒ "You lose!"

498 ⇒ "You lose!"

48 ⇒ "You win!"

Helping Fuzzing

```
x = int(input())
if x > 10:
    if x^2 == 152399025:
        print "You win!"
    else:
        print "You lose!"
else:
    print "You lose!"
```

Let's fuzz it!

1 ⇒ "You lose!"

593 ⇒ "You lose!"

183 ⇒ "You lose!"

4 ⇒ "You lose!"

498 ⇒ "You lose!"

42 ⇒ "You lose!"

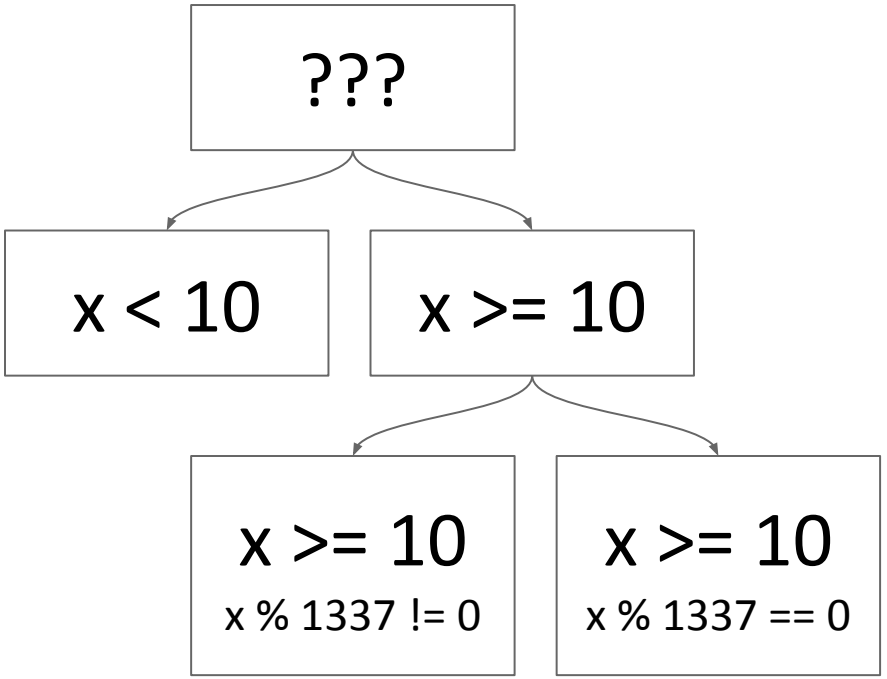
3 ⇒ "You lose!"

.....

57 ⇒ "You lose!"

With Symbolic Execution

```
x = input()
if x >= 10:
    if x % 1337 == 0:
        print "You win!"
    else:
        print "You lose!"
else:
    print "You lose!"
```



