Million Dollar Baby

An 'angr'y attempt at the Cyber Grand Challenge

Nick Stephens stephens@cs.ucsb.edu

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Shellphish

- Who are we?
  - A team of security enthusiasts
    - do research in System Security
    - play Capture the Flag competitions
    - released a couple of tools

Mini-primer: What's a CTF?

- Security competition:
  - exploit a vulnerable service / website / cryptosystem
  - reverse a binary
  - …
- Different formats
  - Jeopardy – Attack-Defense
  - Online – Live
  - …
- Basic idea: find the secret, submit to organizers, … *profit*

Shellphish

Roadmap

- **DARPA Cyber Grand Challenge (CGC)**
  The (almost-)Million Dollar Baby

- Our Cyber Reasoning System (CRS)
  Fancy term for auto-playing a CTF

- Automated Vulnerability Discovery
  Driller

- Automated Vulnerability Exploitation
  How it works

- Auto-exploitation demo using angr
  Open-source binary analysis framework

Cyber Grand Challenge (CGC)

- 2004: DARPA Grand Challenge
  - Autonomous vehicles

Cyber Grand Challenge (CGC)

- 20**14**: DARPA **Cyber** Grand Challenge
  - Autonomous **hacking!**

Cyber Grand Challenge (CGC)

- Qualification event: ONLINE
  - ~70 teams → 7 qualified teams
  - $750k per team

- Final event: DEFCON 24
  - Winning CRS will also play against humans!

cybergrandchallenge.com / cgc.darpa.mil


SHELLFISH

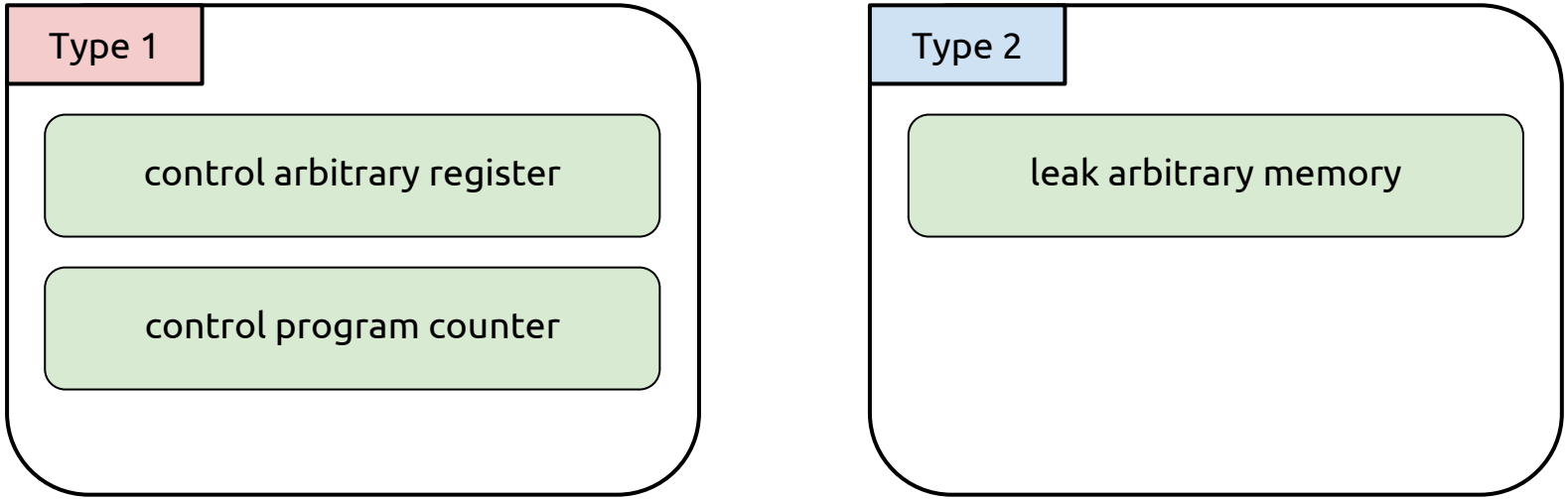
CGC Rules

- Attack-Defense CTF
- ~~Solving security challenges~~ → Developing a system that solves security challenges
- Develop a system that **automatically**
  - Exploits vulnerabilities
  - Removes vulnerabilities
- No human intervention

CGC – Rules

- Exploits
  - “getting a flag” (how? where?)
  - For the quals: exploit = **crash**
  - For the finals: exploit = **demonstrate PC control**
- Defend
  - int main() { return 0; }
    - Functionality checks
  - SIGSEGV => exit(0)
    - No easy “out-of-band” error handling
  - QEMU-style interpreter: interrupts => exit(0)
    - Performance cost (CPU, memory, file size)

CGC Final Round Exploits



CGC Qualification Event – Rules

- Basic idea:
  - Real(istic) programs
  - No “extra” complications

CGC Qualification Event – Rules

- Architecture: Intel x86, 32-bit
- OS: DECREE
  - Linux-like, but with 7 syscalls only
    - `transmit / receive / fdwait (≈select)`
    - `allocate / deallocate` (even executable!)
    - `random`
    - `_terminate`
- no signals, threads, shared memory
- “Bring Your Own Defense” approach (and pay for it)
  - Not even “the usual”: stack is executable, no ASLR, …

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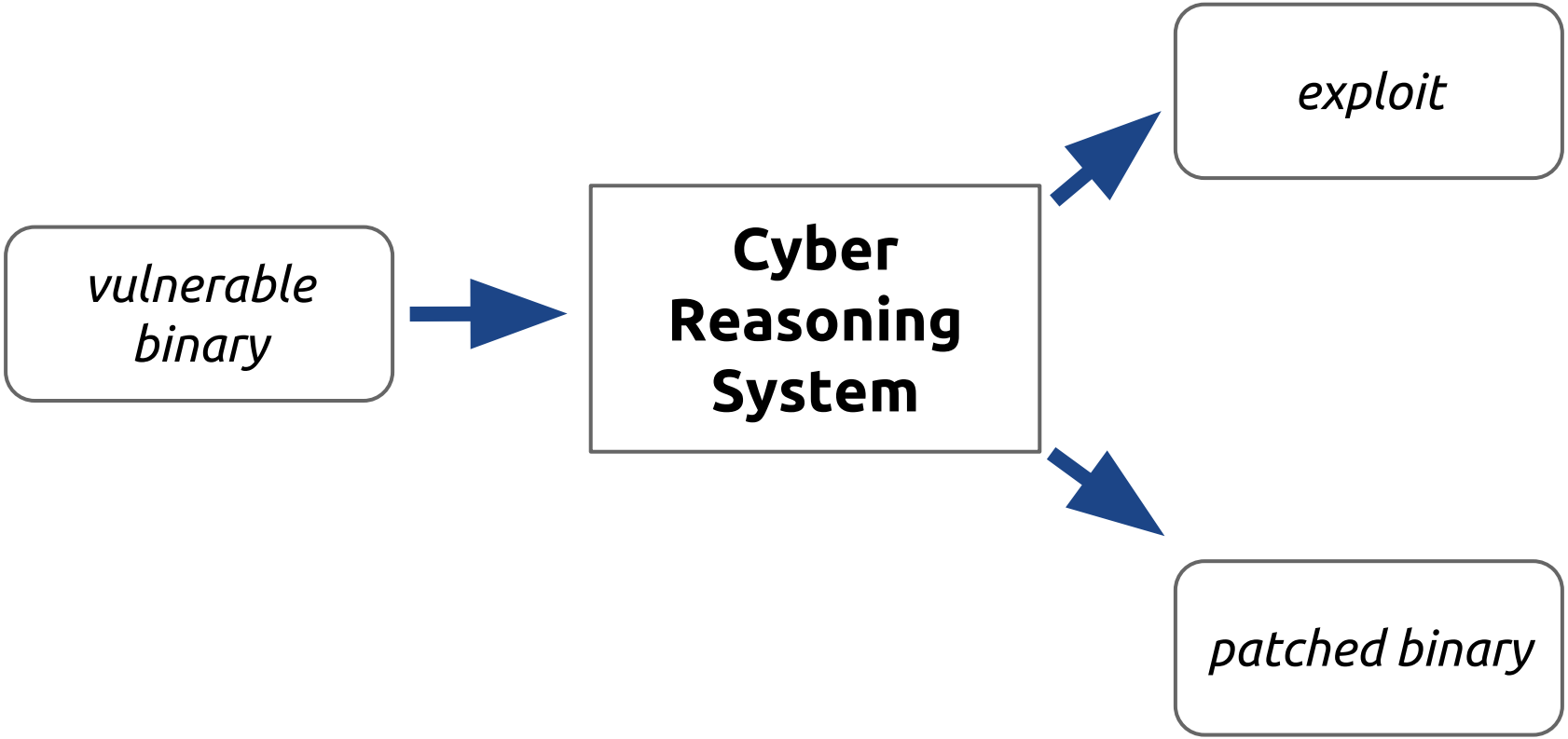
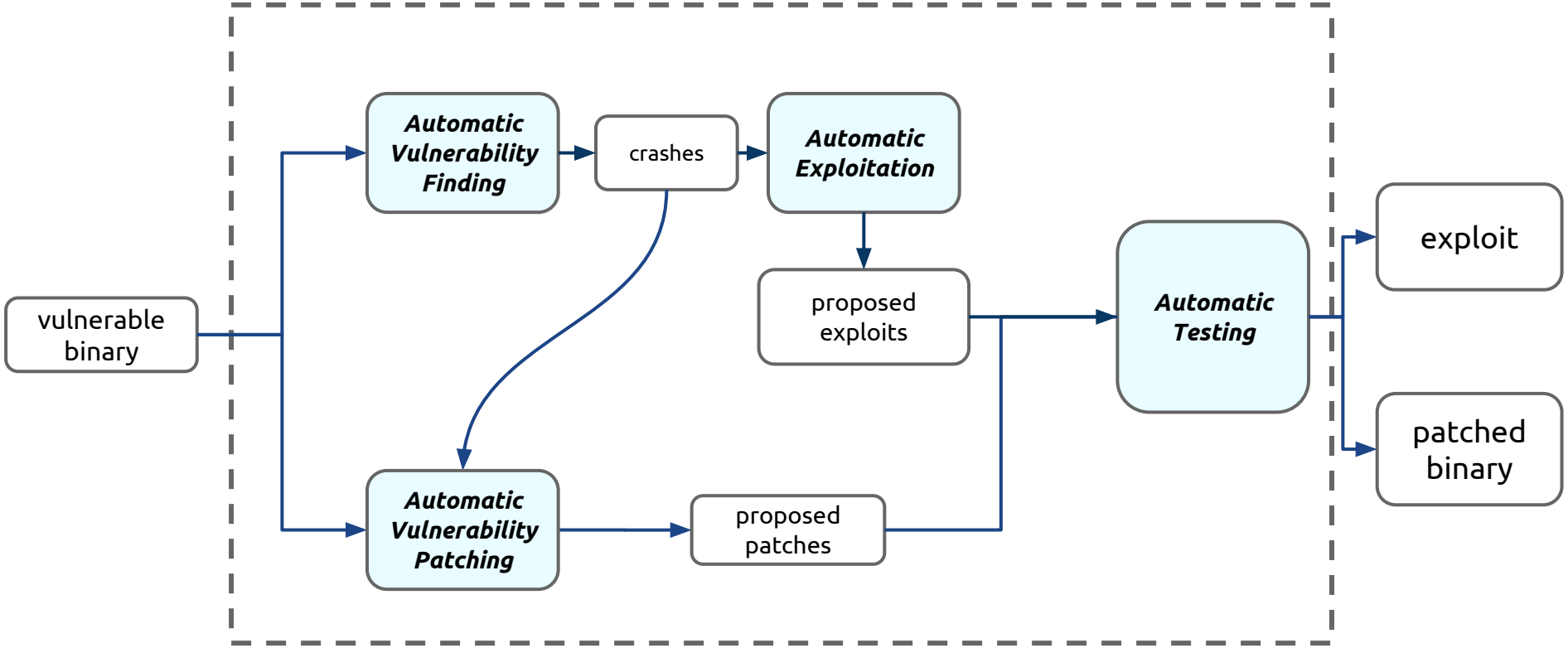
Shellphish CRS



Shellphish CRS



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Quals Approach to Finding Bugs

Fuzz a binary

… and …

Symbolically explore a binary

Finding bugs

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!"