With Symbolic Execution

```
x = input()
if x >= 10:
   if x % 1337 == 0:
      print "You win!"
   else:
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else:
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```
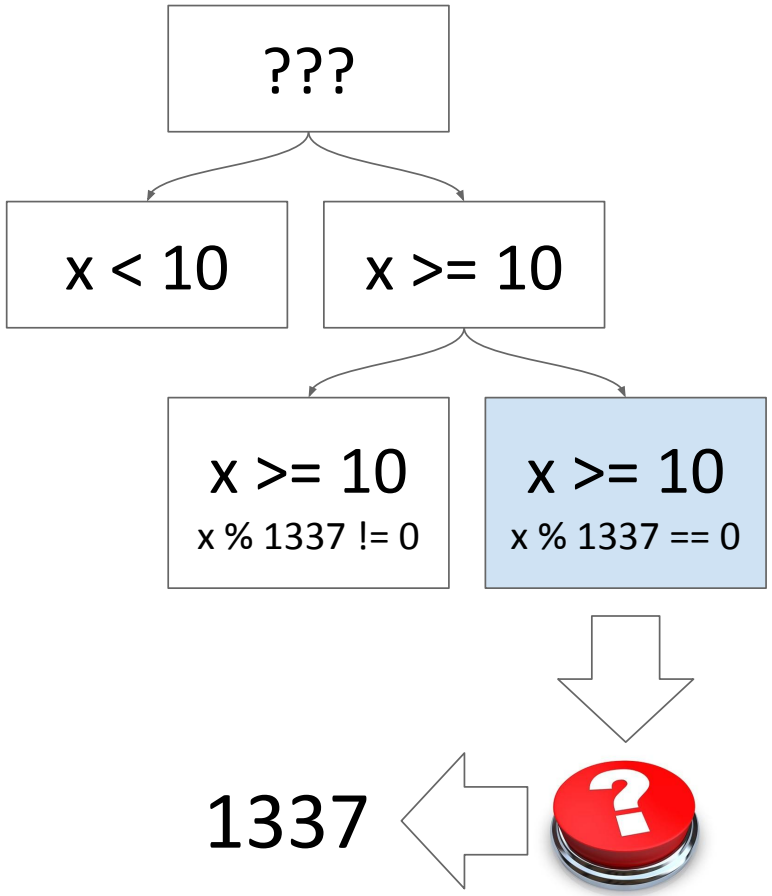



Different Approaches

Fuzzing

- Good at finding solutions for general conditions
- Bad at finding solutions for specific conditions

Symbolic Execution

- Good at finding solutions for specific conditions
- Spends too much time iterating over general conditions

Fuzzing vs. Symbolic Exec

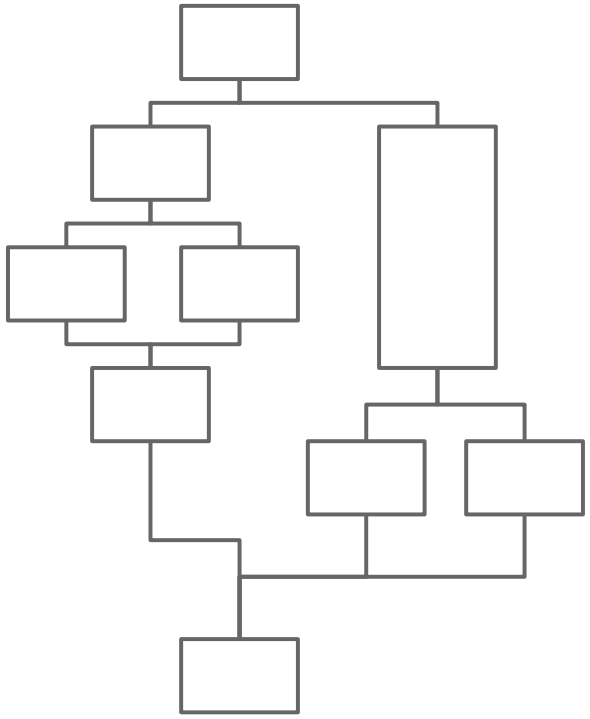
```
x = input()

def recurse(x, depth):
  if depth == 2000
    return 0
  else {
    r = 0;
    if x[depth] == “B”:
      r = 1
    return r + recurse(x
[depth], depth)