Catching Bugs

- Monitors program for crashes

```
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!"

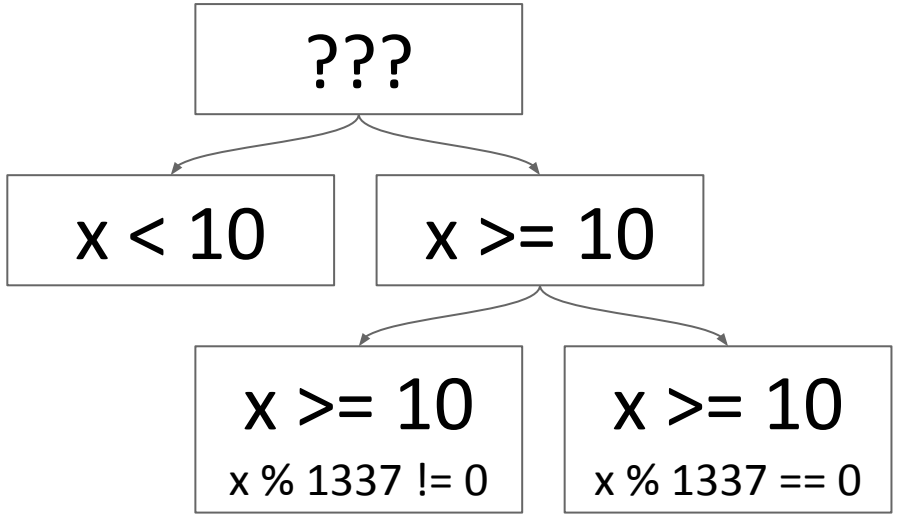
.....

57 ⇒ "You lose!"

Finding bugs

Symbolic Execution

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



```
x = input()
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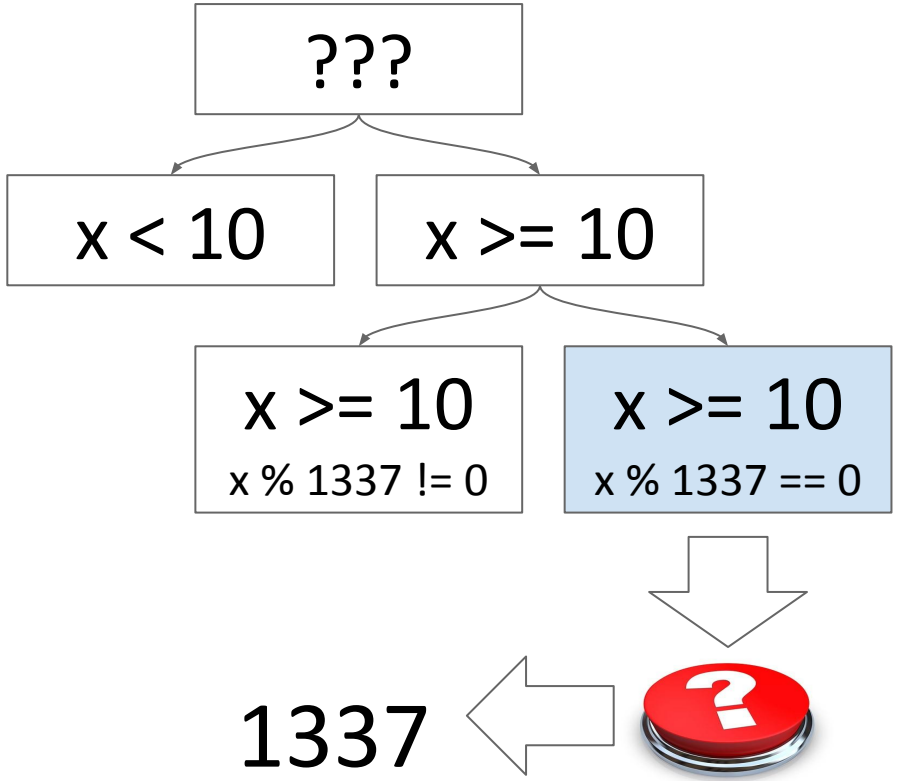