if recurse(x, 0) == 1:
  print “You win!”
```

Fuzzing Wins

```
x = int(input())
if x >= 10:
    if x^2 == 152399025:
        print "You win!"
    else:
        print "You lose!"
else:
    print "You lose!"
```

Symbolic Execution Wins

Combining the Two

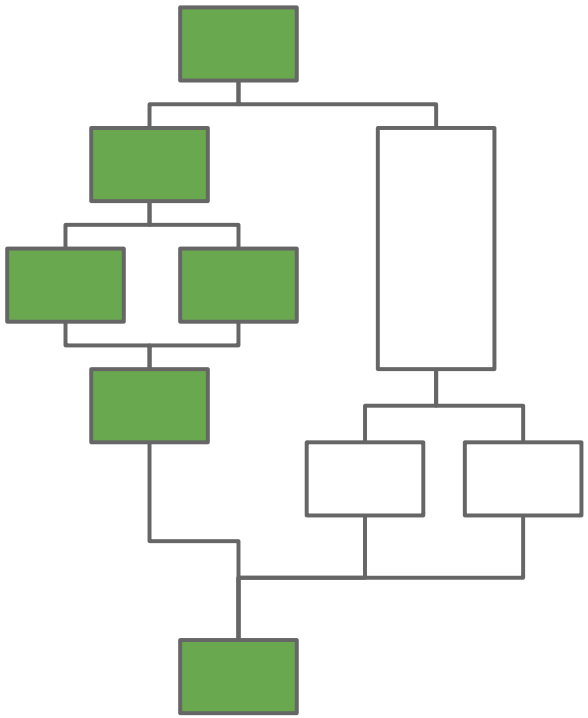


Control Flow Graph

Test Cases

Combining the Two

"Cheap" fuzzing coverage



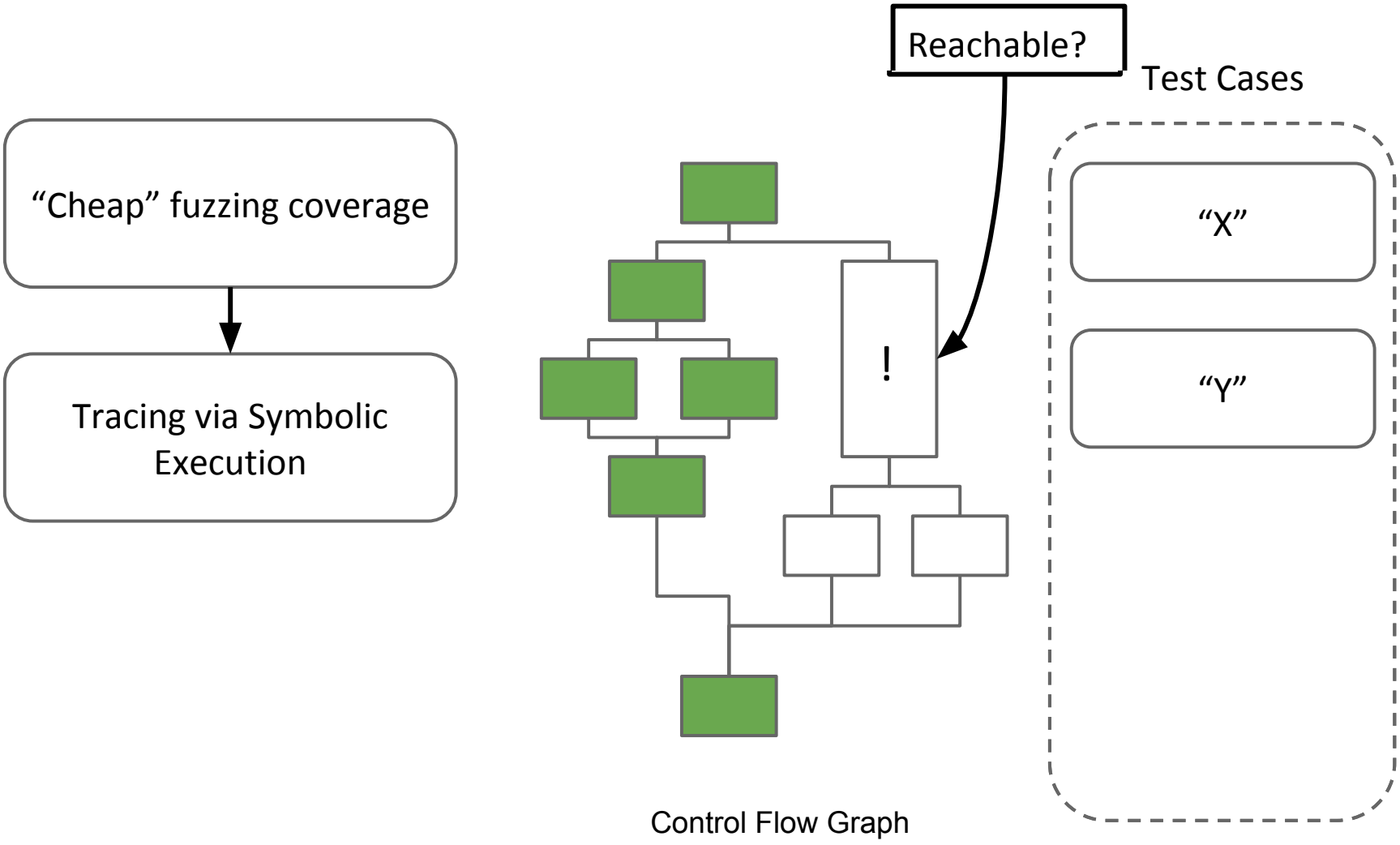
Control Flow Graph

Test Cases

"X"

"Y"

Combining the Two



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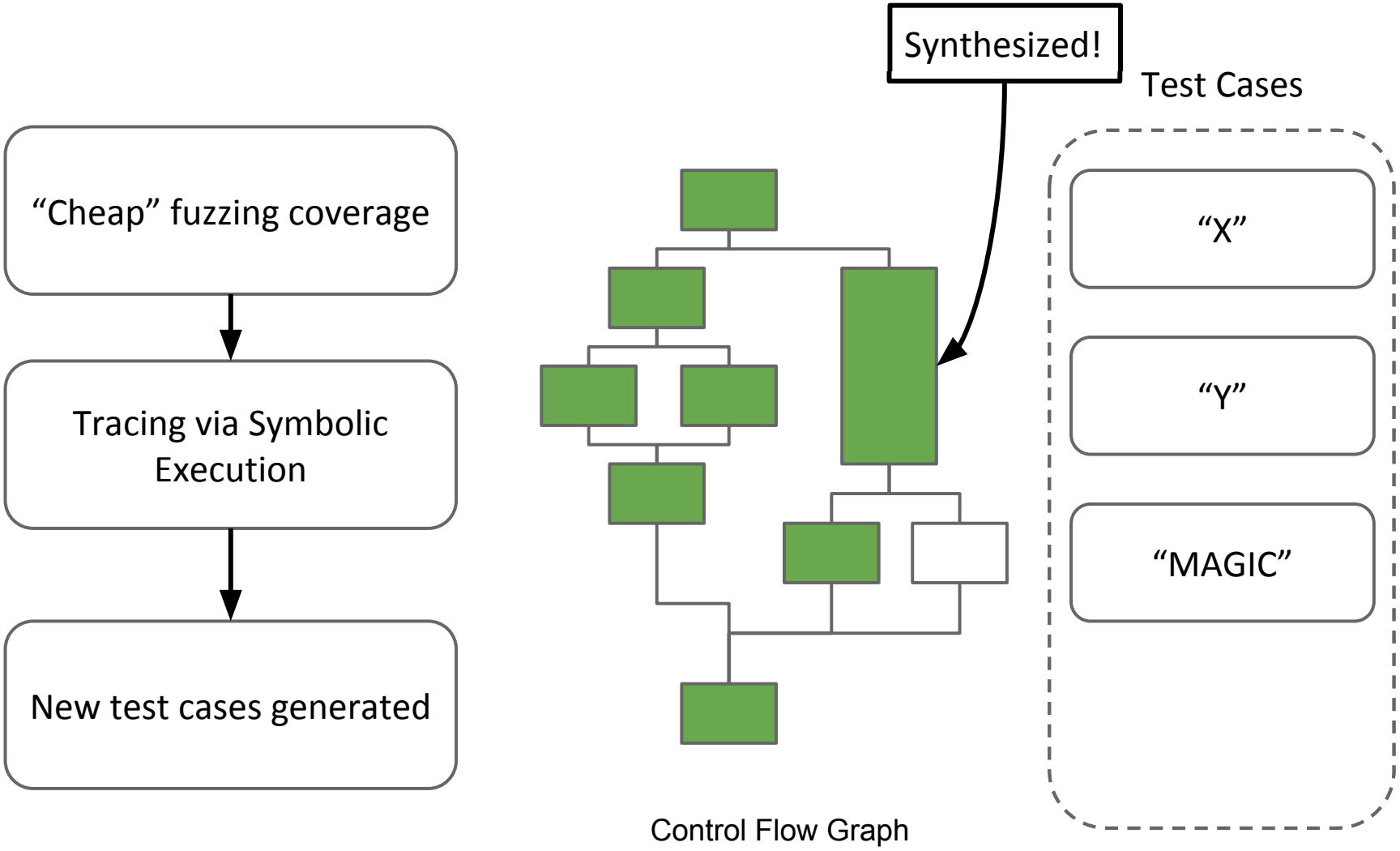
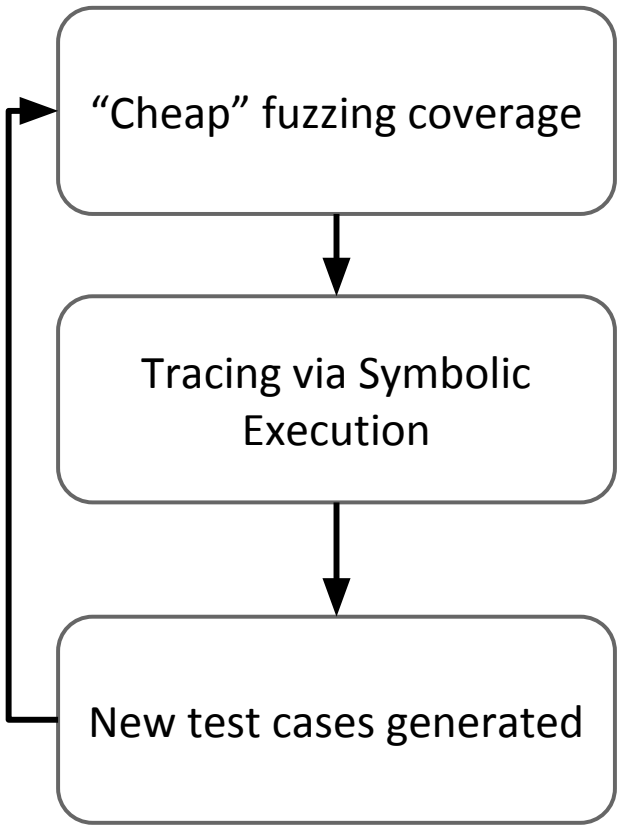
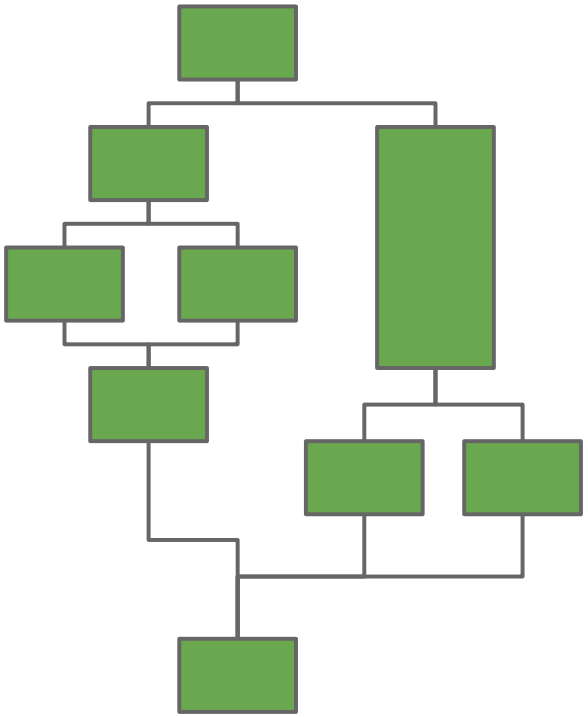


Combining the Two

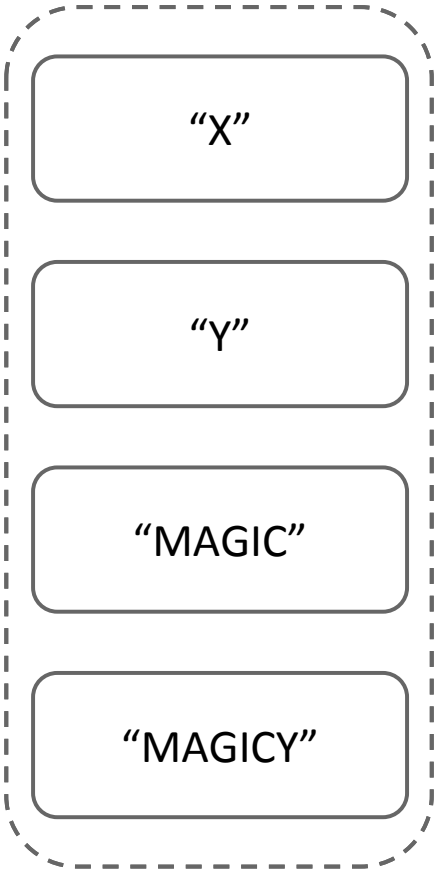
Towards completer code coverage!