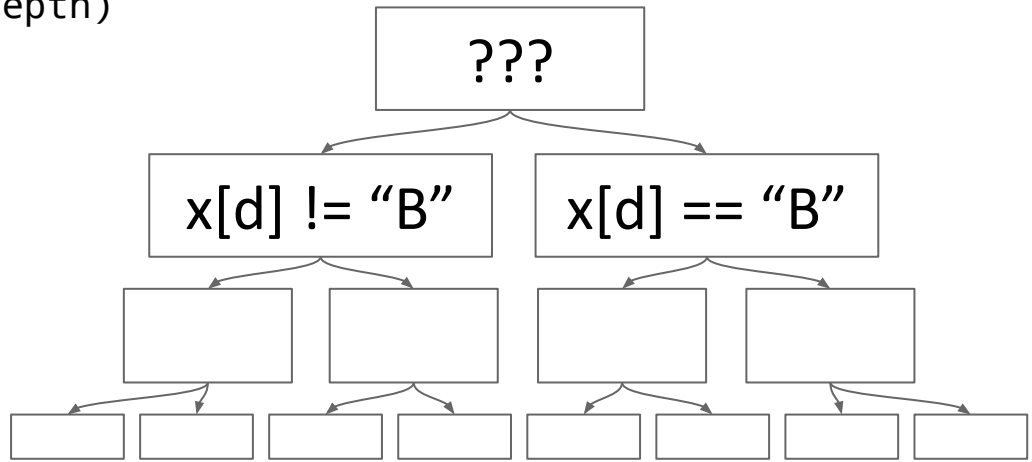
Catching Bugs

- Checks each state for safety violations
  - symbolic program counter
  - writes/reads from symbolic address

```
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)

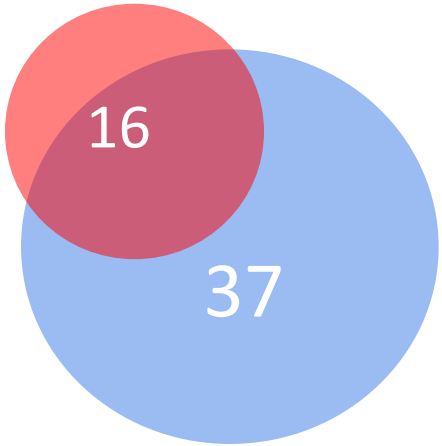
if recurse(x, 0) == 1:
  print “You win!”
else:
  print “You lose!”
```



Quals Performance

- Symbolic Execution (angr): 16
- Fuzzing (AFL): 37

Total: 44 / 128



… need something better

Driller: Augmenting Fuzzing through Selective Symbolic Execution

NDSS 2016

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 Execution

```
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)

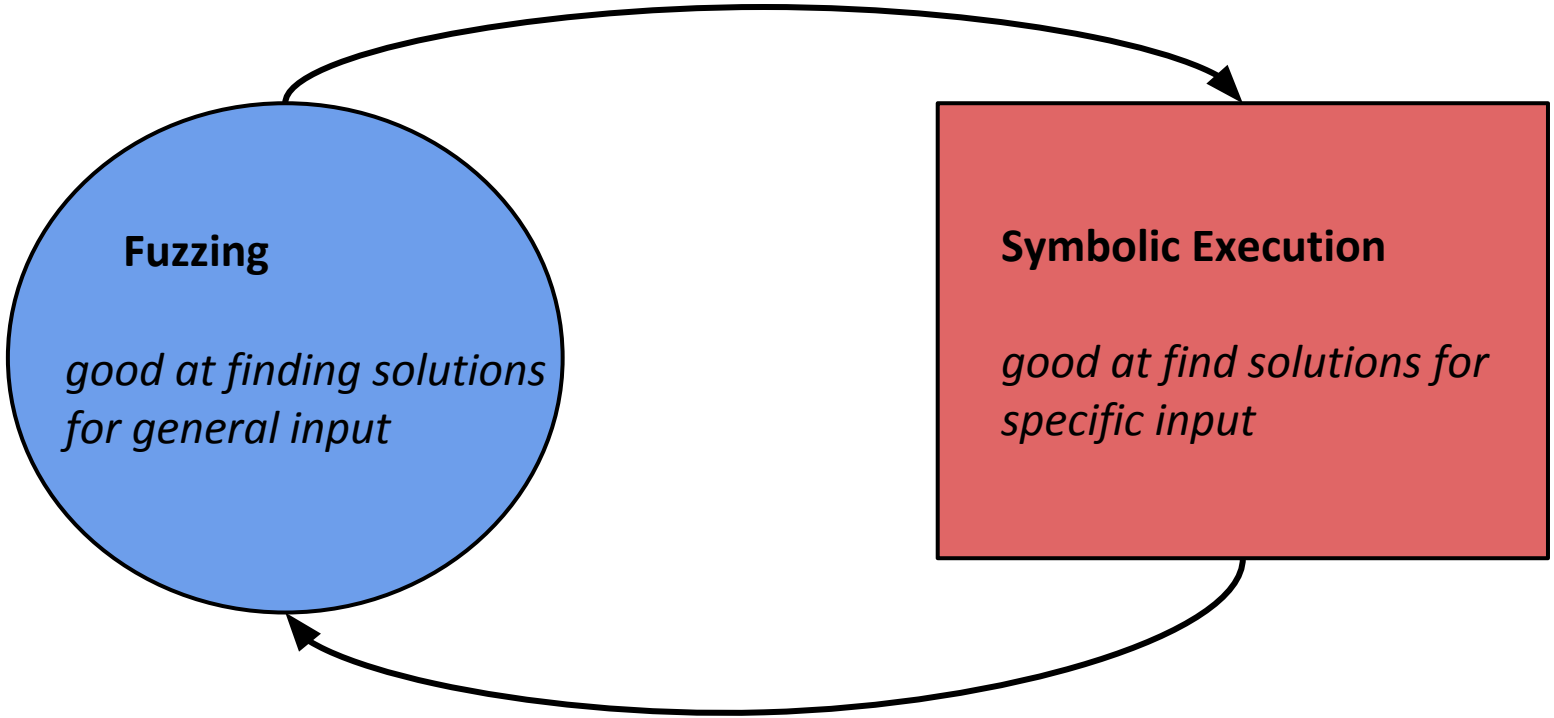
if recurse(x, 0) == 1:
  print “You win!”
```

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

The Goal


Fuzzing
good at finding solutions for general input
Symbolic Execution
good at find solutions for specific input

American Fuzzy Lop + angr

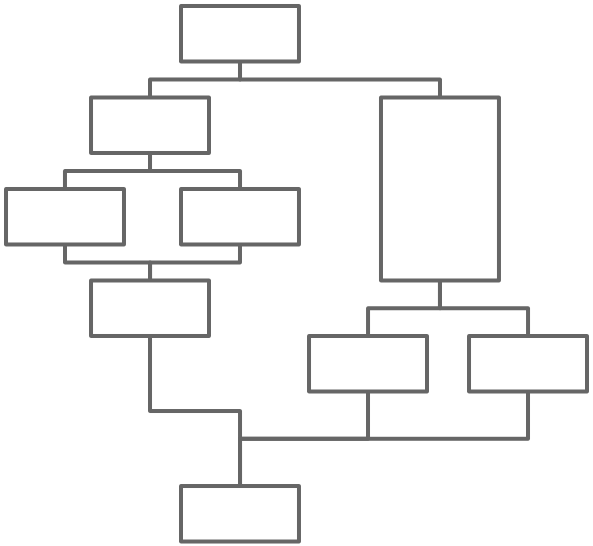
AFL

- state-of-the-art instrumented fuzzer
- path uniqueness tracking
- genetic mutations
- open source

angr

- binary analysis platform
- implements symbolic execution engine
- works on binary code
- available on github