Control Flow Graph

Test Cases



Combining the Two

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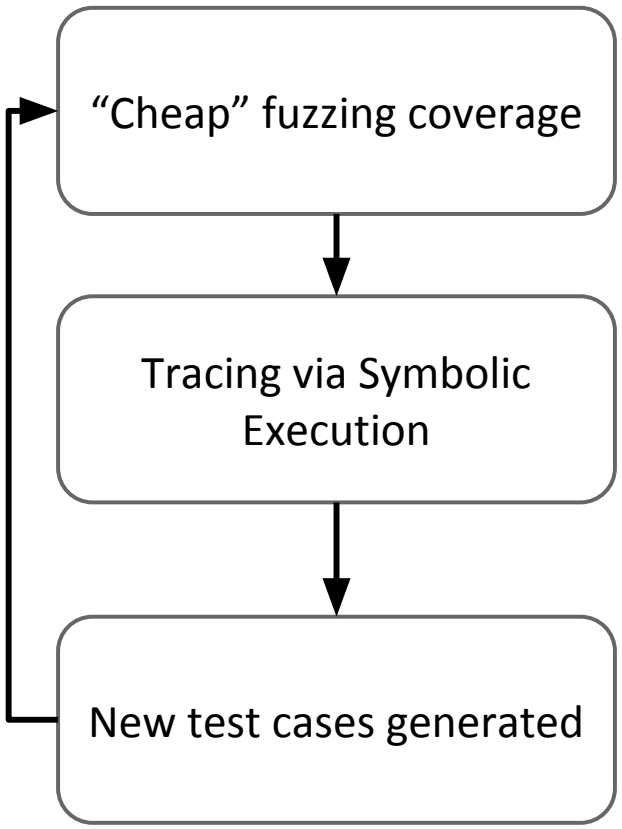
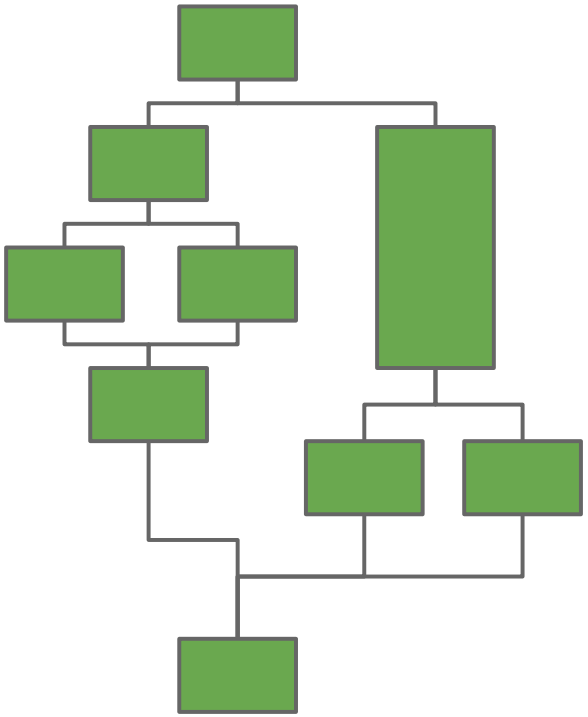
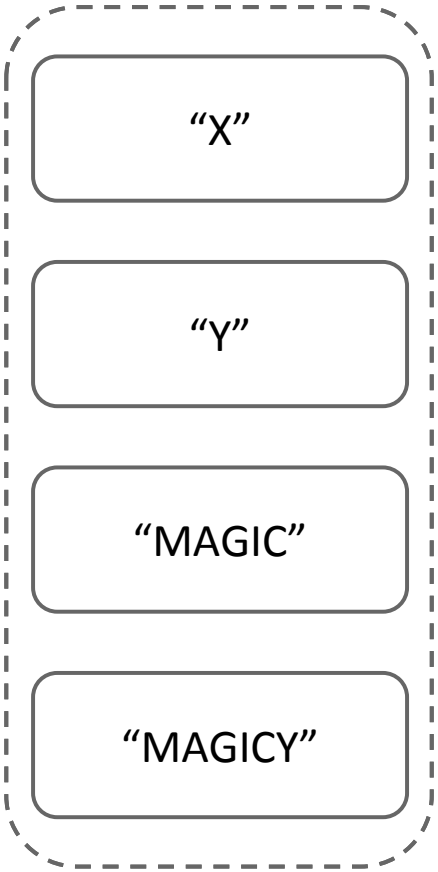
Towards completer code coverage!





Control Flow Graph

Test Cases



Take Away

- Goal is to detect vulnerabilities in our programs before adversaries exploit them
- One approach is dynamic testing of the program
  - Fuzz testing aims to achieve good program coverage with little effort for the programmer
  - Challenge is to generate the right inputs
- Black box (Mutational and generation), Grey box, and White box approaches are being investigated
  - AFL (Grey box) is now commonly used