Combining the Two (High-level)

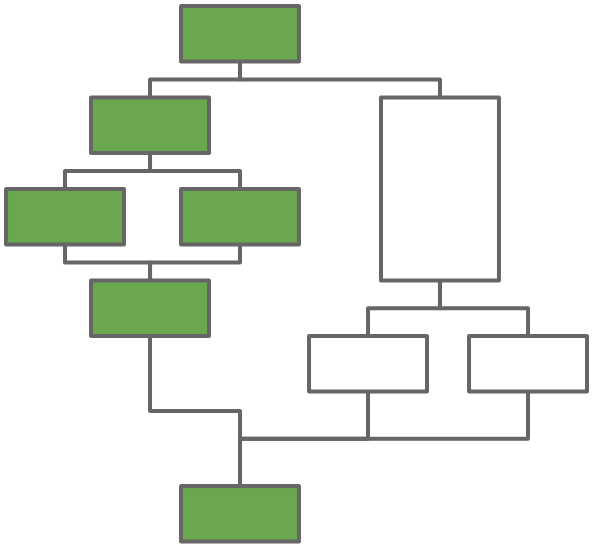


Control Flow Graph

Test Cases

Combining the Two

"Cheap" fuzzing coverage



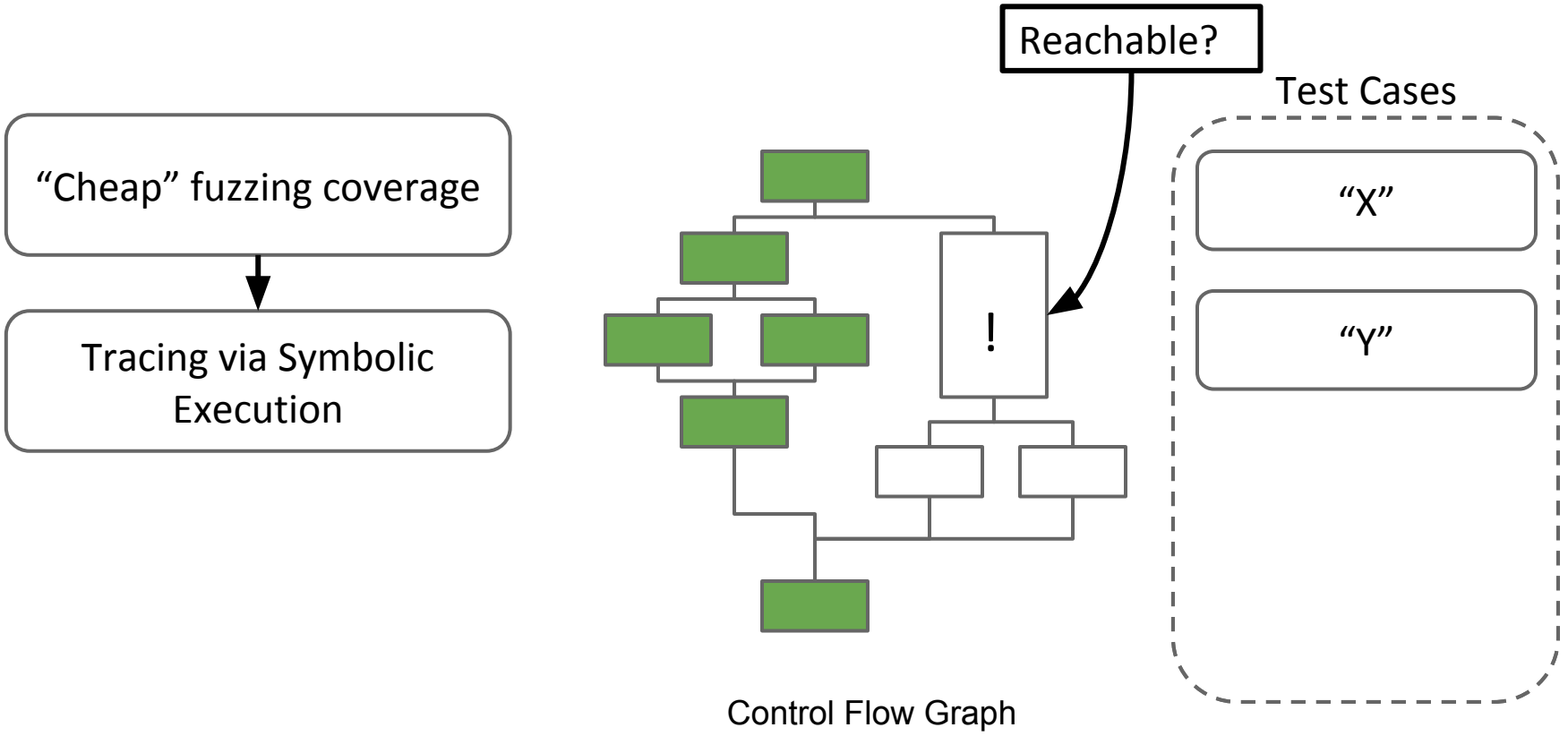
Control Flow Graph

Test Cases

"X"

"Y"

Combining the Two



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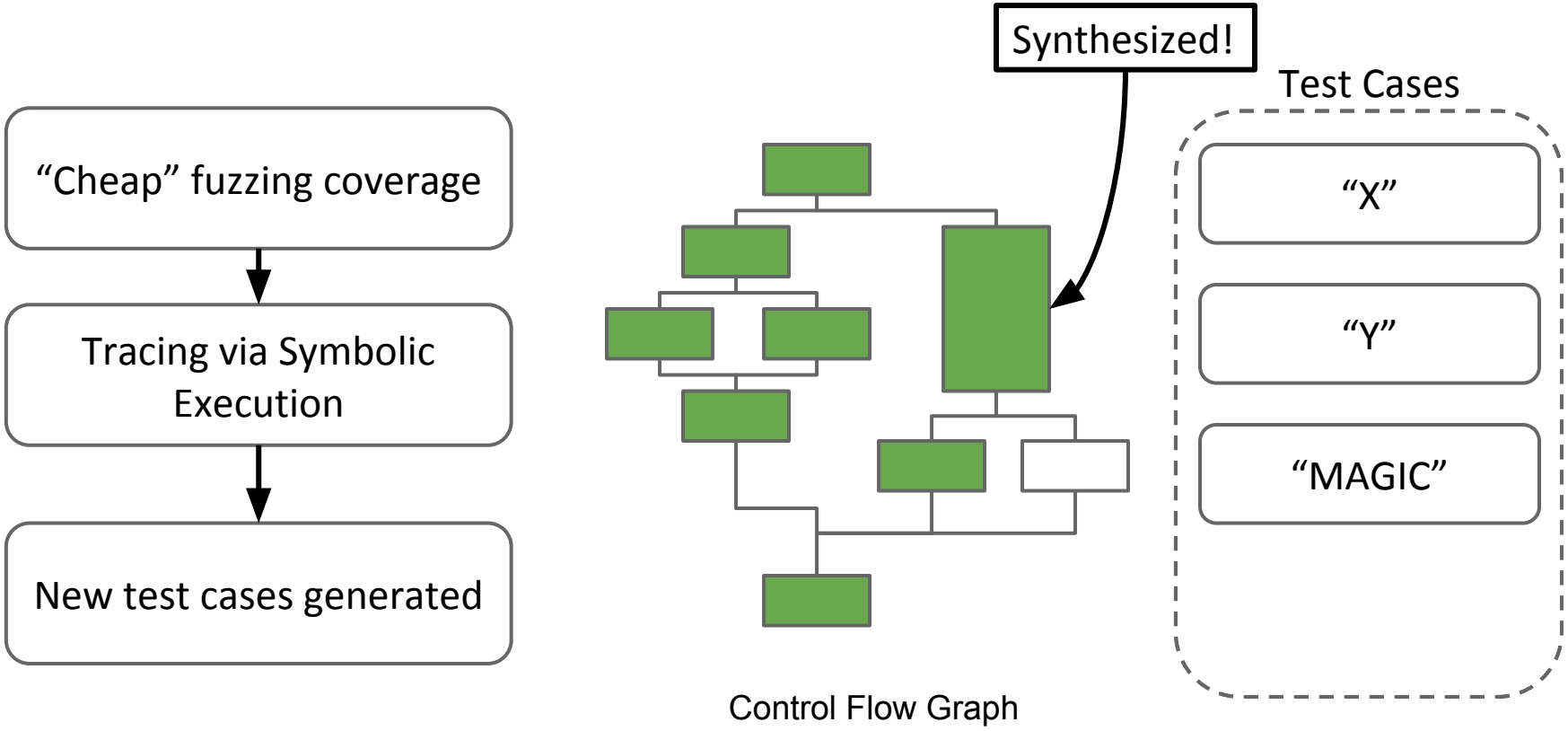
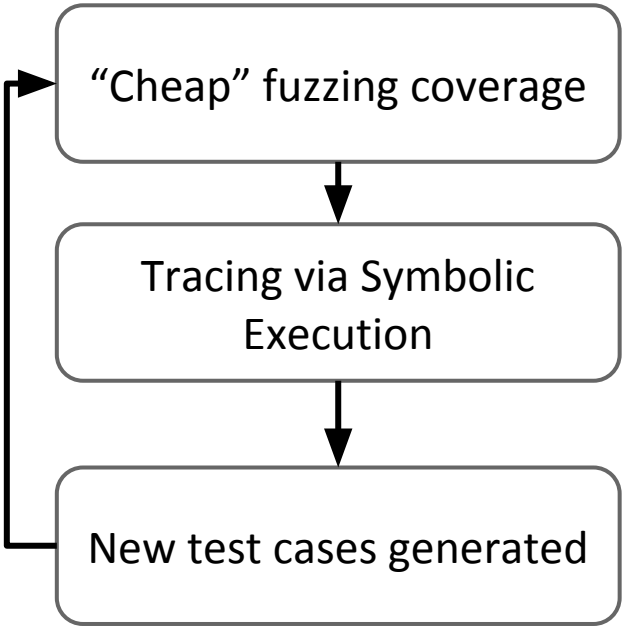
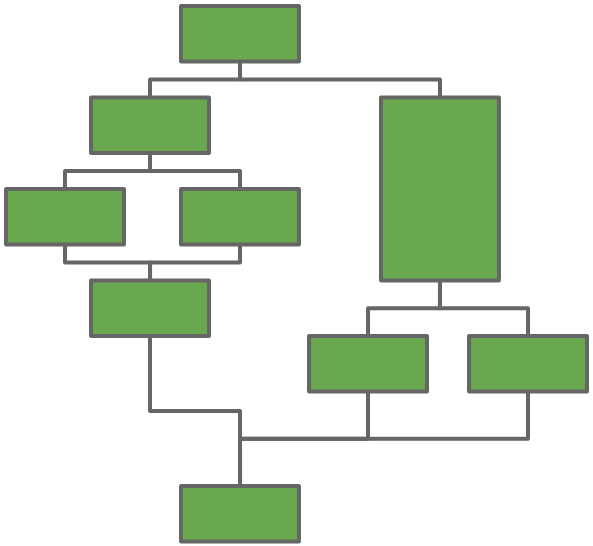


Combining the Two

Towards completer code coverage!





Control Flow Graph

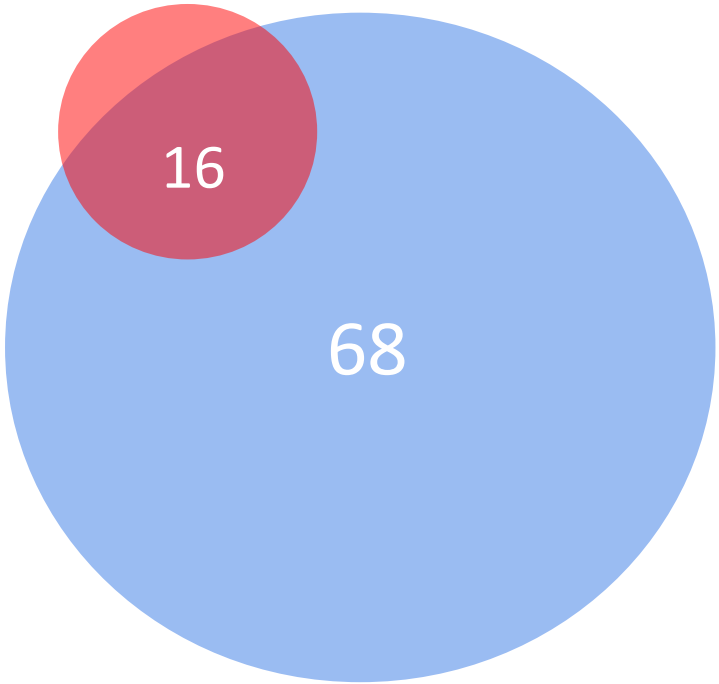
Test Cases

- “X”
- “Y”
- “MAGIC”
- “MAGICY”

CGC Fuzzer Optimizations

- Symbolic Execution (angr) - 16
- Fuzzing (AFL) - 68 total
- S & F Shared - 13 total

71 / 128 binaries

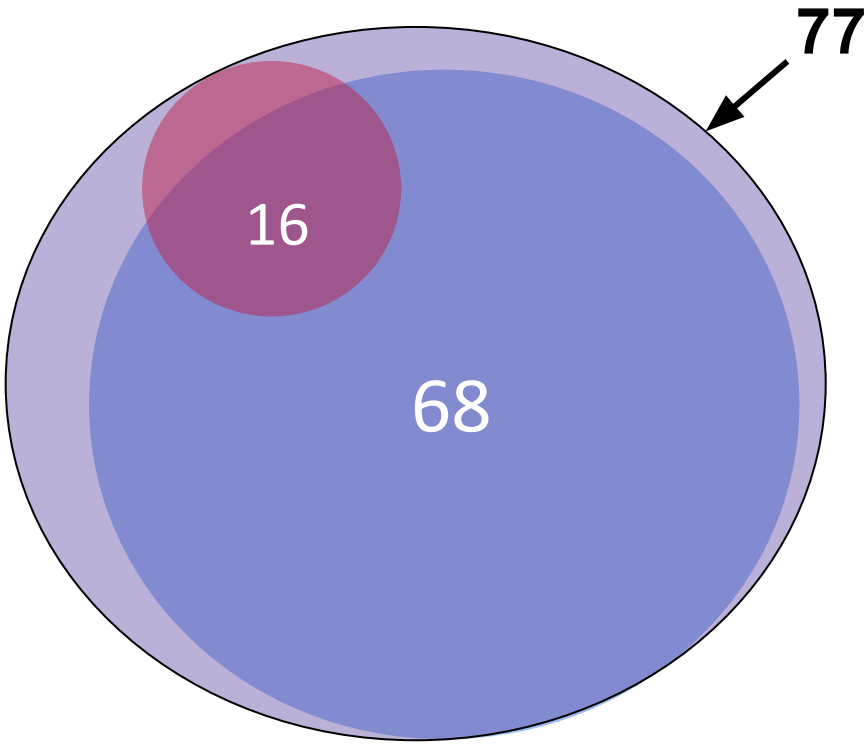


Binary Crashes per Technique

Driller Results

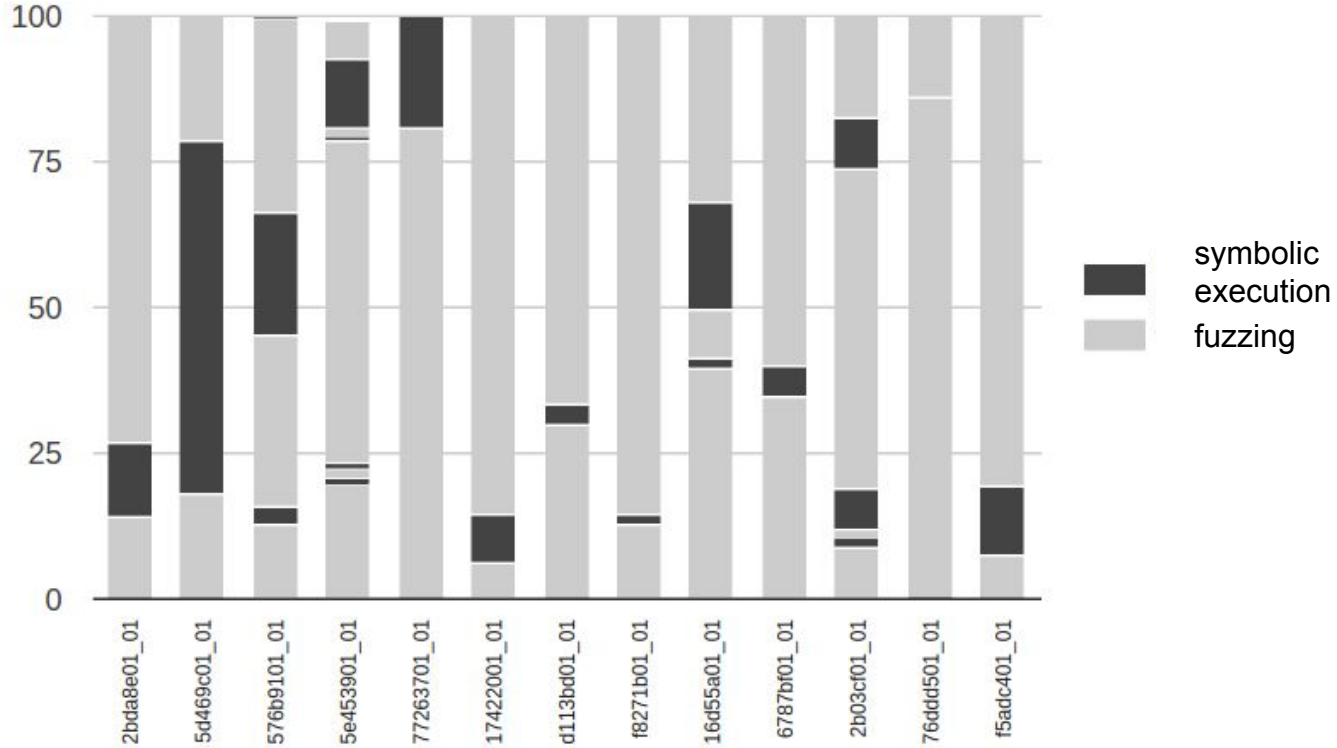
- Symbolic Execution (angr) - 16
- Fuzzing (AFL) - 68 total
- S & F Shared - 13 total
- Driller - 77 total

77 / 128 binaries



Binary Crashes per Technique

Distribution of Transitions Found as Iterations of Symbolic Execution and Fuzzing



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Previous Work

- Automatic Generation of Control Flow Hijacking Exploits …
  - Sean Heelan

- AEG: Automatic Exploit Generation
  - Thanassis Avgerinos, CMU

- Unleashing MAYHEM on Binary Code
  - Sang Kil Cha, CMU

- Q: Exploit Hardening Made Easy
  - Edward J. Schwartz, CMU

- More work being done by Julien Vanegue, as far as I know still largely theoretical at this point

Auto Exploitation - Simplified

- Find a path with safety violations

- Exploit it

Auto Exploitation - Simplified

```
typedef struct component {
      char name[32];
      int (*do_something)(int arg);
} comp_t;

comp_t *initialize_component(char *cmp_name) {
      int i = 0;
      struct component *cmp;

      cmp = malloc(sizeof(struct component));
      cmp->do_something = sample_func;

      while (*cmp_name)
            cmp->name[i++] = *cmp_name++;

      cmp->name[i] = '\0';
      return cmp;
}
x = get_input();
cmp = initialize_component(x);
cmp->do_something(1);
```

HEAP

Symbolic Byte[0] Symbolic Byte[1] Symbolic Byte[2] Symbolic Byte[3] Symbolic Byte[4] Symbolic Byte[5] Symbolic Byte[6] Symbolic Byte[7] ...
Symbolic Byte[32] … Symbolic Byte[36]
'\0'

call <symbolic byte[36:32]>

Auto Exploitation - Simplified

Turning the state into an **exploited** state

angr

```
assert state.se.symbolic(state.regs.pc)
```

Constrain **buffer** to contain our shellcode

angr

```
buf_addr = find_symbolic_buffer(state, len(shellcode))
mem = state.memory.load(buf_addr, len(shellcode))
state.add_constraints(mem == state.se.bvv(shellcode))
```

find_symbolic_buffer is not included in the angr project, but an implementation of this will be shown in the demo

Auto Exploitation - Simplified

Constrain **PC** to point to the buffer

angr

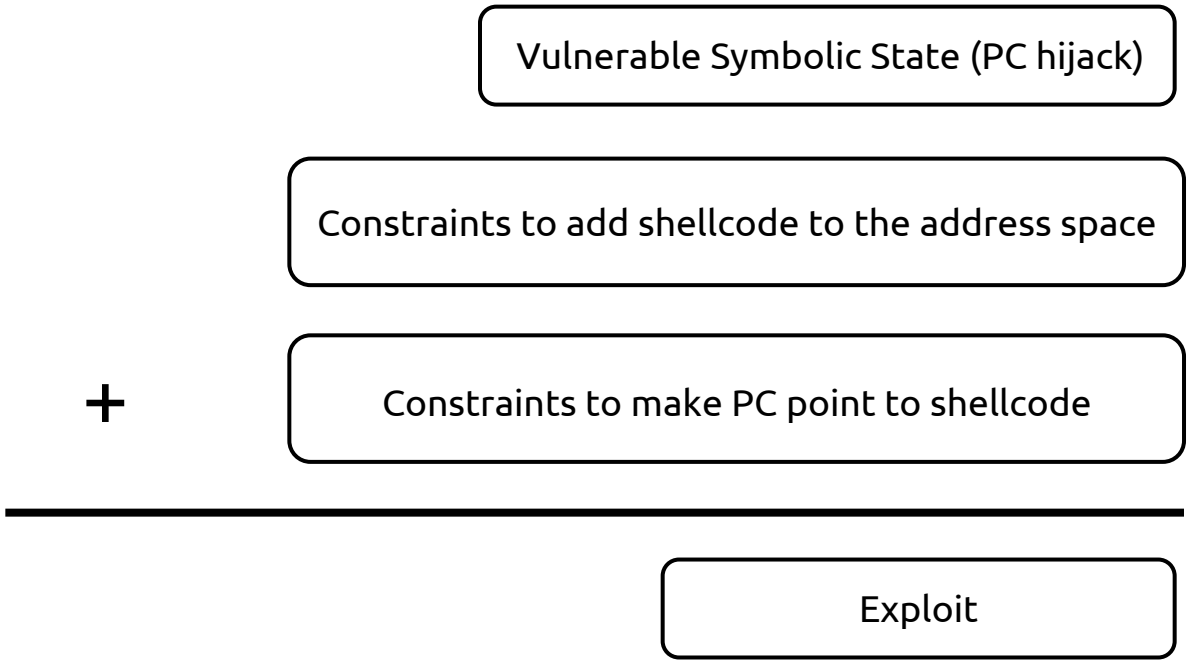
```
state.se.add_constraints(state.regs.pc == buf_addr)
```

Synthesize!

angr

```
exploit = state.posix.dumps(0)
```

Auto Exploitation - Simplified



Auto Exploitation - Advances

- ROP chain generation and ROP placement (**angrop**)
  - state-aware ROP
- Write primitives and Read primitives
- Forced leaking
- Shellcode distribution

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Demo

Available at:

https://github.com/angr/angr-doc/

examples/insomnihack_aeg